The Competitiveness of Alternative Hydrogen Pathways

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Abstract

The paper surveys the literature on the competitiveness of alternative hydrogen pathways in the transport sector. The competitiveness of the alternative systems can be differentiated in the "well-to-tank (WtT)" and "tank-to-wheel (TtW)" sections of the pathway transforming primary energy to transport services and in market competitiveness and societal competitiveness. The major societal competitive advantage of hydrogen is its convertibility to electricity and from any other source of energy. This enables a flexible use of natural gas and primary electricity as transport fuels. The major advantage in market competitiveness is the energy efficiency of the fuel cell. This advantage is, however, to some extent balanced by the costs associated with conversion, transport, and storage. The balance between these factors required for market competitiveness is identified.

Keywords: Hydrogen and fuel cell technology, well-to-wheel analysis, market competitiveness, societal competitiveness.

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The Competitiveness of Alternative Hydrogen Pathways

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1. Introduction

1.1 Competitiveness of Alternative Fuel Pathways

Existing automotive systems consisting of fuel infrastructure, pathways and drive technology are expected to be replaced by systems based on alternative fuels in the future. A number of these are tested and demonstrated in the Zero Regio (ZR) project.

The socioeconomic component in the ZR-project aims at developing the information basis for public as well as private decisions on future investments in the sector.

The choices of transport services today are determined by the choices of technologies and policies in the past and the choices of policies and technologies today will similarly set the stage for choices of transport services in the future. For instance, today Brazilian consumers can choose to substitute gasoline for ethanol when gasoline prices become too high because of decisions in the 70s to develop the ethanol pathways. Wind energy has been added to the range of reasonably cost competitive options between which energy planners can choose because of the experience gained from wind energy deployment programmes in the recent past before this technology was cost competitive. Considerably more safe nuclear reactors are on the market today because of the investment in innovations driven by the failure of earlier vintages of the technology.

In all these cases, information about the current as well as the potential competitiveness of the future systems forms an important basis for the decision process. It includes the current and potential cost performance and other characteristics relevant to consumer or investor choices. It also includes the system performance with respect to societal concerns, such as energy security, environmental pressure, and energy efficiency. And it includes various approaches to weigh this information together.

For the innovation of hydrogen pathways a range of questions are important to address, including: How is the present and the future competitiveness of the pathway with respect to costs and other parameters, relevant to consumers and investors? How is its competitiveness with respect to societal priorities? How can these two types of competitiveness analytically be integrated? How can conflicts between market competitiveness and societal competitiveness be reconciled? How does the innovation policy affect the routes of pathway innovation?

The purpose of the study is to describe the state of the art of such systems and of the economics of hydrogen analysis in order to identify the systems supported by the technologies tested and demonstrated in the Zero Regio project and to assert the expected competitiveness of these systems.

The study also serves as preparatory study to the research in how the test results of the Zero Regio project can be transformed into more certain estimates of the costs related to alternative technological solutions.

For the pathways involved in the ZR-project, this paper will address the following questions: Which are the nearest "competitors"? What will it take to make the ZR-pathways the most competitive? What can we learn from the ZR-project about making these pathways the most competitive?

The ex ante answers to these questions will be based on the assumptions in the literature reviewed in this paper, but the results obtained throughout the ZR project will provide very robust data on technology in actual use and therefore reduce the uncertainty about the competitiveness parameters considerably.

1.2 Method

The paper identifies the pathways involved in the ZR project and attempts to make an account of what is known about their competitiveness prior to the project. The expected performance of the systems is then compared with the actual performance in daily use during the project period.

The competitiveness of an alternative fuel pathway is defined as market competitiveness as well as societal competitiveness.

The *market competitiveness* is defined by parameters such as accumulated costs and market value relevant to the market situation. All are accounted for in prices net of taxes and subsidies. The cost concept relates to the physical use of labour, capital goods, fuels, etc. in technically efficient use. That is, only the use of these goods that are necessary for producing the output is accounted for. Excessive use of inputs, e.g., due to lack of competition for cost efficiency is not accounted for. Furthermore the prices on the market are affected by taxes and subsidies according to local or national priorities.

The market value is the price that consumers are willing to pay. It depends on the cost of competing pathways offering similar transport services, but also a range of quality characteristics of which some are to some extent subjective.

Societal priorities play a role for the preference of one pathway for another at the level of society. In addition to the desirability the whole of the system can have more or less desirable properties according to societal priorities. Accordingly, the pathways are also analysed in terms of their *societal competitiveness*.

The social priorities relevant for societal competitiveness include energy security, energy efficiency, and environment. Employment and growth prospects that are related to a pathway can be important parameters too.

A vast bulk of studies has suggested answers to these questions and some of them have done so in the perspective of the entire fuel chain or the entire fuel pathway with its particular infrastructure and vehicle stock. In this study, we take particular advantage of four such studies, including Edwards, Griesemann et al. (2004), National Academy of Science (2004), Ogden, Williams et al. (2004), and Sorensen (2005). We then attempt to confront the findings with studies of more partial aspects of the issue.

The most comprehensive and thorough analyses of hydrogen pathways are the Well-To-Wheel (WTW) studies and Life Cycle Cost Assessments (LCCA) performed by Edwards, Griesemann et al. (2004), National Academy of Science (2004), and Ogden, Williams et al. (2004) backed by a all-encompassing review of natural science, engineering and socioeconomic problems by Sorensen (2005). In this study, we take departure in the results of the study by Edwards, Griesemann et al. (2004) offered with a considerable detail and in a European context.

In the following sections the results of a number of the most recent Well-to-Wheel (WtW) studies will be used to compare alternative pathways for the hydrogen fuel chain. They include Edwards, Griesemann et al. (2004), National Academy of Science (2004), Ogden, Williams et al. (2004), The Alternative Fuels Contact Group (2004), and Sorensen (2005). Additional studies are included to highlight specific problems in the individual links of the hydrogen fuel chain.

2. Hydrogen Pathways

2.1 Production, Transport, and Use of Hydrogen

Most hydrogen is produced by steam reforming natural gas because it is a relatively inexpensive hydrogen carrier. Other hydrogen carriers can be relevant as natural gas prices increase and technological advances makes other carriers useful. Recent research has shown that even a hydrogen carrier like ammonia that is made of hydrogen and nitrogen could potentially assume a central role because it is easier to store and transport than natural gas as well as hydrogen.

Hydrogen is also produced with electricity by electrolytic decomposition of water in hydrogen and oxygen. Inexpensive electricity is available at off-peak times, where the capacity otherwise benefits low value uses.

Hydrogen is also produced as a co-product of chlorine and caustic soda from salt (NaCl) dissolved in water.

Finally, technological advances suggest that hydrogen potentially can be produced as a co-product with electricity and captured CO2 from coal.

In the last two cases, hydrogen produced as a by-product of industrial production or as a co-product with electricity and CO2, production has to be central due to the nature of the process.

In the first two cases, hydrogen produced from a hydrogen carrier or from electricity, the issue of central or decentral production has been central in the research on alternative fuel distribution infrastructures.

The classical options for distribution from a central production site to filling stations then include pipelines, compressed hydrogen by truck, or liquefied hydrogen in tanks by truck.

The options for decentralised production include transport and storage of natural gas or electricity to a network of conversion units. Natural gas can be reformed to hydrogen at the filling station ("on-site") or in the vehicle ("on-board"). Electrolysis can convert electricity to hydrogen practically everywhere.

Recent research has suggested that it could become advantageous to convert the centrally produced hydrogen to energy carriers, such as ammonia or methanol that are easier to transport and store. In that case, we have central as well as decentralised production. This technology could potentially change the competitiveness of the latter three forms of central hydrogen production – electrolysis, by-product, and carbon capturing and sequestration.

The ambitious goal of the Edwards, Griesemann et al. (2004) study is to perform WTW analyses of all the potential fuel pathways that could potentially succeed the gasoline and diesel pathways on which modern transportation is built. Their method is to split the WTW pathway in a Well-To-Tank (WTT) pathway and a Tank-To-Wheel (TTW) pathway that produce comparable characteristics and can be combined in various configurations.

Based on the analysis, the results can lead to conclusions on the characteristics of the entire fuel and vehicle chain as to technical parameters (energy consumption, greenhouse gas emissions) and economic parameters (unit costs, investment requirements).

The results are comparable with a similarly thorough study by the National Academy of Science (2004) but in a United States context.

The cost properties of the fuel and vehicle chains are further scrutinized by Ogden, Williams et al. (2004), and the European investment requirements by the Joint Research Centre of the EU Commission (2004).

2.2 The Zero Regio Pathways

A pathway is the route, followed by an energy source to its purpose as useful automotive fuel. Edwards, Griesemann et al. (2004) offer a diagrammatic exposition:

Figure 1. The Structure of an Automotive Fuel Pathway

Source: Edwards, Griesemann et al. (2004).

The pathways tested and demonstrated in the Zero Regio project comprise the processing and the conditioning and distribution. These pathways include conversion from natural gas to hydrogen centrally and on-site (OS) and use of the hydrogen in vehicle fleets. In the case of central production, hydrogen is transported to filling stations by pipeline and by truck, compressed and liquefied. The conversion of natural gas is accomplished as a co-product with chloride, by methane steam reforming, and by partial oxidation.

The project enables the project consortium to harvest test-data concerning a close to real life operation of these technical solutions over 10-12 quarters. Comparing the test data for alternative pathways and with data from similar studies will reveal information about the competitiveness of the alternative technical solutions to one-another and to other technical solutions that are not included in the project. Additionally, this information will improve the appraisal of costs and effects of the future similar projects in the EU (light-house projects, hydrogen communities, road-maps, etc.)

3. Market Competitiveness

3.1 Well-to-Wheel Studies

The interesting end user costs of the alternative hydrogen pathways are the costs per transport service (€/vehicle kilometre (vkm)). It is expedient to split them in the Well-to-Tank (WtT) component, hydrogen costs, and the Tank-to-Wheel (TtW) "fuel economy" hydrogen consumption per transport service. In the following some recent analyses of these topics are reviewed.

3.2 Tank-to-Wheel, Vehicle Related Costs

3.2.1 Fuel Cells and Energy Efficiency

The future efficiency of FCVs are difficult to assess, but The National Academy of Science (2004) made the following standard assumptions of the fuel efficiency of future powertrain technologies.

Table 1Assumptions of Energy Efficiency Advantage for Future Vehicle Technologies

Technology	Energy Efficiency Advantage
Current conventional ICEV	1.00
Future GHEV	1.45
Future DHEV	1.45-2.40
Future FCV	2.40

Source: National Academy of Science (2004)

The fuel cell vehicle referred to here is equipped with Proton Exchange Membrane fuel cells (PEMFC) fuelled directly with hydrogen since this technology is considered superior to all other fuel cell technologies in automotive transport. Based on these assumptions the energy efficiency advantage of hydrogen fuel cell vehicles (FCV) is extraordinary large. However, there is a possibility that very efficient diesel engines in hybrid electric vehicles could represent a very serious competition.

3.2.2 Dynamic Economies of Scale

The current costs of fuel cells and the entire fuel cell drive system does not allow commercialisation except for special niche products. The future costs of H_2 FC vehicles are difficult to estimate. They depend first of all of expected breakthroughs in the production of fuel cells, but also of the division of labour that will emerge from the H_2 FC technology. For instance, it is possible that the individual labels of FC vehicles will be designed on a common frame or board opening up for extended scale economies.

