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Deliverable 7.1

Work Plan Competitiveness

Work plan for research in the competitiveness of hydrogen pathways

Zero Regio Project, Task 7.1

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Market and Societal Competitiveness

The Zero Regio project contributes to the introduction of hydrogen in the transport sector by testing and demonstrating full scale well-to-wheel solutions to infrastructure and vehicle operation requirements and addressing the prospects for market penetration. The core problem to be analysed is how each of the hydrogen pathways tested and demonstrated in the ZR project performs to other solutions to the same problems. We refer to this as "the competitiveness of hydrogen pathways".

The competitiveness of the individual pathways are analysed in terms of their attractiveness to consumers and societies compared to the attractiveness of competing systems. Thus, we refer to the attractiveness to consumers as "Market competitiveness" and the attractiveness to societies as "Societal competitiveness".

The literature on these problems has been reviewed to produce a meta-analysis of the competitive of the hydrogen pathways and the results are presented in appendices A and B.

The literature refers to experience with the performance of alternative technical solutions in different countries and locations and at various points of time during the recent 15 years. There is a huge task in adjusting all of these results to comparable figures and further to infer from them, the competitiveness of the pathways at the time when they will be introduced in large scale in Europe. As an analytical convention, we aim at assessing the competitiveness in the timeframe of 2015-2025.

It is difficult to predict exactly which technologies, the ZR pathways will compete with at that time, but a rough distinction can be made according to fuel (oil and gas based, bio-fuels, and hydrogen) and according to engine technology (internal combustion engine (ICE), hybrid electric (HE), and fuel cell (FC)).

All cost components will be analysed net of taxes and subsidies. The question of taxes and subsidies and their importance for the pace of market penetration will then be addressed explicitly in task 7.3.

In addition to the issue of comparability of competitiveness indicators, the hydrogen and fuel cell technologies are new and rapidly developing. As a consequence, the performance of the technologies must be expected to improve over the next decades due to learning economies, scale economies, and technological breakthroughs (in total referred to as "experience economies"). Assessment of the competitiveness in 2015-2025 thus requires that such processes are taken into account.

The ZR project will provide test data that can be compared with the previous results and indicate the future competitiveness position of the pathways demonstrated in the project. The major risk for the quality of the data lies in the risk of getting so low rates of capacity utilisation that the cost and technical performance under normal capacity utilisation will be difficult to assess. This will depend on the size of the vehicle fleets at the two test fields.

A draft list of the test data as well of the data supplied from producers of equipment in the ZR-project are presented in appendix C. The list will be thoroughly discussed with each of the partners supplying the data.

In the following, the core competitiveness criteria, addressed in the project are described. All the criteria will be compared to fuel chains that are competing with the hydrogen and fuel cell pathways on important parameters.

Market Competitiveness

General Issues

On the basis of the literature, market competitiveness depends on performance of the costs per transport service provided by each solution and other consumer criteria. The costs per transport service can be measured in €/vehicle kilometer (vkm) and are generally composed of the costs of hydrogen (€/kg), the costs of vehicle operation (kg/vkm) and the cost of vehicle purchase (€/vkm).

Costs per transport service

Hydrogen

Hydrogen costs depend on the feedstock of hydrogen as well as the energy loss and other costs throughout the well-to-tank section of the fuel chain. On the basis of the literature review, the price at pump level that will make hydrogen competitive with gasoline in 2015-2025 is assessed to 2-3 €/kg, assuming a 60% energy efficiency advantage of the hydrogen and fuel cell vehicle (HFCV) compared to the gasoline fuelled vehicle, a 0.35-0.55 €/l gasoline price (net of taxes and subsidies), and identical purchase and maintenance costs.

The likeliness of hydrogen costs to meet this requirement depends on the use of feedstock and the progress in infrastructure solutions. The alternative feedstock options as well as conversion, transport, and storage technologies are addressed with respect to their prospective cost development.

The progress in the technologies is rapidly advancing and the costs of hydrogen conversion, transportation, and storage in the ZR project will probably be significantly lower in 2015-2025. It is important to identify the potentials for cost reduction through learning and up-scaling.

The ZR test and demonstration facilities will allow identification of the processes in the fuel chain that are anticipated to be less costly in the future and thus allow for a more accurate appraisal of the foreseeable experience economies. They will also allow a more accurate assessment of the learning costs at plant level expected until a state of routine operation is attained.

Criteria:

Hydrogen unit costs (€/kg)

Vehicle operation costs

The Tank-to-Wheel efficiency of the vehicles determines the vehicle part of the costs per transport service. The testing of vehicles in the ZR-project will allow harvesting of operation data including contingencies that are part of normal vehicle's life and learning costs for the consumer. At the same time the reliability of the vehicle will be assessed. It is an extremely important issue for the future consumers and for the vehicles' producers, as it allows estimation of the real costs of operation and maintenance.

Criteria:

Unit hydrogen consumption (kg/vkm)

Vehicle owner costs

At the present FC vehicles are prototypes, that is, they are hand built and with many experimental components to be tested and improved. It means extraordinarily high production and maintenance costs. Therefore, the costs of the vehicles at the test fields are not informative of the costs of large scale produced vehicles. However, the performance and durability of the individual components together with expert opinions on costs in large series can provide useful information for the assessment of potential future costs.

Additionally, these features can be compared to available information on previous results and the theoretically potential performance to obtain insight in the experience economies of the individual technologies. In particular we will attempt to estimate the potentials for cost reduction through learning and up-scaling.

Criteria:

Levelised anticipated purchase costs and maintenance costs (105.000 km, 7 years) (€/km).

Other consumer criteriaConsumer operation and Maintenance

In addition to the costs directly paid for operating and owning the vehicle, the consumer also spend time for operating the vehicle and loose days for maintenance.

The test results from the test fields of the ZR project will provide data for the time spend for refuelling whereas the time spent for driving to the filling station must be estimated on the basis of other studies of network density, for instance, natural gas filling station networks.

For the above mentioned reasons, the number of days, the owner will have to do without a car due to regular and contingency service will probably be much lower in 2015-2025. However, in combination with expert judgements some information on the issue could be obtained.

Criteria:

Average filling time (minutes per filling)

Days vehicles are out of operation for service (days/quarter)

Safety and environment

The safety and environmental parameters that are important to consumer choice include potentially three levels of impact: vehicle, local, and global. The ZR project allows harvesting of data on actual emissions and risks as well as operator and neighbor perceptions of these.

Inside and close to the vehicle, the levels of noise and vibration are important as well as the risks of hydrogen leaks during filling, driving, and in garage.

At the local level, the emissions of pollutants and the risks associated with filling stations and hydrogen production, transport, and storage facilities are important. This aspect is particularly important if more cities introduce restrictions for ICE vehicles or incentives for zero emission vehicles (ZEV). On the other hand the environmental issues have to be evaluated with a great accuracy, as the impact on the global and local levels could be rather different.

It is known that the small on-site hydrogen production from natural gas has a bigger environmental impact in terms of non-GHG emissions (SO_x, NO_x, particulates, etc.). And as these solutions are located closer to the areas with a high density of population than large-scale plants, the local negative impact could be considerable.

At the global level, greenhouse gas emissions are of central concern and the perception of "green" hydrogen and the contribution of hydrogen to curbing greenhouse gas emission could play an important role in consumer choice.

Criteria:

- WtW hydrogen leaks and vaporization (%)
- Frequency of severe leaks (episodes/quarter)
- In vehicle noise and vibration levels
- WtW catalyst metals emission ratio (kg ?¹ / kg H₂)
- WtW PM emission ratio (gPM / kg H₂)
- WtW NO_x emission ratio (kg NO_x / kg H₂)
- WtW SO₂ emission ratio (kg SO₂ / kg H₂)
- WtW CO₂ emission ratio (kg CO₂ / kg H₂)

Fuel price stability

Natural gas prices have traditionally been closely linked to oil prices and natural gas as transport fuel has therefore not been considered a real alternative that could escape the price volatility of oil based fuels. However, if natural gas prices as expected will become an independent commodity and its price will be delinked from oil prices, then the price of hydrogen produced from natural gas could achieve a stability, that would be attractive to many consumers.

The test results from the ZR-project cannot in themselves disclose information about this aspect, and the analysis has to rely on other literature and market models as well as on own estimates.

Criteria:

- Responsiveness of hydrogen cost to oil price changes (elasticity)

Societal Competitiveness

Economy-wide goals

Some well-to-wheel configurations are more attractive to particular countries or regions due to their overall compatibility with their societal priorities. This property is referred to as "societal competitiveness".

In addition to the fuel costs, the societal priorities include local and global environmental quality, hydrogen handling safety, energy supply security, and employment and growth prospects. Each of these is important to the pace of penetration of hydrogen in the transport sector.

Energy efficiency

Advances in the well-to-wheel energy efficiency of a particular pathway are traditionally taken to improve the competitiveness of consumer as well as

¹ It is extremely difficult to establish *a priori* the unit of measurement for catalysts. Some of them are measured in meters, other in grams or kilos.

societal competitiveness. However, the value of an energy unit at different stages of the fuel chain is increasing as the fuel approaches its final use.

Therefore, the costs of energy consumption and hydrogen leaks in the process as well as the potential of recovering waste energy at each link in the fuel chain are of central concern to the assessment.

As the ZR project is designed to demonstrate full-scale well-to-wheel solutions to hydrogen in automotive transport, the project provides very good opportunities to collect consistent data throughout the hydrogen chain. On the basis of such consistent data, it is possible to construct well-to-wheel accounts for energy, hydrogen, costs, and emissions that will be superior to previous data on the performance of hydrogen pathways.

The collection of these data will be based on gauge and accounting records and thus to a very high degree documented. To be able to trace the learning costs involved in the establishment of new filling stations and other facilities, the data reporting frequency is required to at least quarterly.

The actual performance of the individual facilities, pieces of equipment, vehicles, etc. will be compared to the potential or theoretical performance and to previous performance data for the technology. In this way, we will get insight into the learning properties of the involved technologies. The necessary information will be obtained by the questionnaires submitted to the partners of the project (see Appendix C) and by interviews with partners and independent experts.

Criteria:

Unit energy consumption (MJ_{NG}/MJ_{H_2} , MJ_{el}/MJ_{H_2})

Environment and Safety

The environmental properties of the hydrogen and fuel cell technology in automotive use are described above. In addition to these, the issue of hydrogen leaks upstream in the fuel chain is a societal concern. The well-to-wheel accounts of hydrogen will enable a comparison of risks of hydrogen leaks with their severity and the costs of preventing them.

Similarly, the well-to-wheel accounts of emissions will document the critical environmental factors and enable comparisons with critical environmental factors in competing fuel chains. The choice between renewable and fossil fuel based hydrogen is either a choice of a private investor based on prevailing incentives and regulations or a choice of an authority pursuing specific policy guidelines. Therefore this problem can not be solved outside of its context with other energy and environmental regulation. The consequences of such choices will be addressed in relation to the actual energy-environmental policies implemented in and by the European Union.

Criteria:

Emission ratios and hydrogen leaks (cf. above)

Energy Supply Security

The prospects of dwindling non-OPEC oil reserves and the recent rise in oil prices have given new impetus to the efforts to advance hydrogen and fuel cells in automotive uses. This is because automotive transport remains almost exclusively fuelled by oil based fuels and because hydrogen potentially is convertible to and from any other energy carrier. The diversification of energy

sources for automotive transportation is thus a prominent societal priority and the hydrogen is generally expected to provide an important contribution to this end.

The only hydrogen feedstock demonstrated and tested in the ZR project is natural gas through steam reforming and partial oxidation and hydrogen as a waste stream from chlorine-soda production. Therefore, the analysis of this issue must be widely based on other studies of hydrogen feedstock and conversion processes and on data collected from hydrogen producers.

Criteria:

European cost estimates and price data for hydrogen production (€/Nm³)

Responsiveness of hydrogen cost to oil price changes (elasticity)

Employment and Growth

Apart from the supply security and price stability, a diversified feedstock for hydrogen production can include domestic sources. Thus, a larger segment of the value added along the fuel chain can potentially be in the created domestically rather than imported from abroad. This prospect is of major societal concern along with the prospects of the vehicle and infrastructure component industries.

Data from the ZR-project will not be directly useful in investigating these prospects, and the analysis will primarily draw on the literature, statistics, and market models about the competitiveness and market shares of European energy and automotive industries.

Business strategies

While the assessment of the competitiveness of the demonstrated hydrogen pathways needs a strong basis in cost analysis, it is also necessary to take into account the strategies pursued by companies involved in the development and exploitation of these pathways.

The ride down the learning curve does not happen without somebody doing the learning, i.e. engaging them selves and committing resources. The reduction of costs in the H₂ chain shall require efforts over a long time-span and these efforts will need to be huge and highly dedicated. A key issue is therefore the strategies pursued by each company within the chain, the strategic interaction between companies, and the strategic cooperation between business and the public sector. Results will depend not only on the amount of resources being used, but also on the quality of strategic leadership and the effectiveness of the strategies being pursued, at the actor level and in synergy between actors.

The Zero Regio studies on competitiveness (task 7.1) therefore includes a study of

- interactions between the major business actors involved in the demonstrated pathways, and the effects of their interactions on competitive performance,
- SME-involvement and strategies to strengthen it, and
- strategies for reduction and allocation of financial risk and for development of access to low-cost finance.

The study of interactions with the public sector is part of the regulation studies (task 7.3). There will be a need for coordination between the strategic aspects of the competitiveness and the regulation studies.

The study of business strategies will be based on qualitative methodologies, such as in-depth interviews with actors and experts, studies of company reports, and reviews of the business press and academic literature.

The first task addressed will be the assessment of SME-involvement and strategies to strengthen it. A deliverable dedicated to the results of this study is being proposed for month 30. The topic of SME involvement has been chosen as the first task in strategy analysis, as the ability to provoke and benefit from SME development is often a key indicator of the dynamic potential of a sector in the knowledge economy. Additionally, an initial focus on this topic will help provide an overview of the sector and its developmental problems and prospects, and will provide key inputs to studies of public sector policies in the regulation task (7.3). It is also a topic well suited for up-front studies, whereas the other tasks within the strategy studies are better dealt with in the demonstration stage, as strategies will be more mature at this stage and problems will be more transparent.

