Long-term developments in the transport sector – comparing biofuel and hydrogen roadmaps

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Abstract
In view of climate change and rapidly declining oil reserves, alternative fuels for transport meet ever-increasing attention. Two promising options are biofuels, of which the market penetration has already started, and hydrogen, which, when used in fuel cell cars, could lead to zero-emission vehicles. This paper draws on the results of two ongoing EU projects - Refuel and HyWays – in which roadmaps are being developed for respectively biofuels and hydrogen . An analysis of synergies and possible conflicts between these road maps indicates that their most important potential conflict lies in competition for biomass as a feedstock. In this context, the hydrogen-fuel cell route has the advantage of a higher efficiency (in terms of km driven per ha or tonne biomass) than biofuels. Furthermore, hydrogen is more flexible in feedstock, since it can also be produced in a climate-friendly way from fossil resources such as coal. The key technology development synergy between biofuels and hydrogen is in gasification technology. This technology is required both for biomass-to-liquids, one of the more promising biofuels, and for hydrogen production from biomass and/or coal. The transportation sector will need both options in the long term: while hydrogen may become dominant for passenger cars, greening of long-distance heavy duty transport will become dependent on a bio-based diesel substitute. Finally, although both options are policy-dependent on the short term, policies will be more crucial for hydrogen than for biofuels since the former has a more disruptive character.

Introduction
Recent oil price records have clearly indicated the dependency of the road transport sector on its main energy source crude oil. Consumers are facing increasing fuel prices without having the opportunity to choose for an alternative option. Current oil price levels are not directly related to permanent shortages, but in the future, increasing energy consumption and declining oil reserves will ultimately lead to a strong demand for alternative fuels. Apart from the challenges related to the security of energy supply, the use of fossil fuels in the road transport sector significantly contributes to global climate change and air quality problems in different regions. Although different policies have been developed in recent years to reduce the emission of greenhouse gases in the sector, other sectors have been more successful, as illustrated in *Figure 1*. While most sectors show a decrease in greenhouse gas emissions the transport sector shows a significant increase, despite the different policies aiming at increased fuel efficiency of cars and informing consumers about the fuel consumption of new cars. This is due to the growth in the number of kilometres driven, and the increase in vehicle sizes and weights. As a result, the relative contribution of the transport sector to climate change is increasing. By 2030, the sector is expected to be responsible for 30 % of all greenhouse gas emissions in Europe (European Commission, 2003).

The European Union and its Member States have committed themselves to the UNFCCC Kyoto Protocol and herewith to contributing to avoid dangerous climate change. In order to meet the targets set for the first commitment period (2008-2012), policies have been developed to reduce the emissions of carbon dioxide in different sectors like industry, the energy sec-

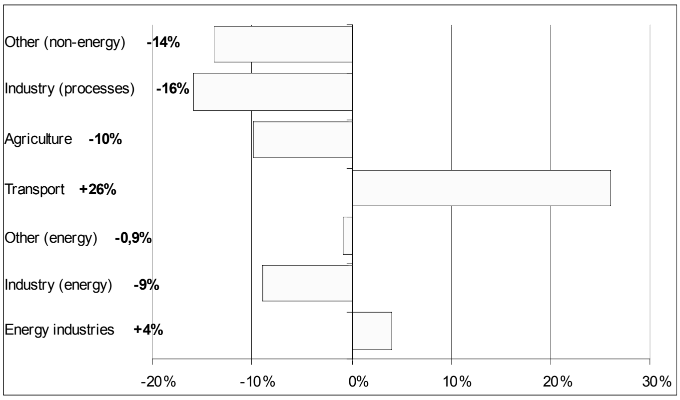

Figure 1. Changes in EU-15 greenhouse gas emissions by gas and by sector 1990-2004 (EEA, 2006).

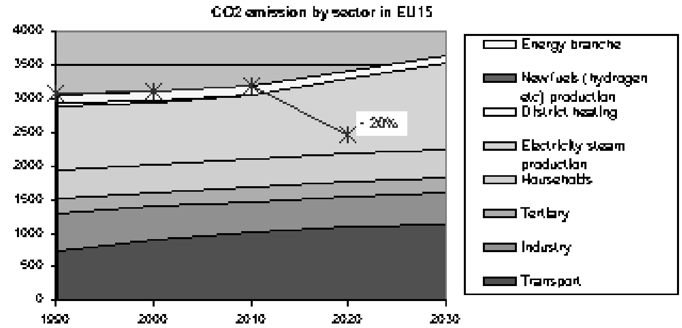

Figure 2. CO_2 emissions levels of different sectors in the EU15. The black line represents the ambition of the European Commission of 20 % reduction in 2020 compared to 1990 levels

tor and the transport sector. For the first commitment period the EU should decrease the emissions of greenhouse gasses by 8 %. However, to avoid dangerous climate change more stringent reductions will be necessary in the future. For this reason, the European Commission has proposed a strategy to decrease Europe's emissions by 20 % in 2020 compared to 1990 levels (European Comission, 2007). For comparison, *Figure 2* illustrates the projected emissions of CO_2 by sector towards 2030 and the ambition level of the 20 % reduction target (European Commission, 2003).

As transport has a dominant role in the emission of greenhouse gasses it is necessary to develop effective policies to reduce these emissions. Although reductions in other sectors might be realised more easily in the short term, in the medium term 'low hanging fruit' options will become scarce. The transport sector not only needs to reduce its emissions significantly, but it probably also needs time as it strongly depends on common infrastructure and conventional vehicle technology. Therefore a transition approach is necessary to support developments in alternative fuel technologies.

This paper discusses the potential of several options for sustainable road transport with most attention to biofuels and hydrogen. The paper will start with discussing the variety of options for the sector, followed by a discussion on the essentials of two road maps currently being developed for hydrogen and biofuels (HyWays and REFUEL) and next, potential synergies and conflicts between the two pathways will be elaborated on. The paper ends with drawing conclusions.