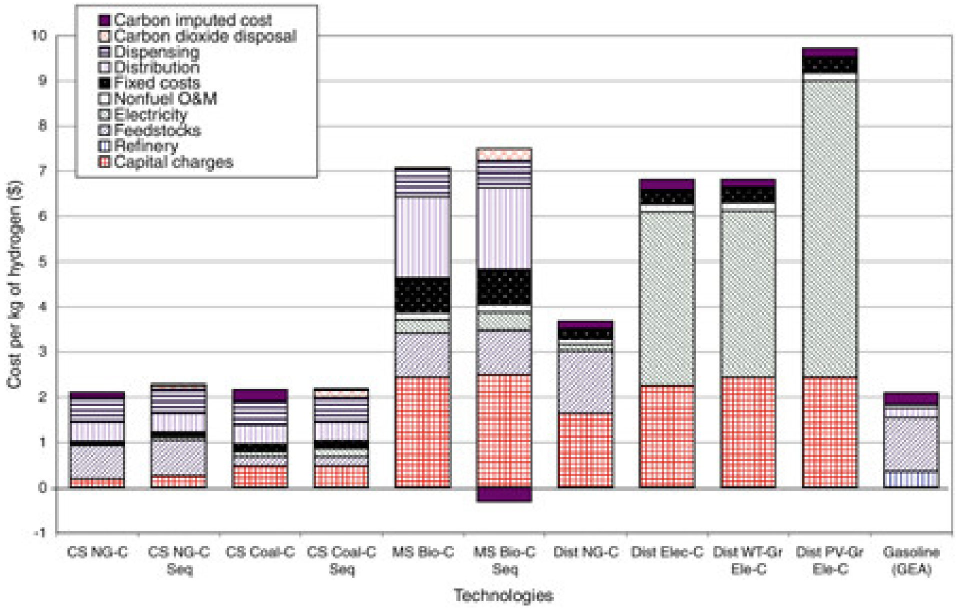
The aspects of H_2 FC vehicle costs are treated in more detail in Chernavs´ka and Lanfranconi (2005).

3.3 Well-to-Tank, the Hydrogen Costs

3.3.1 Retail Hydrogen Costs

A study carried out by National Academy of Science (2004) compared alternative pathways to produce hydrogen in the USA by their costs as anticipated for the near future (10-15 years).The result is shown in the figure below.

Figure 2. Unit Cost Estimates for "Current Technologies" in the US.



Source: National Academy of Science (2004)

The results show a marked difference in hydrogen production in the favour of "Central Station" (CS, 2 mio. vehicles) over "Midsize" (MS, 40,000 vehicles) or "Distributed" (Dist, 400 vehicles) production of hydrogen. The difference between natural gas (NG) and coal is insignificant and so is the difference between carbon sequestration (C Seq).

Gasoline Efficiency Adjusted cost (GEA) represent the gasoline costs (1.27 $/gal) at a crude oil price of 30 $/bbl adjusted for the energy efficiency difference between a FCV and a GHEV. It allows comparison with the cost of the gasoline needed to fuel a GHEV the same distance as 1 kg of H_2 would bring a FCV. At the present, the GHEV is the closest competitor to HFCVs. The analysis shows that theoretically, the best current HFC technology is close to be competitive with GHEV technology, but not more than that.

However, the assumption of 2 mio. vehicles per central station is not realistic in the near future. The underutilised capacity of central stations and their distribution networks could easily elevate the costs of centralised production beyond those of on-site NG reforming.

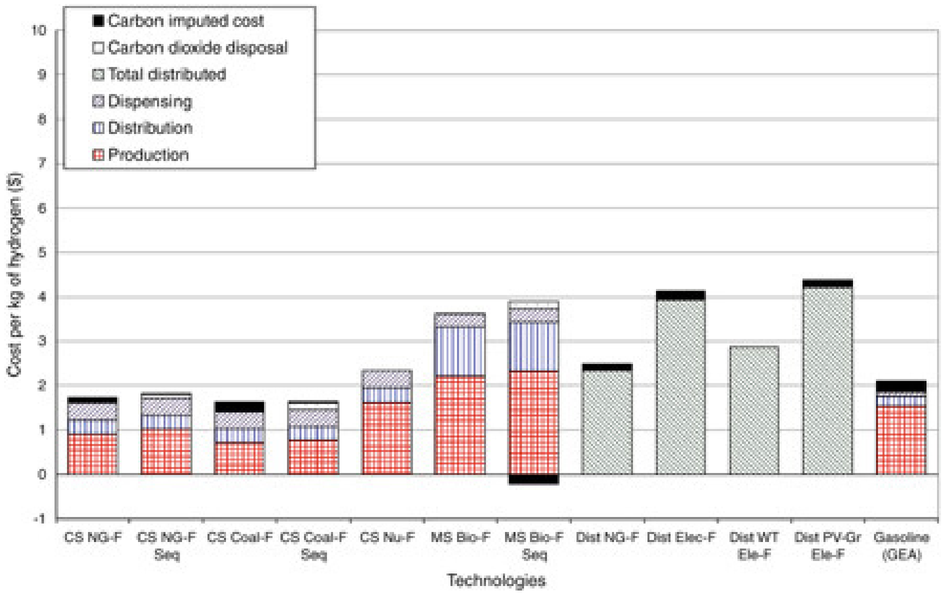
The results rely on the assumption that carbon capturing and sequestration in a central station is very inexpensive (10 $/tCO_2$ or 0.07 $/kg H_2 for coal and 0.19 $/kg H_2 for NG). This estimate is disputed by Anderson and Newell (2004) who finds $200 to $250 per ton carbon (that is, about $55-$68 per ton CO_2) a more realistic estimate.

Electrolysis is still an expensive way of producing hydrogen according to the National Academy of Science (2004). The production cost does not depend on scale and these calculations are based on an assumption of feedstock electricity cost of 0.07 $/kWh for grid electricity and 0.06 $/kWh for wind power. The wind power is, however assumed only to be available 30% of the time, whereas the electrolysis runs non-stop backed up by grid power.

The study further concludes that hydrogen could become less expensive than the efficiency equivalent amount of gasoline as the technology develops. Technological development could also bring nuclear power based hydrogen closer to the low cost sources of hydrogen.

A similar comparison is made for future technologies with performance rates anticipated upon successful completion of R&D projects. In the estimates of future cost performance of the various technologies a dedicated nuclear power based production of hydrogen is added to the list of technological options.

Figure 3. Unit Cost Estimates for "Future Technologies" in the US.

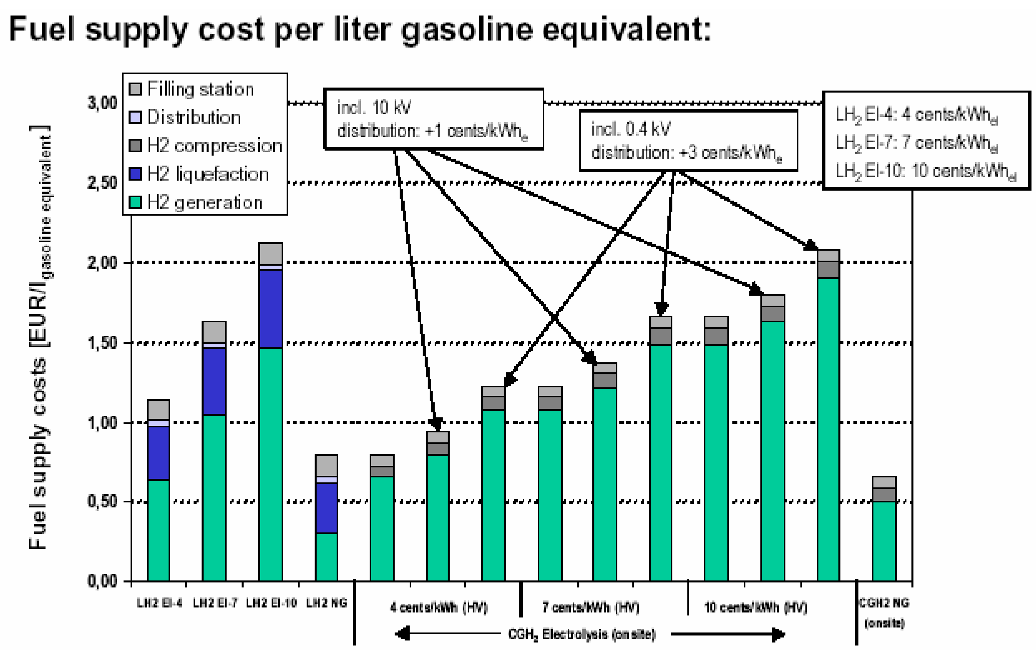


Source: National Academy of Science (2004)

The expectations to the future cost performance of hydrogen production and distribution technologies are that scale economies prevail and centrally produced hydrogen will be cheaper than the comparable amount of gasoline. On-site natural gas reforming and wind-power based hydrogen are, however, anticipated to approach the costs of gasoline – HEV technology, still calculated on a 30 $/bbl assumption.

The Alternative Fuels Contact Group (2004) made a similar study, comparing a wider range of hydrogen production processes. The results are shown below.

Figure 4



Source: The Alternative Fuels Contact Group (2004)

The difference between electrolysis and steam reforming costs are due to a difference in conversion loss but also to higher capital costs of electrolysers. However, in this study an interest rate of 12% was assumed, which also contributes to higher cost estimates for capital intensive production processes.
Ogden, Williams et al. (2004) estimate the costs of hydrogen based on natural gas or coal to $2.2-2.5 per kg depending on carbon sequestration or not.

For comparison the US Environmental Protection Agency (2005) uses a hydrogen cost assumption of $5.80 per kg for comparisons of the fuel economy of 2006 FCV models with other 2006 car models.

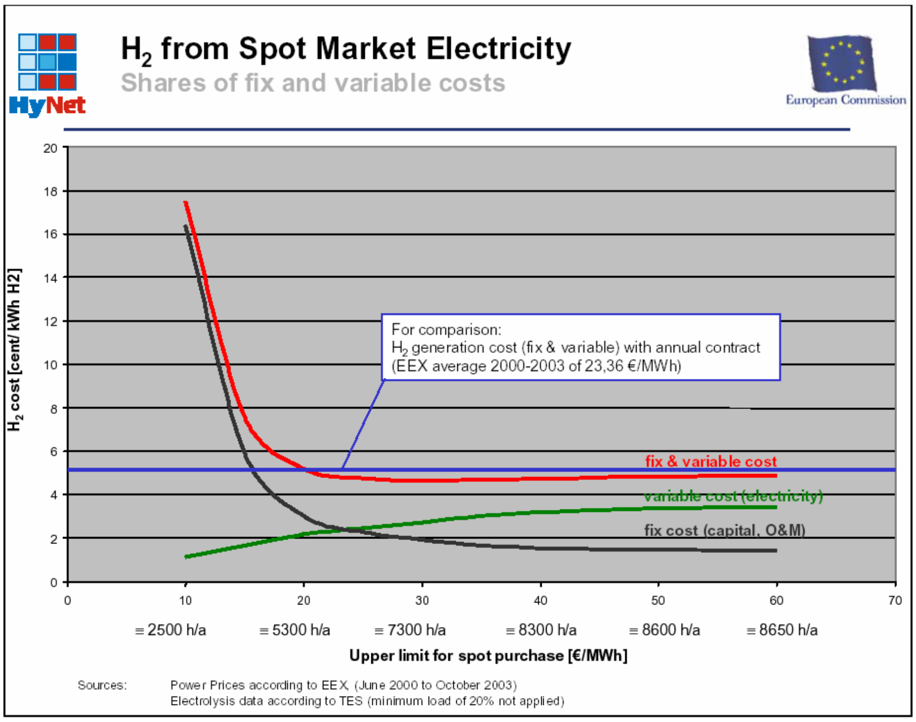
3.3.2 Comparing Natural Gas Steam Reforming with Electrolysis

The studies use different assumptions of oil and gas prices and discount rates/capital charges. Crude oil is assumed to cost 25-30 $/bbl, but this is hardly a realistic prediction for the future decades. This would be of no importance for the relative prices of oil and natural gas if natural gas was proportionally indexed to oil prices, but this is not the case. To the extent natural gas prices are decoupled from oil prices, a considerably higher oil price will increase the competitiveness of not only electrolysis, but also natural gas based pathways relative to petro-fuel pathways.