The remaining tasks will be addressed during the demonstration period, i.e. from month 24 onwards. Strategies for reduction and allocation of financial risk and for development of access to low-cost finance are planned to be reported in a separate deliverable around month 42. The interactions between the major business actors involved in the demonstrated pathways, and the effects of their interactions on competitive performance is planned to be reported in the terminal stage of the project, i.e. around month 57.

Overall Assessment of Competitiveness

Multi Dimension Assessment

The overall assessment of the competitiveness of hydrogen in automotive uses in general and the ZR-pathways in particular depend on several competitiveness criteria. A multi dimension assessment identifies the critical trade-offs between the competitiveness criteria.

Monetarised Assessment

In some economic analyses, the trade-offs are often reduced to monetary ratios and the entire complex of choices can then be reduced to a one-dimensional cost-benefit ratio. The advantage of reducing more to fewer dimensions is the more clear choices, but the disadvantage is the uncertainty added by the assumptions necessary for any reduction of dimensions. The research will also include such an analysis with special focus on the uncertainties involved.

WP7 Contribution to Assessment Framework

The assessment of the competitiveness of the hydrogen pathways tested and demonstrated in the ZR-project relies on the assessment criteria, referred to under each section above. They will be based on two types of data in the assessment framework:

- Start and end data for equipment and facilities and operational performance (Appendix C)

- Quarterly test data for examining the development of unit costs, energy efficiency, hydrogen leaks, and emissions throughout the project period (Appendix D)

The results from the project will be useful in future planning of infrastructure investment as well as policy and programme appraisal. Therefore the data will be combined with other project data in estimating learning curves.

The data described in appendix C and D will be revised through a consultation procedure with each of the Zero Regio partners. The consultation procedure will attempt to establish a consensus on which data are necessary for the analytical tasks of the ZR project. The guiding principles will be that the ZR project must produce additional information, which is in proportion to the financial resources spent on the project and that data can be delivered at a reasonable effort and cost level.

The main problem with cost estimations is the high level of uncertainty related to the all stages of the hydrogen chain, as most of the processes and technologies are at the experimental/prototype level of development. The relatively small changes in the configurations of the same device/mechanism or process could result in the wide range of cost figures and uncertainty.

Different stages of the hydrogen chain have different levels of uncertainty and should be assessed separately. However, a critical condition for getting useful data on the operation of infrastructure facilities is to have a capacity utilisation close to normal. Otherwise, data will be biased towards a low competitiveness of hydrogen.

Rather detailed data are necessary to obtain information on the competitiveness issues and on the cost elements that are likely to be less expensive in the future. Therefore, the data sheets for the assessment framework presented in Appendices C and D of this document are very detailed.

In order to understand the state of art in the hydrogen technologies development and its costs, the meta-analysis of the literature and of the data from other projects have been performed. The main results of this study are comprised in Appendix A and B of this document and they provide the basis for comparison with the data to be obtained from the partners and during the demonstration phase of the project.

Predicting the Future Competitiveness

The estimation of the learning, and in general the experience effects, and up-scaling effects or economies is very important to understand the possibility of using hydrogen as an alternative energy carrier also for the automotive purposes. This is because automotive applications at the present are still at the prototype stage of the development and they could not guarantee the necessary critical mass for the observations of the expected decreasing costs performance. It provides an excellent opportunity for the application of the learning estimations methods (as for example learning and experience curves).

These methods could provide valuable information in order to forecast the future behaviour of the costs of certain critical components/processes of the hydrogen chain. The main difficulty of this approach is related to the necessity of the reliable base/initial data and the reasonable learning rate assumption. In order

to overcome the problems with learning rate choice, the sensitivity analysis will be applied.

As it is very difficult to estimate the experience effects for all the processes and components developed/demonstrated within Zero-Regio project, the range of the most incisive ones will be chosen. The decision will be operated on the base of the critical characteristics of devices/processes for the hydrogen early market introduction, like for example some components of the H2 FC vehicles. A special attention will be put also on the labour costs figures and the labour required for assembling.

As for the estimation of the up-scaling effects, the influence of this issue on the hydrogen diffusion as an alternative motor fuel is evident. The positive impact of the growth in volume on the costs has to be demonstrated.

For both tasks the collaboration of the partners of the project is a critical issue. As detailed and precise data as possible should be obtained and we are hoping the collaboration and help of the actors involved in Zero-Regio project.

Appendices

Appendix A. Critical analysis of the state of the art of the hydrogen chain: focus on technological and economic issues in the ZERO REGIO Project

Appendix B. The Competitiveness of Alternative Hydrogen Pathways

Appendix C. Start and End Data for Technological and Economic Issues in the Assessment Framework for ZERO REGIO Project

Appendix D. Test Data for Competitiveness Analysis in the ZERO REGIO Project



Deliverable 7.1.

Work Plan Competitiveness

Appendix A

Critical analysis of the state of the art of the hydrogen chain: focus on technological and economic issues in the ZERO REGIO Project

By Liliya Chernyavs'ka and Cristian Lanfranconi – IEFE Università Bocconi

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SUMMARY

Hydrogen has often been seen as a potential solution to worldwide energetic and environmental issues because H₂ is an *energy carrier* which shows some very good properties:

- It can be produced starting from many energy sources available on large scale as fossil fuels, renewable energy and nuclear power in order to improve the security of supply.
- It is an energy carrier (as electricity) which can be stored.
- It does not create pollution or CO₂ during its uses (environmental friendly).
- It can be used in many applications (stationary, portable and transport applications).
- It can be transported and delivered by net.

However many important steps have to be realized to overcome some barriers towards use of hydrogen as energy carrier.

- Technological barriers: today H₂ production, transport and distribution as well as storage and end user technologies need improvement in order to make H₂ available to everyone. Chemical industry uses H₂ as chemical substance since long time however quantities as well as cost and performance issues for end users change when we think at H₂ as energy carrier.
- Unavailability of transport and distribution nets that are not realized waiting until the market will be ready which however needs infrastructures to grow up.
- Cost barriers: hydrogen chain (production as well infrastructure systems) have high costs when compared with other energy systems (gasoline or natural gas) and this is also because technology is in a pre commercial stage which do not get benefit from scale economics and mass production.
- Regulations, codes and standards are often still missing and this aspect can lead industries to adopt very high security degrees which can rise costs even more.
- Social barriers: well known technologies are preferred by clients which could be afraid of potential risks coming from use of hydrogen.

Hydrogen on the earth is chemically tied to other atoms into molecules. It is especially present in huge quantity into water and into fossil fuels. Unfortunately, at least for its energetic use, it is not available in its elemental state as diatomic molecule (H₂).

For this reason hydrogen literature correctly refers to hydrogen as energy carrier and not as energy source. From this point of view its energetic meaning is closer to electricity than to fossil fuels, renewable or nuclear energy because both H₂ and electricity have to be produced to make available their use.

However there is a wide difference between these two energy carriers: electricity is produced at the same time it is needed but hydrogen production and use are or can be separate by time because hydrogen can be stored. For instance, hypothetically speaking, hydrogen could be used to stock electricity produced by some kind of renewable energy sources that are not predictable (wind, solar, and some hydro power).

Once produced, hydrogen is a good energy carrier and its energy content per kg is higher than that of gasoline and natural gas. However hydrogen is the lightest substance and this means that its heating value is lower than that of gasoline and natural gas (at same pressure and temperature). Likely this is the main reason concerning technological, energetic and cost problems regarding its transport and storage. H₂ can be stored as gas into very high pressure tanks, into liquid state or in a solid form into some metals or into carbon nanostructures. Storage is a critical issue especially within transport sector where tank (for gaseous H₂) or dewar (for liquid H₂) have to face problems as space, weight and boil off. Gaseous on board H₂ storage unit cost is the cheapest one for small tanks then liquid storage can be competitive.

Refuelling stations have been developed within vehicle development for liquid and gaseous hydrogen. The first seems to be more expensive and complex and anyway hydrogen liquefaction process is high energy intensive one.

Transport of huge quantities of H₂ from a centralized production facility to end user needs a dedicated infrastructure, with still missing normative, standards and cost issues.

Once produced, transported and stored, H₂ can be used as a usual fuel into combustion processes (as into internal combustion engine) however its more interesting use is into fuel cells. Fuel cells are electrochemical devices able to directly convert chemical energy into electricity without any combustion process. This thermodynamic consideration means that fuel cells do not follow Carnot cycle and are not limited to its theoretical yield therefore they can reach very high efficiency without local or global impact on the environment. One of the long term more interesting applications of fuel cells is into transport sector.

In theory hydrogen could offer many energy and environmental benefits in order to set a sustainable energetic system worldwide however a lot of work and big investments are needed into all the hydrogen chain to make real a new energy system based on hydrogen as energy carrier.

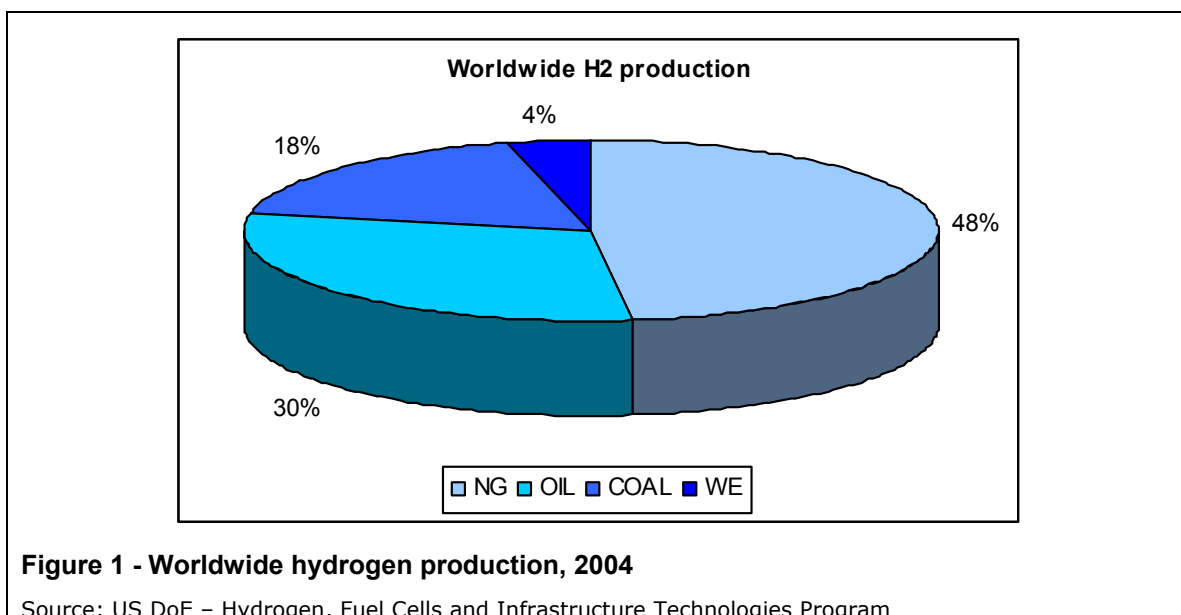
GENERAL DATA ON WORLDWIDE HYDROGEN PRODUCTION

The world wide hydrogen production is estimated about $500\text{-}550 \cdot 10^9 \text{ Nm}^3/\text{year}^2$, almost completely based on fossil fuels.

Worldwide hydrogen production		
Source	Annual production	%
Natural gas	$240 \cdot 10^9 \text{ Nm}^3/\text{year}$	48%
Oil	$150 \cdot 10^9 \text{ Nm}^3/\text{year}$	30%
Coal	$90 \cdot 10^9 \text{ Nm}^3/\text{year}$	18%
Electrolysis ³	$20 \cdot 10^9 \text{ Nm}^3/\text{year}$	4%
Total	$500 \cdot 10^9 \text{ Nm}^3/\text{year}$	100%

Source: U.S. Department of Energy, Hydrogen, Fuel Cells and Infrastructure Technologies Program⁴

Table 1 - Hydrogen Production by Sources



According to DoE, during 2002 48% of the whole hydrogen production was from natural gas (NG). The most widespread process was steam reforming of NG.

However from literature analysis it seems that many H₂ production processes are theoretically available. A few of them, based on fossil fuels, are widely used into industry and meet all hydrogen demand. Many other are in different stages of R&D.

² Gerald Parkinson, Chemical Engineering (2001)

³ Almost completely based on fossil fuels

⁴ <http://www.eere.energy.gov/hydrogenandfuelcells>

INTERNATIONAL OVERVIEW

CANADA

Canada produces $22,5 \cdot 10^9 \text{ Nm}^3/\text{y}$ and on per capita bases Canada is the largest producer and consumer of hydrogen in the world, mainly from NG and H_2S and water. Many plants are located in Alberta where more than half of country H_2 production (55%) and use (63%) takes place.

CHINA

There is an increasing trend in H_2 production. mainly from steam reforming of hydrocarbons. At the moment there are 23 plants and production overcome 0,5 million Nm^3/year .

INDONESIA

In Indonesia there are two big plants ($1,8$ and $2,1 \cdot 10^9 \text{ Nm}^3/\text{y}$). Hydrogen is used into refineries and ammonia and methanol synthesis. H_2 come from steam reforming of natural gas.

SOUTH AFRICA

Company SASOL has 48 production facilities ($2,1 \cdot 10^6 \text{ Nm}^3/\text{h}$) and hydrogen comes from gasification and serves to produce synthetic fuels; 38% of the gas is used in petrochemical industry.

USA

Hydrogen ($83\text{-}100 \cdot 10^9 \text{ Nm}^3/\text{y}$) comes from natural gas (95%); main uses are into refineries and chemical industry. A small quantity is used as energy carrier by NASA.

Next table synthesizes H_2 production capacity in some countries.