Options for sustainable road transport

Many options exist to make transport more sustainable. Which options should be preferred depends on the main goals governments want to achieve. As air polluting emissions can be reduced to a level of no effect for almost all vehicle concepts (clean engines with particle filters and NO_x-catalysers) the main remaining drivers will be avoiding climate change and improvement of security of energy supply. In general, three different types of solutions exist: reducing the number of kilometres driven, reducing the energy use per kilometre, or reducing the fossil carbon content of the fuels. Reduction of transport kilometres is mainly a political issue, to which we do not pay further attention here, whereas fuel efficiency and low carbon fuels are technical issues. For the latter two, and overview of options is given in *Table 1.* All options are a combination of energy source, fuel type and vehicle concept, e.g. a fuel cell vehicle running on hydrogen which is produced from biomass. Certain options are more sustainable than others and the applicability differs from R&D phase (e.g. fuel cell vehicles) to commercially available (e.g. natural gas vehicles).

As for the fuel efficiency, incremental improvements are possible by improving the efficiency of the engine or downsizing of the engine or the entire vehicle. More can be gained by hybridisation and the application of light materials. New production technologies for steel or carbon fibres make the use of less steel or strong and light weight carbon fibres affordable without having to make sacrifices to costs or safety. Hybrid powertrains can improve fuel efficiency significantly. By applying hybrid technologies, the internal combustion engine can be downsized and used more efficiently at higher average loads, without decreasing the performance of the vehicle. By regenerating energy during idling or by using the braking energy,

Table 1. Overview of options for sustainable vehicle technology

Drivetrain	Options
Internal combustion engine (ICE)	Efficiency improvements Hybrid technology Small/light vehicles Alternative fuels (biofuels, FT-diesel, hydrogen, DME or methanol, natural gas) Fossil fuels combined with CO2 capture and storage (CCS) Small changes in engine technology might be required
Fuel cell vehicle (FCV)	Hydrogen (from coal, natural gas, renewables or nuclear energy) (possibly with CCS) Bioethanol, methanol (from coal, natural gas or biomass) – on board reforming
Electric vehicle (EV)	Electricity (from fossil, renewable or nuclear sources) (CCS) Plug-in hybrid (electric car with a small ICE)

more savings are feasible (Lovins, 2004). These improvements of relatively conventional technologies will be important to reduce vehicle emissions, but in order to come to low carbon vehicles, alternative fuels based on renewable sources or fossil sources combined with CO_2 capture and storage (CCS) are necessary (VROM, 2004). It is expected that for the short to medium term, none of these fuels will be able to fulfil the entire energy demand in the transportation sector and so different fuels might exist next to each other (Van den Brink, 2003).

Which fuels will be most attractive to attain the policy goals is not clear yet. Combinations of different conventional and innovative fuels and technologies are possible and it is expected that different options will coexist next to each other. Costs will be important as well and although the precise levels are uncertain for most sustainable options, they are expected to be relatively high, at least on the short term. Also compared to emission reduction options in other sectors, reduction costs of greenhouse gasses in the transportation sector will be relatively high (over 100 EURO/ton CO_2) initially. New fuelling infrastructure will be necessary for options such as hydrogen and developments of innovative vehicle technologies depend not only on commitment of governments and industry, but also on consumers' willingness to purchase them once on the market.

A roadmap for hydrogen

In the last couple of years, a number of roadmaps for hydrogen in Europe have been published. Examples are the Vision report of the High Level Group (see www.hfpeurope.org), the HyNet roadmap (see http://www.iphe.net/europeancommission.htm) and various strategic documents on technology deployment and research priorities issued by the Hydrogen and Fuel Cell Technology Platform (www.hfpeurope.org). These roadmaps vary in scope from a general vision on the role of hydrogen to specific recommendations on R&D support. The roadmap that is being developed within the HyWays project differs from the above mentioned roadmaps due to the use of a quantitative (modelling) framework combined with a comprehensive stakeholder consultation process (see www.HyWays.de).

THE HYWAYS ROADMAP

The aim of the HyWays project is to build a validated and well accepted roadmap for hydrogen in transport and stationary applications.[1] The road map should reflect real life conditions, taking into account country specific as well as non techno-economic barriers. Over 50 stakeholder workshops have been carried out in 10 EU-countries. Major aim of the workshops was to discuss the long term vision for hydrogen and the consequences for the short and intermediate period. The discussions on the long term vision were fed by the results of the model calculations. The outcomes of these discussions were then used to revise and validate the model calculations.[2]

Since the conclusion and recommendations to be drawn from the roadmap should hold for several years, it needs to be independent of 'spirit of the times', induced by e.g. sharply increasing or fast dropping oil prices or economic growth. Therefore, it was decided to base the analysis on widely accepted European energy scenarios such as the Energy Trends 2030 scenario (European Commission, 2003) and the WETO-H2 study (European Commission, (2006). The potential to reduce CO_2 emissions is one of the main drivers for the introduction of hydrogen. It is assumed that CO_2-emissions in Europe have to go down by 35 % in 2050 in comparison to the 1990 level. On purpose, no very ambitious CO_2 reduction target was chosen in order to show the value added of the hydrogen transition with 'mild' climate constraints. With higher emission reduction targets, the cost competitiveness of (carbon free produced) hydrogen increases, and hydrogen may enter the energy system more easily.

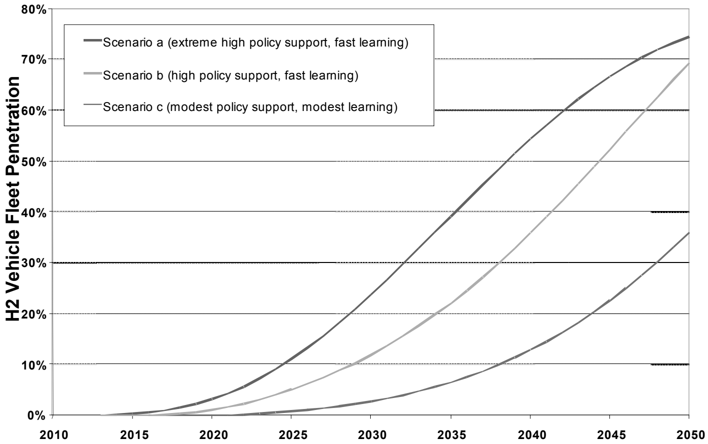

Figure 3. Development of the penetration rate of hydrogen vehicles. Only passenger cars: both fuel cell vehicles and the hydrogen ICE.