Discount rates and capital charges also play a role for the results because higher discount rates or capital charges increase the difference between facilities that are capital intensive or long enduring and those that are not.
Thus, there are good reasons to recalculate the cost estimates on the basis of alternative sets of economic assumptions that are internally consistent.

An often discussed question is whether it is reasonable to use the average electricity price for estimating costs of electrolysis when the electricity could be used at off-peak hours where prices are lower. A study by The Alternative Fuels Contact Group (2004) highlights the question of the relation between electricity prices and H_2 costs.

Figure 5. Electricity Spot Prices and H2 Costs.



Source: The Alternative Fuels Contact Group (2004).

The figure shows that the variable costs of electrolysis are indeed lower at off peak hours, but if the electrolysers are restricted to operate in that period, the considerable capital costs of electrolysers will more than offset that advantage. This means that electrolysis cost on the one hand differs from steam reforming by its lack of scale economies, but on the other hand are very sensitive to the utilisation rate of its capacity.

3.3.3 Geographical Context

The hydrogen supply density – measured as e.g. the time required for finding a filling station – is important for the attractiveness of FCVs to the consumers and therefore for the geographical hydrogen demand density. The geographical demand density is on the other hand the economic basis for the density of the distribution network.

Vehicles and fuel chains can be combined in a number of ways, but the range of optional combinations depend on the time and space content in which they are introduced. The natural gas grid is, for instance, not covering every single spot of Europe and central hydrogen production requires a certain minimum demand to be efficient. Thus, the competitiveness of a particular pathway relative to competing can differ from place to place in Europe.

Most of the studies of efficient scale points to central production of hydrogen distributed in compressed form by pipeline or by truck. Thereby the scale economies in reforming, storage, and carbon sequestration can be utilised.

The central production facilities analysed in National Academy of Science (2004) requires each a demand from about 2 mio vehicles. The study asserts that the US market will need 20 central production units with appropriate transportation networks. In the transition phase, this requirement is challenges by the diffusion of H2FCVs in the vehicle stock of the geographic area in question. In this perspective, distributed hydrogen production could be necessary to supply the local H2FCV stock in the phase of which it is build up. Alternatively, the central production unit would have a large spare capacity in this period. This feature means that in the transition phase, the scale economies in reforming, storage, carbon sequestration, etc. will either be abandoned because hydrogen production is distributed or be unattainable because of spare capacity.

This means that the comparisons of distributed hydrogen production with central hydrogen production do not reflect the real competitiveness of the alternative pathways in the transition phase. A careful re-examination of different the relative performance of the systems in their geographical context is necessary.

On the other hand, The Alternative Fuels Contact Group (2004) points to the flexibility of liquid H_2 production where scale economies allegedly are less important.

In sparsely populated or motorised areas, renewable electricity based hydrogen could possibly be a more economic option, even if a hydrogen pipeline network is the economic choice in areas with high concentrations of motorised transport. Prince-Richard, Whale et al. (2005) arrive at an additional electricity cost of 1-3 USc/kWh for distributed electrolysis and filling facilities. In that case, geographical circumstances could make a big difference for the competitiveness of on-site NG reforming as compared with distributed electrolysis.

For example, in islands and mountainous areas, truck accessibility and demand basis for pipeline extension can be too limited for centrally produced hydrogen. If it is also too limited for delivery of natural gas, renewable electricity (wind and biomass) could easily be the competitive feedstock.

The property that ultimately makes H2FCVs competitive to the of EVs is the accessible range on tank (power-load) and the time required for reloading. If this difference in vehicle performance is less important in the same areas, it is perfectly possible that the cost competitive solution in such areas will be renewable electricity with grid connected EVs or HEVs, whereas the cost competitive solution in agglomerations will be on-site reforming of hydrogen from the NG grid in the short perspective and centrally produced hydrogen in a longer perspective.

Grid operators may have a supply obligation and thus a grid extension, which is not competitive to other solutions. The same could be the case for a hydrogen pipeline network. However, the cost competitiveness of the alternative pathways without supply obligation remains important information for the planning process.

Most of the European land area is somewhere between these extremes, and it is important to get closer to the question of competitiveness in different geographical contexts. This study does not command resources to provide a complete coverage of the European land area, but it is possible to arrive at some conclusions about minimum efficient scale and economies of scope, etc. in various geographical contexts.

3.3.4 Filling Station Costs

The European Parliament had an analysis carried out on the socioeconomic aspects of hydrogen (Mario, Iacobazzi et al. (2003)). The study calculated the costs of an accelerated introduction of hydrogen in EU in the 20s leading to a hydrogen substitution of automotive fossil fuels by 22% in 2030. Apart from the investment in the hydrogen production capacity, the study assumes a hydrogen distribution network of 14,000 refuelling stations fuelling 66 mio vehicles (first fleet-vehicles, then household cars). The result was a need for finance of €467 bio. This should, however, be compared to the alternative finance requirement related to conventional and bio fuels.

Another report made for Linde AG estimates the costs of a 7000 Nm^3/day capacity filling station to €0.3-1.5 depending on the concept chosen (E4tech (2005)). The least expensive concept is based on central hydrogen production delivered and stored at the station as liquid H_2. Two alternative concepts include a natural gas steam reformer or an electrolyser.

3.3.5 Dynamic Economies of Scale

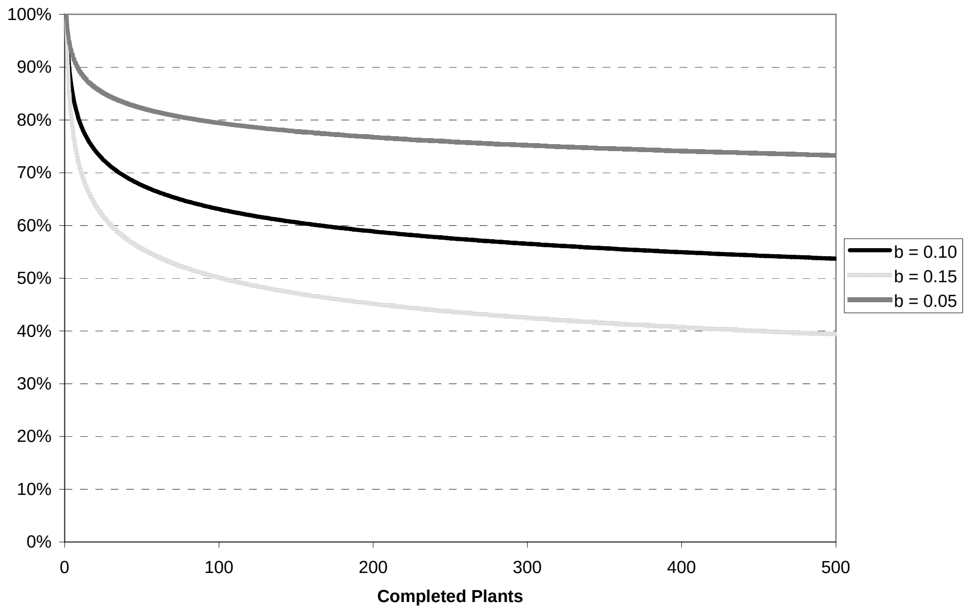
The E4tech (2005) report estimates that the first "vintages" of filling stations will be several times more expensive than the cost levels assumed in the longer term. The assumed cost levels are 2-3 times higher in the first year than in the second year of the investment programme. After this they decline moderately throughout the programme period.

The Alternative Fuels Contact Group (2004) uses the following formula for determining the investment I of the n^{th} plant:

(1) $$I = a\, n^{-b},$$

where *a* is the investment for the 1^{st} plant and the parameter *b* has the value of 0.1. The parameter value is based on comparative studies of the economies of scale in the field of chemical and process engineering. This assumption intends to reflect the dynamic economies of scale or in other words the extra cost of learning to master a new technology before it becomes routine. Thus, the cost of the first plant may be considerably above the long term cost of plants. The time profile of learning as reflected in the exponential learning function is shown in the following diagram.

Figure 6. Investment Costs of N'th Plant Under Alternative Learning Rate Assumptions



Assuming a learning rate of 10% implies learning costs in addition to the long term (say, more than 100 plants) costs of 50-80% to the first plant. If the learning rate is 15%, the first plant will be 100-150% more expensive, but if the learning rate is 5%, the first plant will only cost 25-50% more than the long term plants. Any estimate of the future competitiveness of equipment and facilities in the hydrogen infrastructure is thus highly dependent on the assumed learning rate, which makes it crucial to devote a considerable amount of research effort to attempt to quantify the learning costs.

Learning effects appear on industry level as well as plant level and for processes as well as products. To distinguish between industry and plant level, the term "experience" is often used for industry-wide learning instead of "learning". For the hydrogen infrastructure, the important learning costs are in the establishment of filling stations and infrastructures (products) as well as in the operation of these (process). The diagram above can represent the process learning as well if the title of the horizontal axis is changed to "Cumulated Number of Vehicle Fillings".

The Zero Regio project in itself can contribute with knowledge about the plant level process learning costs since it runs over 10-12 quarters. The project will, however, not provide information about experience effects that is, industry-wide learning or general knowledge in the industry about how to run a hydrogen filling station.

The contribution to knowledge about the long term costs of infrastructural facilities and equipment will be much more limited, but some information can be obtained through identification of the components of plant investment costs that are sensitive to learning. These can be compared with available other data from other hydrogen filling stations and transport and storage facilities.

3.4 Other Consumer Criteria than Costs

Other features than vehicle purchase cost, operational (fuel) cost, and maintenance costs are important for the value, customers attach to a vehicle. They include several parameters of quality and design, range (between refueling) and refueling convenience, passenger/cargo space, performance (acceleration, speed, ride quality, acceptably low levels of noise, vibration, and harshness), and safety (National Academy of Science (2004)).

The most important factor will probably be the density of the hydrogen distribution network.

The safety parameter includes risks associated with heat, cold, pressure, flammability, toxicity, etc. The documented performance with respect to these risks is important information for infrastructure planning and regulation, but it is the perceived or subjective risks that are important at the market place.

