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Will hydrogen be competitive in Europe without tax favours?

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ABSTRACT

Hydrogen is one of the alternative transport fuels expected to replace conventional oil based fuels. The paper finds that it is possible for non-fossil-based hydrogen to become the lowest cost fuel without favourable tax treatment. The order of per kilometre cost depends on performance in hydrogen production, the international oil price, and fuel taxes. At low oil prices, the highest per kilometre costs were found for non-fossil power-based hydrogen, the second highest for natural gas-based hydrogen, and the lowest for conventional fuels. At high oil prices, this ranking is reversed and non-fossil power-based hydrogen becomes the most cost competitive fuel. General fuel taxes lower the threshold at which the international oil price reverses this competitiveness order. The highest fuel tax rates applied in Europe lowers this threshold oil price considerably, whereas the lowest fuel taxes may be insufficient to make hydrogen competitive without tax favours. Alternative adjustments of the EU minimum fuel tax rates with a view to energy efficiency and CO_2-emissions are discussed.

1. Introduction

Hydrogen and fuel cell technology are seen as a potential successor to the technology of petroleum-based fuels in an internal combustion engine (ICE) that has been the basic technology for automotive transport for almost a century. The hydrogen and fuel cell technology programmes in the US and the EU aim at initiating the transition at some time in 2015–2025.

It is a major challenge to develop fuel cell cars that can be produced at costs comparable to the costs of other energy-efficient cars that already are in the market. Assuming that this will occur at some time between 2015 and 2025, the paper discusses whether hydrogen will be a cost-efficient alternative to the conventional fuels, petrol and diesel. If not and if the transition nevertheless is a societal priority, hydrogen will need subsidies or tax favours to oust the conventional fuels. In Europe, where fuel tax rates are high the support would be in the form of a lower tax rather than a subsidy.

Earlier studies such as Ogden et al. (2004) and International Energy Agency (IEA) (2005) find that hydrogen will need subsidies or tax favours. There is not much doubt that subsidies and tax allowances/reductions will be necessary to establish the first basic hydrogen infrastucture and the initial fleet of hydrogen cars. Subsidies or favourable tax treatment to the fuel itself would, however, have important drawbacks from an economic point of view. It would weaken the incentive to economize with energy and the ability of the market to respond to emerging alternatives with a better impact on the societal priorities. Moreover, it would weaken the plausibility of an unceasing transition to hydrogen through decades if the fuel continuosly required direct or indirect government support. The societal desirability of the transition is closely tied to the superior fuel efficiency of the hydrogen and fuel cell technology. Finally, the assumptions used in many of the previous studies do not correspond very well to the oil prices and supply on the car market that can be expected in Europe in 2015–2025. For these reasons this paper reconsiders the competitiveness of hydrogen as a transport fuel.

The hydrogen competitiveness model developed for the analysis of these questions is a fuel chain model of cost-effectiveness, where simplicity is preferred for complexity. The approach is to avoid detailed assumptions about technologies that will be used in 2015–2025, but of which key components are not invented yet.

Furthermore, the analysis is delimited from the question of the finance of initial infrastructure and of vehicle taxation. It focuses exclusively on the fuel cost.

The next section provides a short description of hydrogen as an alternative transport fuel. In the Section 3, the hydrogen competitiveness model is explained and the parameter estimates used in the model are documented in section four. In Section 5, the present state of fuel taxation in the EU is described and Section 6 contains analyses of various taxation scenarios. Finally, the conclusions are summed up in Section 7.

2. Hydrogen as an alternative transport fuel

There are two important properties that make hydrogen an attractive alternative to petrol and diesel. First, it enables the use

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of the energy-efficient and zero-emission electro-motor power train with a system density and driving range comparable to the conventional solution. Second, the indigenous energy resources of Europe mainly come in the form of electricity and hydrogen is an energy carrier that could serve as a link between power resources and automotive transport.

In addition to the already known hybrid electric vehicle (HEV), the announced reintroduction of battery electric vehicles (BEVs) and the introduction of plug-in hybrid vehicles (PHEVs) in 2009–2010 offers a range of opportunities for electric driving long time before the fuel cell electric vehicle (FCEV) will be commercialised.

The diverse electric vehicle solutions do not address the same market segments. In particular, the BEVs are for car users that do not require a driving range of more than 150 km per day and are able to recharge the car every day or night. This market segment may be enhanced if networks of service stations capable of replacing flat batteries are established. PHEVs will also provide additional range, because batteries are supplemented with liquid fuels and an ICE (internal combustion engine). The FCEV will, however, eventually offer a full electric-mode driving range comparable to that of ICEVs.

Rather than comparing FCEVs with a large number of specific technical solutions, we compare with a class of very efficient vehicles that use ICE technology to varying degrees. This is because the FCEV solution probably will compete with such solutions rather than with vehicles with a low fuel efficiency.

"Early commercialisation" of the FCEV concept could take place in 2015–2020, whereas "mass roll-out" can be expected from 2020 onwards (Committee on Assessment of Resource Needs for Fuel Cell and Hydrogen Technologies-National Research Council of the National Academies, 2008; European Technology Platform for Hydrogen and Fuel Cells (HFP), 2007). The European Technology Platform for Hydrogen and Fuel Cells (HFP) (2007) (now the Joint Technology Initiative for Fuel Cells and Hydrogen (JTI-FCH)) envisages an introduction of FCEVs on the European market in numbers 400,000–1,800,000 a year from 2015 to 2020. The exact timing depends on the advances in the development of key technology components of the system. Particularly important is the development of fuel cells with catalysts that are less expensive and with a longer life than the catalysts used today.

On the current hydrogen market, hydrogen is a chemical rather than a fuel. Refineries use increasing amounts of hydrogen for desulphurisation and upgrading of heavier oil fractions. Ammonia production is another large hydrogen application. It is also used for numerous chemical processes involving a.o. metal, methanol, and plastics.

Hydrogen is not an energy source, but an energy carrier. Thus, the cost competitiveness of hydrogen depends on the cost of the feedstock used for hydrogen production. Most of the hydrogen is supplied by steam reforming of fossil fuels, in particular natural gas. A small fraction is supplied by coal gasification or electrolysis. It is produced as a by-product as well as an on-purpose product (Schoots et al., 2008).

Future technologies for hydrogen production may in addition include a development of coal (and biomass) gasification with carbon capture and storage (CCS), high-temperature electrolysis based on solar or nuclear energy, microbiological processes, and various biomass-to-hydrogen technologies. These technologies are, however, still under development and any cost estimate would be very speculative. In any case, they will have to be competitive with the technologies mastered to day. Consequently, the model only specifies the two well-known routes of hydrogen production: steam reforming of natural gas and water electrolysis.

Water electrolysis using power from fuel combustion makes little sense as the cumulated energy loss through such a series of consecutive energy conversions easily could exceed the energy loss in the entire Well-to-Wheel chain of conventional fuels. Direct conversion of combustible fuels to hydrogen would be more energy efficient. Thus, electrolysis is considered only from non-fossil power generation, in practice mainly hydropower, nuclear energy, and wind energy.

3. The hydrogen competitiveness model

The competitiveness of a transport fuel can be measured by the fuel cost per kilometre compared to that of competing fuels. This is the purpose of the hydrogen competitiveness model. It is not to describe price formation, market shares, etc. on the hydrogen market. The ambition of the analysis is only to quantify conditions for cost-effectiveness of the alternative transport fuel solutions, not the behaviour of transport fuel users.

The model is deliberately kept as simple as possible and formulated in as broad terms as possible. This is because of the huge uncertainties surrounding the potential hydrogen and FCEV solutions. Some of the key technology components such as durable and inexpensive alternatives to platinum in fuel cells are not yet developed.

One of the properties of future hydrogen production that is known with certainty is that the costs of transport fuels are cumulated along the fuel chain, where each link of the chain adds value to the throughput of energy. Energy-consuming processes in this transformation include conversion, conditioning, transport, and storage.

The model specifies a general system efficiency covering all of these transformation processes rather than each of them. This is because the technical opportunities are not known yet. For instance households and firms may prefer to make their own hydrogen rather than buying it at a service station if allowed by the technical solutions available. In either case the costs can be decomposed in energy and non-energy costs. Energy costs include fuel throughput and transformation loss while non-energy cost includes infrastructure and operation costs other than energy.