CONDITIONS AND UNCERTAINTIES

The main factors which will determine the introduction pace of hydrogen vehicles into the market are the time needed to build up production capacity, the replacement rate of old vehicles as well as the time needed to incorporate learning effects in the production process. In *Figure 3* the development of the penetration of hydrogen passenger cars, both fuel cell vehicles and the ICE on hydrogen, is given for three scenario's, reflecting differences in policy support intensity and *learning rate*, e.g. the speed at which cost reductions take place. Before 2020, the market share of hydrogen vehicles is expected to be limited.

Another crucial condition for a large penetration of hydrogen vehicles is that they are affordable. The development of the costs of hydrogen vehicles has been assessed using a learning curve approach (Neij, 1997). On a component level, the (potential) cost reduction as a function of the total cumulative production has been calculated for the various new components in a hydrogen vehicle. In *Figure 4*, the development of the costs of a medium size fuel cell vehicle for fast technology learning (optimistic PR) and less optimistic learning as well as the costs of the reference vehicle.[3] In case of optimistic assumptions on

1. For stationary applications, only end-use application using hydrogen as a fuel is considered. The potential impact of fuel cells on natural gas (with a reformer) is not analysed within HyWays

2. A wide range of models are used: an optimisation model, and input/output model, an GIS-based infrastructure model as well as a general equilibrium model.

3. Not only the fuel cell vehicles decreases in costs due to technology learning but also the reference vehicle. However, since the total cumulative production of the conventional vehicle is very high, cost reductions are hardly visible on this scale.

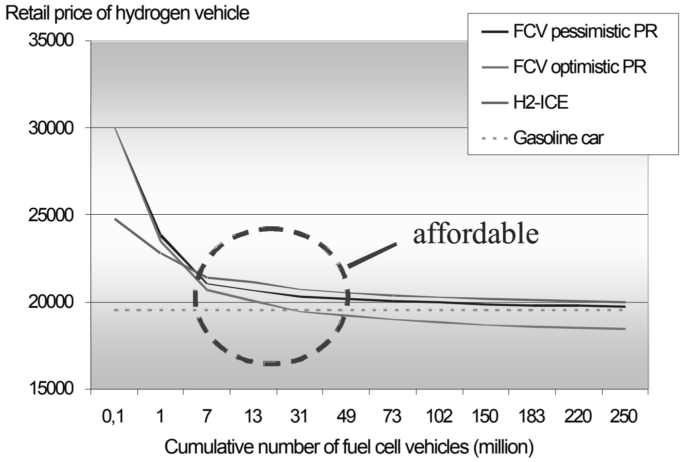

Figure 4. Projection of the retail price of a hydrogen vehicle (EURO). FCV = fuel cell vehicle, PR = progress ratio, ICE = internal combustion engine.

technological progress, the fuel cell vehicle will become cheaper than the conventional vehicle after a cumulative production of around 25 million vehicles. The analysis shows that in time the hydrogen vehicle can become cost effective. However, significant investments have to be made in order to reach the cost competitive level, explaining why (as any disruptive technology) hydrogen is not able to enter the market without significant policy support.

Total costs for hydrogen in transport are not only determined by the retail price of the vehicle but also strongly by fuel efficiency and fuel costs. Due to the high efficiency of the fuel cell vehicle, it can become cost competitive even though the retail price is still higher than for a conventional vehicle. In *Figure 5*, the impact of key factors on total costs, expressed in EUROc/km, is given. Internalisation of CO_2 reduction costs has a small impact on the cost per kilometre. The source for hydrogen production and the development of oil (fossil fuel) prices have higher impacts on total costs.. However, the learning rate of the power train of the fuel cell vehicle has by far the most important impact on total costs. Unfortunately, the factors that have the largest influence on total costs can, at best, only be influenced partially. Increasing R&D expenditures will have a positive impact on the likelihood that the required technological progress actually takes place. However, technological breakthroughs can never be guaranteed, despite a substantial budget for R&D.1

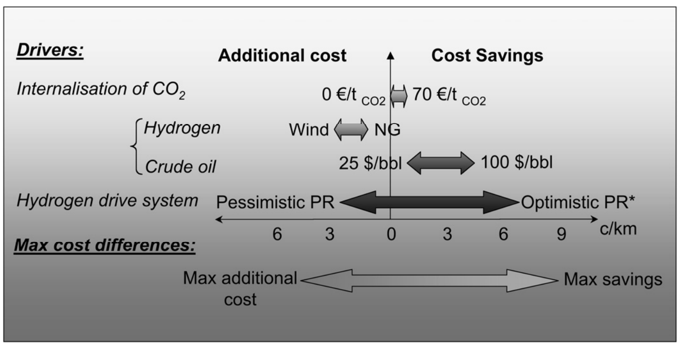

Figure 5. Cost factors and their impacts on driving costs (in EUROc/km) in a fuel cell vehicle

IMPACTS

The impact on emissions of the introduction of hydrogen depends on the market share as well as on the production method. When using a fuel cell, the hydrogen is converted in the end-use application without any emissions. Emissions are transferred to the point of production. Hydrogen can be produced with low or even zero CO_2 emissions using fossil fuels with carbon capture and sequestration, nuclear or renewable energy. Due to the low carbon content of the hydrogen, the total emission reduction is approximately proportional to the market share. Besides on CO_2 emissions, the introduction of a zero emission fuel such as hydrogen also has a positive impact on the reduction of other pollutants such as fine dust, NO_x, SO_x and VOC.

The impact on security of supply depends on the hydrogen production chain. A major strength of hydrogen is that it can be produced from (almost) all resources. However, this implies that it is very difficult to predict in what way the hydrogen in future will be produced. Sensitivity analysis shows that costs of hydrogen production from coal with CCS is comparable to the costs of hydrogen produced from biomass. It should be noted however that projections of the availability of biomass at reasonable costs have a very wide range. The costs of hydrogen produced from natural gas strongly depend on assumptions on the coupling of oil and gas prices, development of the oil prices as well as estimates with respect to the development of the gas price independent of the oil price. Calculations show that after 2030, hydrogen production from natural gas is likely to be more expensive than hydrogen production from coal and biomass. Hydrogen production from renewable electricity, such as wind power, is more expensive than hydrogen production from the other resources. Only in case hydrogen is produced from excess electricity (very low marginal costs), this option can become cost competitive. It is however questionable whether the power sector will evolve into a direction where such large imbalances do exist. The introduction of hydrogen leads to a sharp decrease of the dependency on oil. Since hydrogen can be produced from basically all resources, there is little to no risk that oil is substituted with a fuel that in time will impose new security of supply threats, specifically since a number of production pathways with comparable price levels is available.