National Hydrogen production: some examples		
Country	Yearly production	Average Hourly production
Canada	$22.525 \cdot 10^9 \text{ Nm}^3/\text{y}$	$2.5 \cdot 10^6 \text{ Nm}^3/\text{h}$
China	$5.1 \cdot 10^9 \text{ Nm}^3/\text{y}$	$0.582 \cdot 10^6 \text{ Nm}^3/\text{h}$
Germany	$19.1 \cdot 10^9 \text{ Nm}^3/\text{y}$	$2.2 \cdot 10^6 \text{ Nm}^3/\text{h}$
Indonesia	$3.9 \cdot 10^9 \text{ Nm}^3/\text{y}$	$0.445 \cdot 10^6 \text{ Nm}^3/\text{h}$
Italy	$2 \cdot 10^9 \text{ Nm}^3/\text{h}$	$0.23 \cdot 10^6 \text{ Nm}^3/\text{h}$
South Africa	$18.4 \cdot 10^9 \text{ Nm}^3/\text{y}$	$2.1 \cdot 10^6 \text{ Nm}^3/\text{h}$
USA	$83\text{-}100 \cdot 10^9 \text{ Nm}^3/\text{y}$	$9.5\text{-}11.4 \cdot 10^6 \text{ Nm}^3/\text{h}$

Table 2 - H2 production by Country, some example

Source: IEA (1999)

The table reports some of the biggest plants in the world.

Big hydrogen production plants: some examples					
Site	Technology	Capacity (Nm ³ /h)	Client/Use	Process	Notes
Fort Saskatchewan (Canada)	Uhde	260000 (2x130000)	Shell Refinery	Steam Reforming	Biggest plant in the world
Josè (Venezuela)	Uhde	196000 (2x98000)	Sincor C.A. Refinery	Steam Reforming	Biggest Latin American plant
Leuna (Germany)	Linde	140000 units (4)	Serves about 40 industrial clients	Steam Reforming	Located in a industrial gasses plant
Rotterdam (Netherland)	Shell	118000	Shell Pernis refinery	Gasification	H ₂ used in refinery
Assuan (Egypt)		33000		Electrolysis	

Table 3 - Big production plants in the World, some examples
Source: author elaboration

GERMANY

The estimate value of hydrogen production in Germany in 1998 was about 19.1 10⁹ Nm³, coming from oil (46%), coal (30%) and natural gas (19%). H₂ uses are non energetic by 33%, into petrochemical industry by 19% and direct energetic use as fuel gas (coke gas) by 48%. A recent report⁵ (2005) indicates that 45 % of the hydrogen is produced from crude oil, 33 % from natural gas and 15 % from coal. The remaining 7 % come from electrolysis.

The main gas consumes happen into petrochemical industries and non energetic uses. It has been evaluated that a quantity as high as 8 10⁹ Nm³/year of hydrogen is an unwanted co-product of chemical industrial processes and has burn without energetic profit.

According to German Hydrogen Association the situation in Germany is similar to that in other industrial countries where most of the hydrogen is produced and used into chemical industry. Esteem shows that only 5% of all gas is merchant hydrogen. Steam methane reforming is the main technology for merchant gas. CO₂ sequestration is concretely ignored.

ITALY

H₂ production in Italy is about 1,5-2,5 10⁶ Nm³/y. Industrial hydrogen is based on steam reforming. However there is also a refinery off gas gasification plant. Moreover

⁵ Strategy Report on Research Needs in the Field of Hydrogen Energy Technology by Hydrogen Strategy Group of the Federal Ministry of Economics and Labour, January 2005 - DRAFT

some other hydrogen production projects (by coal gasification and refinery waste) are on their course.

Hydrogen Production in Italy: some examples				
Site	Company (technology)	Capacity (Nm ³ /h)	Process	Notes
Salerno	Sol	Some hundred	Steam reforming	Technical gas
Ravenna	Sol			Technical gas
Cuneo	Sol			Technical gas
Brindisi			Chemical process	
Ferrandina	Sapio		Steam reforming	
Ferrara	Sapio		Chemical process	
Mantova	Sapio		Steam Reforming	
Marghera	Sapio		Chlorine soda	
Piombino		200	Steam Reforming	
Verbania			Chlorine soda	
Milazzo	Linde	53000	Steam reforming	H ₂ s used into refinery
Osio Sopra	Siad	600	Steam reforming	
Terni	Linde	2500	Steam reforming	
Sarroch (Ca)	Refinery Sarlux	40000	Visbreacking waste (TAR)	H ₂ s used into refinery
Falconara	API refinery		Refinery waste gasification	
Sannazzaro	Agip refinery Petroli	42000	Steam reforming	H ₂ s used into refinery
Sannazzaro	Agip Refinery Petroli		Visbracking waste gasification	Planned start up: 2005
Cremona	Tamoil	30000-35000	Catalytic reforming of heavy nafta	H ₂ s used into refinery
Source: author elaboration from different data				

GENERAL DATA ON WORLDWIDE HYDROGEN USES

Hydrogen is used in different industrial sectors. A preliminary classification could be related to capacity of the plant and to specific application. Huge hydrogen production plants are usually located into industrial parks as refineries or ammonia and methanol production facilities. Typical capacities range between some tens of thousand to a few hundred thousand Nm³/h.

Main hydrogen uses from different literature sources ⁶				
Ammonia	Refinery	Methanol	Other uses	Space transport
50%	37%	8%	4%	1%
62.4%	24.3%	8.7		4.6%

Table 4 - Main hydrogen uses from different literature sources
Source: Bellona Report n.6 (2002), Spath and Mann NREL (2000)

In addition to hydrogen uses into chemical plants, there are some other industrial applications of small and medium scales from some tens to some hundreds of Nm³/h into pharmaceutical (100-700 Nm³/h), food (50-350 Nm³/h), electronic (10-100 Nm³/h) and glass industry (20-200 Nm³/h), metallurgy (200-800 Nm³/h) and power stations which cover a little part (5%) of the global production.

Merchant Hydrogen demand in USA excluding refineries and ammonia and methanol plants	
Market	Year 2000
Chemicals	3.36 10 ⁹ Nm ³
Electronic	0.39 10 ⁹ Nm ³
Food	0.13 10 ⁹ Nm ³
Metallurgy	0.11 10 ⁹ Nm ³
Others	0.45 10 ⁹ Nm ³
Total	4.44 10 ⁹ Nm ³

Table 5 - Merchant hydrogen demand in USA
Source: John N. Armor, 1998

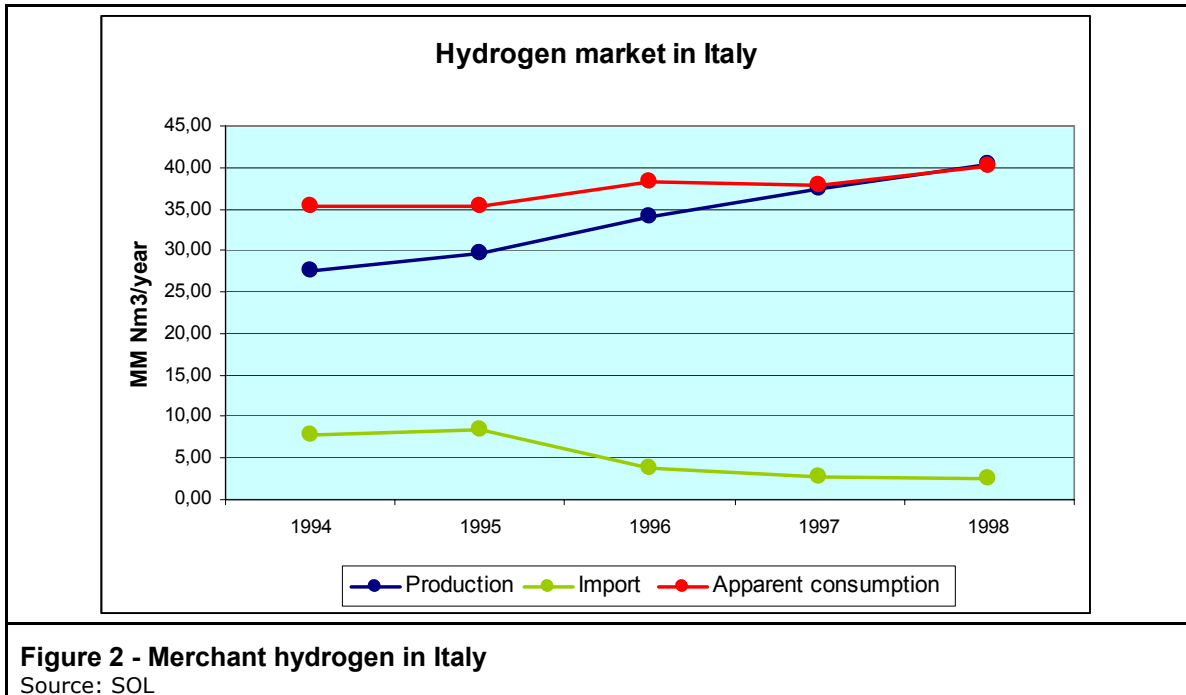
MERCHANT HYDROGEN IN ITALY

In Italian peninsula technical gas industry produces merchant hydrogen for some kind of sectors and applications. The demand has been slowly growing and the internal production could be just below or have achieved 50 MM Nm³/y.

Italian hydrogen market as technical gas - MM di Nm ³ diH ₂ /year					
	1994	1995	1996	1997	1998
Production	27.6	29.7	34.0	37.4	40.3
Import	7.7	8.5	3.8	2.8	2.5
Export	n.s.	n.s.	0.0	0.0	0.1
Apparent consumption	35.3	35.3	38.2	37.8	40.2

Table 6 - Merchant hydrogen in Italy
Source: SOL

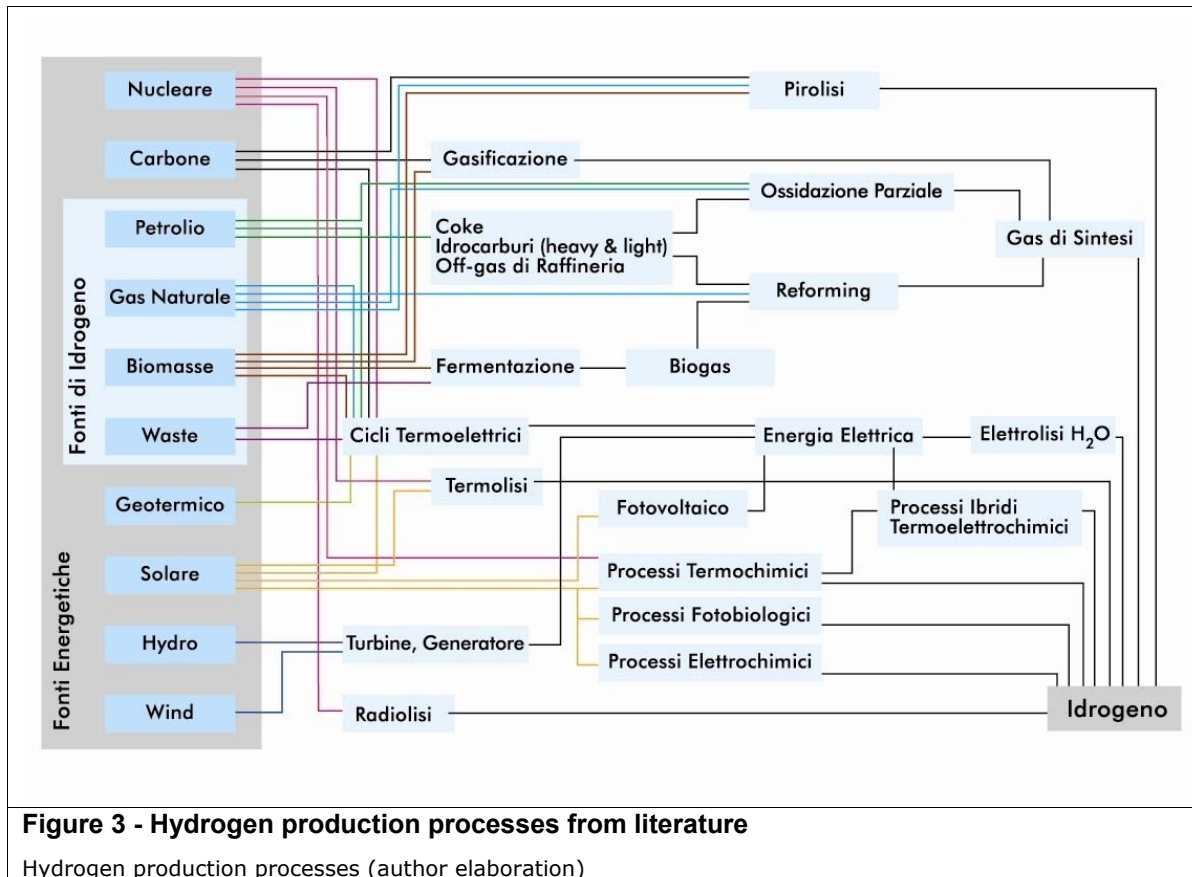
⁶ Bellona Report n.6, 2002 and NREL, 2000



PRODUCTION

It is not simple to completely identify all the possible hydrogen production processes from literature; we tried to synthesize them here:

- Steam Reforming (SMR)
- CO₂ Reforming (Dry Reforming)
- Partial oxidation of hydrocarbon (catalytic POX and non catalytic POX)
- Coal gasification
- Auto thermal reforming
- Hydrogen from coke
- Hydro cracking of heavy oil
- Hydrogen from refinery off-gas
- Hydro-gasification
- Thermal conversion of coal
- Biomass or waste gasification and pyrolysis
- Hydrogen from methanol and ammonia
- Metal oxide redox
- Thermal cracking
- Steam iron process
- Gasification with melted iron
- H₂ from H₂S
- Electrolysis
- Photo biological technologies
- Electrochemical technologies
- Water radiolysis
- Water thermolysis
- Thermo chemical cycles
- H₂ from waste water
- Chlorine and soda process (H₂ as waste steam)



As the list shows, in literature there are many proposed processes. A few of them see commercial applications and are based on fossil fuels.