Some consumer segments additionally put a value on environmental performance. Experience from the US hybrid car market seems to reveal that a relatively large group of consumers are willing to pay a higher price for a hybrid vehicle. Motivations for this can be many, but two motives are quite intuitive: First, a fuel efficient vehicle - even if it's higher cost out balance the fuel savings - also makes the household budget less prone to unexpected rises in fuel prices. This "oil-price insurance" is worth something to many consumers. Second, a hybrid car allows consumers to drive in urban areas without harming other people through air and noise pollution. This quality of a vehicle seems to be increasingly valuable for many consumers. The choice of vehicle is more exposed to the public than most other consumer choices and therefore this choice can to a very high degree be affected by the preferences to establish a particular identity as a socially responsible citizen or the like.

The market for vehicles that runs solely or optionally on biofuels similarly offers the quality of being able to escape the "dictatorship" of oil prices. To some consumers the ability to be achieve independence of the market power present at the oil market, represents a value in itself.

In the future, even the "clean-ness" of the primary energy feedstock could be a parameter, parallel to the value put on organic farming. This would improve the competitiveness of renewable electricity based pathways compared to fossil fuel and nuclear electricity based pathways.

These issues are dealt with in detail in task 7.2 about the consumer acceptability.

4. Societal Competitiveness

The market competitiveness of a pathway that is a fuel chain with its particular infrastructure of transportation, conversion, and storage facilities and its feedstock manifests itself in the end use costs that cumulate all costs along the fuel chain. Whereas costs and prices reflect our preferences as consumers, political priorities reflect our values as citizens.

For hydrogen infrastructure solutions, the criteria include the major priorities of energy policy, industrial policy and transport policy.

The goals of energy policy include in practically all countries fuel supply security, environmental pressure, and energy efficiency that support these goals as well as cost competitiveness. Industrial policies are aimed at getting most out of domestic productive resources. Transport policies are aimed at increasing mobility, accessibility, and safety, but these are only remotely linked to the fuel infrastructure. In the following we will, based on the relevant literature, define more exactly the criteria on which hydrogen infrastructure can be assessed according to these general priorities.

4.1 Fuel Supply Security

Fuel supply security has been at the hearth of European cooperation since the original coal and steel union. It can be categorised in three levels:

1. **Security safeguarding against supply disruptions due to technical failure, sabotage, or bottlenecks in the individual links of the supply chain.**
2. **Short term readiness to maintain the fuel flow in case of disturbances in fuel supply due to changed behaviour of fuel suppliers.**
3. **Long term measures to meet challenges of anticipated trends in fuel markets.**

Short term supply security became a high priority after the supply disturbances in 1973-74, 1979-80, 1991, and recently by the destruction of refinery capacity in 2005. Low short run demand elasticity and the critical role, transportation pays in the economy, makes supply disturbances harmful to the economy. Governments prepare for this type of events by maintaining a buffer stock of oil and promoting diversification and substitutability of fuels.

In a recent report to the ExternE project Markandya and Hunt (2004) attempts to quantify the economic effects of a shortfall of oil supply to the international oil market. A review of the literature on macroeconomic models reveal a wide dispersion in GDP growth effects. Markandya and Hunt (2004) use the assumption that a \$10 per bbl increase from \$25 causes a loss of 0.5% GDP in the EU and \$178 bn on world scale. They address the issue of whether and how the uncertainty of future price increases can be quantified and the policy implications.

Even if the costs of oil supply insecurity could be quantified with a degree of certainty that makes the result sufficient to make a difference in the choice of energy security policies, the importance of this for the hydrogen transition is ambiguous. Hydrogen is only one of several alternatives to oil, and the extent to which they can provide a ceiling over oil prices hardly depend on the share of hydrogen in the total supply of alternative fuels. Alternative fuels and progress in energy efficiency should be seen as a whole when analysing their effect on oil demand.

To the extent that the primary fuel base of hydrogen supply will be provided by domestic sources this fuel supply security problem is generally supported by introduction of hydrogen. The issue has been raised that natural gas based hydrogen substituting petroleum fuels indeed will reduce the risk to EU automotive fuel supply of supply disturbance from oil producing countries. Natural gas supply is to a higher extent provided by domestic resources and less risky imports from other countries. But reliable natural gas flows from a limited number of countries (Russia and Algeria) will still be crucial for the resilience of natural gas markets in Europe.

Again the ability to convert electricity (and possibly coal and biomass) to hydrogen will provide Europe with a higher degree of short term automotive fuel supply provided that the capacity is installed.

The anticipated long term growth trends in supply of and demand for transport fuels has made long term fuel supply security a high priority in most countries. Not only must prices be expected to rise over a long period, but a tight market is also more vulnerable to events causing short term supply disturbances. In addition to the low demand elasticity, supply elasticity is also low in short run.

The long term fuel supply security is accentuated by the depletion of the non-OPEC oil fields leaving an oil market with a strong market power for the remaining oil producers and potential conflicts over the sources a long time before exhaustion of the reserves themselves become critical.

The main instrument to prepare for this long term fuel supply security problem is diversification of the fuel supply structure and energy conservation. In the recent decades, the primary energy sources for heat and electricity has been significantly diversified and considerable progress in heating efficiency and electricity use have been achieved. Automotive energy use, however, still relies almost exclusively on petroleum based fuels and energy efficiency on average is progressing slowly. This is probably the single most important factor driving the emphasis on development of hydrogen and fuel cell technologies.

The contribution of hydrogen and fuel cell technology to fuel supply security in general is therefore basically that it opens up for the highest degree of diversity in the fuel supply and as a result of this establishes an open competition between alternative technical solutions to production, storage, transport, etc.

In this perspective the supply security of the individual infrastructures are not crucial to the overall fuel supply as long as the diversity itself is maintained. Rather, diversity is a planning objective in itself.

4.2 Leaks and Safety

Hydrogen leaks occur necessarily throughout the hydrogen fuel chain. The significance of this for the environment and for safety is not yet completely understood. However, leaks by filling or driving are a matter of concern for FCV designers who equip vehicles with grounding cables and hydrogen sensors in the cabin.

Farrell, Zerriffi et al. (2004) reviews the literature on what makes fuel supply infrastructures more brittle or more resilient. Centralised systems are considered less resilient than decentralised systems with a high degree of independence between modules. A centralised system is not more resilient than the central nodes on which the rest of the network depends. Measures to safeguard the security of a single fuel infrastructure include requirements of redundancy and buffer storage, back-up facilities and emergency plans, access control and other security routines. The resilience of the entire fuel supply does, however, depend on the diversity of supply chains and its integration with neighbour countries' fuel infrastructures. All of these measures are also found in the instruments used by the European Union and the member states in their efforts to secure fuel supply.

On the basis of such considerations, the electricity network is found to be the most vulnerable, then the natural gas network, then petroleum product infrastructure, and finally coal (Farrell, Zerriffi et al. (2004)). It could be added that then a future biomass based fuel infrastructure must be the at least as resilient as the coal infrastructure.

The bearing of these observations on the fuel infrastructures considered in this report is that the systems share the vulnerability of the natural gas systems or electricity networks, they extend. Although they definitely represent new technological challenges in the individual links of the chain, they do not as systems represent new vulnerabilities.

The main effect on fuel supply security is that the convertibility of any energy source, including electricity, to hydrogen makes a much higher degree of diversity possible. In this respect, progress in the applicability of hydrogen technologies supports fuel security *per se*.

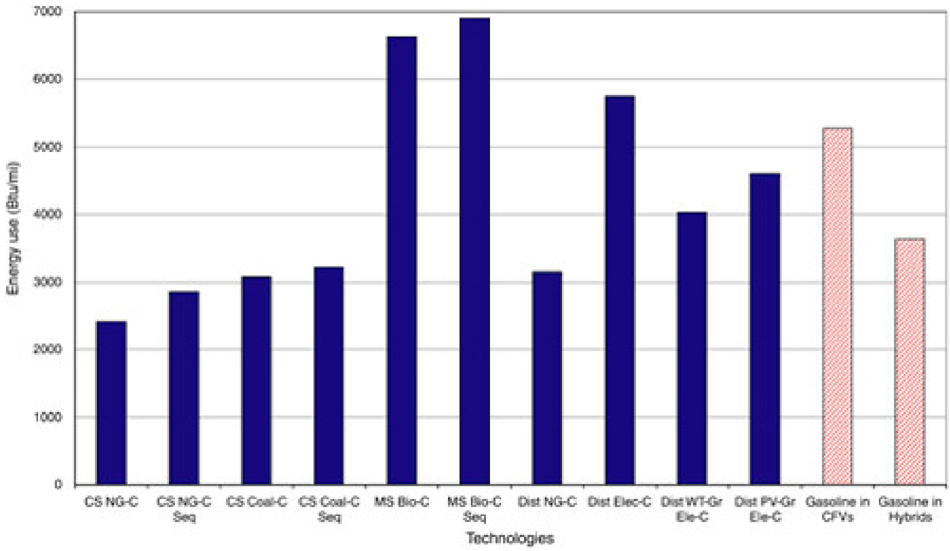
However, it can be argued that occupation and transport safety is at risk the more explosive and chemically reactive the fuel is. Hydrogen carriers such as fossil energy based fuels, methanol, and ammonia are generally perceived to be less demanding for additional security technology compared to the technology used today. In particular, storing of ammonia in natrium chloride for on-board reforming could have some competitive advantages compared to compressed or liquid hydrogen as to security in handling along with the advantages of a high energy density.

4.3 Efficiency

Progress in fuel efficiency supports the other policy objectives (cost efficiency (or market competitiveness), fuel supply security, and environmental concerns.

One the studies from National Academy of Science (2004) is summarised in the figure below.

Figure 7. WtW Energy Consumption per Vehicle Mile of Alternative Hydrogen Pahways (Present Technology).



Source: National Academy of Science (2004).

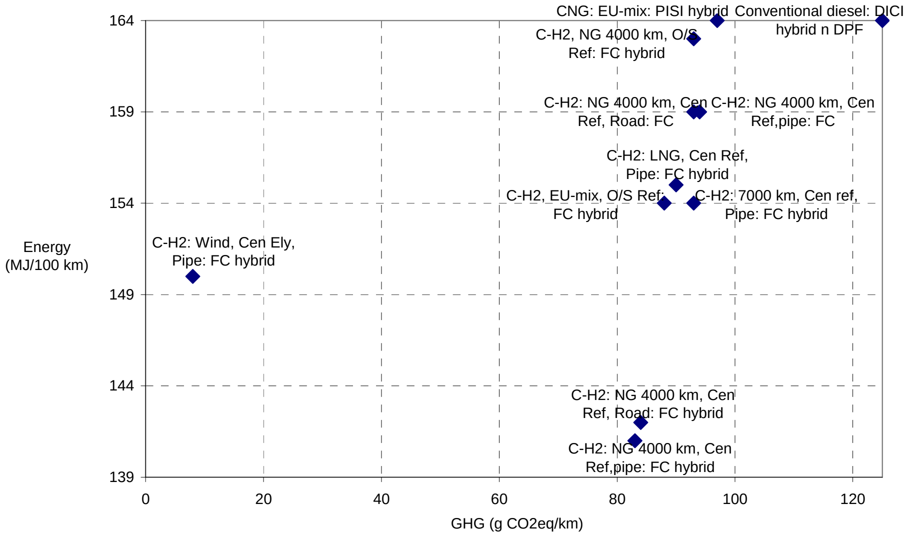
The results shown in the figure, indicates that fossil fuel based hydrogen pathways are considerably more energy efficient than the conventional gasoline fuel pathway ("Gasoline in CFVs"), but only marginally more energy efficient than the GHEV-pathway. Moreover, the present stage of electricity based pathways are less energy efficient than the GHEV-pathway because of the energy loss in electricity generation and electrolysis. Biomass based hydrogen pathways seem to be the most energy consuming of all the considered pathways.