A POLICY FRAMEWORK FOR THE INTRODUCTION OF HYDROGEN VEHICLES

Hydrogen is at the brink of making the step from the R&D stage towards the (early) deployment stage. This means that new policy measures that support deployment rather than R&D have to be designed and implemented (see www.HyLights.org). Even though the long term prospects for hydrogen to become cost competitive are good, serious investment hurdles have to be overcome before hydrogen can compete on all aspects with the conventional technology. A main characteristic of a disruptive technology such as hydrogen is that barriers with different characteristics have to be overcome in all parts of the energy chain. A more complex framework is needed in comparison to incremental innovations which fit quite well in the current energy system.

In the early deployment phase, the learning potential of a new technology is still high and the competitiveness does improve fast due to cost reductions and performance increase.

If the policy support framework, e.g. subsidies, is not able to adapt to these changes, its effectiveness is reduced considerably (subsidies are too high and therefore the budget may explode). The policy framework should be able to take all these aspects into account: address various barriers in all parts of the energy chain and be responsive to changes in the competitiveness of the technology.

A major complication in the case of hydrogen is that the additional costs of e.g. the vehicle, infrastructure of the production facility are difficult to asses. However, deployment related support schemes are in general based on reduction of additional costs. A sound comparison with the reference option can only be made based on total costs (EUROc/km), including both vehicles costs as well as fuel costs. A single support scheme that takes total costs as final indicator and addresses diverging barriers in all parts of the energy chain would be very complex and therefore offer insufficient flexibility to adapt to the changing competitiveness of the fast developing technology. By setting targets for fuel costs as well as vehicle costs in a way that the total costs are comparable to the reference option, additional costs of both the fuel and the vehicle can be assessed. As a next step, tailor made but less complex support schemes for hydrogen as a fuel as well as for hydrogen vehicles can be developed and implemented (Jeeninga et al., 2006).

A roadmap for biofuels

In the European REFUEL project a biofuels road map until 2030 is being developed, see also (Londo et al., 2006) and www.refuel.eu. To phrase it in travelling terms, the project pays attention to:

- *The route*: A cost-effective mix of biofuels reaching a 25 % target, including corresponding biofuel chains, conversion technologies, feedstocks, and other parts of the supply chain.
- *The purpose of the journey*: An impact assessment, including greenhouse gas emissions, security of supply, socio-economics, impacts on the whole energy system, and other environmental and land use issues.
- *What to do at the wheel*: An analysis of required actions from stakeholders, in terms of technological innovations, learning, and market introductions, and corresponding implementation options and barriers
- *How to pave the way*: Required policies on related fields, such as agriculture, energy, technology development and trade, to reduce barriers and create incentives for stakeholders to act.

Much attention is paid to assessment of the merits of different biofuel chains, including their required biomass feedstock, conversion technologies, and distribution and end use issues. The analysis includes all types of biofuels, of which the most relevant ones are:

1. Conventional, or 1st generation biofuels:
   - Biodiesel from oil crops such as rape seed or palm, produced by transesterification;
   - Bioethanol from sugar or starch crops such as sugar beet or wheat, produced by fermentation and distillation;
2. Advanced, or 2nd generation biofuels:
   - Biomass-to-liquids (BTL), or FT-diesel, from woody feedstock, produced by gasification and Fischer-Tropsch synthesis;
   - Bioethanol from cellulosic materials such as wood and straw, produced by enzymatic hydrolysis, fermentation and distillation.

THE REFUEL ROAD MAP

Point of departure for the road map is that a biofuels share in the order of magnitude of about 25 % would be feasible in 2030. This target range was also formulated in the vision document of the Biofuels Research and Advisory Council (Biofrac). Generally, the foreseen pathway is that currently available conventional biofuels will be overtaken by the 2nd generation. This mainly because advanced biofuels use relatively low-grade feedstock (wood, other lignocellulosic materials) compared to the conventional agricultural crops for the 1st generation; their conversion technologies and cropping practices are relatively new and therefore have a better potential for cost reduction by learning; and in terms of cost per avoided tonne of CO_2, 2nd generation biofuels outcompete 1st generation biofuels, since the CO_2 balance of the 2nd generation biofuel chain is generally better.

The introduction of these advanced biofuels, however, still requires some technological break-throughs (particularly for 2nd generation bioethanol) or currently meets techno-economic barriers (for 2nd generation diesel substituents in particular). Therefore, it is expected that the biofuel mix will remain dominated by conventional biofuels in the short run, but after 2010 the advanced biofuels have a substantial share of new capacity development. This change has major consequences for feedstocks, and for all related stakeholders in the supply chain, as illustrated in *Figure 6*.