Commercial production processes	Status of technology
Steam reforming of natural gas	Mature
Partial oxidation of hydrocarbons	Mature
Coal gasification	R&D / Mature
Water electrolysis	Mature
Table 7 - H2 commercial production processes	
Source: (Momirlan and Veziroglu, 2002)	

Other processes are more or less ahead into research and development stage.

We would like to focus our attention especially on three processes related with ZERO REGIO project that are Steam Reforming of natural gas, Catalytic Partial Oxidation of natural gas and H₂ from waste stream of chlorine soda chemical process.

HYDROGEN PRODUCTION PROCESSES

STEAM REFORMING (SMR)

Starting from natural gas or other light hydrocarbons, steam reforming (SR) produces a gaseous mixture containing hydrogen. SR is a process technologically mature and economically competitive especially in relation to large production scale. However research has been developing also medium and small on site production facilities. The process yield varies in wide range (65-90%) depending on capacity of the plant, feed characteristics and heat recovery. Plant sizes vary from a few 100 Nm³/h to 260.000 Nm³/h but a 600.000 Nm³/h new hydrogen production facility project is on course.

Main disadvantages of the process are related to common problems of fossil fuel (security of supply and CO₂ co-production). SMR can be represented in the next scheme:

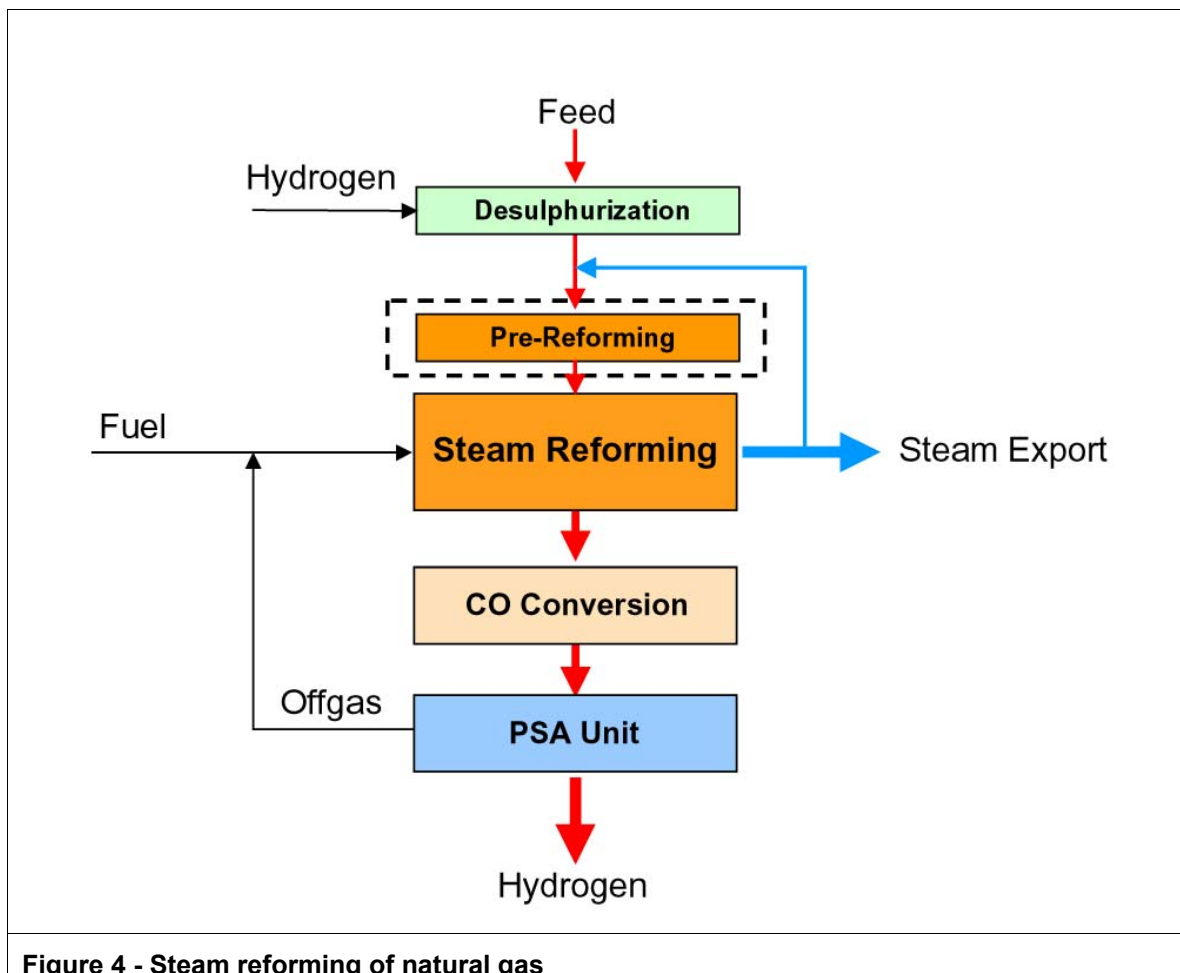
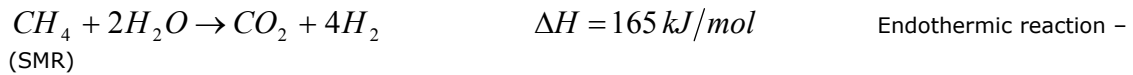


Figure 4 - Steam reforming of natural gas

Main important reaction of the process is reforming of methane (CH₄) with steam.



How ever many other catalytic reactions take place into a steam reforming plant. Some literature data on production cost are reported into following table.

Some literature data on Hydrogen production cost from Steam Methane Reforming			
Facility Size (million Nm ³ /d)	Reference	Specific TCI (\$/GJ)	Hydrogen Price (\$/GJ)
Large Facilities			
1.34 (602 GJ/h)	Leiby 1994	14.74	7.46
2.14 (962 GJ/h)	Leiby 1994	12.61	6.90
2.80 (1258 GJ/h)	Kirk-Othmer 1991	9.01	6.26
6.75 (3033 GJ/h)	Foster-Wheeler 1996	10.00	5.44
25.4 (11415 GJ/h)	Blok et. al 1997	10.82	5.97
Small Facilities			
0.27 (121 GJ/h)	Leiby 1994	27.46	11.22
Table 8 - Hydrogen production cost by SMR: some literature examples			
Source: Survey of the Economics of Hydrogen Technology – Padrò, Putsche (1999)			

PARTIAL OXIDATION (POX)

The process consists in the partial oxidation of hydrocarbons. It could be helped by a catalytic converter (CPOX) for small scale or matched with steam reforming in a process called auto thermal reforming (ATR) for huge capacities.

Partial oxidation is able to convert to hydrogen feeds as heavy gaseous or liquid hydrocarbons for which SR is not recommended. Although the efficiency is lower (55-80%), partial oxidation shows quicker response to transitory and the reactor is simpler and cheaper than steam reforming tubular one.

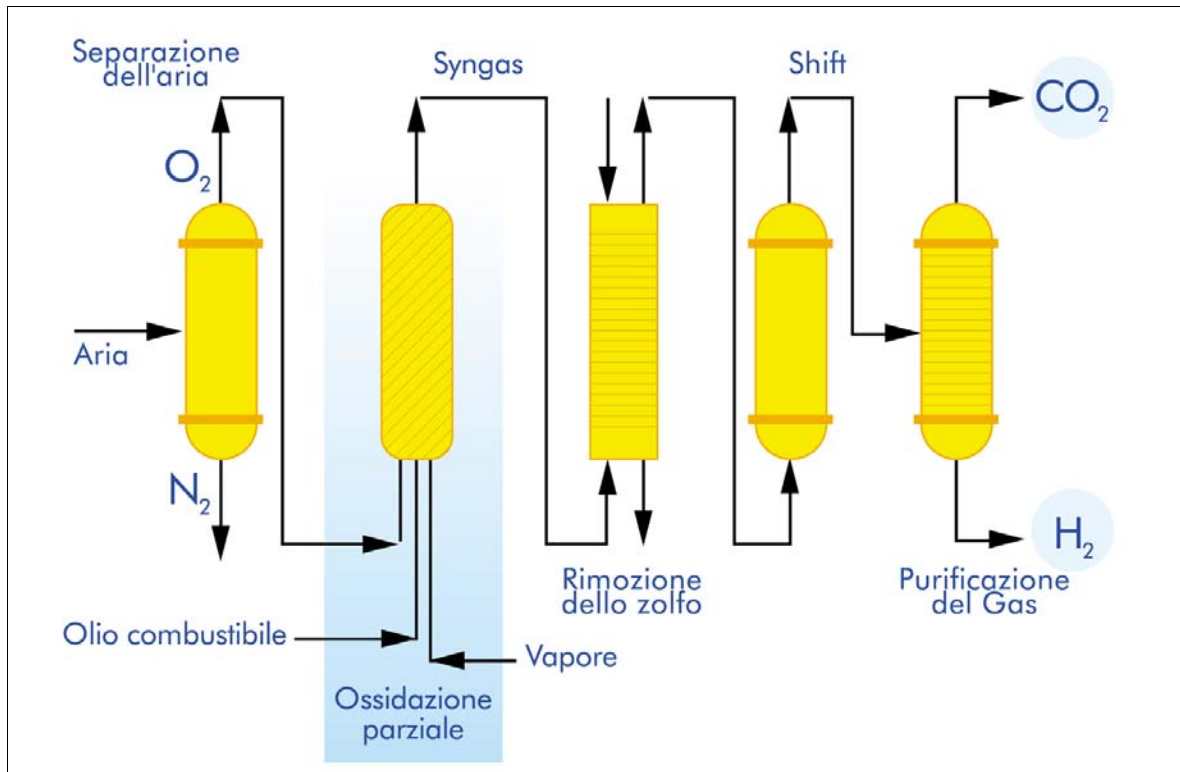


Figure 5 - Partial oxidation of Hydrocarbons

Main important reactions of the process are oxidation of hydrocarbons with O_2 (from air and steam and shift reaction as well).

$C_n H_m + (1/2)nO_2 \rightarrow nCO + (1/2)mH_2$		POx with O_2 (from air)
$C_n H_m + nH_2O \rightarrow nCO + (n + m/2)H_2$		POx with steam
$CO + H_2O \rightarrow CO_2 + H_2$	$\Delta H_0 = -40.8 \text{ KJ/mol}$	Shift

Some literature data on production cost are reported into following table.

Some literature data on Hydrogen Production Costs from No catalytic Partial Oxidation				
Facility Size (million Nm^3/d)	Reference	Feedstock	Specific TCI (\$/GJ)	Hydrogen Price (\$/GJ)
Large Facilities				
1.34 (602 GJ/h)	Leiby 1994	Coker off-gas	11.24	7.39
2.14 (962 GJ/h)	Leiby 1994	Coker off-gas	9.63	6.94
2.80 (1258 GJ/h)	Kirk-Othmer 1991	Residual oil	22.2	9.83
Small Facilities				
0.27 (121 GJ/h)	Leiby 1994	Coker off-gas	21.96	10.73

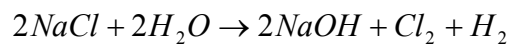
Table 9 - Hydrogen production cost by POx: some literature examples

Source: Survey of the Economics of Hydrogen Technology – Padrò, Putsche (1999)

CHLORINE SODA PROCESS

Currently a significant amount of hydrogen is produced from the chemical industry and chlorine –soda process is the only large scale industrial technology supplying hydrogen as by-product of the production facilities. In a year time, related to chlorine production, $20 \cdot 10^9 \text{ Nm}^3$ of hydrogen are produced worldwide, an amount almost equal to than that coming from water electrolysis. Frequently hydrogen is vented into atmosphere or burnt without use (Zittel, 2002) if it is not needed on site. Often it has said that industry of chlorine has not got the characteristics to satisfy a wide scale of hydrogen production.

Chlorine soda process leaves caustic soda and mercury into hydrogen stream which need to be purified before use (Granite et al.,2000) to obtain purities of 99.9%. Main reaction is:



From literature analysis, H2 production unit cost depending on commercial process and capacity are synthesize in the table. We report data concerning Steam Reforming, Non Catalytic Partial Oxidation, Coal Gasification and Water Electrolysis.

From our deeper research on literature analysis and research into industries we found out more specific data about H2 commercial production processes. The table shows influence of scale up and feed cost.

H₂ unit cost via Catalytic partial Oxidation or via waste stream by chlorine soda plant is not contemplated in literature⁷; ZERO REGIO can help to cover this gap.

⁷ At least from public literature we investigate

HYDROGEN PRODUCTION UNIT COST

Nowadays hydrogen production come from four processes: steam reforming of natural gas, partial oxidation of hydrocarbons, coal gasification and water electrolysis. H₂ production process yield and H₂ unit cost by commercial processes are reported in the following table. Costs are reported for many plant capacities.

