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Will Hydrogen be Competitive in Europe without Tax-Favor?

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Abstract

The paper analyses the problem of the competitiveness of hydrogen. Provided that the technological progress in the durability and cost of fuel cells and all the other achievements targeted in the European and US technology development programs, will hydrogen then be a competitive transport fuel or will it need tax favors to be cost competitive to the consumer? The answers are that tax favors are not necessary in Europe. The high fuel taxes in Europe will amplify the competitiveness effect of the superior energy efficiency of the fuel cell-electric drive system. Depending on the oil price at the time of introduction of hydrogen and fuel cell technology in automotive transport, there will be a tax rate in the span of European fuel tax rates (€10-20/GJ) that will make hydrogen competitive. If the difference in fuel taxation between Europe and the US persist when hydrogen and fuel cell technology is commercialised, it will be competitive in Europe a long time before it will in the US. The conventional wisdom of natural gas as the primary energy basis for hydrogen in the introduction phase should be reconsidered in the light of the high oil and gas prices. In particular if fuel taxes are designed to promote the achievements of the goals of European energy policy.

Keywords:

Hydrogen, competitiveness, fuel taxes

Introduction

Introduction As the prospects for the future supply and price of oil look still more bleak, European industry and the EU[1] are devoting still more innovative resources to the development of a hydrogen and fuel cell technology that can make other energy sources than oil useful in automotive transport[2]. In stationary applications, the technology also offers a marked progress in fuel efficiency and in portable applications similarly in off-grid operation time. The European Union has selected hydrogen and fuel cell technology as one out of five technology areas on which the union will concentrate in a public-private partnerships called Joint Technology Initiatives[3] (Commission of the European Communities 2006; European Commission 2008).

The perhaps most promising property of the hydrogen and fuel cell technology is that it can make all other energy resources than oil available for automotive transport. Europe has very limited fossil resources, but is rich in renewable and nuclear energy resources that predominantly take the shape of electricity, which is difficult to store. Battery technology has sufficient storage capacity to satisfy the needs of vehicles that only run a limited range every day and stay in the garage every night. The energy density of batteries have improved considerably in recent years, but it is a common viewpoint that it never can reach an energy density comparable to that of oil products and an internal combustion engine (ICE). On the other hand, battery technology proponents point to possibilities of enhancing the energy density of batteries by adding control systems and by establishing a battery replacement infrastructure. How far the limits of battery technology can be pushed is difficult to say, but on the other side of that limit is the hydrogen and fuel cell technology that can provide an energy density comparable to that of oil products and ICEs.

1 As well as other industrialised and emerging economies.

2 One of these is the Zero Regio Project that demonstrates the workability of a hydrogen refilling station with a small fleet of fuel cell vehicles (FCVs) in Frankfurt a.M. and Mantova (Italy). This project – and, thus the present paper as well – is financially supported by the EU FP6 program, which is gratefully acknowledged. Moreover, it naturally gives rise to question of whether the technologies demonstrated by the project will be economically viable.

3 The other high priority technologies include medicine, computing, aeronautics, and nanotechnology.

This paper addresses the question of whether hydrogen will be an economically viable alternative fuel at the time when all the technology development efforts are crowned with success. Can hydrogen, by then, be produced at a competitive cost or will it require tax-favor in the form of subsidy or tax exemption to compete with petrol and diesel?

Government Research, Development, and Deployment Plans

The strategy for hydrogen and fuel cell technology developed in the public-private partnership specifies targets or milestones for the development of the technology. Central 2015 targets include fuel cell drive systems with a durability of 5000 hours and a cost of €100/kW at a production rate of 150,000 vehicles (HFP 2007). This target is probably less ambitious than the 2015 target of $30/kW and 5000 hours at a production rate of 500,000 in the corresponding US Department of Energy (DOE) plan[4] (US DOE 2005; US DOE 2007). Both strategies, however, aim at developing the technology to a level where fuel cell vehicles (FCV) can be produced at a cost level comparable to internal combustion engine vehicles (ICEV) and hybrid electric vehicles (HEV) at some point of time beyond 2015.

The 2015 target for hydrogen production costs is €2,5/kgH_2 at the pump in Europe whereas the US DOE 2012 target is $2-3/kg$H_2$ ($2/kg$H_2$ for natural gas reforming and its 2017 target is $3/kg H_2 for water electrolysis and biomass based hydrogen[5]). These targets are supposed to ensure hydrogen competitiveness provided that the oil price is $34 per barrel and the FCVs are 140% more efficient than ICEVs and 66% more efficient than HEVs[6]. Both strategies envisage that far most of the hydrogen will be produced with fossil fuels as feedstock.