The competitiveness measure used in the model is the per kilometre fuel cost obtained by relating the cost functions of each fuel to the fuel efficiency of the relevant vehicle. A per kilometre cost function for each of the three alternative fuels ("diesoline", hydrogen from natural gas, and hydrogen from non-fossil power) is specified as follows:

(1) per kilometre cost of diesel and petrol ("diesoline") (€/km) = $(a+bP)/\mathrm{EP}$

(2) per kilometre cost of natural gas-based H_2 (€/km) = $(e+(c+dP)^{*}f)/\mathrm{EH}$

(3) per kilometre cost of non-fossil-based H_2 (€/km) = $(g+h^{*}i)/\mathrm{EH}$

Hydrogen will be competitive with conventional fuel, when conventional fuel cost per kilometre exceeds that of hydrogen. Such a threshold oil price will exist if oil price increases have a larger impact on the per kilometre costs of conventional fuels than of hydrogen. The threshold oil price for competitiveness of natural gas-based hydrogen can be derived from (1) and (2) as

(4) $P^{*} = (a + ak - c - de)/(df - b - bk)$

The threshold oil price for competitiveness of non-fossil hydrogen is similarly obtained from (1) and (2) as

(5) $P^{*} = (g + hi - a(1 + k))/b(1 + k)$

Variable list:

a	feedstock price independent costs per GJ oil-based fuel incl. taxes (€/GJ)

b	fuel price dependency on crude oil price (regression coefficient)
c	oil price independent costs of natural gas (regression coefficient) incl. taxes (€/GJ)
d	natural gas dependency on oil price (regression coefficient)
e	energy independent costs of NG-based H_2 incl. taxes (€/GJ)
f	NG-based H_2 cost dependency on natural gas (inverse system efficiency)
g	feedstock price independent costs of non-fossil H_2 incl. taxes (€/GJ)
h	non-fossil electricity cost (oil price independent) incl. taxes (€/GJ)
i	non-fossil H_2 cost dependency on electricity cost (inverse system efficiency)
P	crude oil price (Brent, dated) ($/bbl)
EH	km/GJH_2
EP	km/GJ "diesoline"

"Diesoline" is a composite conventional fuel—an average of diesel and petrol (see below).

"Taxes" include energy taxes as well as cost of EU allowances according to the Emission Trading Scheme (ETS) and paralleling CO_2-taxes outside the ETS (see below).

4. Data and parameter estimates

4.1. Parameter overview

In this paper, the content of energy in an energy commodity is measured as its lower heating value (LHV) (or net calorific value (NFC)) in order of magnitude multiples of joules. Costs and prices are given in euro at 2008 purchasing power (2008 prices) and converted at 2008 average exchange rates if not otherwise stated. All current prices are deflated with the GDP-deflator for EU15.

The cumulated transformation efficiencies and non-energy costs appear from Table 1.

The data forming the empirical basis for the parameter estimates are collected from energy and economic statistics, technical reports, and databases. Only few of them have been reported in peer-reviewed journals.

4.2. The oil price and fuel efficiency

The competitiveness of hydrogen depends crucially on the oil price and on the energy efficiency of the FCEVs relative to the competing alternatives.

Many studies of the economic and technical potentials of hydrogen as a transport fuel conclude that hydrogen probably would require some tax favour or subsidy to be competitive with conventional fuels and/or that the first generation of hydrogen as a transport fuel would be based on natural gas or coal with CCS. These conclusions were, however, based on assumptions of very low oil prices on the one hand and on the other hand a very high efficiency advantage of FCEVs.

The Alternative Fuels Contact Group (2004) based such predictions on assumptions of 100% efficiency advantage of the FCEVs above ICEVs and an oil price of $25/bbl. The US National Academy of Science (2004) similarly assumed a 66% efficiency advantage of FCEVs over ICEVs and an oil price of $30/bbl. Ogden et al. (2004) based their societal lifecycle costs on an oil price of around $25–30/bbl and efficiency advantage of 100%. In a global analysis of prospects for hydrogen and fuel cells IEA (2006) assumed an oil price of $25–35/bbl (2000 prices) and an efficiency advantage of 82%. The European Well-to-Wheel database (Edwards et al., 2007) assumed oil prices of $25 and $50/bbl and an efficiency advantage of 100%. The HyWays Project (2008) uses a more moderate assumption of efficiency advantage and an assumption of $50/bbl of crude oil, but with a considerably higher oil price in alternative scenarios.

Whereas these assumptions about future oil prices have been shared by many oil market analysts in 2000s, including the International Energy Agency, there is now a growing consensus that such assumptions are unrealistic. IEA (2008c) assumes an oil price in 2020 of 110 dollars per barrel (2007 prices) ($120/bbl in 2030) and states that "the era of cheap oil is over" (p. 3). The hydrogen competitiveness model uses a span of oil prices from $0 to $200, thus showing cost results under "cheap oil" as well as "expensive oil" assumptions.

FCEVs will most likely be competing with other fuel-efficient vehicles when they are introduced. In the period 2015–2025 there will be alternative energy-efficient solutions available such as advanced ICEVs, HEVs, or PHEVs. The relevant alternative to FCEVs presented to the consumer will hardly be a vintage 2000 ICEV, but a range of these energy-efficient solutions. This analysis focuses on the per km cost of hydrogen in FCEVs in competition with solutions with a 4 l/100 km fuel efficiency. In this competition, it can be assumed that FCEVs will have an efficiency advantage of 50% above the alternatives.

4.3. Conventional fuels and natural gas prices

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 by simple OLS-regression.

The data for crude oil price and for calculation of the European "diesoline" price were obtained from IEA (2008a,b) whereas the industry prices for natural gas and electricity are the EU15 structural indicators from Eurostat (2009). The "diesoline" price was calculated as the ratio of the total value of petrol and diesel

Table 1
Parameter values used in the model[a].

Primary energy feedstock	Feedstock cost (€/GJ)	Fuel processing		Fuel efficiency (km/GJ)
		1/system efficiency or regression coefficient	Non-energy cost (€/GJ)	
Crude oil → "diesoline"	Oil price	1.21	4.07	4 l/100 km
Crude oil → natural gas	Oil price	1.08	3.34	
Natural gas → hydrogen	3.34+Oil price*1.08	1/0.70 = 1.43 (1/0.65 = 1.54)	11 (15)	+50%
Non-fossil power → hydrogen	17 (25)		12 (16)	+50%

[a] Worst case in parenthesis.

expenditure to the total energy content of petrol and diesel consumption by households in Europe with data for 1989–2006.

In the case of natural gas, the oil price is lagged 1 year. The dependency of natural gas on crude oil is mainly caused by the substitutability of natural gas and oil and the resulting practice of linking the price of future gas deliveries to the price of oil product spot markets in long-term natural gas contracts.

The relevance of this practice has, however, been questioned as oil-based power and heat generation increasingly have been replaced by other energy sources. For estimates of future natural gas prices, it is also important that it is a high-priority goal of the EU to develop gas-to-gas competition instead of an oil-to-gas competition on the internal European market.

Such a market development is likely to increase efficiency in downstream operations on the internal market, but can hardly change the upstream concentration of natural gas suppliers, which is a result of the geographical location of remaining natural gas reserves.

Recent studies of the spot markets in the UK (Panagiotidis and Rutledge, 2007) and parallel studies of the the US market (Brown and Yücel, 2008) show that the natural gas spot market price has only been decoupled to some degree from the international oil price in the short run, but not in the long run.

It is also important to be aware that the substitutability providing the underlying cause of the close link between oil and gas prices still exists. Although the use of petroleum products in the power and heat sector of EU27 has diminished from 12% of all energy inputs in 1990 to 5% in 2006 (calculated from Eurostat, 2009), it still exists. Natural gas is also still competing with oil in household and industrial heating and in the future increasingly with conventional transport fuels.

Thus, the assumption maintained in this study is that the natural gas price will follow the crude oil price as closely in the future as in the past. The patterns in the past of the link between the industrial consumer price of natural gas and the crude oil price is shown in Fig. 1 along with the link between the crude oil price and the "dieseoline" price at-pump.

Although the material basis for the coefficient to the crude oil price is the cumulated energy loss along the fuel chain to the end-use of the fuel, the coefficient cannot be interpreted as exactly the inverted well-to-tank transformation efficiency. The coefficient reflects all price elements that vary with the oil price.

4.4. *Non-energy costs by natural gas reforming*

The non-energy costs involved in natural gas reforming would according to Edwards et al. (2006) (WTW app. 2, p. 13) amount to €11/GJH_2 by 2010+.

Weinert (2005) standardised a range of widely varying cost estimates from pilot projects for capacity, capacity utilisation, learning, standardised installation, etc. and found that this standardised non-energy cost could be expected to decline from current cost to €11/GJH_2 in 2020. National Renewable Energy Laboratory (NREL, 2006) takes this approach further and estimates the non-energy costs to be €12/GJH_2. The US Department of Energy (DOE, 2007) sets the target of reducing non-feedstock costs of hydrogen to €9/GJH_2.