Process	Efficiency	Capacity (Nm ³ /h)	Cost		Notes	
			(Euro/Nm ³ H ₂)	(Euro/GJ) ⁸		
Steam Reforming (commercial)	70 - 90%	56000 - 1058000	0.06 - 0.07	5.56 - 6.49	NG price: 4-8 Euro/GJ	
		35000	0.09 - 0.16	8.34 - 14.83		
		11000	0.11	10.20		
		5000	0.12 - 0.19	11.13 - 17.62		
		1000	0.22 - 0.29	20.40 - 26.89		
		200	0.65 - 0.72	60.27 - 66.76		
		100	1.12 - 1.19	103.84 - 110.33		
<u>Non catalytic</u> Partial Oxidation POX (commercial)	55 - 80%	167000	0.10	6.31	From CH ₄ with air	
		89000	0.07	11.45		
		56000	0.07	11.45		
		11250	0.11	4.46		
		200	0.051	4.73		
		100	0.065	6.03		
		200	0.053	4.82		From CH ₄ with O ₂
		100	0.50	8.36		
		200	0.049	4.64		From CH ₄ with free O ₂
100	0.46	15.35				
Coal gasification (commercial)	55 - 60%	360000	0.085	7.88		
		282500	0.097	8.99		
		117000	0.11	4.46		
Electrolysis (commercial)	60 - 90 ⁹ %	281000	0.20	13.02	e.e. cost: 0,04-0,08 Euro/kWh	
		117000	0.24	6.02		
		4000	0.28	23.03		

⁸ LHV basis

⁹ Just electrolyser yield

	1000	0.29 - 0.46	26.89 - 42.65	High pressure
	200	0.42 - 0.59	38.94 - 54.70	AWE ¹⁰
	100	0.54 - 0.72	50.07 - 66.76	
< 10% ¹¹		1.2-2.6	111.26 - 241.06	PV and AWE
	10300 (2000)	0.20	13.02	Wind
	11600 (2010)	0.11	4.46	Wind (R&D)
50 - 80%		0.48	12.05	High temperature
		0.043	3.99	(R&D)

Table 10 – Hydrogen production cost for commercial processes and influence of capacity

Source: Own elaboration on industrial data

¹⁰ Advanced Water Electrolysis

¹¹ Global yield

SCALING UP: THE STEAM REFORMING vs. ELECTROLYSIS

Let see an example of economies of scale related to H₂ production, where comparing H₂ unit cost of hydrogen obtained by steam reforming of natural gas and by water electrolysis. At small production capacity electrolysis is available at less cost than steam reforming. This is because of SR plant reduces hydrogen unit cost when scaling up as often happens for chemical plants¹². Electrolysis comes interesting for small demands, far away from central production plants, requiring high purity gas and when clients are not able to stock H₂ on site. The graphic shows the performance of unit cost of H₂ production by steam reforming and water electrolysis with different cost of electricity (0,04 and 0,08 Euro/kWh) and natural gas prices (4 and 8 Euro/GJ).

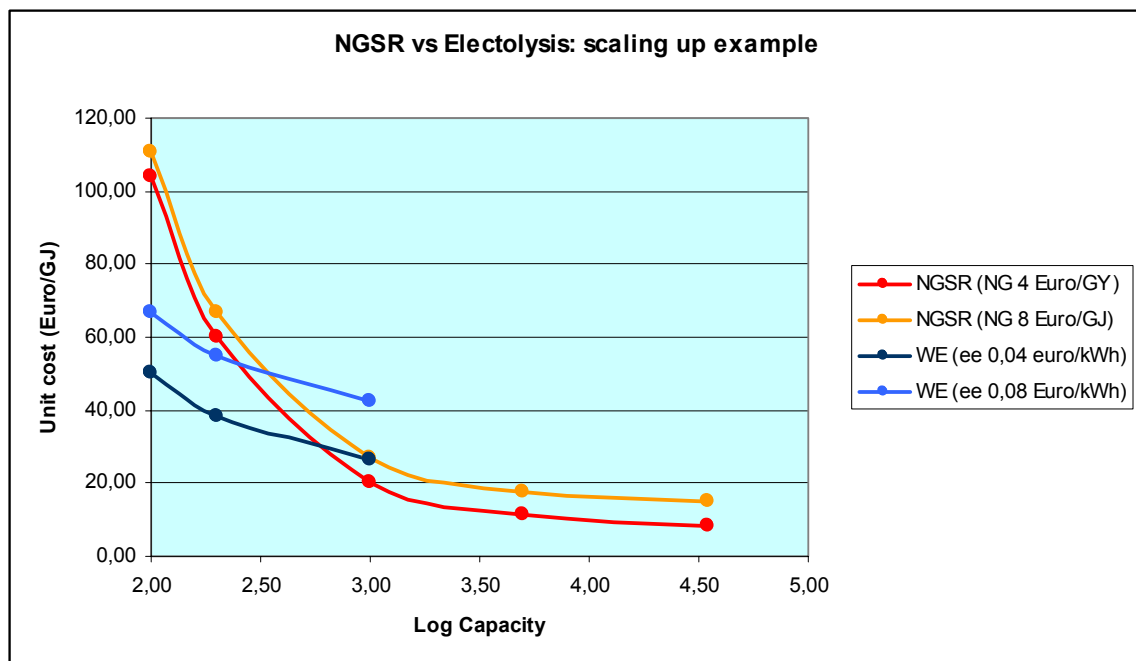


Figure 6 - H₂ unit cost by SMR vs Water Electrolysis

Source: confidential

CONCLUSIONS:

From the analysis of the graphic we can argue that:

- Small capacity: electrolysis is competitive to steam reforming up to a few hundred Nm³/h.
- Unit cost estimate goes quickly down from 100 to 1000 Nm³/h especially for SR however research has been developing also medium small on site production

¹² Fuels and Chemical Manufacturing. Guidelines for Understanding and Minimizing the Production Costs. J. P. Lange (Shell R&T Centre, Amsterdam)

facilities because of development of this technology and recovery of waste heat which seem to make small production facilities less expensive than in the past.

- Advanced water electrolysis with high power cost (0,08 Euro/kWh) is less expensive than SR up to a few hundred Nm³/h (300 Nm³/h) H₂ production and up to 500-1000 Nm³/h for electricity cost about 0,04 Euro/kWh depending on natural gas price (4-8 Euro/GJ).
- Electrolysis doesn't exploit great economies of scale over 500 Nm³/h H₂ production rate because it is a modular technology.
- Medium and big capacity: Steam reforming shows a cheaper H₂ production unit cost than electrolysis as capacity grows up. This is because of scale effect that in general is a common point of chemical plants.
- As capacity grows up, feed price becomes even more important on production unit cost and for big plants it is about 80-90 % of it.

From the point of view of the small on site catalytic partial oxidation production plan (SCT POX by ENI Tecnologie) it is of interest to estimate H₂ unit cost and its economic validity when compared to water electrolysis because this data doesn't come out from literature.

PHYSICAL PROPERTIES OF HYDROGEN AS ENERGY CARRIER AND THEIR IMPLICATIONS ON ITS TRASPORT

Once produced, hydrogen turns out to be a good energy carrier.

H₂ lower heating value on mass basis is as high as 120 MJ/kg therefore 2,7 times that of gasoline (44 MJ/kg) and 2,4 times the Lower Heating Value (LHV) of natural gas (50 MJ/kg).

H₂ has the lowest density between gasses (0,089 kg/m³, T = 15°C), about eight time less than that of natural gas (0,65 kg/m³) at the same conditions of temperature and pressure. Liquid hydrogen (Teb=-253°C) has got higher density than that of the H₂ in gas state (71 kg/m³) but however about ten time less than that of gasoline (700 kg/m³).

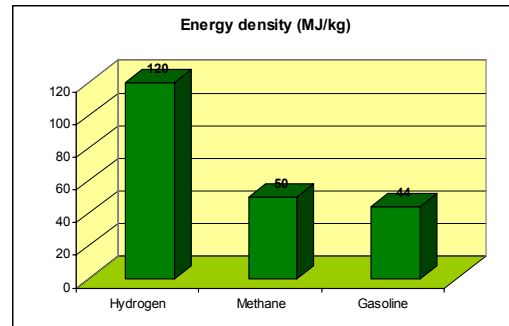


Figure 7 - Energy density of hydrogen, methane and gasoline

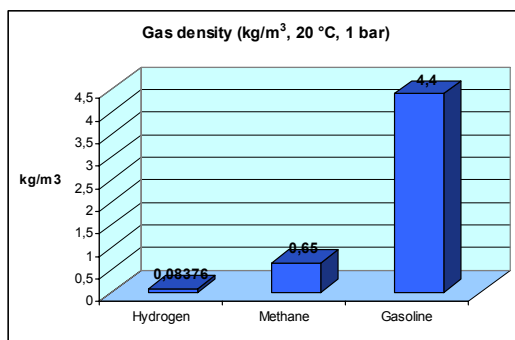


Figure 8 - Gas density of hydrogen, methane and gasoline

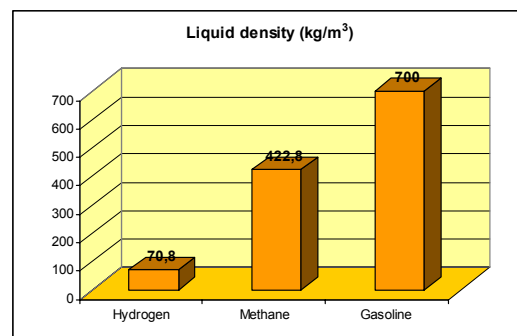


Figure 9 - Liquid density of hydrogen, methane and gasoline

All those remarks mean that energetic density for a unit volume of gaseous and liquid H₂ are respectively about one third of those of natural gas and gasoline. These considerations denote a fatal and negative influence of H₂ density on hydrogen transport for both energetic and economic point of view.

TRANSPORT OF HYDROGEN

Hydrogen use as energy carrier requires availability of the gas at the user. Commercial choices for gas transport are on road as gaseous or liquid H₂ and in pipelines as gaseous H₂. We report some literature data to allow some general consideration on costs.

Some literature data on Hydrogen Transport as a Compressed Gas via Truck			
Trip Distance (km)	Quantity Transported (GJ/yr)	TCI (\$/GJ)	Transport Cost (\$/GJ)
16	458,000-45.8 million	4.10	4.70
161	458,000-45.8 million	8.20	10.60
322	45,800-45.8 million	13.7-16.4	18.30-18.60
805	45,800-45.8 million	30.20	41.10
1,609	45,800-45.8 million	57.60	79.10-79.70

Table 11 – Unit cost of gaseous compressed H₂ on road transport: some literature examples
Source: Survey of the Economics of Hydrogen Technology – Padrò, Putsche (1999)

Some literature data on Hydrogen Transport as a Liquefied Gas via Truck		
Trip Distance (km)	TCI (\$/GJ)	Transport Cost (\$/GJ)
16	0.44-11.0	0.24-1.60
161	0.77-11.0	0.52-1.84
322	2.20-11.0	1.0-2.20
805	2.70-11.0	2.00-3.10
1,609	5.10-11.0	3.90-4.70

Table 12 - Unit cost of liquid H₂ on road transport: some literature examples
Source: Survey of the Economics of Hydrogen Technology – Padrò, Putsche (1999)

Main variables in order to choice technology and minimize unit cost are quantities of transported gas and delivery distance. However literature data are not detailed as production costs are.

Indicative literature values for a 100 km road trip distance from production plant to client has a transport cost in best case that range between 0,5 Euro/GJ (liquid H₂ not considering liquefaction cost) to 4-6 Euro/GJ (gaseous H₂).

Huge quantities of H₂ (several GJ/s) transported by a 1000 km pipeline could show a cost of 0,8-1,5 Euro/GJ in the best circumstances but many factors can change these numbers.

TRANSPORT ON ROAD

From comparison between transport of liquid or gaseous H₂ and gasoline it is clear that low density of hydrogen penalize on road transport as table shows. The table reports the mass transported in a load of gasoline and compares it to transport of a load of liquid or gaseous hydrogen. Main evidence of energetic inefficiency is shown by the number of trip to deliver the same amount of H₂ which contain the same energy of one gasoline tank trip. (2,55 for liquid and 16 for gaseous hydrogen).

	Unit	Gasoline	Liquid H ₂	Gaseous H ₂
Transported mass	Kg	24000	3370	530 ¹³
LHV	MJ/kg	43	120	120
Transported energy	GJ	1032	404.4	6306
Energy transported compared with gasoline	%	100	39.2	6.2
Number of trips to deliver the same amount of energy		1	2.55	16.23

Table 13 - Transport of gaseous and liquid H₂ vs gasoline
Source: Ennio Macchi (2003)

COMPRESSION

The transport of gaseous hydrogen needs compression (today up to 200 bar) in order to increase energy density of volume unit which require a significant energy expense. Ideal isothermal compression has the cheapest energetic expenses however it is impossible to be realize in partice. The real process is closer to an adiabatic compression which increases gas temperature during the process. Energy required for adiabatic compression process is higher that isothermal one and changes with kind of gas. Methane compressione needs less energy that gaseous H₂ compression as shown into next table.

¹³ Compressed gaseous H₂ is delivered al 200 bar but discharged tanks are not empty but they still contain H₂ at 40 bar. Which data means that just 80% of the transported H₂ load is really delivered to user.

Compression energy demand: H₂ vs CH₄

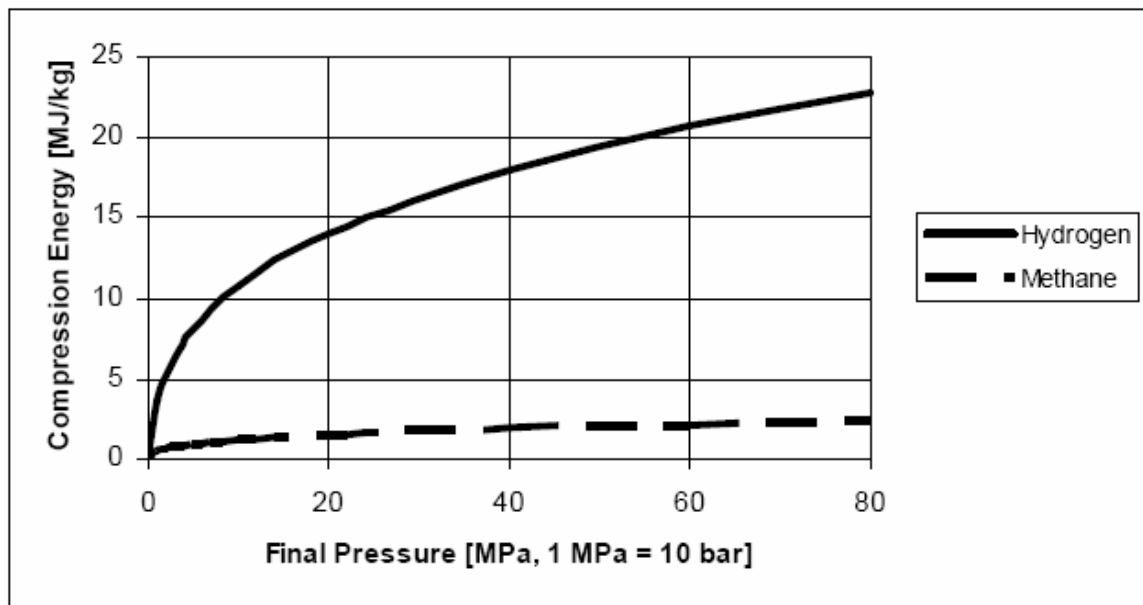


Figure 10 - Energy demand for adiabatic H₂ and CH₄ compression process

Source: The Future of Hydrogen Economy: Bright or Bleak? Ulf Bossel and Baldur Eliasson, 15 april 2003, updated 26 genuary 2005

In order to reduce energy consumption inter cooled multi stage industrial compressors are used. The point to be underline is how much energy is required for hydrogen compression process related to his heating value.