However, compared to other pathways, a low energy efficiency of biomass does not constitute a relative weaker competitive position. Energy efficiency is important because it supports the overall goals of cost effectiveness, environment, and fuel security. For a given pathway the standard priority would be that a higher cumulated energy efficiency is better than a lower. But the energy efficiency of a biofuel pathway can be lower than the energy efficiency of an alternative pathway and yet be better in terms of costs, environment, and fuel security. This can occur if biomass is abundant – and thus inexpensive – and can be used for processing of biomass to valuable biofuels. The core issue is the value of the biomass and other resources in question in alternative uses.

Thus, the result of comparing of pathways based on very scarce primary energy sources with pathways based large untapped and low cost sources should be interpreted with care.

Two technological breakthroughs seem to be necessary for getting the full benefits of the H_2FC technology in transport. One is to develop low cost methods of electrolysis.

Figure 8. Estimated Energy Consumption and GHG Emissions for the Top Ten Alternative Fuel Pathway/Powertrain



Co
mbinations.

Source: Edwards, Griesemann et al. (2004) and Authors' calculations.

The Edwards, Griesemann et al. (2004) WTW study compares 372 combinations of fuel pathways and powertrains with respect to energy efficiency and greenhouse gas emissions. The top performing conventional pathway/powertrain in 2010 is expected to be a conventional diesel pathway in a hybrid vehicle. If we take out all the combinations of alternative fuel pathway/powertrains that are better with respect to energy efficiency and emissions, we get the ten combinations shown in figure 1.

The CNG fuelled hybrid with port injection is a near market technology that would potentially be less polluting and as energy efficient as its diesel sister. "EU-mix" stands for the present mix of sources of natural gas and thus the average distance, it has to be transported.

In the future, it is expected that additional EU natural gas supplies have to come from the Caspian Sea Region or Siberia, respectively 4000 and 7000 km away. Longer transport distances imply larger energy losses, but in the case of 4000 km transport, the energy cost of transport to a filling station with on-site (O/S) reforming can be compensated for by the fuel efficiency of a hybrid fuel cell vehicle (HFCV). "Hybrid" in this context means with recovering of brake energy.

Energy efficiency can be further improved if the natural gas is centrally rather than on-site reformed, even the vehicles don't recover brake energy. There is no significant difference with respect to either parameter whether it is transported from the central production facility to the filling station by pipeline or by truck.

Further improvements are obtained if brake energy recovery is assumed, even if the distance is raised to 7000 km or the gas is transported as LNG, which both are energy consuming options.
The present average transport distance for natural gas in the EU reformed to hydrogen on-site and used in an HFCV is more efficient (but not much more) than all of the above options.

Two alternatives stand out as the significantly best: 1) Wind power with central production of compressed hydrogen by electrolysis, pipeline transport, and use in a HFCV. This option is particularly favourable for energy security and environmental sustainability. 2) Natural gas from a distance of 4000 km, with central reforming to compressed hydrogen, used in an HFCV. This option is particularly favourable for energy efficiency. Again, there is no significant difference as to whether it is transported by pipeline or by truck to the filling station.

The study was based on the available literature and updated as far as possible by expert opinions. There are, however a broad range of uncertainty surrounding the estimates. The ZR project tests a range of the top ten solutions, including central to filling station by pipeline, truck, and LHG, in-site reforming of natural gas, fuel cell vehicles (with or without brake energy recovery?).

Therefore, the data collected during project can be used to narrow down these uncertainties considerably for the benefit of future investments and research efforts in hydrogen pathways and their infrastructures.

Detailed records of hydrogen transportation, energy consumption at the individual links in the chain, and hydrogen leaks and evaporation are obtainable from the project. They will be used to assess systematically, the robustness of the conclusions such as the insignificant difference between pipeline and truck transport when a very high pressure in the pipeline is used or the difference in energy efficiency between central and on-site reforming.

A range of biofuel pathways are included in the report. They include hydrogen, synthetic diesel, methanol, ethanol, SME, RME and FAME from wood, agricultural crops, or biomass waste. They generally fall short of the top ten list because of their energy requirement. This result, however, crucially depends on the assumptions that they are produced domestically (i.e. in the EU) and on the assumptions of the share of energy and emissions in production associated with the fuel.

The assumption of domestic sourcing of biofuels limits the availability of low cost biofuels. If the supply perspective, however, if elevated to the global level, biomass based pathways could provide an abundant automotive fuel supply (e.g., Hoogwijk, Faaij et al. (2005)). This requires immense changes of the agricultural structures in tropical regions and of international trade patterns. But in a half century perspective, this is not unreasonable. Thus, it is premature to exclude biomass based fuel pathways as seriously “competitors” to the hydrogen pathways.

4.4 Environment

4.4.1 Environmental Pressure of Fossil Fuel Based Pathways

Automotive transport consumes 47% of world oil supply and contributes with 21% of global CO_2 emissions. Despite continuous efforts to improve energy efficiency these shares are expected to increase to 23% and 54% respectively in 2030 (International Energy Agency (IEA) (2004)). Additionally, it contributes to health damaging urban air pollution (NO_X particles, etc.) and to acidification of precipitation (NO_X, SO_2 etc.). Primary energy sources as well as infrastructures are also area demanding and therefore restricting the potential for other uses of the areas.

These trends make it interesting to examine how the alternative pathways and their primary energy feedstocks will perform with respect to emissions and area requirements.

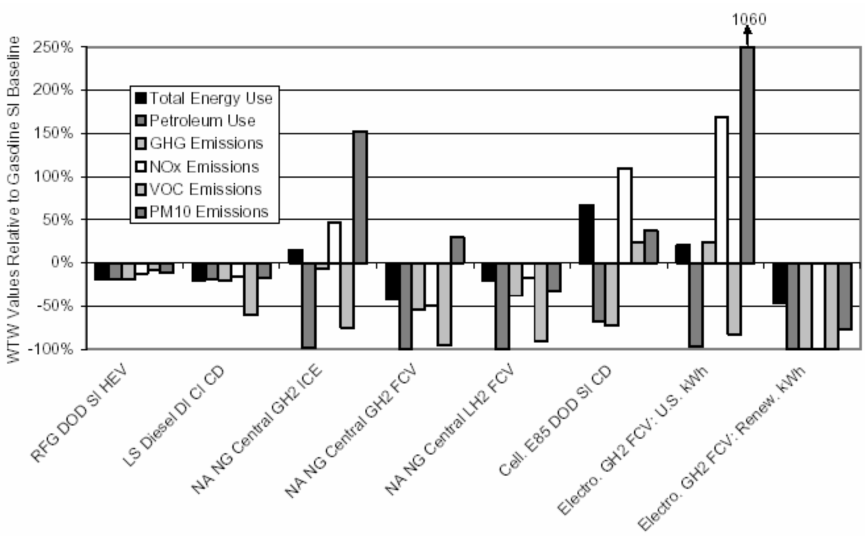
A useful measure to analyse and compare the environmental performance of each pathway is the environmental pressure per kilometre associated with each pathway.

4.4.2 Urban and Regional Air Pollutants

The competitiveness of the NG O/S H_2FCVs pathway relative to GHEVs on the urban air parameter is by definition rather limited since the idea of HEVs is to use the battery power in urban areas where speeds are low. On regional air pollution parameter, the difference depends on the on-site reforming process and the requirements of car exhaust.

A recent study based on the GREET model at Argonne National Laboratory compares emissions associated with alternative pathways with a gasoline spark-ignition internal combustion engine vehicle. The results are shown below.

Figure 9 Well-to-Wheels Energy Use and Emissions for Selected Pathways

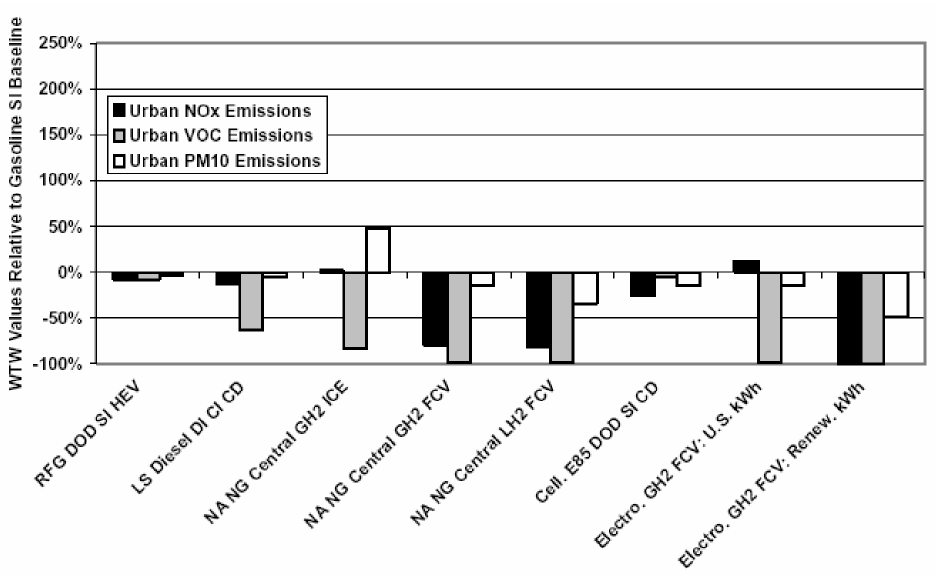


Source: Brinkman, Wang et al. (2005)

The results show as expected that FCVs supplied by renewable electrolysis produce less emissions NO_X, VOC, and PM10 than any of the alternatives in a WtW perspective. Natural gas based centrally produced liquid hydrogen is still cleaner than the baseline vehicle, but less so than the renewable based pathway. Compressed hydrogen technology seems to emit more PM10 than the baseline, but less NO_X and VOC than liquefaction. Hydrogen fuelling an ICE vehicle emits considerably more PM10 than the baseline and also more NO_X. Electrolysis based on grid power causes very high emissions of NO_X and PM10, but is competitive in VOC emissions. Hybrid vehicles with reformulated gasoline and displacement on demand represents some progress relative to the baseline and so does advanced diesel engine technology, whereas ethanol 85 is no benefit for local and regional pollution.

The damage caused by local and regional pollutants obviously depends on where they are emitted. The report offers an analysis of the urban located emissions of the pollutants.

Figure 10. WTW Emissions in Urban Areas for Selected Pathways



Source: Brinkman, Wang et al. (2005)

The results show that the alternative hydrogen pathways are more equal as to urban air pollution except for the emissions of NO_X and PM10 from hydrogen ICE vehicles and NO_X from electrolysis based on grid power.