Against this backdrop, we will assume that the non-energy part of the costs of transforming natural gas to hydrogen is €12/GJH_2 in the best case and €16/GJH_2 in the worst case.

4.5. *Costs of electrolysis based on non-fossil power*

Hammerli (1984) modelled the cost of hydrogen production along lines similar to this analysis. He found that hydrogen could be produced with non-energy costs of only €2.27/GJ (converted from Canadian 1980 dollars). This cost figure could be expected to be even lower in 2015–2025 due to learning effects. Hammerli (1984) found indicators of progress in electrolysis technology from 1981 to 1983, but Schoots et al. (2008) were unable to identify learning economies in electrolysis over a longer period of time. The latter could, however, be due to the nature of the primary data.

DOE (2007) aims at reducing the non-feedstock costs of medium-scale electrolysis (distributed hydrogen production) from €16/GJ in 2006 to €6/GJ in 2017 (at a 70% capacity factor), whereas the European Technology Platform for Hydrogen and Fuel Cells (HFP) (2007) aims at modular electrolysis system costs (i.e. non-energy costs) of €11.8/GJH_2 in 2015.

The choice of parameter value for non-energy costs of electrolysis is based on realisation of the European cost target, and thus €12/GJH_2 in the best case and €16/GJH_2 in the worst case.

Several cost assessments estimate nuclear and wind energy costs to be at the same level. Edwards et al. (2007) estimate the

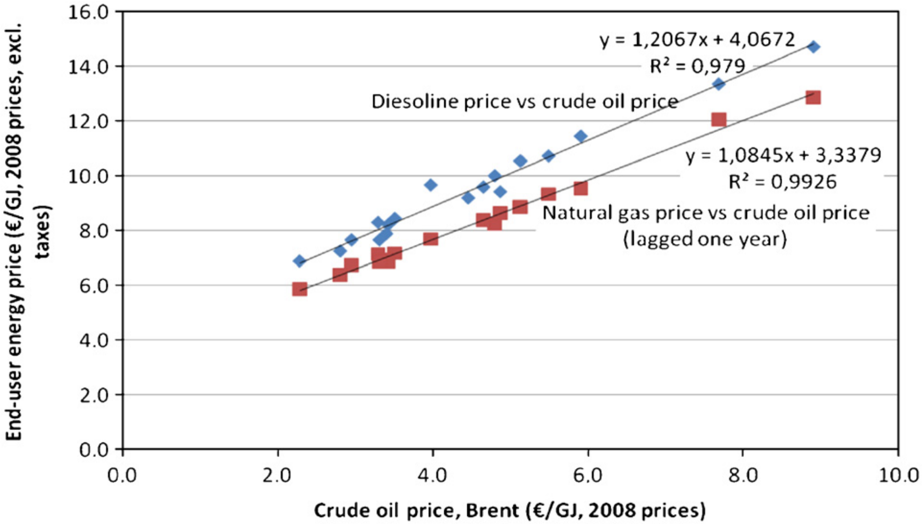

Fig. 1. Association of EU end-user energy prices with the crude oil price. 1989–2007. *Sources*: International Energy Agency (IEA, 2008a,b), Eurostat (2009), and author's calculations.

cost level to €c7.8/kWh (€21.7/GJ), whereas the IEA (2006) calculates a cost range of €c3.7–4.4/kWh (€10.3–12.2/GJ) for the two power sources. The Commission of the European Communities (2008) assumes nuclear and onshore wind power to cost €16–27/GJ and offshore wind power €19–34/GJ.

Off-peak power from these sources as well as excess wind power is often seen as potential energy sources for low-cost production of hydrogen for transport. With the high share of wind power in electricity generation that can be expected in Europe up to 2020, this source will grow as well. However, reducing the operation of electrolysers to off-peak and excess wind hours would raise the non-energy cost per kWh because fewer kWh would bear the amortisation costs. Floch et al. (2007) identified the optimal balance between the use of low-price electricity and the amortisation of the investment in electrolysers at the French PowerNext market. Optimally, the electrolyser would be operating in 64.3% of the time with a power-supply price of €14.3/GJ. Jørgensen and Ropenus (2008) found in a similar study of the NordPool area (Northern Europe), the optimal operating time to be above 90% at wind penetration rates below 50%. The study assumed a mean electricity price of €12–14/GJ plus grid connection charge of €7/GJ. System efficiency of electrolysis was assumed to be 60% and non-energy cost €5–6/GJ.

Economies associated with by-products may lower the cost of electrolyser hydrogen too. Gorensek and Forsberg (2009) and Taljan et al. (2008) point to oxygen (as an industrial gas) as well as ordinary co-production of heat and power. According to the study, oxygen could bring in approximately 0.85–1.25 per GJH$_2$. Hammerli (1984) additionally points to heavy water, and for natural gas reforming and coal gasification steam export.

Gorensek and Forsberg (2009) also point to local conditions such as proximity to industrial use of hydrogen (refineries, ammonia, and other chemicals production) and good conditions for underground hydrogen storage as factors that can lower costs of electrolytic hydrogen.

The parameter values are based on the EU commission estimates of nuclear and wind power at €16-27/GJ. Off-peak, excess power and possible network charges pull different ways and it is difficult to assess the net-effect. Against this backdrop, it is assumed that the electricity cost of electrolytic hydrogen can be €17/GJ power in the best case and €25/GJ power in the worst case. These assumptions correspond to €61–90/MWh.

4.6. Transformation efficiency

Electrolytic transformation of power to hydrogen includes in addition to the conversion process itself energy-consuming processes such as power transformation, purification, and compression. The system efficiency can be calculated as the product of the efficiencies of these processes.

In a study of cost of electrolysis in industry (Levene et al., 2007) it was found that the standard conversion efficiency in the US industry is about 65%. With a 50% FCEV efficiency advantage and a system efficiency of conventional fuel production of 90% efficiency, the system efficiency of hydrogen production would have to exceed 60% for hydrogen and fuel cell technology to provide a more energy-efficient transport technology. A number of demonstration projects in Europe such as The CUTE Project (2008) have shown that it is a challenge to reach even this level of system efficiency.

The European Technology Platform for Hydrogen and Fuel Cells (HFP) (2007) aims for a conversion efficiency rate by low-temperature electrolysis of more than 70% in 2015 and DOE (2007) for 74% system efficiency in 2017.

For the system efficiency of natural gas reforming, the US target is 75% in 2017, whereas there is no European target.

Against this backdrop, we assume that 70% system efficiency applies for both natural gas reforming and electrolysis. The worst-case assumption for both hydrogen production technologies is the system efficiency of 65%.

5. European fuel taxes and CO$_2$-emission allowances

Fuel taxes enter the model as non-energy costs of hydrogen. Vehicle taxes (registration and circulation taxes) are not considered in the model, but tax favours in taxation of FCEVs as well as BEVs and PHEVs have already been announced in some European countries.

The European Union Fuel Taxation Directive (European Council, 2003) prescribes minimum tax rates to be imposed on the various energy commodities. The tax rates for the various commodities are shown in Fig. 2.

The principles of energy taxation applied in the member states are reflected in the agreed minimum taxes as well. In Fig. 2, propellants are taxed heavier than other energy commodities. The

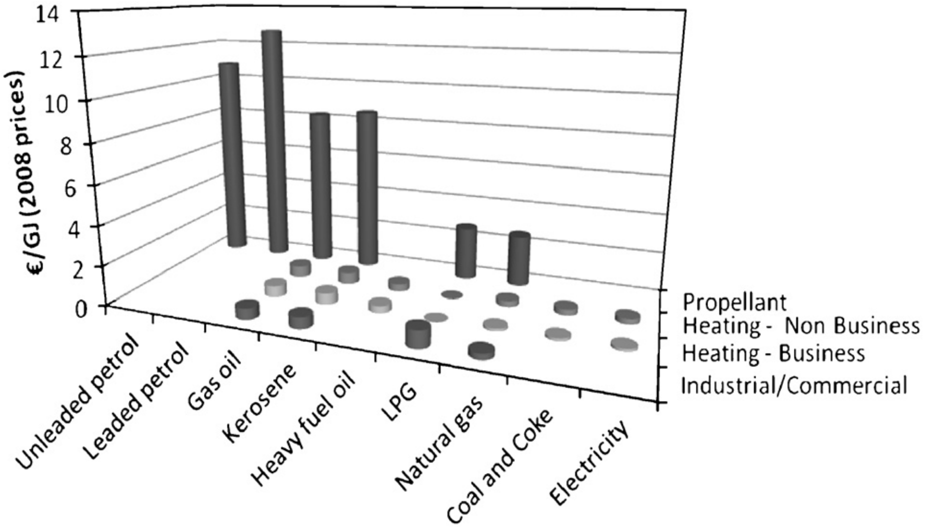

Fig. 2. EU minimum energy taxes. July 1, 2008. *Source*: Eurostat (2008) and author's calculations.

higher tax rate for leaded petrol reflects environmental concerns and they are also reflected in lower tax rates imposed on fuels with high contents of biofuels, low contents of sulphur, etc.