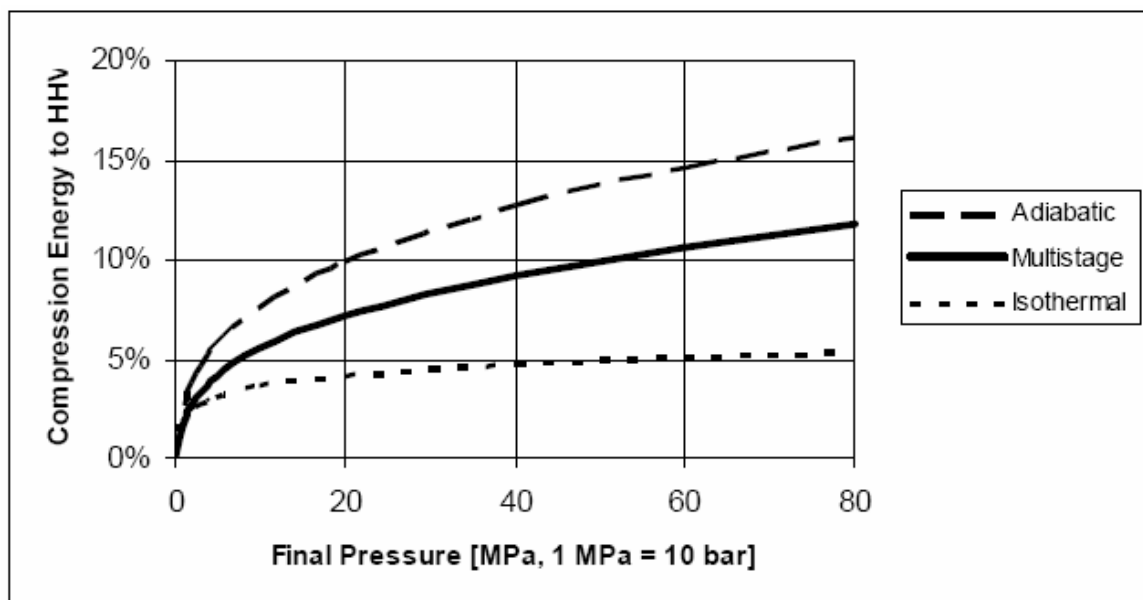
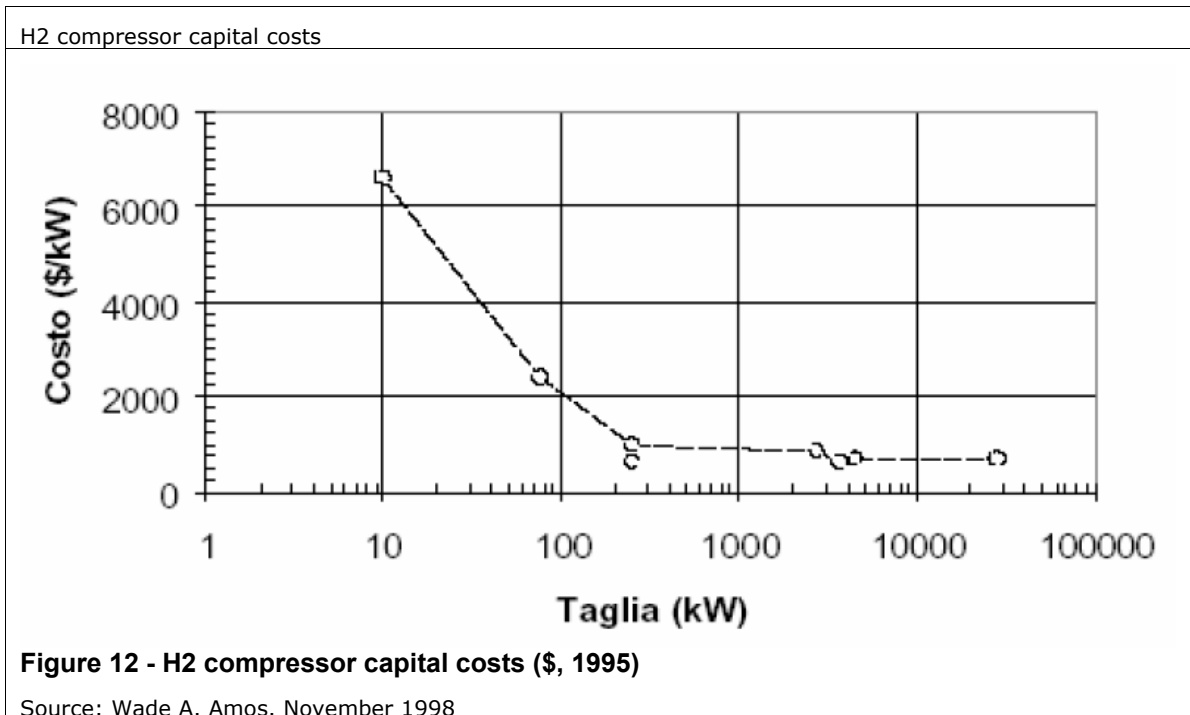


Figure 11 - Compression energy demand compared to H₂ Higher Heating Value

Source: The Future of Hydrogen Economy: Bright or Bleak? Ulf Bossel and Baldur Eliasson, 15 april 2003, updated 26 January 2005

Energy required into inter cooled multi stage H₂ compression process varies between 8% (200 bar) and 14% (800 bar) of HHV for 1000 kg/h flow rate and this data do not include mechanical and electric losses so energy could be as high as 20% of H₂ HHV. Finally it is clear that power has to be generated and this decrease even more the overall yield of compression process (Bossel and Eliasson 2005).



As shown from figure above H₂ compressor capital cost per unit power (\$/kW) decrease as compressor power increase. Operating unit costs vary between 0,4 and 1,6 Euro/GJ of H₂.

LIQUEFACTION

Liquid hydrogen has higher density than gaseous H₂ (200 bar) however liquefaction process shows expensive energetic demand (Bossel and Eliasson 2005) related to the cryogenic temperatures involved (T_{eb}=-253 °C). Current big H₂ liquefaction plants require energetic expenses over 40 MJ/kg, one third of LHV of the gas.

Typical energy requirements for the liquefaction of 1 kg hydrogen as a function of plant size and process optimization

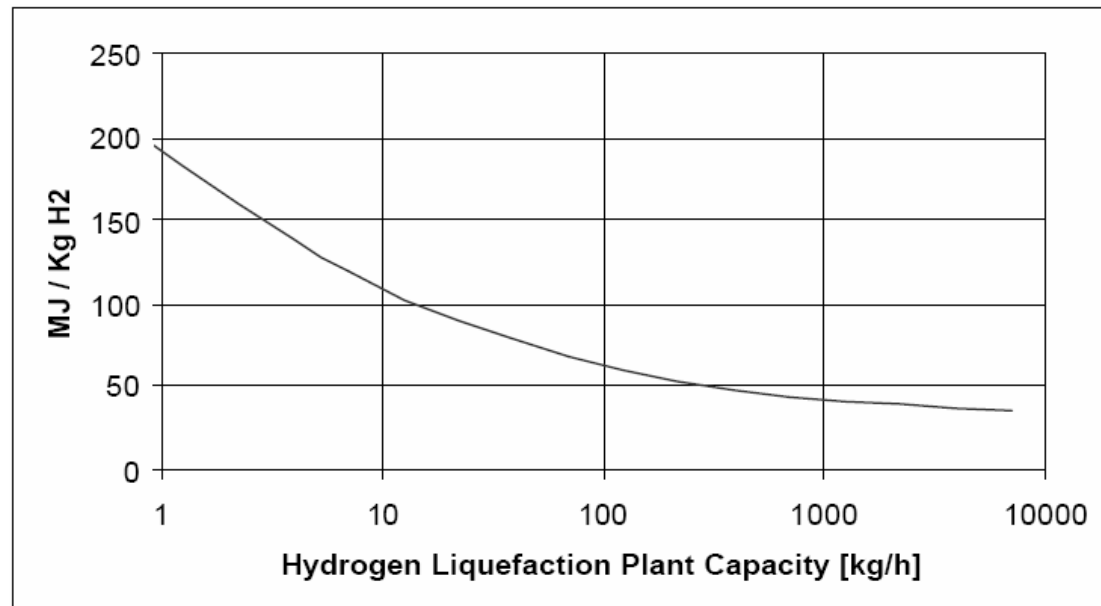


Figure 13 - Energy input for hydrogen liquefaction process

Source: The Future of Hydrogen Economy: Bright or Bleak? Ulf Bossel and Baldur Eliasson, 15 april 2003, updated 26 January 2005

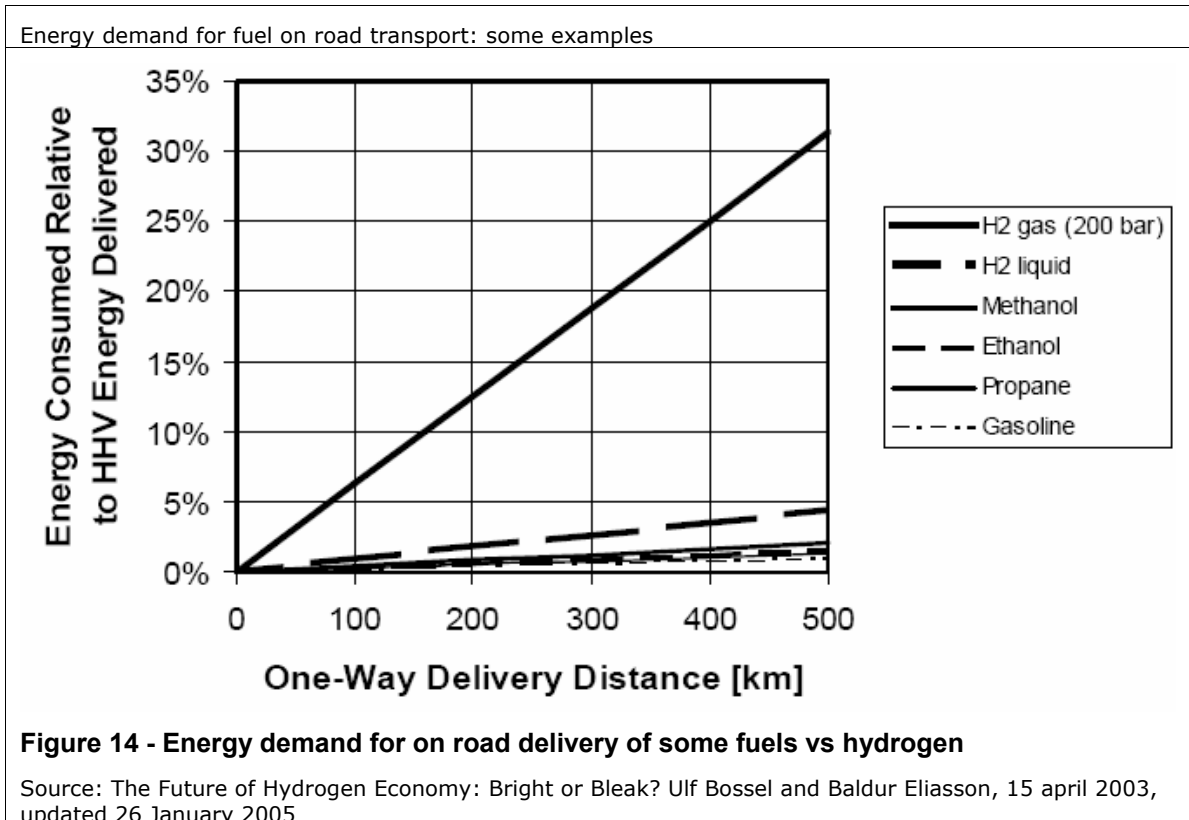
From literature data hypothetical a big H₂ liquefaction plant shows a unit cost range from 12,8 Euro/GJ (120 t/day) to 6,1 Euro/GJ for very gigantic and innovative plant (700 t/day¹⁴). Today the biggest plant worldwide produces 60t/day and is the one realized in USA during Apollo project. Commercial liquefaction plants have capacity up to 40 t per day.

Higher liquid H₂ density could offer a cheaper on road transport cost than that of gaseous H₂ as quantity increase.

¹⁴ Ennio Macchi. 2003

CONCLUSIONS

Energy demand for H₂ on road transport is higher than for other energy vectors as shown in next figure. It is worth to underline that liquid H₂ transport cost is similar to other fuel ones because it does not contain liquefaction cost.



Analyzing deeper, main costs of H₂ transport on road (gaseous or liquid) are related to:

- Investment costs related to truck
- Expenses related to general costs for tyre transport as staff wages, insurance, fuel, operation & maintenance.

How to deliver hydrogen?		
	Small quantities	Big quantities
Short distances	Gaseous transport	Liquid on road or gaseous in pipelines?
Long distance	Liquid transport	

Compressed gas on road transport is reasonable for short distances and small volumes.

Liquid H₂ transport could become competitive when delivering big quantities of H₂ and short distance because liquefaction process has high energetic cost and is heavily influenced by plant scaling up.

TRANSPORT IN PIPELINE

When H₂ delivered quantity and distance increase, pipeline transport can become competitive with liquid on road one from economic and energetic point of view. At present days there are H₂ pipelines as long as about 720 km in Europe and 1500 km in USA working at 10-20 bar not for energetic uses. The first H₂ pipeline was realised in 1938¹⁵. We report some literature data on hydrogen pipeline transport to show that in general transport unit cost goes down when transported amount and distances increase.