Government coordination and planning is obviously required because of the chicken-or-egg problem and several other market failures (see, e.g., some of the contributions to (Sperling and Cannon 2004)). The chicken-or-egg problem is that carmakers will not produce hydrogen-fuelled cars before there is a market for them. People will not buy hydrogen cars before there is a hydrogen supply. And potential hydrogen

[4] US dollars in 2002 price level.

[5] The US DOE targets are in 2005 US dollars (= €0.8 in 2005) whereas the purchasing power of the Euro-targets is ambiguous.

[6] That is, with efficiency factors of 2.4 and 1.66, respectively.

producers will not invest in supplying a hydrogen market that doesn't exist. Thus, the whole thing is unlikely to materialise without government coordination and market intervention. To get out of this undesirable strategic equilibrium, some initial government (I.e., tax) funds are required.

The initial as well as the future government finance can take the form of subsidies, fuel and vehicle tax exemption, or income tax allowance. These tax-favors can be granted to hydrogen, the feedstocks or plants used for hydrogen production and distribution, the vehicles or components of them, or the service facilities for the vehicles. Governments in Europe, the US, Japan, and elsewhere have already adopted tax incentives for fuel cell vehicles although they have not entered into serial production yet. This will advance the day when they become attractive to a larger audience and it reduces the economic risk of vehicle producers worried about the returns to their investment in technological development. This analysis concentrate on fuel taxation.

Can automotive HFC technology be economically viable?

Critics of hydrogen as a transport fuel have argued that it takes more simultaneous technological breakthroughs to achieve the targets than one could hope for and that the conversion losses in the "Well-to-Tank" (WtT) part of the hydrogen fuel chain may outweigh the superior energy efficiency in the "Tank-to-Wheel" (TtW) part (see e.g., (Romm 2006) and (Bossel and Eliasson 2003)). It is a fact today that the technology did not advance as fast as many had hoped for by the turn of the century and that conversion losses in the fuel chain are still considerable compared to petroleum based fuels. Still, there is plenty of evidence to support that the WtW efficiency of hydrogen and fuel cell technology can be superior to even the most efficient ICE technologies such as advanced diesel and ICE-electric-hybrid technologies.

A number of detailed planning and scenario studies supporting strategic choices in the development of the hydrogen economy have countered this criticism. Some of these studies are reviewed below. Generally, they show that a fuel chain of fossil energy to hydrogen to power and, eventually, to wheel rotation can be competitive with the present fuel chain of crude oil to transport fuels to combustion to rotation. Later on, the fossil energy can be replaced by renewable and nuclear energy. They differ, however, in their answers to the question of fuel taxation.

One of the early bodies for public-private bodies on this issue (The Alternative Fuels Contact Group 2004) found that hydrogen would be around twice as costly as petrol or diesel. Nevertheless, it would be able to compete in the long run given that the energy efficiency of the fuel cell system was twice the efficiency of ICE system. However, this calculation was based on an assumption of an oil price of $25 per barrel. The contact group recommended a total fuel tax exemption in an unspecified phase of introduction.

This recommendation was backed up by an industry initiative suggesting an infrastructure investment plan financed by industry on the basis of a full fuel tax exemption for hydrogen (E4tech 2005).

The US National Academy of Science (US National Academy of Science 2004) similarly found that coal and natural gas based hydrogen[7] in FCVs would be competitive with gasoline in ICEVs assuming a 66% efficiency advantage of FCVs over ICEVs. However, the oil price assumption was $30 per barrel. According to this study, a subsidy should not be necessary and an early market penetration for FCVs similar to that of HEVs starting at a cost level of $100/kW should be realistic.

A research team on societal lifecycle costs (Ogden, Williams et al. 2004) found the lifecycle fuel costs of a future FCV to be almost as high as those of an ICEV. The extra cost of the fuel cell drive system compared to an ICE drive system was, indeed, estimated to $2500, yielding net incremental lifecycle costs of about $2000. These extra costs are, however, more than justified by the reduced external costs. The study further shows that internalising these external costs would increase the competitiveness of advanced ICEVs and HEVs relative to ICEs, but would also increase the competitiveness of FCVs relative to advanced ICEVs and HEVs when the time comes. This study assumes apparently an oil price of around $25-30 per barrel and assumes that FCVs will be three times as fuel efficient as conventional ICEVs.