The unleaded petrol and diesel tax rates are in the region of €10/GJ and they are also shown in Fig. 3 along with tax rates as of July 1, 2008 in the individual member states.

Some of the new member states have transitory arrangements for their energy taxes. Fig. 3 also shows that many of the member states impose much higher taxes on petrol and diesel than the required EU minimum taxes—some of them more than twice the minimum tax rate.

In addition to the minimum taxes, the EU has established an Emission Trading Scheme for the largest fossil fuel-consuming industries in Europe accounting for roughly half the European CO_2-emissions (The European Parliament and the Council of the European Union, 2003). The ETS requires plants with installations of more than 20 MW for fossil fuel combustion to buy EU allowances for every ton of CO_2 emitted. The EU allowance price expected by the Commission of the European Communities (2008) for 2020 is €44/tCO_2 in 2008 prices and this EUA price is assumed in the calculations below.

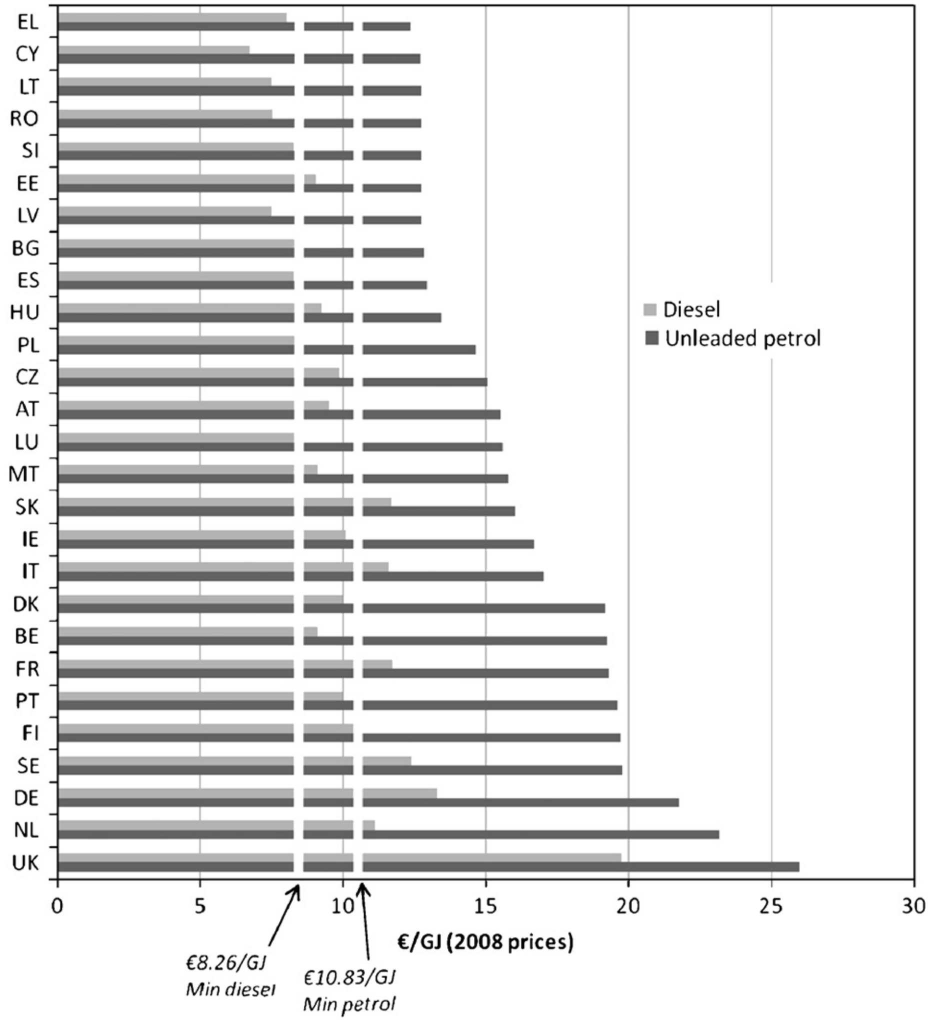

Fig. 3. EU minimum tax rates and member state applied tax rates for unleaded petrol and diesel. July 1, 2008. €/GJ. *Source*: Eurostat (2008) and author's calculations.

Table 2
End-user fuel cost of the existing energy tax, EUA and equalizing CO_2-tax. €/GJ fuel. Best case.

EUA price: €44/tCO_2	CO_2 cost to end-user by fuel (€/GJ) (either EUA or CO_2-tax)		Total EUA+CO_2-tax	Energy tax	Total energy and CO_2-tax/EUA
	End-use CO_2-tax	Process CO_2-tax/EUA[a]			
Crude oil → "diesoline"	3.08	0.34	3.42	10.00	13.42
Natural gas → hydrogen	2.42	1.04	3.46	10.00	13.46
Non-fossil power → hydrogen	0	1.04	1.04	10.00	11.04

[a] CO_2 cost*[(1/system efficiency)-1]. Hydrogen produced with worst-case system efficiency of 65% would get additional costs of €1.30/GJH_2 instead of the €1.04/GJH_2 in the table.

When an incentive such as the EUA is only applied in the ETS sector and not in other industry, it causes distortions. For hydrogen production, it would mean that central production in large scale by natural gas reforming would be required to pay the EUA price for every ton of CO_2 emitted, whereas on-site natural gas reforming (i.e., at a service station) should pay nothing. That could cause more hydrogen to be produced at the less-efficient on-site installations. In the following, it is assumed that the EU by 2015–2025 has introduced an equalizing minimum tax on CO_2-emissions on firms that are not comprised in the ETS sector.

The end-use cost of EUAs and an equalizing CO_2-tax can be calculated as $(1/w-1)^{*}tz$, where t is the tax or EUA price, z is the CO_2/GJ ratio and w is the system efficiency. Assuming an EUA price and tax of €44/tCO_2, system efficiency of 90% for conventional fuels and 70% and 65% for conventional fuels will result in rather modest end-user costs shown in Table 2.

Summing up, the economic incentives relevant to transport fuel choices include energy taxes according to the energy taxation directive, EU allowance prices according to the EU emission trading scheme, and equalizing CO_2-taxes with tax rates corresponding to the EUA price.

6. Impact of fuel taxation on the competitiveness of hydrogen

In the first case considered, there is no energy tax imposed on the fuels. Only EUA prices in the ETS sector and an equalizing tax on CO_2-emissions outside the ETS sector. For the fuel cost, however, it is of little importance compared to the tax on the end-use of the fuel.

Figs. 4 and 5 show how the per kilometre cost of not only conventional fuels, but also natural gas-based hydrogen follows the oil price. There is a threshold price of crude oil at which the per kilometre cost of hydrogen becomes lower than that of conventional fuels when the slope of the hydrogen cost curve is less than the slope of the “diesoline” cost curve. In the best case it is at \$299/bbl for natural gas-based hydrogen and \$125/bbl for non-fossil power-based hydrogen. Thus, without tax effects natural gas-based hydrogen will hardly be able to compete with “diesoline” in 2015–2025 or later. Hydrogen based on non-fossil power is much closer to be competitive under best-case assumptions. Under these conditions, it will be competitive to natural gas-based hydrogen at oil prices below \$100/bbl. This applies to industrial use of hydrogen too. Under the worst-case assumptions, the lower system efficiency in natural gas reforming means that the hydrogen and “diesoline” curves will not intersect in any relevant oil price interval.

Whereas the assumption of no fuel taxes could have some relevance in economies such as the US economy, it is far from the reality of European economies. As described above, the EU countries have agreed on a minimum tax rate on transport fuels in the region of €10/GJ (higher for petrol and lower for diesel).