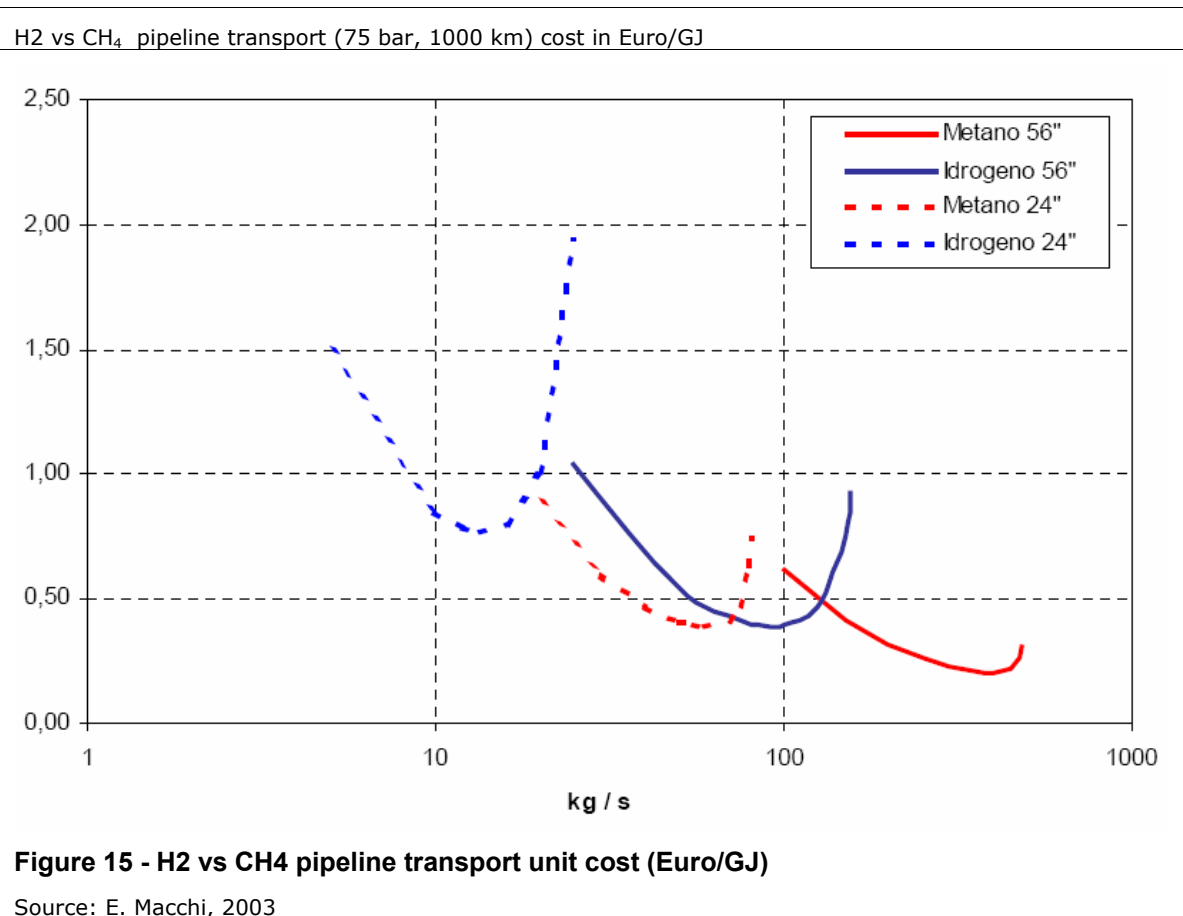
Some literature data on Hydrogen Transmission Costs via Pipeline						
Transmission Rate (GW)	Distance (km)	Reference	Specific TCI (\$/GJ delivered)	Hydrogen Transmission Cost (\$/GJ)	Cost	
0.15	161	Amos 1998	21.22	2.83		
	805	Oney et al. 1994	14.14	2.03		
		Amos 1998	106.24	13.84		
	1609	Oney et al. 1994	67.53	8.87		
		Amos 1998	210.32	27.23		
		Oney et al. 1994	134.18	17.41		
	0.5	161	Oney et al. 1994	4.80	0.83	
		805	Oney et al. 1994	20.81	2.88	
		1609	Oney et al. 1994	38.82	5.44	
1.0	161	Oney et al. 1994	2.66	0.57		
	805	Oney et al. 1994	10.80	1.60		
	1609	Oney et al. 1994	20.80	2.88		
1.5	161	Amos 1998	2.83	0.83		
	805	Oney et al. 1994	2.13	0.49		
		Amos 1998	11.59	2.09		
	1609	Oney et al. 1994	7.47	1.17		
		Amos 1998	22.30	3.53		
		Oney et al. 1994	14.13	2.03		

Table 14 - H₂ transport unit cost by pipeline: some literature examples
Source: Survey of the Economics of Hydrogen Technology – Padrò, Putsche (1999)

Comparing pipeline gaseous H₂ and NG energetic expences for transport of a energetic unit of the two gases, literature often show that the first is four or five time more expensive than the second because those authors do not compare the economic optimum unit cost for transport. When some authors do it correctly it comes out that pipeline H₂ transport unit cost results, in best case, 1,5-2 times more than NG pipeline one¹⁶.

¹⁵ Source ENEA

¹⁶ Ennio Macchi, 2003



CONCLUSIONS

Unit cost of a H₂ pipelines depends on a long list of hypothesis as pipe cost (steel, pipe covering, transport, use of the land, assembly, engineering,...) compression plants, land, and O&M (salary, power,..). However it is very important amortisation period and discount rate as well.

It is significant to underline that transport distances in a possible H₂ economy could hypothetical be shorter than that of natural gas. Moreover H₂ production unit cost will be higher than NG cost (feedstock); from this point of view transport will engrave H₂ unit cost less NG one (Ennio Macchi, 2003).

At present time literature data on transport of huge mass of hydrogen by centralized production pathway shows that could be a break even point between gaseous pipeline and liquid cryogenic on road trailer. However more research is needed in order to exactly identify this point.

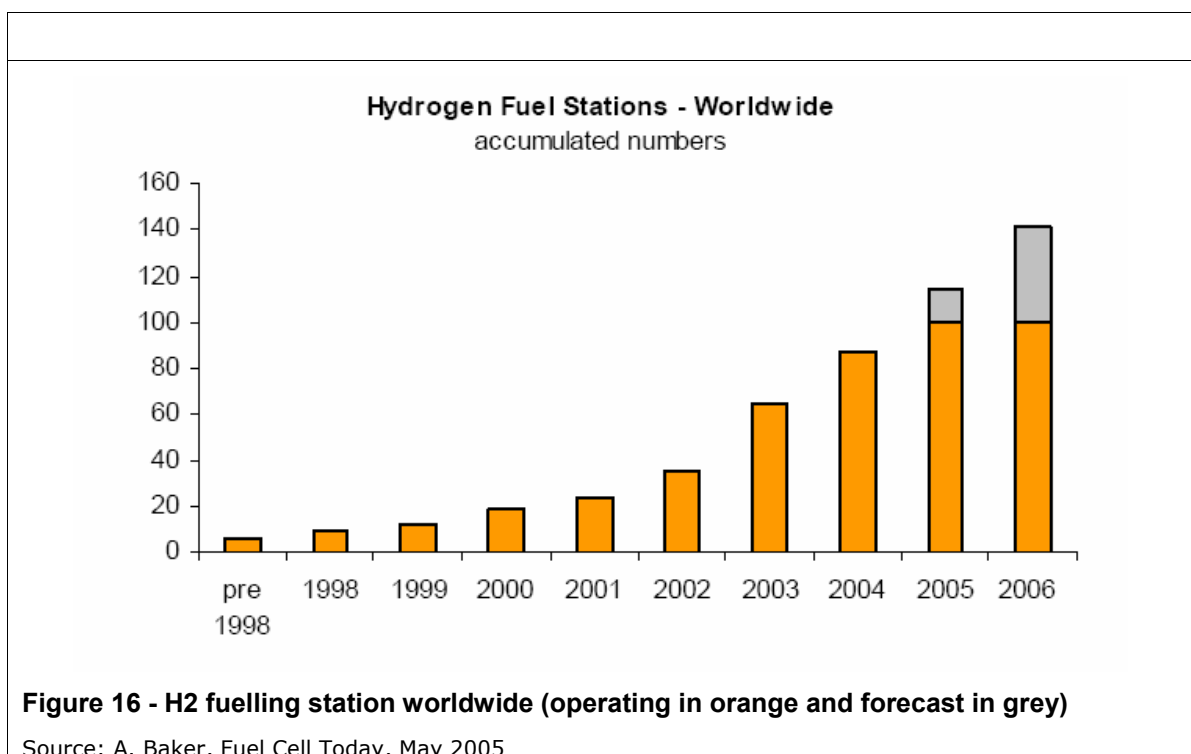
Zero Regio has the chance to investigate deeper hydrogen transport economy.

INFRASTRUCTURES

Also regarding hydrogen infrastructure investment cost there is not a clear and common vision on literature. For instance some recent reports indicate a wide range of value from a 3-6 Bn Euros (E4Tech, 2005) to more than 170 Bn. Euros with an average value about 47 Bn Euro to meet H2 2020 EU target (Mulder and Girard, 2004). However this value comes from a large spread of different pathway so it is not representative. In general centralized production options are cheaper than on site ones. Liquefied transport and pipeline gaseous one are in competition. Investment costs are related to targets (for instance 5% 2020 EU target), on site vs. centralised production, H2 transport pathway, refuelling station cost.

REFUELLING STATION

In 2005 there are 100 H₂ refuelling station worldwide and another 15 will be finished before the end of the year. Other 30-40 stations will be ready next year.



Compressed hydrogen dispenser seems to be preferred to liquid one. Most of the refuelling stations are in North America as next figure shows.

H2 refuelling station by type and by region

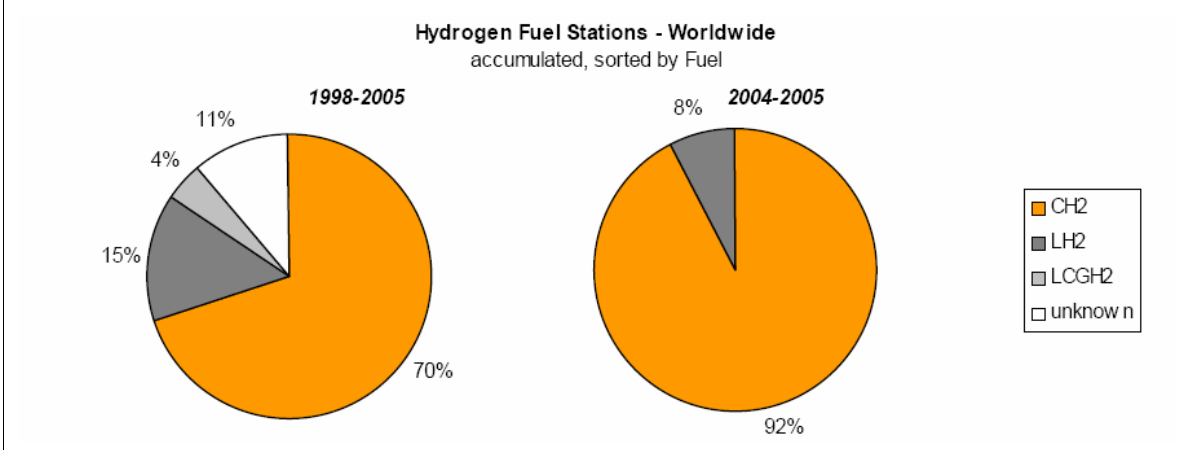


Figure 17 - H2 refuelling station by type (Liquid vs gaseous H2)

Source: A. Baker, Fuel Cell Today, May 2005

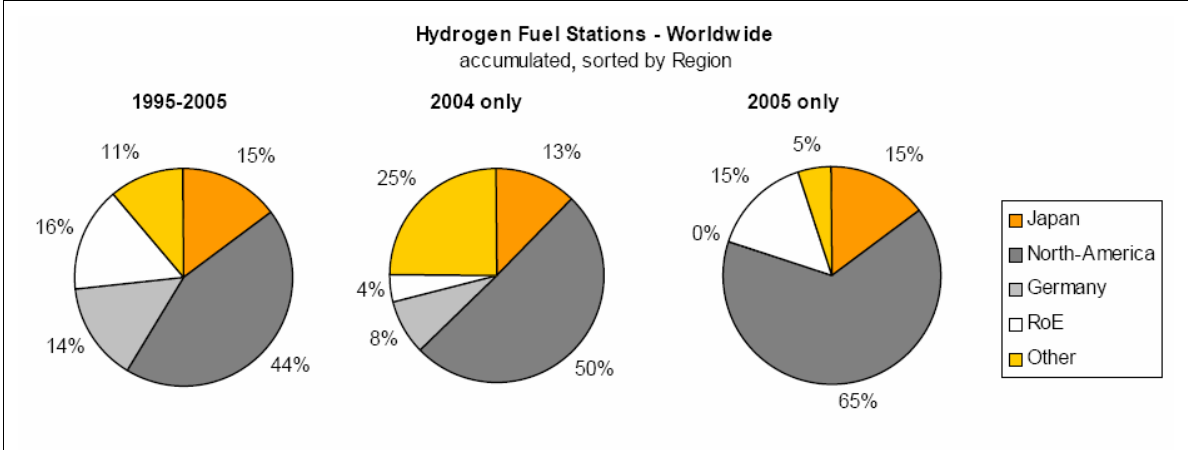


Figure 18 - H2 refuelling station by region

Source: A. Baker, Fuel Cell Today, May 2005

From literature data refuelling station requires an investment cost roughly specking in the range between 500.000 to 4.000.000 Euro. Station sizes in literature vary from 36 GJ/ day (300 kg/day) to 96 GJ/day (800 kg/day) but also bigger stations are sometimes considered. From the graphic cost should be decrease with increasing of station number.