A global analysis of the prospects for hydrogen and fuel cells (International Energy Agency 2006) assumes that the FCV cost declines to about $65/kW in 2025. This is, however, insufficient for hydrogen and fuel cell technology to achieve any significant market share even though hydrogen in the base scenario is exempt from fuel taxes in the beginning and like other alternative fuels only gradually increasing to 75% of the

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7 Produced with carbon capture and sequestration (CCS)

gasoline tax in 2050. This study is based on an assumption of a future oil price of $25-35 per barrel (2000-prices) in 2015-25 and an efficiency factor of 1.82 relative to advanced ICEVs[8].

According to these studies, hydrogen and fuel cell technology will definitely be an economically viable alternative to oil based transport. A very comprehensive study of all thinkable drive trains and fuels (Edwards, Griesemann et al. 2007) did, however, arrive at a different result, albeit only for the very near future (2010+). A substitution of 5% of the European ICEV transport by FCV transport would entail extra costs of €c7-8 per km, primarily due to the high cost of the fuel cell drive system and the hydrogen infrastructure. In this study, all cost calculations are based on oil prices of $25 and $50 per barrel and an FCV fuel efficiency twice the fuel efficiency of the conventional ICEV.

The Hyways project (The HyWays Project 2008) uses a *backcasting* rather than a *forecasting* approach. Starting from an assumption of a future competitive hydrogen and fuel cell technology, it develops roadmaps of how to get there. From 2050 and backwards in time it calculates the required preceding step back to the demonstration projects of today. It does so under the assumption of $50 per barrel of crude oil, but with a considerably higher oil price in alternative scenarios.

The above list of studies is far from exhausting, but it covers the typical choices of assumptions and conclusions in the literature on transition to hydrogen. All of the studies conclude that fossil fuel - primarily natural gas - based hydrogen is the least costly fuel supply for the FCVs. Thus, natural gas (and, later on, coal with CCS) will form the primary energy basis for hydrogen in the first decades. However, this finding rests heavily on the assumption of an oil price that is much lower than the future oil price anticipated today.

There is no consensus among economists about the level of oil prices in 2015-2025, but an increasing share of analysts expect significantly higher oil prices than the roughly $30-60 (USD with 2008 purchasing power) assumed in the studies reviewed above. Higher oil prices affect not only the cost of petrol and diesel, but also the cost of natural gas and even coal. Since most of the hydrogen in the scenarios reviewed above is produced from natural gas and coal, the cost of fossil based hydrogen will depend on the oil price too. The studies reviewed above, however, have not even considered how the economics of the hydrogen and fuel cell

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[8] That is, a 82% efficiency advantage of FCVs over advanced ICEVs.

solution to automotive transport would look with oil price levels of $100-140 per barrel as we have experienced in the first half of 2008.

The studies also agree that the time for take-off for the FCV market will be at the earliest in 2015 (if at all), but not about exactly when and in which pace and where market shares can be achieved.

They don't agree upon the market situation that FCVs will face when introduced. Some assume an efficiency advantage of 100-200% over the competing vehicle solutions, other 66% or 50%.

The studies apply specific assumptions of costs and efficiencies of specific technologies. The amount of detailed assumptions about technical properties makes it difficult to compare assumptions across studies. Moreover, the technologies under investigation are a set of "next generation" technologies that we can know very little about today. Thus, it is, worth considering the level of detail in such scenarios. Maybe conclusions that are more robust could be drawn at a more general level.

The studies address the question of hydrogen competitiveness as a question of the cost of hydrogen versus petrol at particular points of time. It is exactly as difficult to say anything about the cost of fossil based hydrogen at a specific point of time as it is to predict the oil price at that time. Instead, this study aims at reaching conlusions about the conditions, in particular as to the oil price, that must be present for hydrogen to be a competitive transport fuel without specific subsidies. In the next section, a model is developed with the aim of determining the *threshold* or *break-even* oil price that will make hydrogen competitive.

The hydrogen competitiveness model

As noted above, it is difficult to establish realistic assumptions about next generation technologies that are not commercialised today and some of which are not even invented or patented. On the more general level, however, it is known that fuel chains can be described by a series of conversion and transport operations. The conversion efficiencies reflect the ratio of energy output to energy input of each link in the chain. They form the technical basis for the cost functions describing output costs as a function of input costs. In addition to this, the conversion and transport infrastructure involves non-energy costs. Assumptions about conversion efficiencies, non-energy costs, and primary energy costs should suffice to calculate the at-pump cost of the competing fuels. In the present paper the assumptions about details of specific technologies are avoided. Instead, only the transformation efficiencies and non-energy costs that can be achieved by a number of technological solutions are assumed.