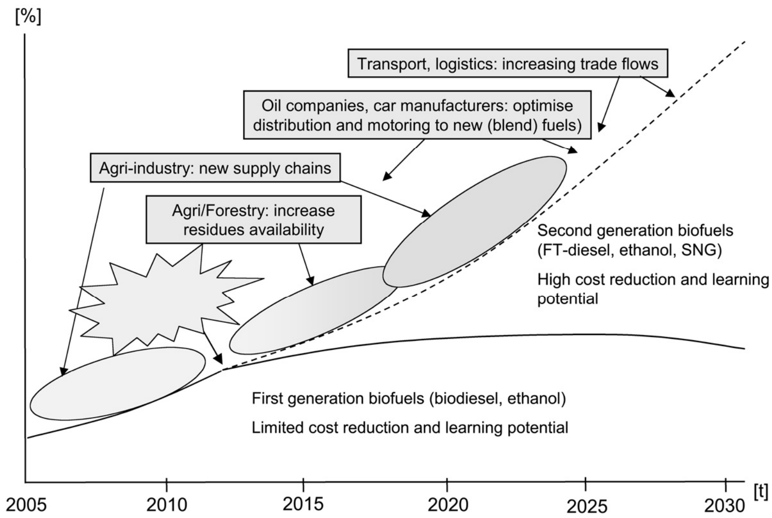

Figure 6. Illustrative biofuels development pathway

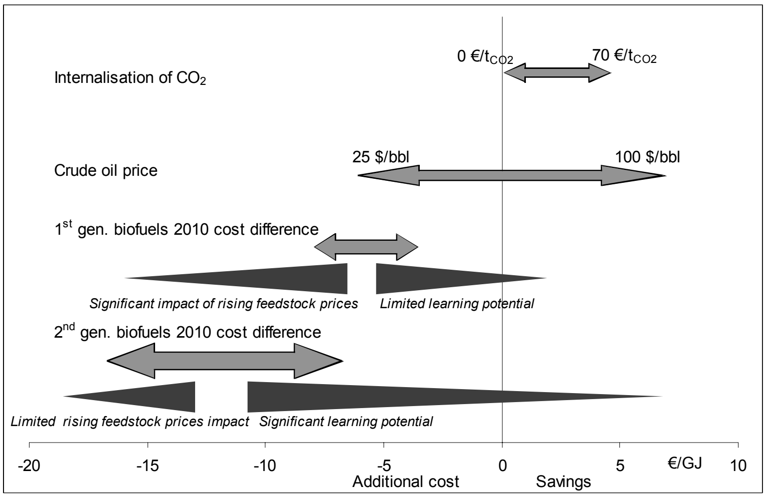

Figure 7. Cost factors and their impacts on Well-to-tank cost differences with fossil fuels. Cost assumptions for 2010 from Concawe/EUCAR; reference oil price 60 $/bbl.

CONDITIONS AND UNCERTAINTIES

As for most renewable options, biofuels are currently not cost-competitive with their fossil equivalents. The situation can be roughly sketched as in *Figure 7*. Key variable for biofuel competitiveness is the crude oil price. For example, at an oil price of 100 $/bbl, a wide variety of biofuel options becomes competitive. Pricing of avoided CO_2 emissions can contribute significantly to an improvement of biofuels' competitiveness. It should be noted, however, that CO_2 performance varies widely between biofuels, with 2nd generation options scoring between 60 and 70 kg CO_2/GJ fuel, but conventional biofuels achieving significantly lower, to even negative CO_2 reductions. Furthermore, costs of biofuels will be influenced by learning rates (in biomass feedstock production as well as in conversion technology, and by possible upward pressures on feedstock prices due to increasing land scarcity at high demand levels. Note that second generation biofuels have higher 2010 costs, but a higher learning potential and less susceptibility to land scarcity. In short, internalisation of CO_2 emission cost, significant cost reductions due to learning and sTable oil and feedstock prices will lead to a situation in which several types of biofuels will become competitive.

Key uncertainty in the development pathway of biofuels is the introduction of the 2nd generation biofuels. The 2010 indication of its introduction strongly depends on technological innovations and further development of a biofuels market. If the EU policy perspective, for example, would lag behind, these options may meet significant delay.

The perspective of all biomass-based options strongly depends on developments in food consumption and agriculture. Via competition for land, biofuels are related to the food sector, and changes in human diet and agricultural productivity directly affect the potentially available land for energy crops. The envisaged rationalisation and intensification of agriculture in Central and Eastern European countries is also relevant in this context. Feedstock availability is a key issue, and potentials among studies vary between almost zero and the equivalent to total current global energy demand. While advanced biofuels are somewhat less susceptible to the uncertainties related to this spread, they do influence the opportunities.

IMPACTS

Concerning security of supply, the project evaluates impacts in terms of net energy imports and diversity in supply. As an illustration, the recent TREN scenarios contain a high-renewables scenario with a 14 % share of biofuels in total gasoline and diesel use for road transport (Mantzos and Capros, 2006). If these biofuels are fully produced domestically, this leads to an overall import dependency in the transportation sector of 85 %, compared to 95 % in the baseline. Furthermore, biofuels significantly broaden the fuel portfolio and, if not all feedstock is produced domestically, improve variety in the related regions of origin. Concerning greenhouse gases, a first-order indication from VIEWLS (Wakker et al., 2005) is that a 25 % target for 2030 will reduce overall greenhouse gas emissions of the transport sector by almost 20 %, provided the biofuels portfolio is dominated by the 2nd generation by then. Socio-economic impacts will also be quantified in the REFUEL project. It may be clear that biofuels entail employment and income in all parts of the value chain, with biomass production and conversion as the main parts, but the macro-economic impacts are not a priori clear, as there might be job losses in other sectors.

A POLICY FRAMEWORK FOR THE INTRODUCTION OF BIOFUELS

Development of competitive biofuels chains requires a consistent set of policies in several policy domains, as illustrated in *Figure 8*. From the European point of view, technology development and learning can be enhanced via programmes in the field of DG-RTD, DG AGRI could support biomass supply development and learning in cropping systems, DG TREN provides a protected market for biofuels to start up, and DG ENV enhances the introduction of CO_2 pricing mechanisms.

Synergies and possible conflicts

In this section, the roadmaps for hydrogen and biofuels are compared, highlighting synergies and possible conflicts in terms of resources, conversion technologies, distribution and end-use, timing, and policies.

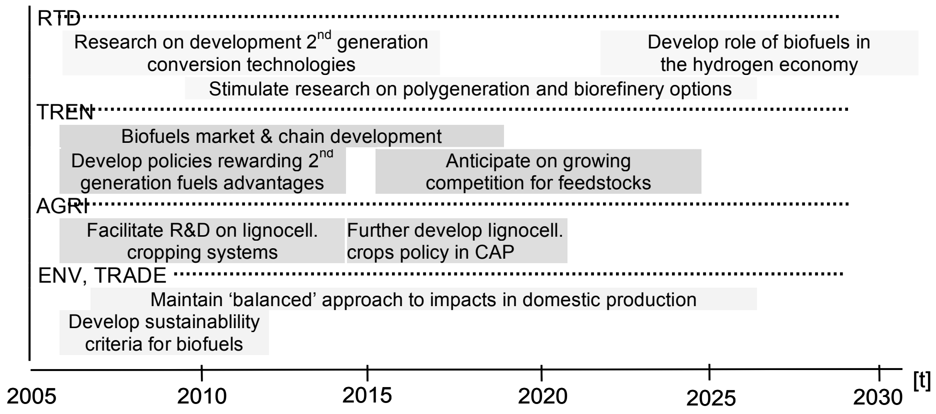

Figure 8 Overview of consistent policies in different fields to stimulate biofuels