Figs. 6 and 7 show the impact of a fuel tax of €10/GJ on the end-use of the fuels including hydrogen as a transport fuel. The fuel tax

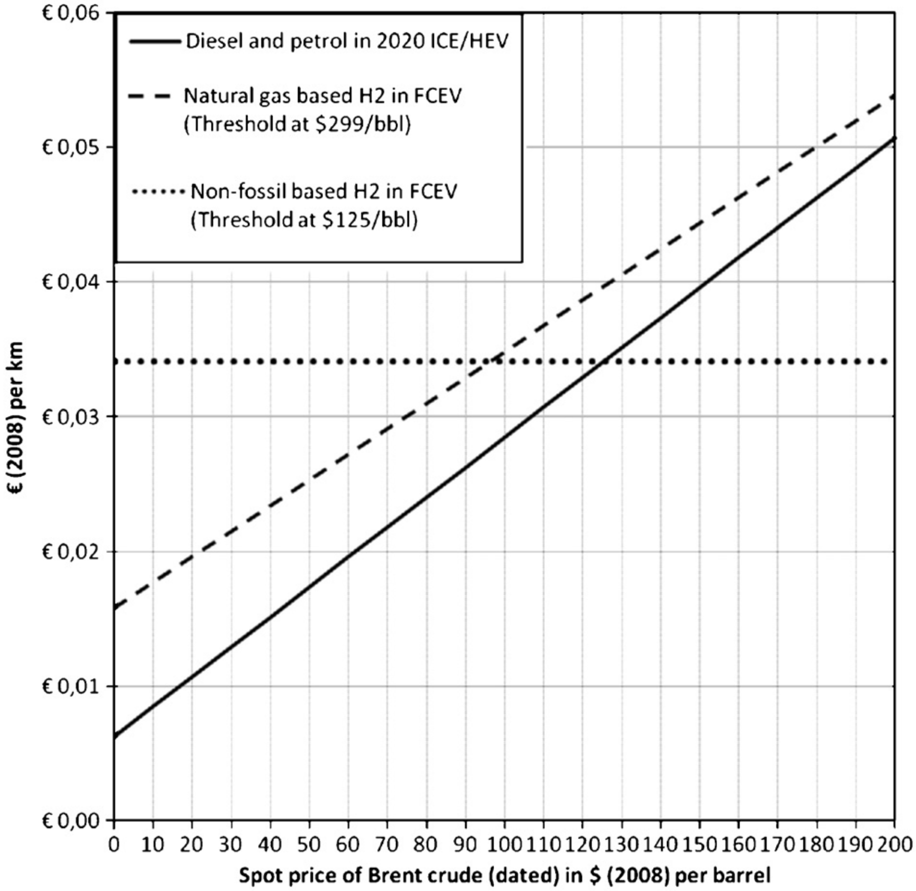

Fig. 4. Best case: no fuel taxes, only CO_2-allowances or equalizing CO_2-tax on process.

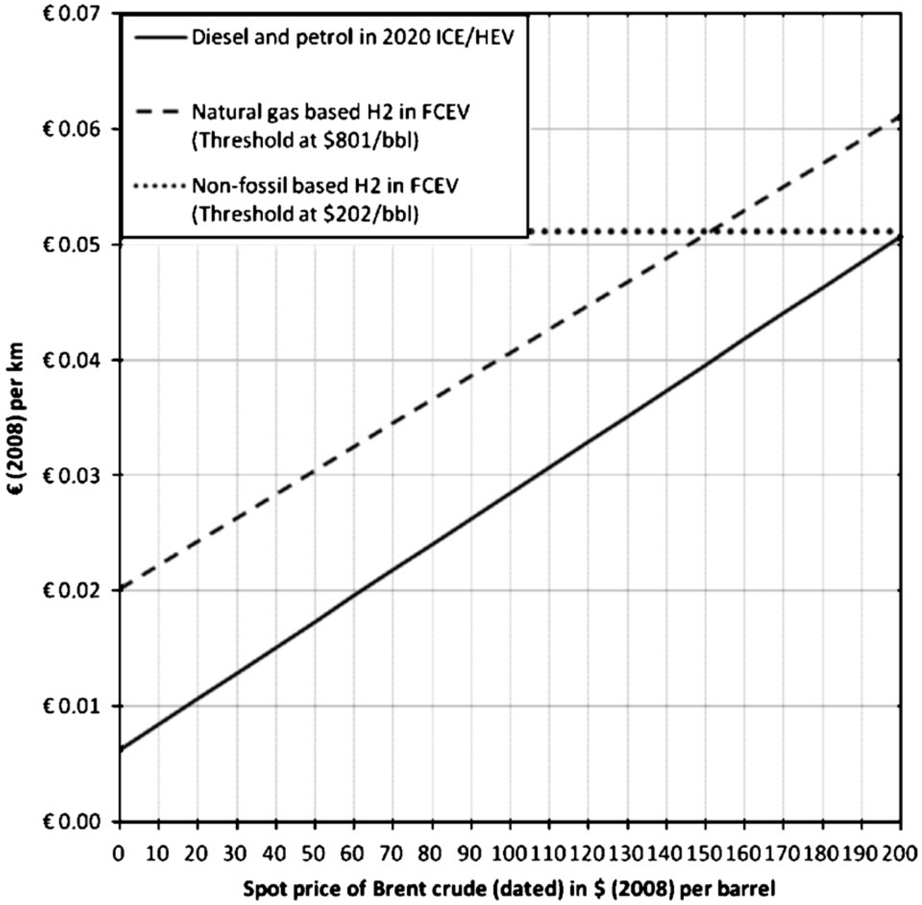

Fig. 5. Worst case: no fuel taxes, only CO_2-allowances or equalizing CO_2-tax on process.

shifts all the curves upwards, but less so for hydrogen because of its higher efficiency in use as a propellant.

Under the best-case conditions the non-fossil-based hydrogen will be the least expensive alternative at an oil price of $104/bbl, whereas natural gas-based hydrogen would require an oil price of $154/bbl to be competitive. This is because the effect of fuel tax is to make the more energy-efficient solutions more competitive in comparison with the less energy-efficient solutions. Thus, in a scenario with future oil prices above $100/bbl a uniform fuel taxation rate €10/GJ could turn out to be sufficient. Under worst case conditions, however, an oil price of $181/bbl would still be required.

The €10/GJ is only the minimum tax rate. As shown in Fig. 3 some countries apply much higher fuel tax rates. Raising the uniform tax rate to higher levels makes hydrogen competitive at even lower oil prices. This is illustrated in Figs. 8 and 9.

Figs. 8 and 9 show that €15/GJ would be sufficient to make hydrogen competitive already at oil prices well below $100/bbl under the best-case assumptions. With the worst-case assumptions of lower system efficiency even this higher tax rate is not enough to make hydrogen competitive at oil prices below $170/bbl and tax favours would definitely be required.

Alternatively, the fuel could be taxed by imposing the equalizing CO_2-tax on end-use of the fuel as well. This would favour non-fossil hydrogen compared to natural gas-based hydrogen. However, then there would be no additional incentive to improve system efficiency in electrolysis. In order, to maintain an incentive for improving system efficiency in electrolysis in addition to the value of hydrogen itself, a tax could be imposed on the energy loss in electrolytic hydrogen. The tax rate could be similar to the CO_2-tax (or EAU-price) per GJ as in natural gas reforming. Table 2 provides an overview of these taxes.

Table 2 shows how the total fuel taxation system would look if the taxes in the grey cells were added to the already existing minimum energy tax and EUA/process CO_2-tax. The equalizing CO_2-tax is extended to end-use combustion of "diesoline" and natural gas-based hydrogen. The latter tax must be collected at the hydrogen producer as a CO_2-tax on all natural gas input for which EUAs are not required. The tax on the electrolytic hydrogen production provides the same incentive as in natural gas reforming for system-efficiency improvements.

The result of adding such a tax and the equalizing CO_2-tax on fuels in addition to the already existing minimum tax and EUA/CO_2-tax is shown in Figs. 10 and 11.

Fig. 10 shows that such a tax arrangement would give a result similar to the €15/GJ fuel tax in Fig. 8, but with a higher cost per kilometre for natural gas-based hydrogen. These costs would be higher with a higher EUA price than the €44/tCO_2 assumed here. The tax on energy loss in electrolysis has only minor importance for the cost per kilometre. Fig. 11 shows that lower system efficiency and higher infrastructure costs would make it very difficult to achieve hydrogen competitiveness with these general fuel and CO_2-taxes.