For instance, it is technically possible to connect small scale hydrogen, heat, and power units to the existing electricity or natural gas grid. This could be an attractive option for many households, neighbourhood associations, firms, and even individual households. Whether it will materialise depends on whether it can perform with a conversion efficiency and non-energy costs comparable to that assumed for an infrastructure that looks more like the oil product infrastructure, we know.

Another example is the battery technology the limits of which can be pushed by adding control systems and by establishing a battery replacement infrastructure. To the extent that these developments can take place within the similar efficiency and non-energy cost requirements, we can replace "hydrogen and fuel cell" in the analysis with "battery".

FCVs with hydrogen stored in up to 700 bar pressure tanks have proven a technology that can match the energy density of oil based fuels in ICEVs. It is initially as assumed that the FCVs at some point of time can be offered at a price comparable to the competing cars. The competing solutions include advanced ICEVs and HEVs with diverse battery capacity, but not ICEVs at 20th century standards.

The competitiveness of hydrogen vs oil products is a matter of conversion efficiencies and non-energy costs through the fuel chain. For simplicity, petrol and diesel are weighed together in a "diesoline" fuel. Hydrogen can come from either fossil energy (the cost of which depends more or less on the oil price) or from non-fossil energy (the cost of which is more independent of the oil price). In the period until the early 20s, it is most likely that natural gas will be the typical representative of the former and wind and nuclear power will be the typical representatives of the latter. Current research and development aims at adding hydrogen extracted by advanced fermentation and gasification of biomass, CCS and fourth generation nuclear energy to the hydrogen supply options in the 20s.

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 (or power costs for non-fossil hydrogen)

f = natural gas oil price dependency

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

A more detailed description of the model and data is available in (Hansen 2007; Hansen 2007) and (Hansen 2007).

Data and parameter estimates

The parameters of the model are conversion efficiencies and non-energy costs.

Table 1. Parameter estimates used in the model

Conversion-link	**Efficiency**		**Non-energy costs**	
	Parameter	**Value**	**Parameter**	**Value**
Crude oil to diesoline	b*)	1.26	a	€2.66
Crude oil to NG imports to NG consumer price	f*)	1.06	e	€2.24
Relative advantage in fuel efficiency	k	50%		-
Best case				
NG to hydrogen	d	70%	c	€10
Non-fossil energy resources to hydrogen	d	70%	c	€10
Worst case				
NG to hydrogen	d	62%	c	€15
Non-fossil energy resources to hydrogen	d	65%	c	€15

Source: (Hansen 2007; Hansen 2007)

*) Estimated price coefficients reflecting transformation efficiencies of 1/1.26=79% and 1/1.06=94%, respectively.

The parameter values for the conversion of crude oil to "diesoline" and the influence of the international oil price on the international natural gas price and further to the consumer price of natural gas in Europe was derived as OLS estimates by simple regression. In the case of NG the oil price is lagged one year, but it is not of practical importance when calculating a threshold oil price level in the future. For a further documentation of data, estimates, and model detail, see (Hansen 2007; Hansen 2007).

The close dependency of "diesoline" on the oil price results trivially from the input of crude oil required to get a given output of "diesoline". The dependency of natural gas on crude oil, however, is mainly caused by the substitutability of natural gas and oil in heat and power production. Thus, long term natural gas contracts typically link the price of future gas deliveries to that of the oil spot market.

The relevance of this practice has been questioned as oil as the primary energy basis for the European power and heat sector has been replaced by other energy sources. On the other hand, as long as this substitution goes on, it is still relevant for price formation. Furthermore, natural gas is still competing with oil in household and industrial heating and in the future increasingly as transport fuel as well.

Developing a gas-to-gas competition instead of an oil-to-gas competition in the internal European market is a core element in European energy policy. Whereas it is likely to increase efficiency in downstream operations on the internal market it is debated whether European natural gas prices actually will be decoupled from the oil price. Recent studies of the spot markets in the UK ((Panagiotidis and Rutledge 2007) and parallel efforts in the US ((Brown and Yücel 2008) show that the natural gas spot market price has only been decoupled from the international oil price in the short run, not in the long run. Expectations of large amounts of natural gas supplies entering the European market from Norway and a rapidly expanding LNG production capacity nurture more optimistic views on decoupling of natural gas prices from oil prices. Natural gas demand is, however, rapidly expanding too and the upstream concentration of natural gas suppliers to Europe is not qualitatively different from that of oil suppliers to the international oil market (Hansen 2007).