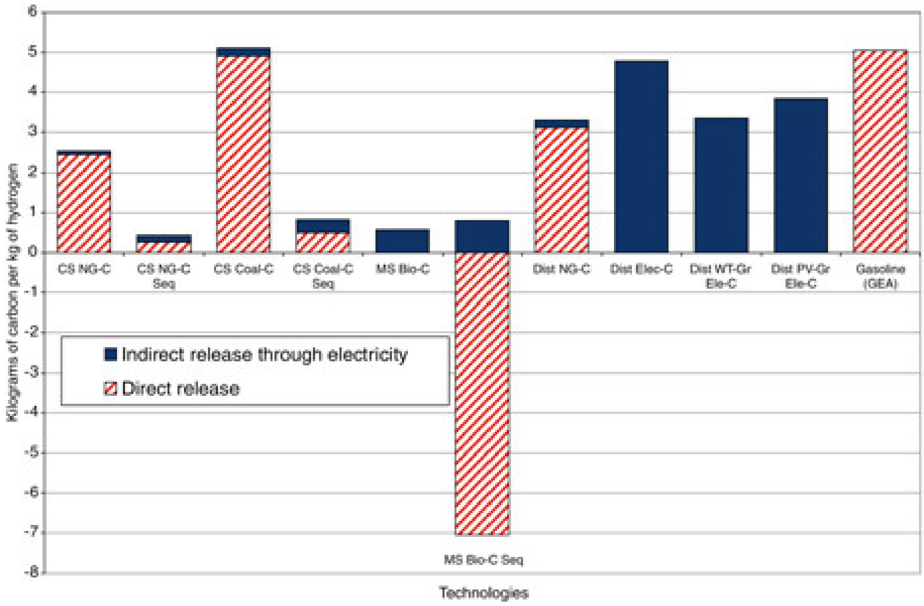
A full lifecycle account of environmental impacts of the hydrogen and fuel cell technologies should include the impacts of vehicle and fuel cell stack manufacturing as well. Full life cycle accounts would add local and regional pollutants as SO_2, CO, benzene, benzo(a)pyrene, and palladium to the pollutants included in the accounts above (Sorensen (2005)). They are, however, localised somewhere else since they result from for instance mining, steel manufacture and fuel cell stack production.

4.4.3 Greenhouse Gas Emissions

The WTW emissions of greenhouse gasses shown in figure 9 are naturally not as low for natural gas based hydrogen as for renewables based fuel, but for power grid based electrolysis, the emissions are higher than the baseline. Advanced gasoline and diesel engine technology again offers some emission reductions.

The study from the National Academy of Science (2004) analyses the CO_2 emissions associated with the current technologies. They are compared with the equivalent amount of gasoline in the figure below.

Figure 11. Unit Carbon Dioxide Emissions by Current Hydrogen Technologies



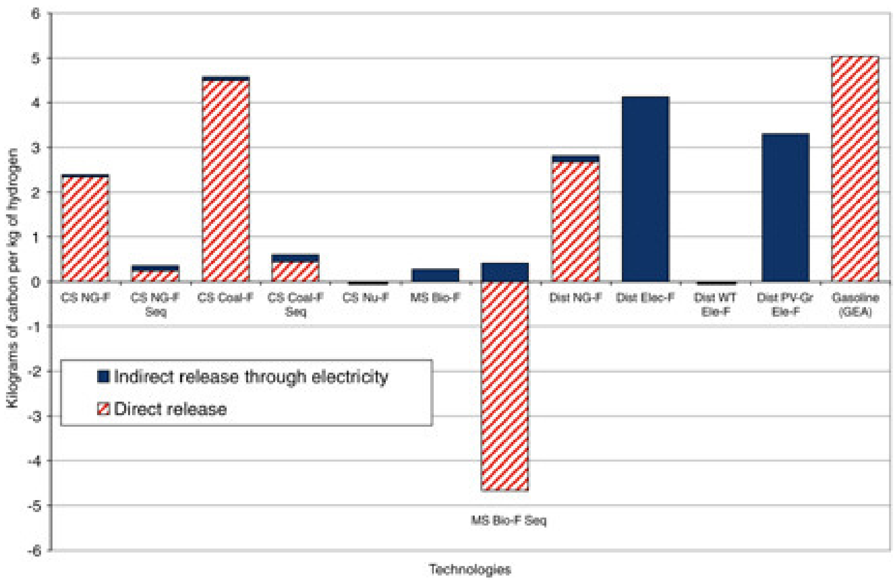
Source: National Academy of Science (2004).

The estimates shown at figure reveal that in the near future, hydrogen technologies based on coal (without CCS) and grid electricity will emit about the same amount of CO_2 as gasoline combusted in HEVs do. Since even wind power and PV is backed up by grid electricity, their CO_2 emissions are significant too.

Distributed gas reforming to H_2 will result in about 30%, but not dramatically lower CO_2 emissions per vehicle kilometre compared to the GHEV. If the study had included a biofuel based GHEV for comparison (which is not unrealistic at the time of large scale introduction of FCVs), the replacement of HEVs by H_2FCVs based on-site natural gas reforming could even lead to higher CO_2 emissions.

Future technological development is expected to change the competitiveness of the alternative hydrogen production technologies.

Figure 12. Unit Carbon Emissions by Future Hydrogen Technologies.



Source: National Academy of Science (2004).

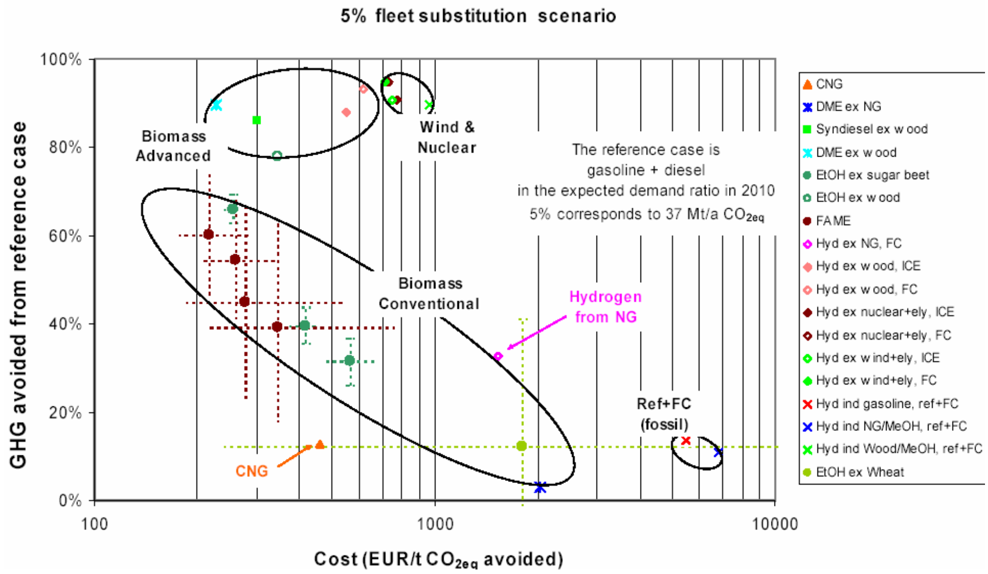
The most important expectations of the competitive position with respect to CO_2 emissions is that electrolysers are expected to be less costly, providing an

opportunity to restrict their operation to the periods where wind power is available. This is partly based on the notion that the progress that is required in fuel cell technology for commercialisation also will be applicable in electrolysis.
The considerations of grid power versus dedicated wind power for electrolysis gives rise to the question about whether it really makes a difference to GHG emissions if one is chosen over the other. The response to the question obviously depends on the assumptions about market reactions in the energy sector and thus on energy policy and in particular GHG policy. It is beyond the scope of this paper to analyse this question in depth and it will be dealt with in a later report.

4.5 CO_2 Reduction Cost

Even when these assumptions are made, the use of biofuels as blends turns out to be cost effective.

Figure 13. CO2 Avoided and Incremental Specific Cost



Source: Edwards, Griesemann et al. (2004).

The results of the cost comparisons as to reduction of GHG emissions are shown in figure 2. The calculations show that if GHG emission reduction is a high priority, biomass based pathways are serious candidates for technical solutions. This is even more important if the biomass supply is not restricted to domestic sources.

However, GHG emission reduction has to be an extremely high priority if this is the only criterion on which alternative fuel pathways are judged. All of the alternative fuel pathways studied involve costs per tCO_2 avoided exceeding those involved in energy efficiency programmes and low CO_2 options for electricity and heat generation several times or even by orders of magnitude. Hydrogen from NG is one of the most expensive ways to bring down CO_2 emissions according to this study. Hydrogen from wind and nuclear power and advanced biofuels are much cheaper and a 5% replacement of the gasoline/diesel vehicle stock by these alternatives would contribute more than twice as much to GHG reductions as hydrogen from NG would. The most competitive alternative fuel pathways in this perspective are FAME and DME from wood.

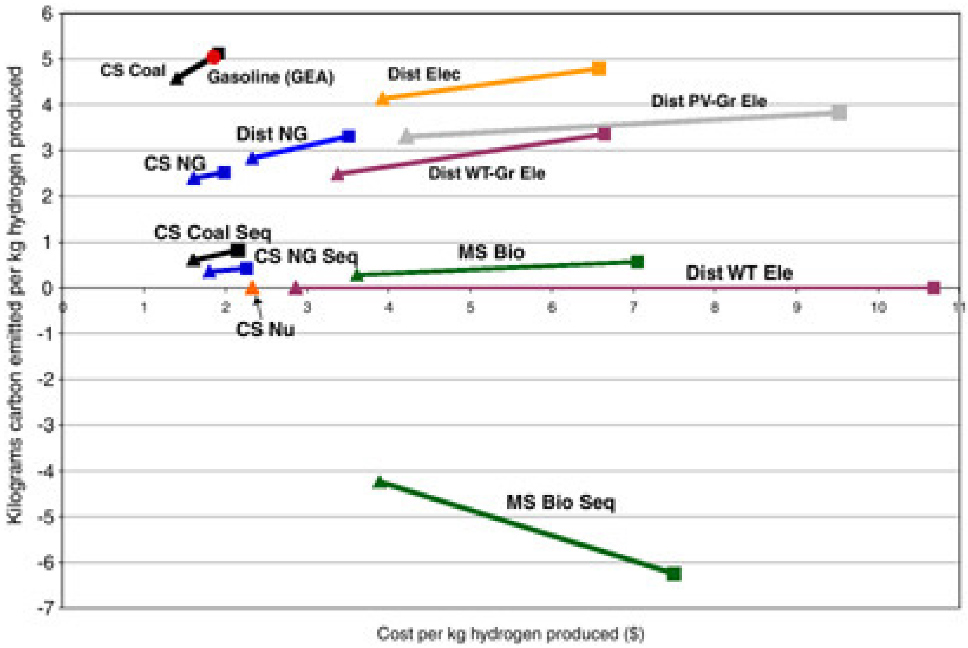
There are several methodological questions involved in the calculations. One follows from the fact that production of biofuels typically takes place in a joint production process where several outputs necessarily result in more or less fixed proportions. It is a classical economic problem how to associate the production costs with the individual outputs and the same problem occurs with energy consumption and emission of pollutants. There is no scientific consensus about one method being universally more correct than another and therefore alternative but as correct assumptions might give different results.

Nevertheless, the study indicates that biofuel based pathways could be the closest "competitor" to hydrogen pathways for the near future. Thus, the competitiveness of the ZR pathways will be assessed with a view to measuring this competitiveness as well as the competitiveness to other fossil and electricity based fuel pathways.

Similarly, the pathways involving fixating hydrogen in hydrogen carriers in the form of liquids (such as methanol) or solids (such as ammonia fixated in natrium chloride) are potential competitors to the pure hydrogen solutions. In the study, methanol too falls short of the top ten list because of the energy requirement associated with an additional conversion process. However, technological breakthroughs could still change the picture and it is probably too early to write off these options.