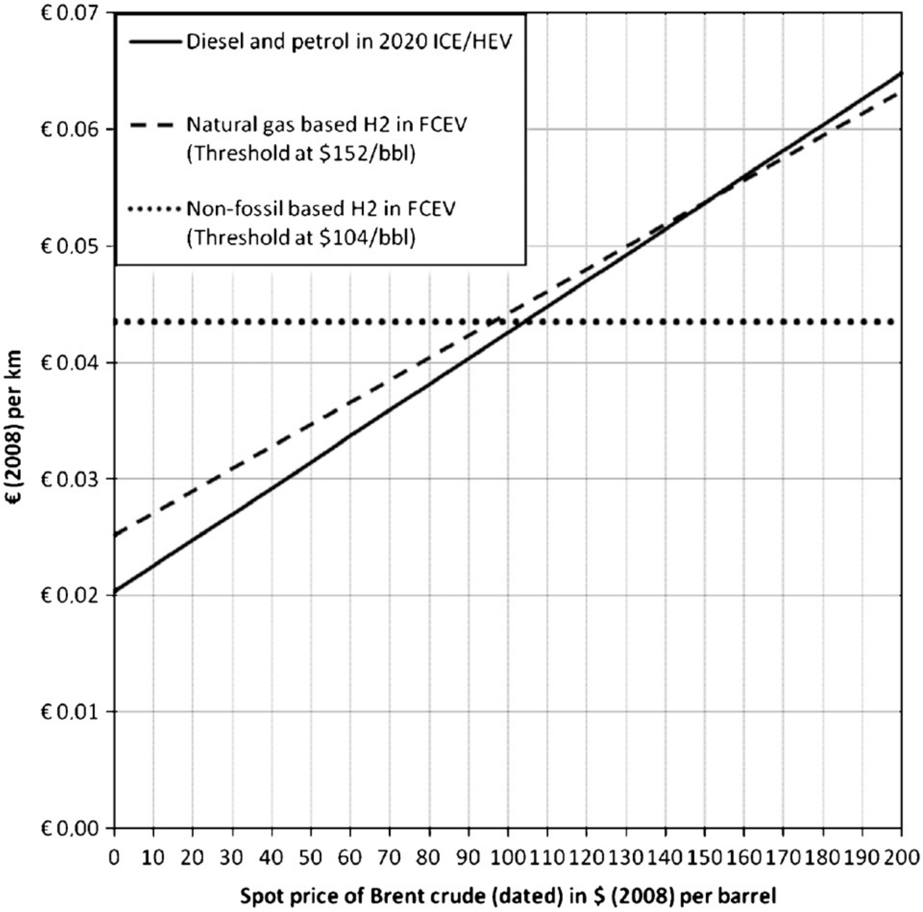

Fig. 6. Best case: uniform fuel tax of €10/GJ+CO_2-allowances or equalizing tax on reforming process.

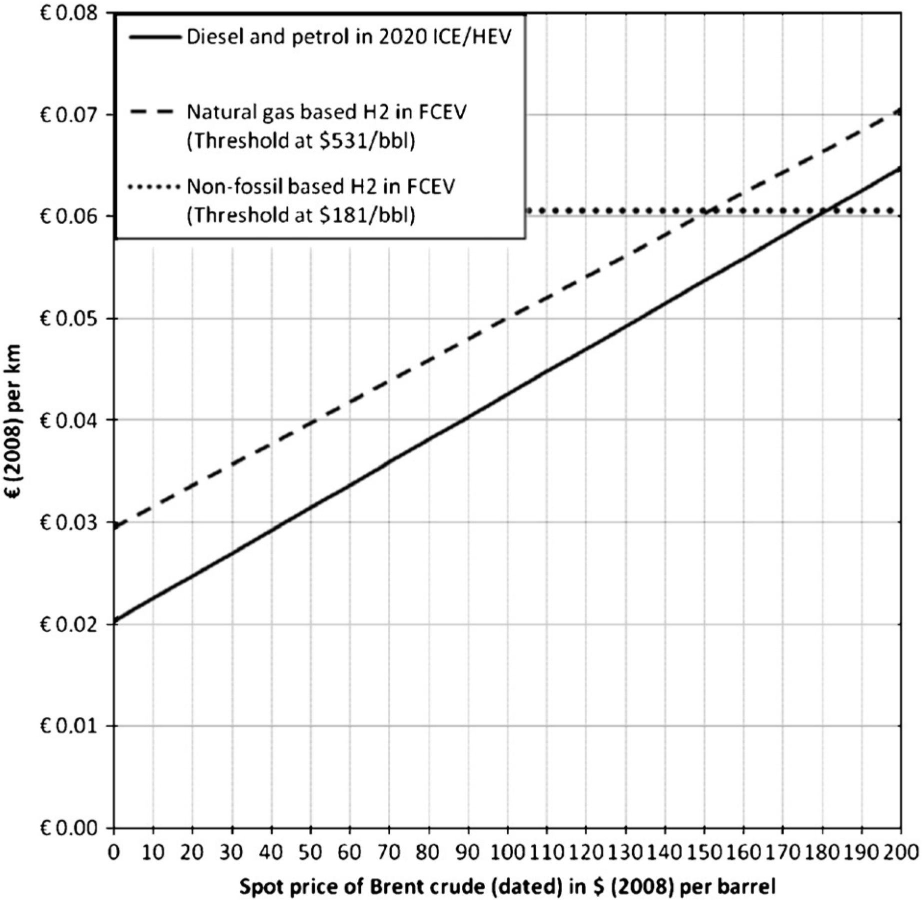

Fig. 7. Worst case: uniform fuel tax of €10/GJ+CO_2-allowances or equalizing tax on reforming process.

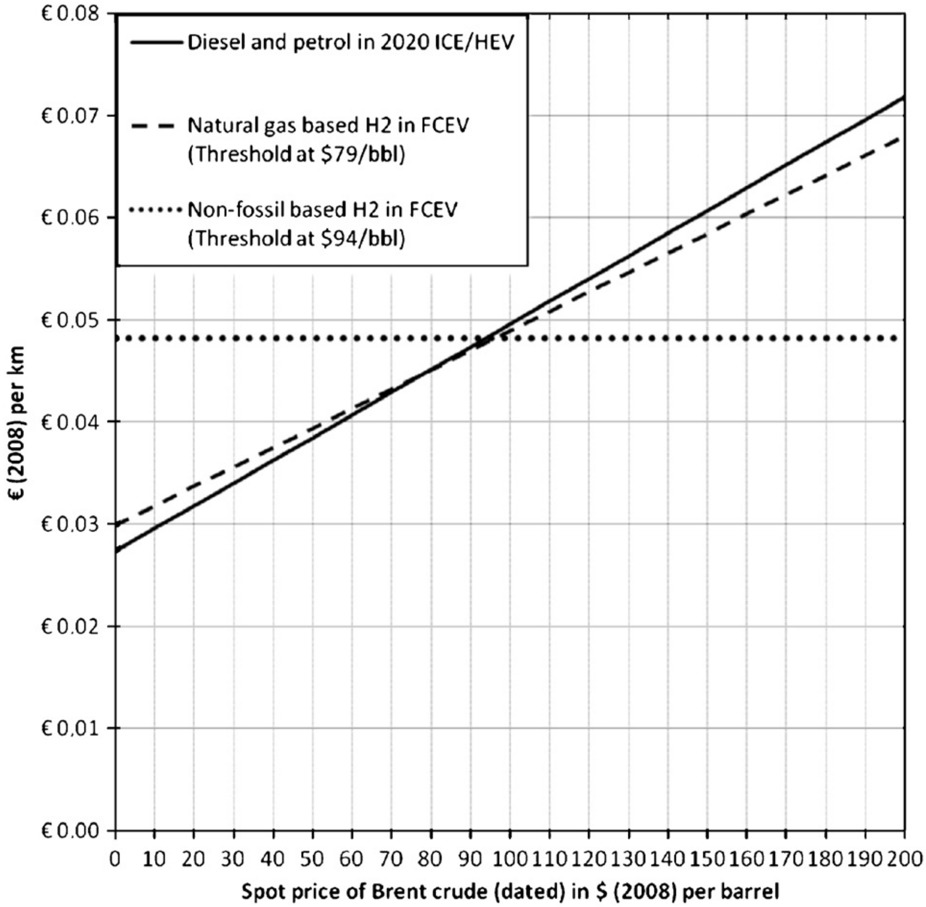

Fig. 8. Best case: uniform fuel tax of €15/GJ+CO_2-allowances or equalizing tax on reforming process.