On this background, it would be too careless to base future planning decisions about the hydrogen transition on an assumption that decoupling will occur. In this analysis, it is assumed that the natural gas import price will depend as much on the international oil price in the future as has been the case in the past.

Gasification with CCS technologies will allow us to derive hydrogen from combustible fuels without emitting CO_2 to the atmosphere. The question of whether gasification with CCS will be more cost effective than renewable and nuclear energy remains to be clarified. A series of CCS test and demonstration projects will be launched by the EU and they will provide valuable information about the prospects of these technologies. Probably, they will even be accompanied by another series of projects. But they can hardly be in time to contribute with any larger share of the European CO2-lean energy supply on this side of 2020. In the 20s, however, the technologies can become very important if the demonstration projects confirm their effectiveness.

Other hydrogen production technologies that are expected to become real options in the 20s and to yield a performance similar to or better than the 70% and €10/GJ assumed here. They include high temperature electrolysis, gasification and microbial technologies extracting hydrogen from biomass and waste, and genetically modified hydrogen producing algae. For this analysis, however, we consider only demonstrated technologies that can be deployed in large scale in 2015-25.

The best case cost components for hydrogen produced on natural gas are based on the most systematic analyses on both side of the Atlantic and from the targets defined by (HFP 2007). Assuming an oil price of $50 per barrel (Edwards, Griesemann et al. 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 of close to €10 per GJ.

A recent comparative study of hydrogen infrastructure costs (Weinert 2005) found that the costs per GJH_2 vary from $42 to $260 in the available reports from test and demonstration facilities. 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 produce comparable estimates based on the same principles of calculation. 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.

A model service provided by the DOE (National Renewable Energy 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.

In a study of the cost of electrolysis in industry today (Levene, Mann et al. 2007) it was found that the conversion efficiency is as low as 65%. The European planning for hydrogen technology development (HFP 2007) aims at a conversion efficiency of more than 70% LHV and non-energy costs of €1000/Nm3 (or €10.8/GJ) in 2015.

The table below shows the result from the European WtW-study of the available technology options and their costs.

Table 2. Expected hydrogen-at-pump costs beyond 2010 assuming $50 per barrel oil (Brent quality).

	NG	Coal	Wood	Nuc	Wind	EU-mix
	€/GJ (2005 price level)					
Electrolysis	44	38	#N/A	47	46	42
Thermal	35	34	21	#N/A	#N/A	#N/A
	€/kg (2005 price level)					
Electrolysis	5.30	4.56	#N/A	5.62	5.54	5.02

Thermal	4.25	4.04	2.47	#N/A	#N/A	#N/A

Source: (Edwards, Griesemann et al. 2006) and author's calculations.

The table shows that at an oil price of $50 per barrel, hydrogen from reformed natural gas is expected to cost €4.25. This is less expensive than any of the electrolysis alternatives. However, hydrogen based on hydrolysis of cellulosic biomass ("wood") is expected to be much cheaper and the far most efficient among the hydrogen production technologies in the table. The resource potential is, however, questioned.

The non-fossil technologies that are available for expansion of the European power and heat capacity in this period – at least until 2020 – include mainly wind and nuclear energy. In particular, the off-peak power generation of the base-load capacity provided by these technologies[9] is seen as an important source for electrification of automotive transport in this near future. Biomass and waste based power and heat is available too, but probably not in such large quantities.

The 20-20-20 targets of the European Union will probably mean that the expanding parts of the European power and heat capacity until 2020 will be based on wind, biomass, and nuclear energy technology. At least as far as wind and nuclear energy is concerned this will create a large quantity of off-peak power supply that could be very well used as automotive transport fuel. Hydrogen and fuel cell technology as well as battery technology can play a key role in making this possible.

With the assumptions used in the WtW study, wind power is €cents 7.3 per kWh. This is in the high end of the assumptions applied by the (International Energy 2006). In its World Energy Outlook 2006, wind power is assumed to cost USc 5.0-7.5 per kWh.

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 course, is to be scrutinised in the many hydrogen infrastructure test and demonstration projects planned in Europe and

[9] Wind power will achieve a base load character too, when sufficiently many wind mills are dispersed across a sufficiently large area because it also blows somewhere. In any case, a considerably larger share of wind power in the European power supply will make large quantities of off-peak power available for hydrogen production.

elsewhere. The scale economies obtainable in a central production of hydrogen cannot be tested definitely, 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 and other benefits of multi-product energy transformation could contribute considerably to the cost competitiveness as it already does in CHP production.