Costs estimates for reducing CO_2 emissions by similar technologies are reported by the National Academy of Science (2004) as well.

Figure 14. Hydrogen Cost and Carbon Emission Intensity of Hydrogen Technologies.



Source: National Academy of Science (2004).

The coal or natural gas based hydrogen production at a central station (with CCS) and the future dedicated nuclear power based technology is estimated to be the most competitive hydrogen production technologies with respect to costs *and* CO_2 emissions. Dedicated wind power and biomass based hydrogen are, however as competitive with respect to emissions whereas central as well as on-site natural gas reforming are with respect to costs in the longer term.

It is not within the focus area of the ZR project to do original research in the biofuel and hydrogen carrier pathways, but the study will examine available research result in order to determine whether these pathways potentially could be competitors to the ZR pathways within a relevant time frame.

5. Comparing Market and Societal Competitiveness

Despite the impossibility of quantifying political priorities in a consistent way, it is sometimes useful to compare market competitiveness with societal priorities. Thus, economic research has for an extended period been engaged in developing methods to convert the qualitative values behind the societal priorities to quantitative figures *as if* they were marketed goods. In this way the sum of competitiveness issues can be reduced to a one-dimensional monetary measure.

Another approach is to retain the multidimensional character of the choice problem, but narrow it down to the least possible number of dimensions. In this case, the expert cannot reach a definitive conclusion of what is overall "best", but must leave this to the decision makers (the political system) who then will apply their qualitative judgement on the now reduced number of dimensions.

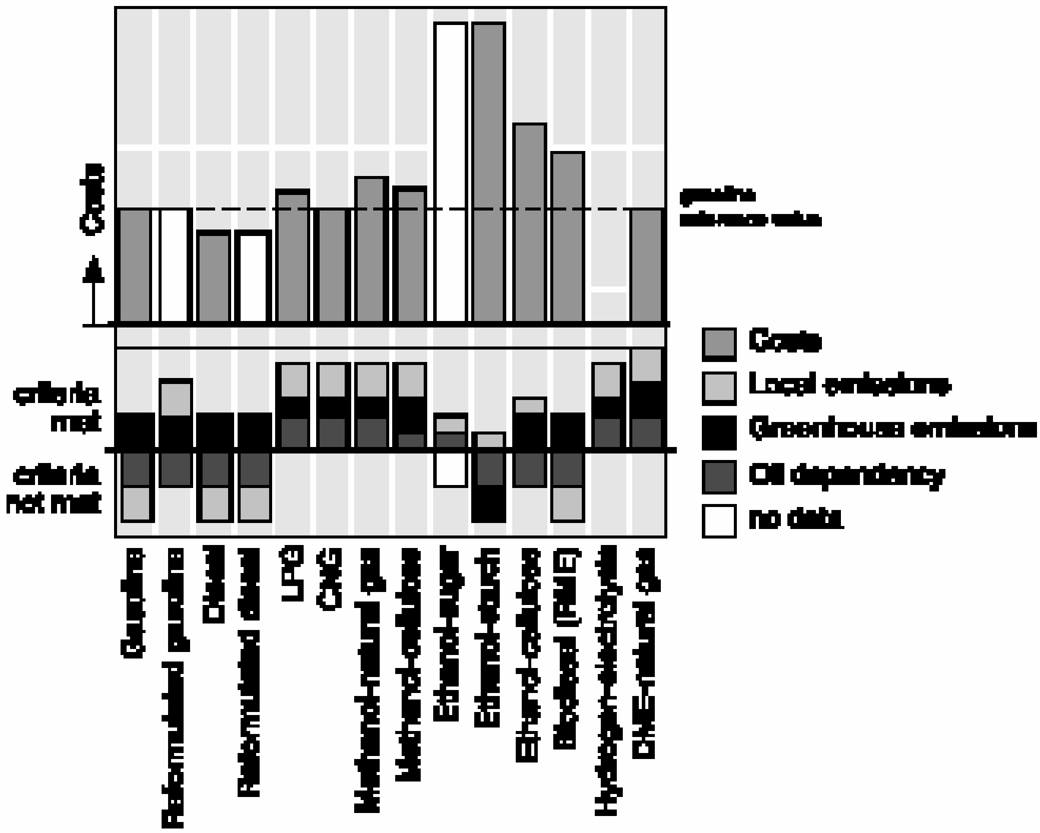
In this paper, both of these approaches are applied.

5.1 Life Cycle Multicriteria Impact

The societal concerns involve a wide range of physical consequences of promoting the hydrogen pathways. Some of these have the same impact and they can be summarised in terms of their impact on urban air, greenhouse gasses, etc. The more they are reduced to fewer dimensions, the more useful they are for policy decisions. However, the more dimensions are reduced, the more assumptions are needed to be made and the less the results are related to real physical properties. Therefore, the more reduction of dimensions, the more will the results reflect the assumptions necessary for reduction and the less they will reflect observed realities.

It is difficult to find the right balance between the need for a reduced set of criteria for decision making and the loss of information by reduction. Although the figures are to some extend outdated, the following result of an IEA study of alternative fuels could serve as a reasonable suggestion of such a balance.

Figure 15. Long Term WtW Performance for Alternative Fuels



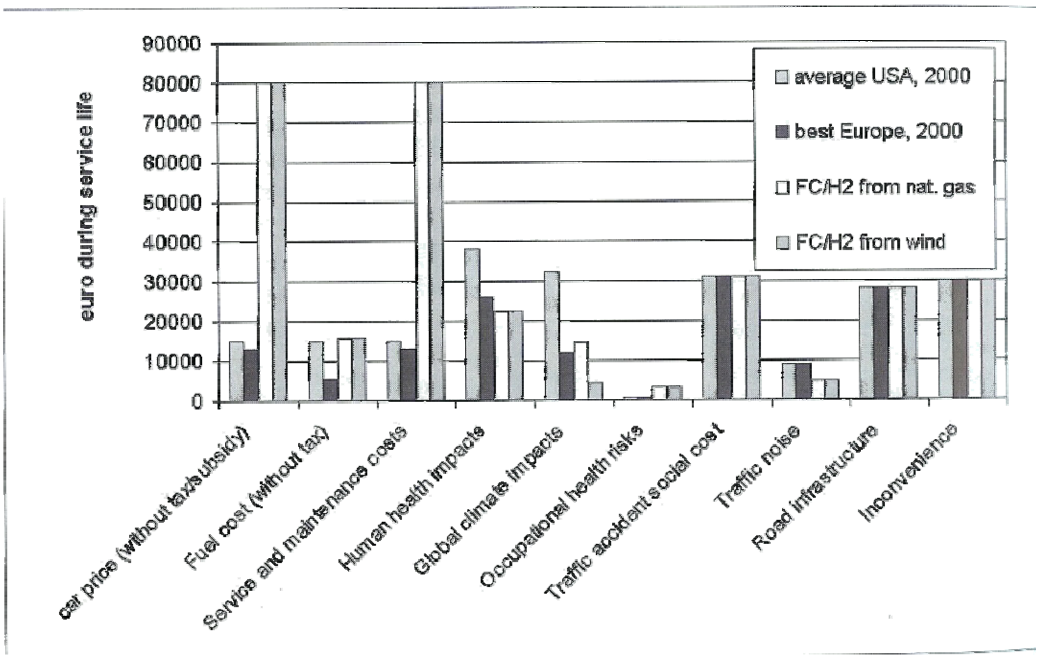
Source: International Energy Agency (IEA) (2000)

5.2. Life Cycle Cost Comparisons

Cost benefit analysis is the ultimate reduction of all dimensions to only one, whereas cost effectiveness analysis reduces dimensions to two. Therefore, the results must be interpreted with caution.

A life cycle cost analysis including comprehensive monetisation of the performance as to societal concerns is provided by Sorensen (2005). The accounts include not only environmental effects, but also occupational risks. Monetisation follows largely the ExternE values.

Figure 16. Life Cycle Private and Social Costs of Alternative Pathways.



Source: Sorensen (2005).

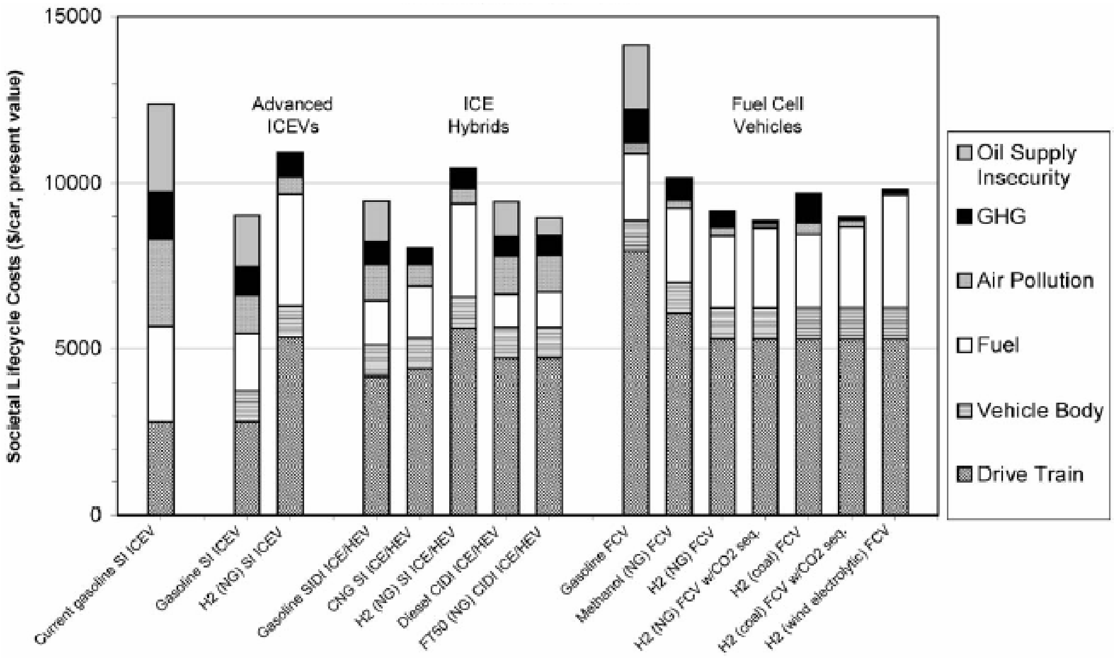
The two petro-fuel pathways included in the study are an average American car (Toyota Camry) and the best performing (mileage) European technology (Lupo). The hydrogen pathways include natural gas based and wind power based H_2, both used in a Daimler Chrysler FCV. The estimates indicate that the presently (2000) poor cost competitiveness of hydrogen pathways relative to the conventional petro-fuel pathway is only to a very limited degree balanced by lower environmental costs. When compared to the best performing diesel and design technology, the environmental advantages are negilible.

The study also includes occupational health indicators, showing a minor advantage in the favour of conventional technologies, but this will most likely be different when fully designed large scale production of FCVs are in place.

Another societal life cycle cost study by Ogden, Williams et al. (2004) compares pathways through three main types of drive configurations: ICEV (Current gasoline, advanced gasoline, and H_2 (NG)), HEV (Gasoline, CNG, H_2, diesel, and FT50), and FCV (Gasoline, methanol (NG), H_2 (NG), H_2 (NG with CCS), H_2 (coal), H_2 (coal with CCS), and H_2 (wind)).