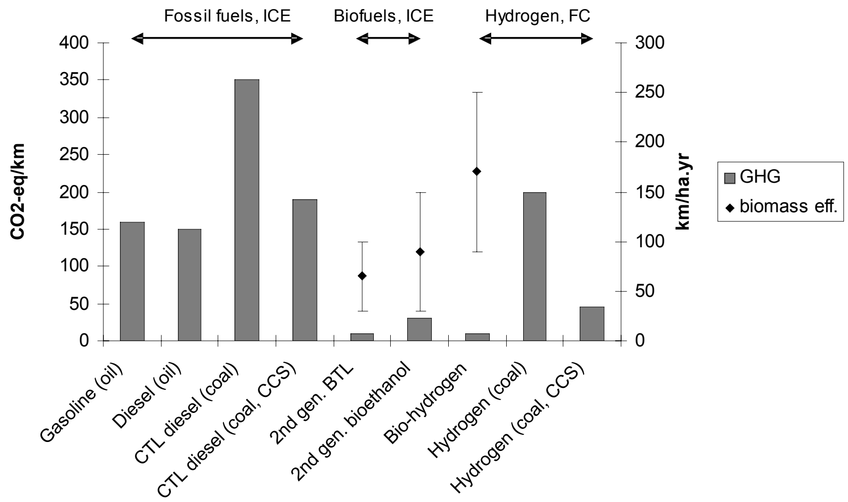

Figure 9: Greenhouse gas emissions and biomass use efficiencies for several fossil and biobased fuel chains. Based on Edwards et al. (2006) and Hamelinck and Faaij (2006).

CONTRIBUTIONS TO DIFFERENT POLICY TARGETS

As mentioned before, the key drivers for both the biofuels and the hydrogen road maps are mitigation of greenhouse gas emissions from transport and improving the sector's security of supply. For hydrogen, the improvement of local air pollution, e.g. city centres, is an additional value added as well as the contribution to energy conservation goals.

In terms of net greenhouse gas emissions per driven km, the most recent CONCAWE update (Edwards (2006), see Figure 9) indicates that the biomass-based H_2FC chain has comparable emissions as BTL in conventional engines; both options have far lower net CO_2 emission than conventional biofuels. So the CO_2 profiles do not provide arguments pro or contra hydrogen or (advanced) biofuels.

With respect to security of supply terms as well as contribution to energy conservation, the hydrogen pathway has advantages over biofuels. First, a key difference in terms of feedstock between biofuels and hydrogen is the relative flexibility of the hydrogen pathway: while biofuels solely depend on biomass, hydrogen can be produced from fossil resources, from biomass and from other renewable resources. That is, advanced biofuel technology such as BTL could also be fed by coal (the coal-to-liquids route, CTL), but even with CCS, this option leads to an increase in CO_2 emissions even in comparison to the conventional fossil fuel route since CTL contains fossil carbon rather than renewable carbon (Edwards et al., 2006). It is therefore only an option in a future with strong constraints on oil supply and negligible climate policy. For hydrogen, the fossil routes increase feedstock flexibility at limited expenses in terms of increased CO_2 emissions compared to biomass-based hydrogen. Secondly, it should be realised that in a biobased world, when we express efficiency on a basis of 'driven km per ha of biomass plantation', the hydrogen fuel cell (H_2FC) chain will be 25 % to 50 % more efficient in its biomass use than even advanced BTL fuels with conventional engines (Hamelinck and Faaij (2006), see Figure 9 above. Therefore, one can argue that hydrogen, when used in fuel cell vehicles, contributes more significantly to both security of supply and energy conservation goals than biofuels do.

RESOURCE: SYNERGIES OR CONFLICTS

Biomass is not only a relevant feedstock for transport applications, but can also be used for electricity generation, heat production (e.g. by conversion to biogas) or as feedstock for fabrication of industrial products. The demand for biomass from these pathways may lead to (either temporary or structural) biomass scarcity and price increases. For example, REFUEL's predecessor project, VIEWLS, indicated that the EU27 has suf-

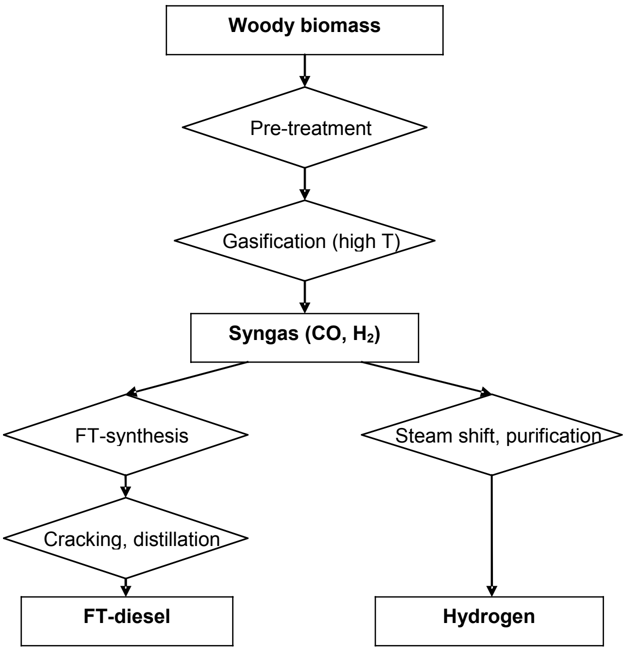

Figure 10: BTL for FT-diesel and hydrogen production

ficient land available for meeting a 30 % biofuels target or higher with advanced biofuels (Wakker et al., 2005), but this study did not account for the biomass demand from other sectors. Several studies indicate that when utilised in the power sector, the impact on CO_2 reduction exceeds the reduction achieved when applied as transport fuel. As shown in the previous section, hydrogen will be the more efficient option of the two in a world with biomass scarcity.

CONVERSION TECHNOLOGY: SYNERGIES OR CONFLICTS

Will short-term deployment of biofuels lead to lock-ins hampering hydrogen introduction, or can synergies be obtained? For the 1st generation biofuels, there are no potential synergies. Current conversion technologies such as transesterification and fermentation/distillation offer no overlap with hydrogen production. Lock-in effects, apart from asserting the position of the conventional vehicle, will also be limited. Related biofuel production plants may become obsolete if hydrogen takes over, but it should be noted that neither biodiesel nor bioethanol production technology is very capital intensive. Furthermore, bioethanol production facilities may be retrofitted to produce 2nd generation bioethanol or ethanol for industrial purposes.