In the best case, we assume that the targets of 70% efficiency and €10/GJ in natural gas based hydrogen production are achieved at the time when the vehicles are introduced. The best case assumption for non-fossil hydrogen includes power at €c5.0 per kWh (€14/GJ) and €10/GJ and 70% efficiency in electrolysis and compression.

In the worst-case scenario for natural gas, the system efficiency is set to 62%. This is because a lower efficiency would make the entire WtW efficiency lower than it would be without FCVs. For electrolysis efficiency, the worst case scenario is set to 65%, corresponding to the standard of today ((Levene, Mann et al. 2007)), whereas the non-energy costs are €15/GJ and the power cost is €c7.3 per kWh (€20.2/GJ).

FCVs will most likely be competing with other fuel efficient vehicles when they are introduced. If the FCV solution fails in this competition, it cannot achieve the volume of production necessary to achieve further dynamic as well as static economies of scale. Thus, the interesting question is how the FCV fuel economy compares to other fuel efficient cars in 2015-2025 rather than to gas guzzlers from the 90s.

Thus, the relative fuel efficiency advantage of 50% (i.e., the efficiency of an FCV is 1.5 times the efficiency of the competing vehicle technologies) is chosen instead of the much higher figures used in the studies reviewed above.

Fuel taxes enter the model as non-energy costs of hydrogen, whereas vehicle taxes (registration and circulation taxes) are instruments to affect the time at which the fuel cell vehicles can be sold at a price comparable to that of the competing fuel efficient vehicle.

It must be underlined that before the worst case performance is achieved, any infrastructure must pass through a phase of low capacity factor and high learning costs. The cost of idle capacity until a satisfactory capacity factor is achieved calls for government support of some sort. Giving this support as subsidy to tax exemption for the produced hydrogen would probably not be an expedient design because some parts of the infrastructure will be up and running on full capacity utilisation whereas other parts will be just starting up. A filling-station-by-filling-station and electrolyser-by-electrolyser subsidy of the initial costs of idle capacity would probably be a more expedient approach.

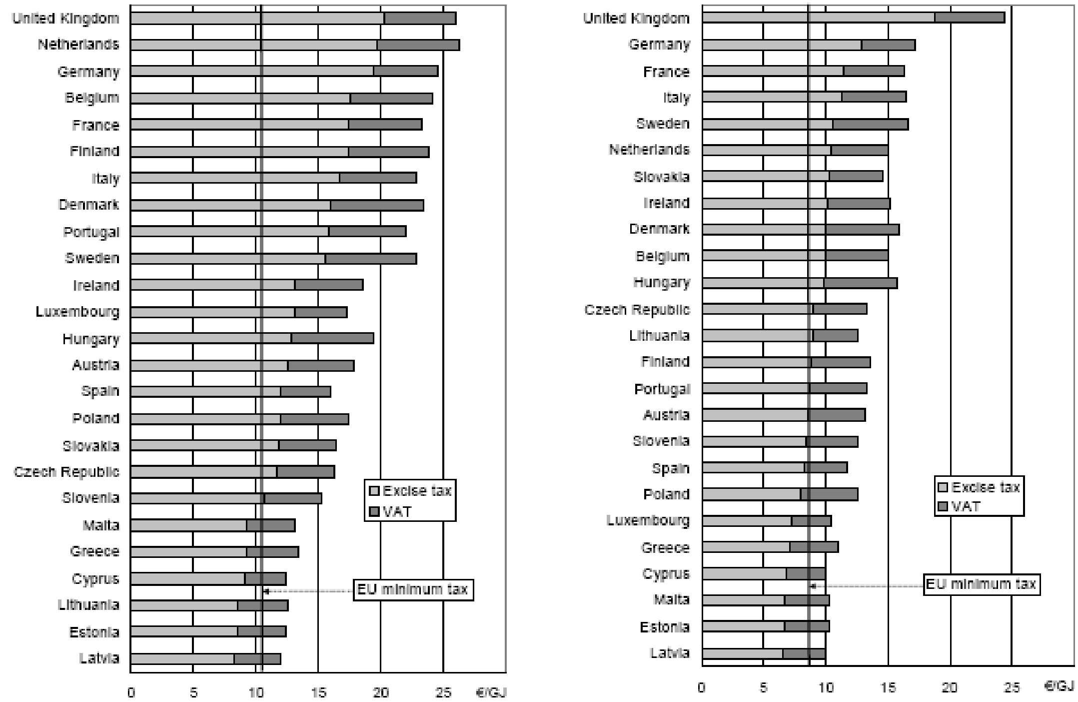
This analysis, however, is not concerned with the “kick-start” arrangements, but rather with whether the hydrogen and fuel cell solution will be able to survive economically in the longer term without particular subsidies or tax exemptions to hydrogen. In other words: Will it be viable under worst case conditions with the prospects of being able to improve to the best case?