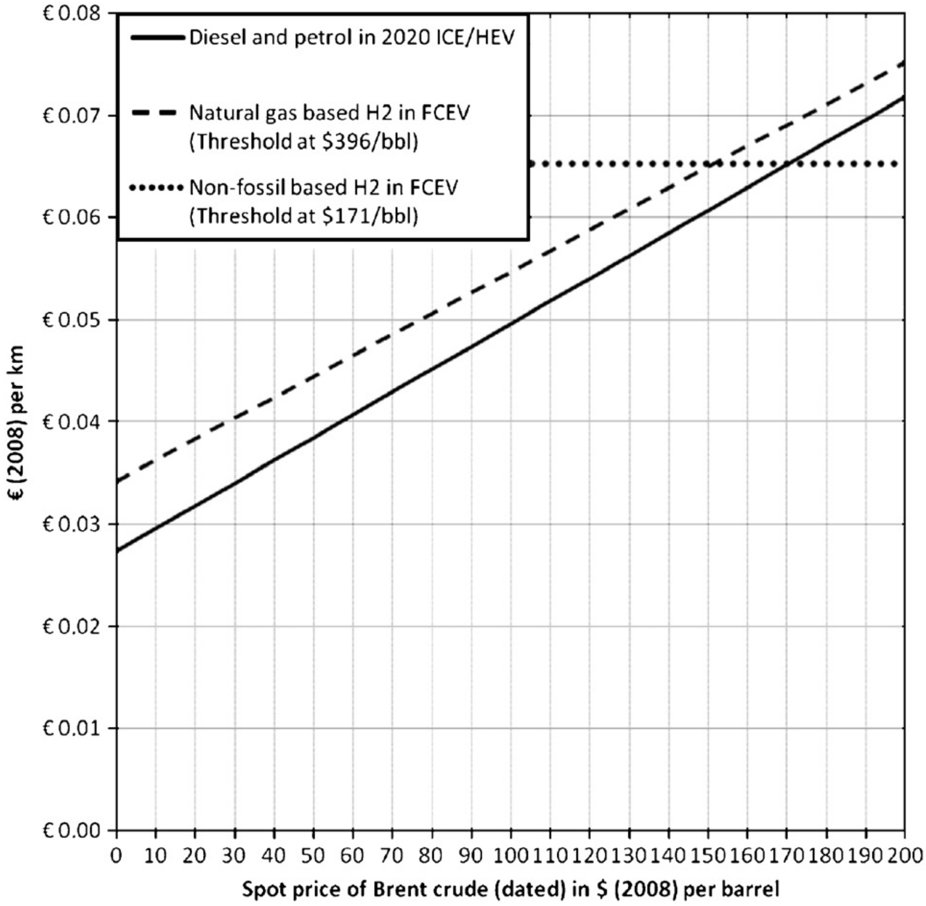

Fig. 9. Worst case: uniform fuel tax of €15/GJ+CO_2-allowances or equalizing tax on reforming process.

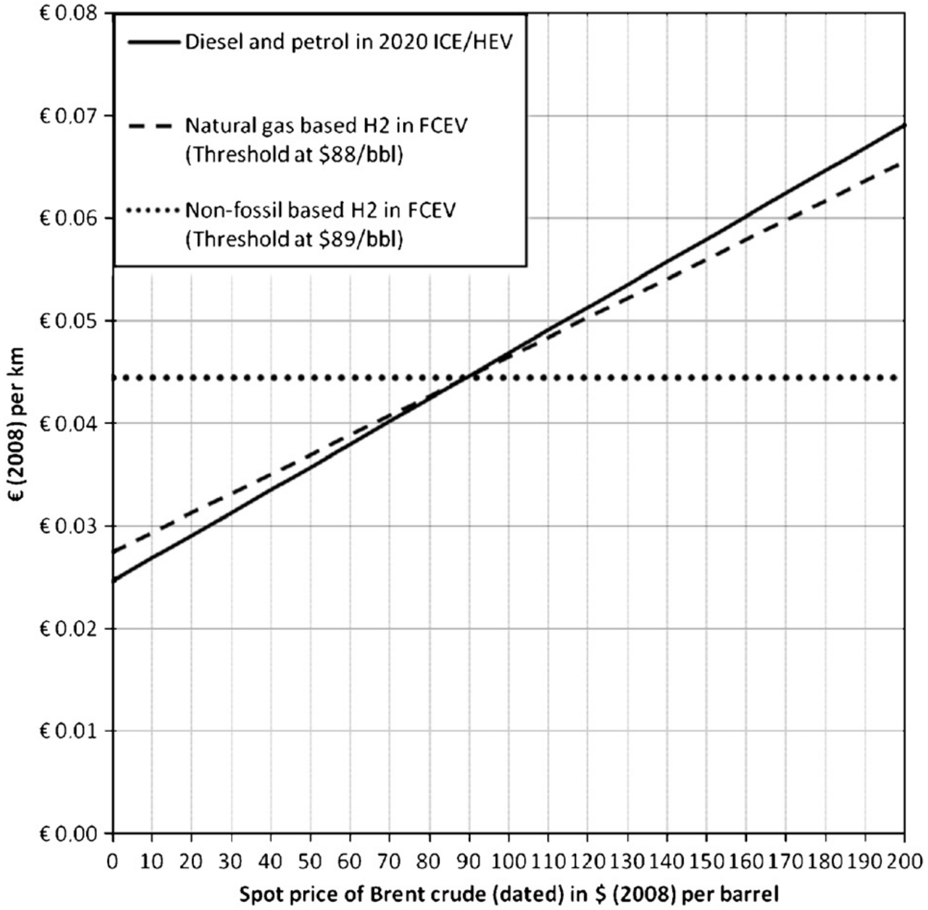

Fig. 10. Best case: uniform fuel tax of €10/GJ+CO_2-allowances or equalizing tax on process+equalizing CO_2-tax on end-use+equalizing energy loss tax on electrolysis.

7. Conclusions

The model results discussed above show that under best-case assumptions, it can be expected that there is a critical level, where the order of fuel cost efficiencies is totally reversed. At low oil prices “diesoline” costs have been lower than those of natural gas-based hydrogen, which in turn have been lower than those of non-fossil-based hydrogen. At higher oil prices conventional fuels cost more than hydrogen, notably non-fossil power-based hydrogen. The critical level is around $100/bbl depending on the taxes. Without fuel taxes, it would be $125/bbl and with fuel and CO_2-taxes within the levels that are already applied in Europe today and it could be in the range $80–90/bbl. Thus, under best-case assumptions, hydrogen and in particular non-fossil hydrogen would be a lowest cost solution at oil prices beyond this critical level. If it is recognized that the oil prices after the 2008 financial and economic crisis will increase again beyond $100/bbl, this perspective becomes very interesting.

Under worst-case assumptions, the system efficiency of hydrogen production is lower and the infrastructure costs are higher. With the assumptions used here, there would still be a critical level, but it would be at such high oil prices that it would require considerable tax favours for hydrogen to be competitive. Thus, only a very well performing and carefully optimised hydrogen infrastructure will be able to deliver hydrogen which is competitive in cost per kilometre terms.

It must be underlined that the model parameters are estimated for Europe as a whole and does not reflect the particular situation in any country. The parameters have been chosen in such a way that they avoid excessively optimistic assumptions. Thus, the results should not be interpreted as forecasts of exact costs and prices in 2015–2025, but rather as some important options, trade-offs, and outcomes that will be faced when hydrogen and fuel cell cars are introduced.

The standard result of many of the earlier studies on the competitiveness of hydrogen as a transport fuel was that hydrogen would be based on natural gas in the initial phase of the transition to hydrogen and that tax favours or subsidies would be necessary for hydrogen to be competitive. The results discussed above show that both of these conceptions need reconsideration if it is recognized that the era of cheap oil really is over.

Hydrogen produced under best-case assumptions from non-fossil power resources will be the least-cost hydrogen supply for industrial use at an oil price above $90/bbl. Used in an FCEV with 50% efficiency advantage above “diesoline” solutions, it will be the least-cost transport fuel at a cost per kilometre basis if the oil price exceeds $125/bbl. However, with the already existing European fuel tax rates and CO_2-emission reduction incentives of €10–20/GJ the critical level could very well be $80-90/bbl.

This difference between $125/bbl and $80–90/bbl could be just enough to give Europe a head-start in the transition to hydrogen as a transport fuel. Consequently, it may involve a potential for Europe to gain a leading role in the transition to hydrogen-based transport.