As for advanced biofuels, synergies with hydrogen production may occur especially for 2nd generation FT-diesel. Biomass gasification and conditioning technologies (including their feedstock supply chains) that are currently being developed further for production of diesel and other liquids can also be used for direct hydrogen production (see *Figure 10*). The only lock-in that may occur when standing capacity for FT-diesel is to be converted to hydrogen production is the FT synthesis process itself, and further cracking and upgrading of the FT-wax into liquids such as diesel. Roughly, these parts amount to ca 25 % of total investment costs for advanced biomass-to-liquids (BTL) plants (Boerrigter, 2006).

Breakthroughs in BTL technology also increase the potentials for coal-based transportation fuel production, either as a liquid (CTL) or in the form of hydrogen. Here one can argue that coal-based fuel production requires a shift towards hydrogen, since hydrogen offers the opportunity for transport applications with very low emissions where the switch to CTL leads to an increase of emissions in comparison to conventional vehicles. In the case of coal-to liquids (CTL), most CO_2 cannot be captured since the fuel still contains fossil carbon, and the CO_2 intensity of the resulting transportation fuel may even be higher than that of current oil-based diesel (see also Figure 9). Hydrogen is a carbon free fuel.

The technologies for advanced bioethanol synthesis do not have any resemblance to (bio-based) hydrogen production; therefore existing capacity for this biofuel may result in a lock-in for hydrogen, especially when biomass-based hydrogen is targeted at. Keep in mind, however, that several production routes for hydrogen are feasible.

DISTRIBUTION AND END-USE: SYNERGIES OR CONFLICTS

The key difference between biofuels and hydrogen is that biofuels can be introduced in the current transportation system without any significant adaptations to either the distribution infrastructure or end-use in vehicles. For hydrogen, new distribution infrastructure must be set up, storage in vehicles is different and an entirely new propulsion system is to be developed. In this sense, hydrogen is a more disruptive technology than biofuels. The barrier of hydrogen infrastructure development will not be affected either positively or negatively by the introduction of biofuels, this bottleneck could possibly be overcome more easily in interaction with innovations in energy supply to households. An advantage is that both technology pathways not necessarily conflict with each other on the end-use side: biofuels applies to the greening the existing fleet, while hydrogen introduces an entirely new technology and way of driving.

CAN WE DO WITHOUT EITHER OF THEM?

From the comparison of roadmaps, it becomes clear that biofuels and hydrogen are to some extent competitors, and to some extent complementary options for increasing the sustainability of Europe's transport sector. Therefore it is interesting to consider the consequences of a possible failing market introduction of either of these options.

First generation biofuels are already quickly gaining market share. However, there is a broad consensus that the prospects of the first generation of biofuels are not favourable in the long run, as the biomass potentials will provide restrictions to growth, and they do not provide sufficient emission reduction. Therefore, the success of second generation technologies will be crucial if biofuels are to have a major and lasting role. Nevertheless, for the next 20 years or so, the lack of alternatives in the transport sector will provide a strong case for biofuels, at least as a transition option until hydrogen is affordable. In this period, biofuels are probably the best option to reduce the oil dependency of the transport sector. Furthermore, for 'greening' freight transport, biofuels are also most suitable, because of the limited action radius of of heavy duty trucks on hydrogen.

Secondly, considering that the CO_2 reduction potential of 2nd generation biofuels is some 80 %, hydrogen does not appear to

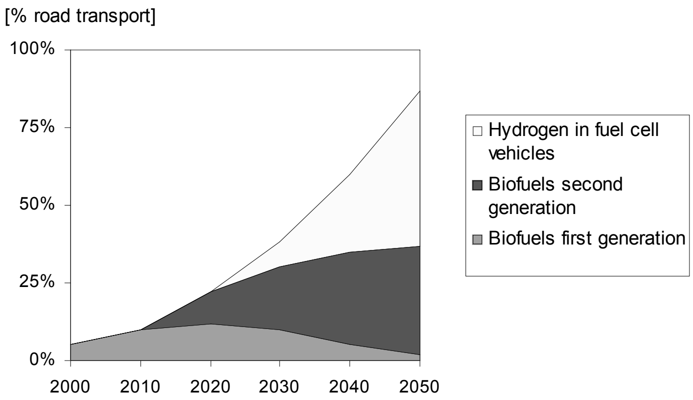

Figure 11. Possible evolvement of market shares in road transport

be indispensable in achieving a low-emission transport sector, although evidently, biomass potentials may become a limiting factor. Alternatives, such as light vehicles do exist, but no other option except hydrogen offers the advantage of zero emission vehicles in cities. On top of that, these light vehicles can also be equipped with a fuel cell, offering even further energy efficiency improvements.

Considering the size of the challenges related to climate change and security of supply, it is likely that both options are needed for achieving the emission reduction ambitions in the transport sector. In the short and medium term, biofuels are essential to reduce the emissions of the current vehicle stock, while hydrogen is needed to allow for the market introduction of new, zero-emission vehicles. The large scale introduction of fuel cell cars therefore also depends on the replacement rate of passenger cars. For energy efficiency reasons as well as the flexibility in required feedstock, hydrogen may also be indispensable on the long run because of the limited biomass potentials and the many competing biomass applications.

In *Figure 11*, these notions are illustrated in terms of the possible market share development of the two options. In terms of mid-term markets sizes, no conflicts can be expected. While REFUEL and other ambitious biofuels visions (e.g. that of the Biofuels Research and Advisory Council (2006)) envision that biofuels will share circa one quarter of total road transport fuel demand by 2030, the hydrogen road map envisages hydrogen to cover 5 to 12 % of the total vehicle market, which implies that the transportation market will be sufficiently large for both options. While the application of biofuels would initially be in both passenger cars and freight transport, this would evolve towards 2050 to application mainly in heavy-duty vehicles. By this time, fuel cell cars could dominate the market for passenger cars and light duty vehicles. The key question is how long it will take until the affordability of hydrogen in the long run is 'sure' enough to attract investors, and whether this will still be in time for setting up a hydrogen fuelling infrastructure for large scale penetration of fuel cell vehicles.