Alternative fuel tax cases

The future taxation of hydrogen and hydrogen vehicles will be crucial for its success. Whereas vehicle taxes affects the time at which FCVs can enter the market, fuel taxation are crucial to the hydrogen competitiveness. (Hansen 2007) offers an analysis of this issue with the competitiveness model described above.

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



Source: (Hansen 2007).

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 levels converge towards the level of UK, Germany, and the Netherlands rather than towards the present minimum level. Especially, if the European countries want to avoid excessive fuel consumption in advance of anticipated oil price increases.

As mentioned in the introduction, one of the most important long term interests of society in the transition to hydrogen is that it enables the European economies to base their future transport more on European energy resources that are primarily non-fossil. This will contribute to the goals of more environmentally sustainable transport and security of fuel supply. But not very much if hydrogen is produced from natural gas and even without CCS. Thus, governments have good reasons to favour hydrogen based on, e.g., wind or nuclear resources, but limited reasons for favouring natural gas based hydrogen. Please, consult (Hansen 2007; Hansen 2007; Hansen 2007) for a more comprehensive treatment of this question.

Finally, it is very likely that fuel taxes in the future will become more differentiated according to the societal preferences for environmental protection. More polluting fuels could be taxed higher per GJ than less polluting fuels. An example of how hydrogen may be taxed in a scenario with fuel taxes differentiated according to environmental impact is presented by (Chernav'ska 2008 – in this issue).

On this background, we consider the following cases:

(1) No fuel taxes

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

(3) End-use taxation of €20/GJ of hydrogen as well as conventional fuels

(4) Taxing conventional fuels and natural gas used as feedstock for hydrogen by €20/GJ

(5) Like 4, but differentiating to a natural gas tax of €16/GJ and non-fossil fuels to €0/GJ.

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 tax cases 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 the taxation scenarios described above. The results are shown in the table below.

Table 3. 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		20		20		20	
Hydrogen tax (€/GJ)	0		10		20		0		0	
Natural gas tax (€/GJ)	0		0		0		20		16/0	
Feedstock (natural gas/non-fossil)	NG	Win	NG	Win	NG	Win	NG	Win	NG	Win
Best case ($/bbl)*)	188	105	86	85	-16	65	159	99	42	-16
Worst case ($/bbl)	542	170	327	150	112	130	639	173	362	49

*) Negative figures means that hydrogen is competitive at any oil price

The results show that even in the best case, hydrogen without taxes would be competitive only if it was produced from other feedstocks than the oil price dependent natural gas. In the worst case, it would require somewhat higher oil prices in 2015-25 for “non-fossil” to be competitive, whereas natural gas would be practically ruled out.

Fuel tax rates of the size of the European minimum tax rate (€10/GJ), make a tremendous difference to the threshold price, even when hydrogen is taxed in exactly the same way (per GJ) as petrol and diesel. In the best case, hydrogen is already competitive at $85-86/bbl, comfortably less than the prevailing price level (≈ $100-140/bbl ≈ $90-130/bbl in 2005 USD) in the first half of 2008. This is because FCVs mainly compete on their fuel efficiency, the competitive power of which is amplified the more expensive, the fuels are. This also means that it is *not* necessary for hydrogen competitiveness to exempt hydrogen for fuel taxation as long as oil prices and taxes in combination keep the fuel prices high.

Comparing case (1) and (2) is instructive for considering the difference between the US and Europe. As long as the difference between US and Europe with high fuel taxes in Europe and almost none in the US persist, hydrogen will become a competitive fuel in Europe a long time before it does so in the US.

Doubling the minimum tax rate to about €20/GJ (case 3) would mean that all member states should apply the high tax rate level that is currently only applied for petrol in the UK, the Netherlands, and Germany. This would be a useful option in case of a temporarily declining oil price like the 90s. Raising tax rates when oil prices decline maintains the incentive to use energy efficiently.