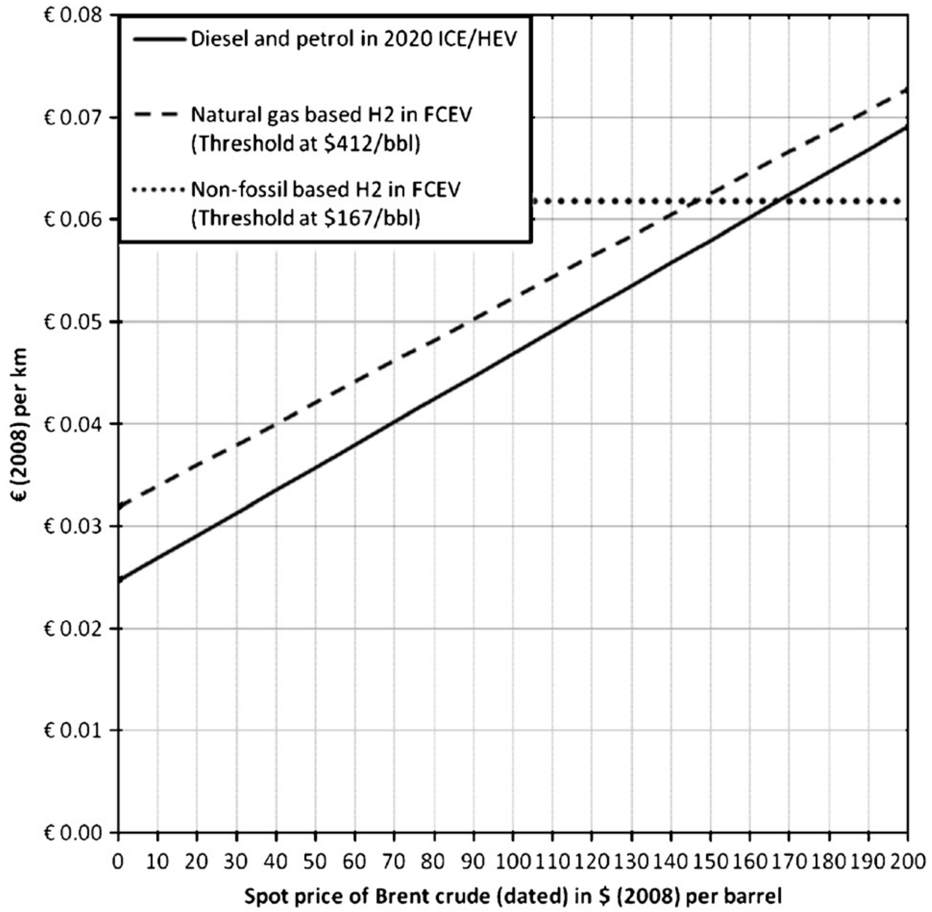

Fig. 11. Worst case: uniform fuel tax of €10/GJ+CO_2-allowances or equalizing tax on process+equalizing CO_2-tax on end-use+equalizing energy loss tax on electrolysis.

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References

Brown, S.P.A., Yücel, M.K., 2008. What drives natural gas prices? Energy Journal 29 (2), 45–60.

Commission of the European Communities, 2008. Energy sources, production costs and performance of technologies for power generation, heating and transport. commission staff working document accompanying the Second Strategic Energy Review an EU energy security and solidarity action plan. COM(2008) 744. 〈http://ec.europa.eu/energy/strategies/2008/doc/2008_11_ser2/strategic_energy_review_wd_cost_performance.pdf〉.

Committee on Assessment of Resource Needs for Fuel Cell and Hydrogen Technologies-National Research Council of the National Academies, 2008. Transitions to Alternative Transportation Technologies-A Focus on Hydrogen. The National Academies Press, Washington, DC.

Edwards, R., Griesemann, J.C., Larivé, J.F., Mahieu, V., 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〉.

Edwards, R., Griesemann, J.C., Larivé, J.F., and Mahieu, V., 2007. Well-to-Wheels analysis of future automotive fuels and powertrains in the European context. Version 2c. 〈http://ies.jrc.ec.europa.eu/WTW.html〉.

European Council 2003. Council Directive 2003/96/EC restructuring the Community framework for the taxation of energy products and electricity. 32003L0096: Official Journal L 283, 231/210/2003 P. 0051–0070. 〈http://eur-lex.europa.eu/LexUriServ/site/en/oj/2003/l_123/l_12320030517en00420046.pdf〉.

European technology platform for hydrogen and fuel cells (HFP) 2007. Implementation plan-status 2006. 〈https://www.hfpeurope.org/uploads/2097/HFP_IP06_FINAL_20APR2007.pdf〉.

Eurostat, 2008. Online database. 2008. 〈http://europa.eu.int/comm/eurostat/〉.

Eurostat, 2009. Online database. 2009. 〈http://europa.eu.int/comm/eurostat/〉.

Floch, P.H., Gabriel, S., Mansilla, C., Werkoff, F., 2007. On the production of hydrogen via alkaline electrolysis during off-peak periods. International Journal of Hydrogen Energy 32 (18), 4641–4647 〈http://www.sciencedirect.com/science/article/B6V3F-4PRJP9T-1/2/370815eaf85957abd1f6db302ceb9b08〉.

Gorensek, M.B., Forsberg, C.W., 2009. Relative economic incentives for hydrogen from nuclear, renewable, and fossil energy sources. International Journal of Hydrogen Energy. In press, doi:10.1016/j.ijhydene.2008.07.083. 〈http://www.sciencedirect.com/science/article/B6V3F-4TDYNT9-9/2/6e530821bafe1e8aca1c0e6d5b91c7bd〉.

Hammerli, M., 1984. When will electrolytic hydrogen become competitive? International Journal of Hydrogen Energy 9 (1–2), 25–51 〈http://www.sciencedirect.com/science/article/B6V3F-498M891-WB/2/51ed4886e23562b6c3bc0788d08f5ab5〉.

International Energy Agency (IEA), 2005. Prospects for Hydrogen and Fuel Cells. IEA, Paris.

International Energy Agency (IEA), 2006. World Energy Outlook 2006. IEA, Paris.

International Energy Agency (IEA), 2008a. Energy Prices and Taxes. Online database. 2008.

International Energy Agency (IEA), 2008b. Oil information. Online database. 2008.

International Energy Agency (IEA), 2008c. World Energy Outlook 2008. IEA, Paris.

Jørgensen, C., Ropenus, S., 2008. Production price of hydrogen from grid connected electrolysis in a power market with high wind penetration. International Journal of Hydrogen Energy 33 (20), 5335–5344 〈http://www.sciencedirect.com/science/article/B6V3F-4THB4BC-2/2/fa96f51432d3557b2eaa332ecdc62b8d〉.

Levene, J.I., Mann, M.K., Margolis, R.M., Milbrandt, A., 2007. An analysis of hydrogen production from renewable electricity sources. Solar Energy 81 (6), 773–780 〈http://www.sciencedirect.com/science/article/B6V50-4MBC95V-5/2/f877c7255ac74b0973438f602f645b44〉.

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〉.

Ogden, J.M., Williams, R.H., Larson, E.D., 2004. Societal lifecycle costs of cars with alternative fuels/engines. Energy Policy 32 (1), 7–27 〈http://www.sciencedirect.com/science/article/B6V2W-47MJ0S9-1/2/5e3dd31d8fee644d0305dc5c502b3b01〉.

Panagiotidis, T., Rutledge, E., 2007. Oil and gas markets in the UK: evidence from a cointegrating approach. Energy Economics 29 (2), 329–347 〈http://www.sciencedirect.com/science/article/B6V7G-4MH2BYY-2/1/0f0a33995ea9677e9ca8e34d8fa7608c〉.

Schoots, K., Ferioli, F., Kramer, G.J., van der Zwaan, B.C.C., 2008. Learning curves for hydrogen production technology: an assessment of observed cost reductions. International Journal of Hydrogen Energy 33 (11), 2630–2645 〈http://www.sciencedirect.com/science/article/B6V3F-4SF9C4W-3/2/b3c83455cd582b9b1fb59f3ba531f355〉.

Taljan, G., Fowler, M., Cañizares, C., Verbic, G., 2008. Hydrogen storage for mixed wind-nuclear power plants in the context of a hydrogen economy. International Journal of Hydrogen Energy 33 (17), 4463–4475 〈http://www.sciencedirect.com/science/article/B6V3F-4T7442Y-4/2/9c49ba3b238b7f1130923ddc05d2b1fc〉.

The Alternative Fuels Contact Group, 2004. Market development of alternative fuels. 〈http://europa.eu.int/comm/energy_transport/envir/2003_report_en.pdf〉.

The CUTE Project (2008). CUTE. Detailed summary of achievements. The CUTE Project. 〈http://ec.europa.eu/energy/res/fp6projects/doc/hydrogen/deliverables/summary.pdf〉.

The European Parliament and the Council of the European Union, 2003. Directive 2003/87/EC of 13. October 2003 establishing a scheme for greenhouse gas emission allowance trading within the Community and amending Council Directive 96/61/EC. Official Journal of the European Union. L 275/32.

The HyWays Project, 2008. HyWays. The European Hydrogen Roadmap. Action Plan Policy Measures for the Introduction of Hydrogen Energy in Europe. Office for Official Publications of the European Communities 〈http://www.hyways.de/docs/Brochures_and_Flyers/HyWays_Roadmap_FINAL_22FEB2008.pdf〉.

US Department of Energy (DOE), 2007. Hydrogen, fuel cells, and infrastructure technologies program. Multi-year research, development, and demonstration plan. Planned program activities for 2005–2015. 2007 rev. 〈http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/〉.

US National Academy of Science, 2004. The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs. National Academies Press.

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. 〈http://pubs.its.ucdavis.edu/publication_detail.php?id=46〉.