POLICIES AND STRATEGIES

Both roadmaps pay attention to the policies and measures necessary to achieve the desired penetration of hydrogen and biofuels, respectively. The drivers differ. While the motivation for stimulating biofuels is mainly based on reduction of oil dependence and – for the first generation – agricultural motives, the promotion of hydrogen in transportation is motivated by emission reduction, improvement of local air quality, energy conservation, and, again but on a longer time horizon, reduction of oil dependence in the transport sector. Therefore, it strongly depends on the underlying policy objective whether policies will target biofuels, hydrogen, or both. Due to its high potential to contribute to various policy goals as well as the long time it needs before hydrogen will have a major share in mass market applications, a support scheme for hydrogen should already be implemented at an early stage. Under these conditions, the technology can learn at the right pace, minimising the still high investment hurdle that has to be overcome in order to reach full competitiveness. In the intermediate period, biofuels, such as 2nd generation FT-diesel, that offer synergies with hydrogen should be stimulated. This type of biodiesel not only paves the way for energy efficient biomass based hydrogen vehicles, but also offers main advantages in terms of land use and CO_2 reduction in comparison to other biofuels, with negligible modification needs for the vehicles or infrastructure.

For biofuels, the following conditions are crucial for a successful market introduction (Van Thuijl and Deurwaarder, 2006).

- Political commitment for a long period of time, which is important to create a favourable investment climate.
- Active involvement of market actors to create a biofuels market.
- Compensation for the financial gap between biofuels and fossil fuels. This is often done by means of a tax exemption, although there is a tendency towards a market based scheme where suppliers are obliged to have a certain share of biofuels in their annual fuel sales. Certification of biofuels and sustainability requirements are increasingly discussed to prevent for undesired side effects of a large penetration of biofuels.
- Creation of end-user demand for pure or blended use of biofuels, respectively in captive fleets or in all passenger cars.

The conditions listed for biofuels generally also apply to hydrogen. However, some additional barriers need to be tackled, because R&D and cost reduction challenges remain in all stages of the hydrogen chain. Particularly the requirement of a distribution infrastructure imposes a large initial cost barrier. A complicating factor is that an infrastructure should ideally be built with a long term perspective, implying that it should be heavily over-dimensioned for the first years of utilisation. Commercial companies will typically not be prepared to pay for this over dimensioning, while in a liberalised market, governments are no longer in charge of this. Therefore it is a challenge to provide the right incentives for a phased infrastructure development with a long term focus. Furthermore, specific incentives will be necessary to persuade consumers to switch from an ICE passenger car to a fuel cell car.

A general distinction can be made between generic and technology specific support schemes. Generic policies, such as emission trading, do not provide a sufficient incentive for hydrogen. Usually, these policies induce competition amongst different emission reduction options. The short term cost optimisation focus of these policies will not favour disruptive technologies such as hydrogen, whereas the potential for substantial emission reductions in long run is not taken into account. Therefore, additional, technology specific incentives will be needed for hydrogen in the early deployment phase. In contrast, the second generation of biofuels may benefit from generic policies, particularly when these are aiming at reducing the oil dependency.

Although there are synergies, there is a need for tailored policy approaches for both types of sustainable transportation fuels. It is clear that biofuels are more easily introduced in the current vehicle stock. And even if the same type of instrument, such as subsidies or tax exemptions, can be used for both biofuels and hydrogen, the support levels will have to be differentiated, just as they differentiate amongst different types of biofuels, or hydrogen produced from different sources. Moreover, depending on policy priorities, flanking measures such as prioritised parking places for environmentally friendly vehicles can be very effective. Policy guidance will also be needed to steer which feedstock for hydrogen production will dominate. This can be done for instance by providing low interest loans for investment in renewable H_2 production facilities. Similarly, biofuel policies could provide incentives for sustainable biofuel cultivation, e.g. by discouraging the use of land with a high biodiversity value.

Conclusions

Europe is aiming at a sustainable, secure and competitive energy system. As the transport sector shows the largest dependency on oil and the fastest growth in greenhouse gas emissions, it plays a key role in future policy design. This paper has evaluated the perspectives of two of the most promising options for a sustainable transport sector, biofuels and hydrogen, and has shown that they can be complementary rather than conflicting.

The only apparent conflict lies in the competition for biomass resources, which can be used for both the production of hydrogen and of biofuels. However, in case biomass resources are limited, hydrogen production from biomass offers major advantages over biofuels due to its higher efficiency. As the bio-based economy evolves, the competition with other applications such as food, electricity and heat production, is expected to increase as well. Efficient use of biomass, as for any feedstock, will become a major issue then. Is this a reason to prioritise hydrogen production from other sources? It is not, because the scarce biomass feedstock is used most efficiently in the transport sector when converted to hydrogen and used in a fuel cell passenger car, thanks to the efficiency of the fuel cell which is higher than that of the ICE. Another argument for aiming at hydrogen use is that from the coal-based competitors of both fuels – Coal to Liquid and coal-based hydrogen respectively – the latter is preferable as it allows for CO_2 capture and storage at the production site, retaining the option of zero-emission vehicles.

As a consequence, biofuels and their use in an internal combustion engine are regarded as transition options rather than the final solution for sustainable passenger transport. However, for heavy duty trucks, this situation is different. Here, hydrogen and fuel cells do not provide similar benefits, because the efficiency advantage of the fuel cell is much less with high continuous loads and the fuel storage potentials are too limited. Therefore, freight transport could provide a lasting and sizable market for the second generation of biofuels. Together with the application in passenger cars for the period until hydrogen in fuel cell cars has become affordable, this justifies the current efforts in developing second generation biofuels.

Consequently, the long-term objective should be to deploy hydrogen in passenger cars and advanced biofuels in trucks. If this is pursued, major synergies can be achieved in the BtL production chain, because the gasification process yields syngas from which either Fischer-Tropsch diesel can be produced, or hydrogen can be extracted. The extraction of hydrogen is probably even a cheaper process, (partly) compensating for the additional hydrogen distribution costs.

Finally, it should be stressed that for disruptive technologies such as hydrogen production, distribution and fuel cells, but to a lesser extent also biofuels, the role of policies will be crucial in achieving substantial market penetration.

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