However, applying the same tax per energy unit on petrol and on hydrogen would be a distorting tax design. This is because hydrogen as described above are produced under massive losses of energy in the conversion, storage, and transport processes. In other words, the primary energy consumption of caused by a GJ of hydrogen is much larger than the primary energy consumption caused by a GJ of petrol or diesel.

To level the taxation burden, it would be necessary to tax the feedstock rather than the hydrogen output. This would also provide an important incentive to accelerated innovation in solutions that improve the conversion efficiency.

The present practice of taxing only the Tank-to-Wheel use of energy is acceptable from an economic viewpoint today because the difference between Tank-to-Wheel and Well-to-Wheel energy consumption is relatively modest whereas the difficulties of international trade in oil products with different Well-to-Tank tax rates would be considerable. Otherwise, a fully efficient tax design should give the same incentives to energy savings in the Well-to-Tank part of the fuel chain as it does in the Tank-to-Wheel part. However, applying the same design to hydrogen production would distort the incentives to an unacceptable degree because of the large energy loss in the process of transforming natural gas to hydrogen. In practice, it would mean that natural gas used for transport would be taxed up to 33% lower than petrol or diesel.

In case (4), the €20/GJ tax is applied to petrol and natural gas as well as feedstocks for hydrogen production. As a result, it would take a somewhat higher oil price for hydrogen to become competitive. It would, however, not be worthwhile to invest in natural gas based hydrogen in this case. Non-fossil hydrogen will be clearly more competitive. This will be in accordance with societal priorities for a cleaner environment and a shift to energy sources that are more secure in supply.

There are also differences between the environmental impact of combusting one GJ of petrol or diesel compared to that of steam reforming one GJ of natural gas and to that of using off-peak power capacity for transport energy. The latter doesn't pollute at all if it is supplied by an expanding wind power capacity in the heat and power sector. Thus, there is a case for differentiating the fuel taxes according to their environmental pressure. In case (5) this is done by taxing natural gas by 80% of the diesoline tax (€16/GJ) and wind and nuclear power is untaxed. The result is, not surprisingly, that non-fossil hydrogen will be competitive at any oil price in the best case and at a very low oil price in the worst case. Even natural gas based hydrogen would be competitive at a modest oil price in the best case.

However, considering the need for maintaining the incentives to economic use of energy, there is a case for *not* reducing taxes on non-fossil hydrogen more than necessary for the fuel to be competitive.

Conclusions

Rather than attempting to forecast the future oil price, this paper has addressed the issue of hydrogen competitiveness as a question of which oil price would make hydrogen a competitive transport fuel (given that the other conditions for competitive hydrogen and fuel cell solutions are in place: FCVs with comparable range per filling, performance, durability, and price). A model specifying worst case conditions that future hydrogen suppliers must be able survive and best case performance that they are able to achieve was constructed. The best case and worst case conditions are formulated in such general terms that the same model easily could apply to battery electric vehicle technology, should the battery technology being able to offer a similar energy density as the hydrogen and fuel cell technology.

The results show that with the oil prices it takes for hydrogen to become competitive, the natural gas based hydrogen is not necessarily the most competitive choice. This level has been reached in 2008.

Moreover, the level as well as the design of fuel taxation is crucial for the competitiveness of hydrogen. The high tax level in Europe will make hydrogen competitive here a long time before it becomes competitive in the US. If the fuel taxes are designed in order to promote the European societal goals (progress in energy efficiency, cost effectiveness in energy savings, reduced air and atmospheric pollution, more secure supply of transport fuels), the non-fossil hydrogen will drive natural gas based hydrogen out of business.

Natural gas based hydrogen requires generally such a high oil price to be competitive under worst case conditions that it probably only will survive if fuel taxes are not designed to promote the EU energy and environmental goals.

These results make clear that the conventional wisdom of natural gas as the dominant feedstock for hydrogen production in the initial phase of hydrogen transition must be reconsidered in the light of the higher oil and natural gas prices. They also show that the high fuel taxes in Europe may give Europe a special leading role in the transition to hydrogen and battery electric automotive transport. Finally, they show that it is possible to build a new hydrogen and battery infrastructure without locking the EU-budget into a new multigenerational subsidy obligation as has been the case with the Common Agricultural Policy. Hydrogen can become competitive in all of Europe if the lowest fuel taxes are raised towards the levels of the highest and if they are applied more on Well-to-Wheel rather than only a Tank-to-Wheel basis, which will be an unavoidable tax design issue when hydrogen is introduced.

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