In addition to the private costs of vehicle and fuel, the study accounts for societal costs of oil supply insecurity, greenhouse gasses, and air pollution using the ExternE figures adjusted to a Southern California context. The following figure shows the results.

Figure 17. Societal Lifecycle Costs of Alternative Fuel/Enginge Configurations of Cars.



Source: Ogden, Williams et al. (2004).

The results show that private costs are lowest in gasoline cars. Even the fuel savings of the advanced gasoline car is swamped by higher vehicle costs. The closest competition comes from HEVs. Among the hydrogen pathways, coal and gas based pathways entail the lowest private costs, whereas it the difference between with and without CCS is insignificant. There seems to be no economic gain of using hydrogen in ICEs.

Adding the societal costs, levels the H_2FCVs (with CCS) with advanced gasoline and the FT50-HEV. The pathway with lowest total costs is, however, the CNG-HEV.

The monetisation of the external effects is based on figures that could as well be very different. In a further sensitivity analysis Ogden, Williams et al. (2004) calculate the societal life cycle costs with smaller and larger values put on the external effects. The result is that if external effects are monetised with very low values, HEVs (except H_2HEVs) come out as the lowest cost option. If they are monetised with very high values, FCVs are the low cost options.

6. Competitiveness Research in Zero Regio

6.1 Key competitiveness: Energy efficiency and convertibility

The core advantages of hydrogen and fuel cell technology in automotive transport are the convertibility of hydrogen and the fuel efficiency of the fuel cell. The convertibility enables automotive transport to include natural gas and electricity in its primary energy base. The key to releasing these potentials seems to depend on breakthroughs in the development of catalysts for electrolysis and fuel cells.

The Zero Regio project is concerned with the inclusion of natural gas, which according to the literature reviewed above will be the most competitive feedstock for hydrogen in the phase of introduction of hydrogen and fuel cells in European transport.

The reviewed literature indicates that the technologies tested and demonstrated in the Zero Regio project are those of the hydrogen technologies that are closest to commercialisation. Despite their technical obstacles they seem to be less expensive and more practical than other hydrogen infrastructure alternatives.

Exactly because of the convertibility and efficiency properties of the hydrogen and fuel cell technology, it is difficult to imagine a long term solution to the pollution problems of energy use without this technology. It is, however, not a given fact that the use of hydrogen and fuel cell technology in itself entails environmentally sustainable energy use. Therefore the question arise how the introduction of hydrogen and fuel cell technologies can contribute to the wider European goals for curbing the environmental pressure of the transport and energy sectors.

Because of the well-to-wheel approach in the Zero Regio project, the links between the hydrogen production, transportation, storage, distribution, and end-use can be analysed in this perspective.

6.2 Nearest competitors

By the time of market introduction of HFC vehicles on the European market, they will hardly be embraced by all consumer segments simultaneously and evenly enthusiastic. The first buyers could for example be environmentally conscious citizens with a bias towards technology fascination or citizens and firms that want to signal that type of values. In that case, these consumers will face a number of alternative choices with some the same properties as hydrogen.

HEVs are natural alternatives to consumers who appreciate a modest environmental impact in urban areas and high overall energy efficiency. If gasoline is more or less substituted by ethanol, the environmental competitiveness to HFCs will be very strong. The fuel base of the HEVs could also shift towards the more energy efficient diesel engines perhaps even fuelled by biodiesel or natural gas. In the latter case, it would further resemble the hydrogen and fuel cell technology by including natural gas in the primary energy basis of transport.

Electrical vehicles (EVs) could also become serious competitors as the battery and flywheel technology advances.

Finally, flexifuel vehicles would also offer some of the advantages that HFCs do.

Even considering the superior environmental and efficiency virtues of the HFCs, they have to make up for a more sparse fuel supply network for quite a period (assuming that fuel and owner costs are competitive).

The ZR project demonstrates and tests compressed and liquefied hydrogen transported by pipeline, truck and cylinder. At the time of market introduction, distribution of hydrogen in solid or liquid hydrogen carriers could offer an alternative to the pathways tested and demonstrated in Zero Regio.

The anticipated progress in fuel cell technology required for market introduction is also expected to e useful in electrolysis. Therefore, at the time of market introduction, electrolysis could be a viable alternative to natural gas reforming or partial oxidation.

Carbon sequestration and electrolysis combined with renewable and nuclear energy could be near competitors to natural gas as the primary energy basis for hydrogen consistent with EU climate policy. These alternatives are not tested and demonstrated in the ZR-project and must therefore be represented by assumptions about their potentials.

To analyse properly the competitiveness of the ZR pathways relative to these nearest competitors, full and accurate accounts of the cost, energy efficiency, environmental, and safety properties of the entire well-to-wheel chains and their individual links are necessary.

6.3 H_2 Costs

The competitiveness criterion for automotive use of hydrogen and fuel cells in Europe can be calculated similar to the gasoline efficiency adjusted costs calculated by the National Academy of Science (2004). Under the assumption that the user and owner costs apart from fuel are identical to the similar costs of a gasoline fuelled vehicle, the gasoline competitive H_2 price at the pump is defined as:

$C_{HFC} / TRS \leq C_{GV} / TRS \Leftrightarrow$

$P_{kgH2} / (E_{HFC} * e_{kgH2}) \leq P_{lG} / (E_{GV} * e_{lG}) \Leftrightarrow$

$P_{kgH2} \leq P_{lG} * (E_{HFC} / E_{GV}) * (e_{kgH2} / e_{lG})$,

Where:

C_{HFC} = Hydrogen cost per period (net of taxes and subsidies) (€)
C_{GV} = Gasoline cost per period (net of taxes and subsidies) (€)
TRS = Transport service per period (vehicle kilometres, vkm)
P_{kgH2} = The price at pump of a kg of hydrogen (net of taxes and subsidies) (€)
P_{lG} = The price at pump of a litre of gasoline (net of taxes and subsidies) (€)
E_{HFC} = The energy efficiency of a fuel cell vehicle (vkm/MJ)
E_{GV} = The energy efficiency of a gasoline fuelled vehicle (vkm/MJ)
e_{kgH2} = 120.1 MJ/kg H_2
e_{lG} = 34.2 MJ/l gasoline

The gasoline equivalent H_2 price as well as the gasoline price is net of taxes and subsidies to ensure viability without incentives. The issue of incentives will be dealt with in a subsequent report.

The gasoline equivalent H_2 price depends on the gasoline price and the ratio of fuel cell vehicle efficiency advantage to gasoline fuelled vehicle efficiency according to the following table.

Table 2. Gasoline Competitive Hydrogen Price at Pump

Gasoline price (€/l)	***0.30***	***0.35***	***0.40***	***0.45***	***0.50***	***0.55***	***0.60***	***0.65***	***0.70***	***0.75***	***0.80***
Efficiency advantage of FCV over GV	Competitive hydrogen price (€/kg H_2)										
10%	1.16	1.35	1.55	1.74	1.93	2.12	2.32	2.51	2.70	2.90	3.09
20%	1.26	1.47	1.69	1.90	2.11	2.32	2.53	2.74	2.95	3.16	3.37
30%	1.37	1.60	1.83	2.05	2.28	2.51	2.74	2.97	3.20	3.42	3.65
40%	1.47	1.72	1.97	2.21	2.46	2.70	2.95	3.20	3.44	3.69	3.93
50%	1.58	1.84	2.11	2.37	2.63	2.90	3.16	3.42	3.69	3.95	4.21
60%	1.69	1.97	2.25	2.53	2.81	3.09	3.37	3.65	3.93	4.21	4.49
70%	1.79	2.09	2.39	2.69	2.98	3.28	3.58	3.88	4.18	4.48	4.78
80%	1.90	2.21	2.53	2.84	3.16	3.48	3.79	4.11	4.42	4.74	5.06
90%	2.00	2.34	2.67	3.00	3.34	3.67	4.00	4.34	4.67	5.00	5.34
100%	2.11	2.46	2.81	3.16	3.51	3.86	4.21	4.57	4.92	5.27	5.62
110%	2.21	2.58	2.95	3.32	3.69	4.06	4.42	4.79	5.16	5.53	5.90
120%	2.32	2.70	3.09	3.48	3.86	4.25	4.64	5.02	5.41	5.79	6.18

Source: Author's calculations.

The table can be used to compare expected vehicle efficiency with expected gasoline prices in a particular period. According to the US Department of Energy and US Environmental Protection Agency (2005), the 2006 models of fuel cell vehicles do not have an efficiency advantage relative to the most efficient hybrid electric vehicles. However, the potentials of the fuel cell compared to the internal combustion engine still makes a significant efficiency advantage possible and realistic.

If it is assumed that around 2020 hydrogen fuel cell vehicles (HFCVs) are 60% more energy efficient than hybrid gasoline-electric vehicles (HGEVs) and that gasoline costs 0.35-0.55 €/l, the competitive hydrogen price will be 1.97 – 3.09 €/kg.

For comparison the US Envrionmental Protection Agency (2005) uses an estimate of 5.80 $/kg of hydrogen to compare the current fuel economy of fuel cell vehicles to other vehicles. The National Academy of Science (2004) estimates the cost of hydrogen at pump for the near future technology filling station with on-site natural gas reforming and serving 854 FC vehicles to be 3.51 $/kg[1]. It is optimistically assumed that this cost can be reduced to 2.33 $/kg in the future after successful completion of promising research and development.

When hydrogen costs are considered in isolation it is from a presumption that FCVs can be bought and operated at prices competitive with gasoline and diesel fuelled vehicles. The US Department of Energy hydrogen R&D program targets a fuel cell cost level of $45/kW in 2010 and $30/kW in 2015. The latter is comparable with the cost of internal combustion engines. Provided that a fuel cell cost target is met and that owner and operation costs are comparable to those of ICEVs or HEVs, the cost and fuel efficiency of hydrogen and gasoline as shown in table 3 above, will indicate the cost competitiveness of the combined production, distribution, and end use system.

The ZR project can provide some important information about the prospects for fuel efficiency and hydrogen costs. Vehicle manufacturers can provide some information on their expected time distance to given benchmark cost levels and the scale of production required for this cost level.

The data collection framework needs a reporting frequency that enables tracking plant-level learning (as opposed to industry level learning) throughout the project period. This will be important information for subsequent investments in

[1] At a 6.50 $/MMbtu HHV natural gas price

filling stations and fleets. On the one hand a weekly or monthly reporting frequency is considered too burdensome whereas an annual reporting frequency is considered too thin. Therefore a quarterly reporting period is preferred.

6.4 Consistency and comparability in Economic Assumptions

To compare the hydrogen pathways with its nearest competitors, it is necessary to be very specific about the interdependence of the various fuel prices. For instance, the price of hydrogen depends for a foreseeable future on natural gas, whereas the natural gas prices to some degree are linked to oil prices. It is difficult to see where the studies really disagree and where differences are merely due to differences in the point of time, the figures refer to, assumptions of fossil fuel prices, exchange rates and discount rates. Therefore, it is necessary to develop a range of internally consistent economic standard reference frameworks for comparing this kind of results or a standard pathway-economic model.

The data from the project will be collected from actual daily use of the technology, which will enable a reduction of the vast uncertainties surrounding the technical and cost estimates. Further more the treatment of economic data can be improved by applying standard economic techniques for comparability and consistency.

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