Station capital cost reductions with mass production from Literature



Figure 19 - Refuelling station capital cost from literature

Source: Mark W. Melaina (2003)

CONCLUSIONS

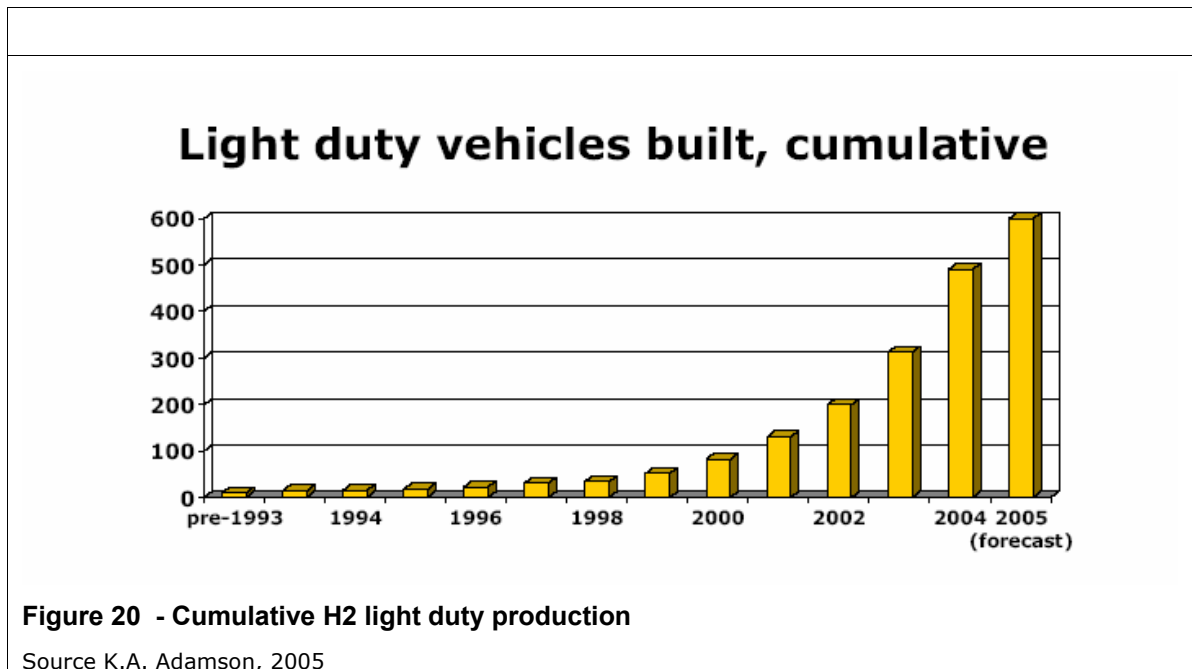
Refuelling station cost can be approximately indicated between 3 and 8 Euro/GJ and are related to:

- On site versus centralized production
- Size and number of stations
- Liquid versus gaseous refuelling gas physical state or both
- Scaling of the station
- Amortisation period

FUEL CELL VEHICLES AND PEM FUEL CELL

Worldwide light duty hydrogen vehicle production counts more than 500 units realized based on fuel cell technology or with internal combustion engine.

Fuel cell vehicles use PEM fuel cell stack with compressed hydrogen except some cases in which liquid hydrogen is involved. Areas of development are high pressure on board gaseous H₂ storage from more traditional 350 to 700 bar and hybridisation with increased range and fuel economy but with higher vehicle complexity and costs (K.A. Adamson, 2005)



Hydrogen fuel cell vehicle cost depends on a long list of parameters. Components (Fuel cells, air compressor, hydrogen container,...) labour, R&D are just some examples that influence unit cost. Evaluations on today cost are difficult to evaluate due to industrial confidentiality. Future cost can be investigated starting from today data which seems to lead to a high uncertainty.

A literature example of fuel cell vehicle price vs. market share

As shown FC vehicle cost should decrease with increasing of market share. However values must be investigate deeper within the project Zero Regio.

Literature pays more attention on proton exchange membrane fuel cell (PEM FC) cost which seems to be the most critical and expensive component of the vehicle. Proton Exchange Membrane (PEM) fuel cells are the most suitable for transport applications

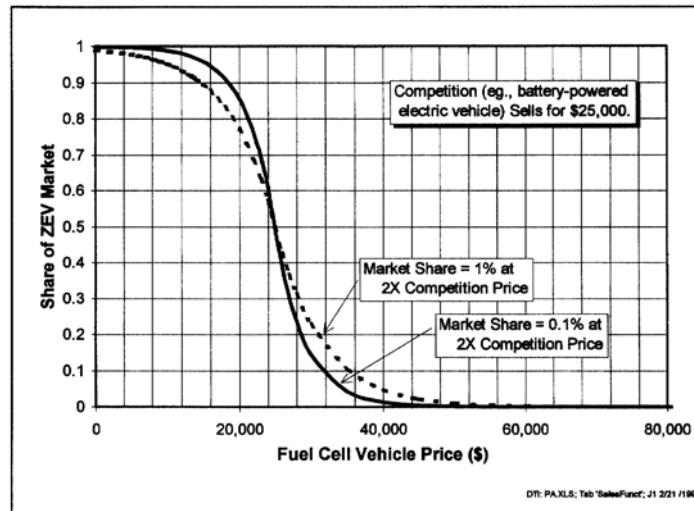


Fig. 2. Fuel cell vehicle market share vs vehicle price

Figure 21 - PEM FC car cost vs market share

Source: Thomas, James and Lomax (1998)

because of their high power density (10 times than other FC except for AFC) and relative low volume and weight. The feed required by PEM FC are high purity H_2 , oxygen from air and water. They can start quickly because of their low operating temperature (about 80 °C).

PEM fuel cells are still away to match conditions for commercial use. This is due both to technical as well as economic topics.

Technical problems regard their reliability and durability. They do not reach the 5000 hours lifetime goal.

At the moment it is extremely not clear how much a fuel cell can cost to a FC producer however the target for automotive industry is to have fuel cell stack at 40-50 Euro/kW or below.

Literature shows values in a wide range of costs from 1800 Euro/kW (Tsuchiya and Kobayashi, 2004) to 20000 Euro/kW (Schlecht, 2003). It is likely that today a fuel cell could have a price ranging between 5000 and 8000 Euro/kW however industrial cost is absolutely top secret.

Cost of fuel cell stack is related to

- Proton Exchange Membrane cost
- Electrode cost
- Bipolar plate cost
- Platinum catalyst cost
- Peripheral materials
- Assembly cost

Some Examples of the wide range of Estimated today Cost of Fuel Cell Systems

An estimation of future cost will be approximately done by mean of learning curve. Difficulties in assessing future PEM cost are related to huge uncertainty of the past and today PEM costs and also in the choice of the suitable progress ratio. Literature studies offer from this point of analysis a wide range of results depending on technology improvement and cumulated capacity.

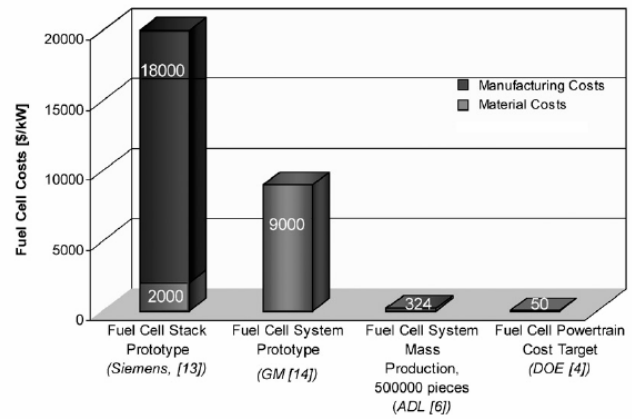


Figure 22 - An example of the wide range of literature data on PEM FC cost

L. Schelcht (2003)

FUEL CELL COST AND LEARNING CURVE

Automotive industry aims to have fuel cell stack at 40-50 Euro/kW or below and therefore it is important to analyze the performance of future cost. Fuel cells have modular structure which means they are appropriate for mass fabrication and cost could be decreased increasing cumulative production. From this point of view, cumulative production let human being able to learn and improve his own experience and knowledge. Industrial processes are often modelled by a "learning curve" or "experience curve", some kind of decreasing exponential function which tries to roughly predict the future cost of a certain production process as function of cumulative volume of production.

The analytic model is:

$$y = kx^{-r}$$

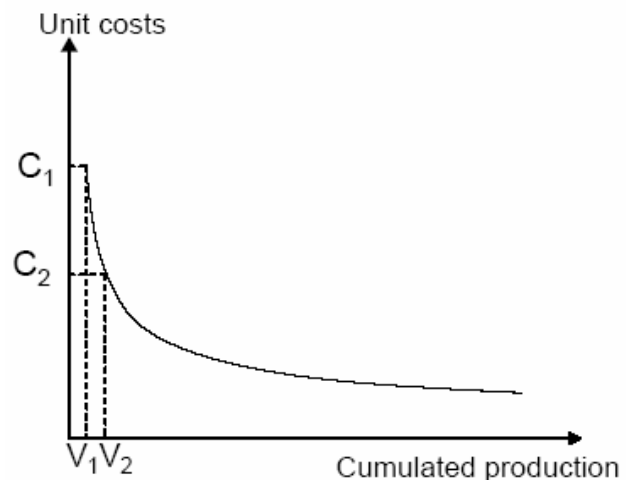
Where

y: production cost

x: cumulative number of products

k: constant

r: experience index



Factor r is better understood when written as $P = 2^{-r}$. P is called progress ratio and represents how much production cost can be decreased any time cumulative production come double.

What is important to obtain most reliable data is the accurate esteem of experience index r ; it can be evaluated by past and present costs of the technology which is affected at least by two main uncertainties:

- First part of the curve could be not enough accurate in case of new technologies which could show instabilities on costs.
- Moreover at the moment it could be known the price of a fuel cell but not the cost due to confidentiality of the information. Price-cost relationship could be the one proposed in the sixties by Boston Consulting Group (not on fuel cell market).

This model comes from empirical evidence; the ratio of this evolution is based on the innovator price strategy. It is divided into four phases. Without going into anyone of these stages we would just underline that price and cost show different relationship depending which phase is going on so attention has to be paid before drawing conclusions on cost from price data.

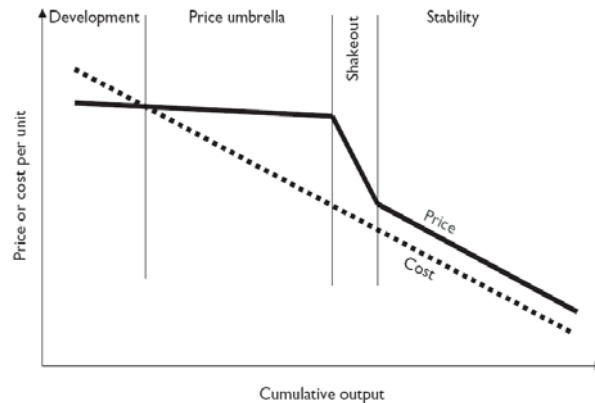


Figure 23 - Price-cost relationship (Boston Consouting group, 1968)

However in finding out PEMFC cost dynamic it has to be understood that the FC are realized by some different parts, anyone of each has own dynamic. On the other hand it is possible to analyze the compound system.

Example 1: analysis realized by Tsuchyia-Kobayashi goes deep into fuel cell parts; authors base their analysis on specific hypotheses tied to technology improvements.

Costs are given by the following function:

$$C_{FC} = \frac{(C_m + C_e + C_b + C_{pt} + C_o)}{P} + C_a$$

where

- C is the fuel cell stack cost per kW (\$/kW)
- C_m the membrane cost (\$/m²)
- C_e the electrode cost (\$/m²)
- C_b the bipolar plates (\$/m²)
- C_{pt} the cost of platinum catalyst loading (\$/m²)
- C_o the cost of peripheral materials (\$/m²)
- C_a the assembly cost (\$/kW)
- P the power density (kW/m²)
- C_{wpt} the weight of platinum catalyst loading (g/m²)
- Y_{pt} the cost of platinum (\$/g)

As shown from the figure, there are some possible different scenarios which go to a wide range of final cost in 2020 for a cumulative production of 5 million FC vehicles. Today cost is assumed as high as about 1800 euro/kW and 2020 FC stack cost would be between 25 and 145 euro/kW with an average value of 80 Euro/kW.

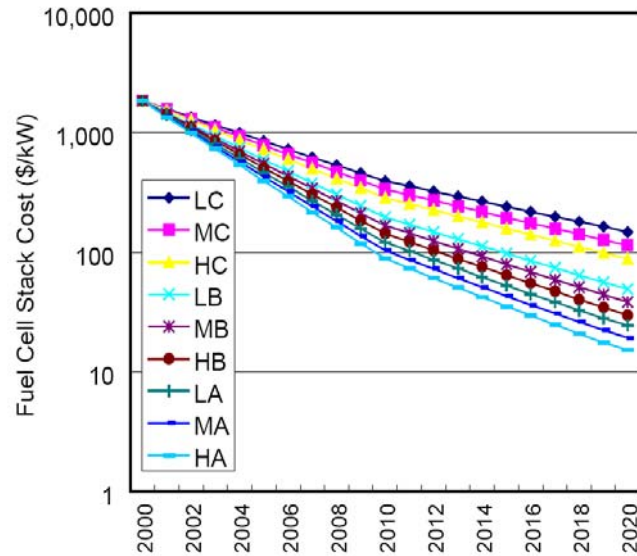


Figure 24 - PEM FC learning curve by literature, example 1

Source: Tsuchiya and Kobayashi, 2004

Example 2: Rogner (2002) esteemed three scenarios for today FC stack cost: 2500, 4500 and 10000 Euro/kW which are higher than Tsuchiya-Kobayashi hypothesis (about 1800 Euro/kW). The results are shown in the logarithmic graphic.

Results diverge from about 25 to 3000 Euro/kW. This example make clear how uncertainty on today PEM stack cost can produce a huge range of cost for mass production.

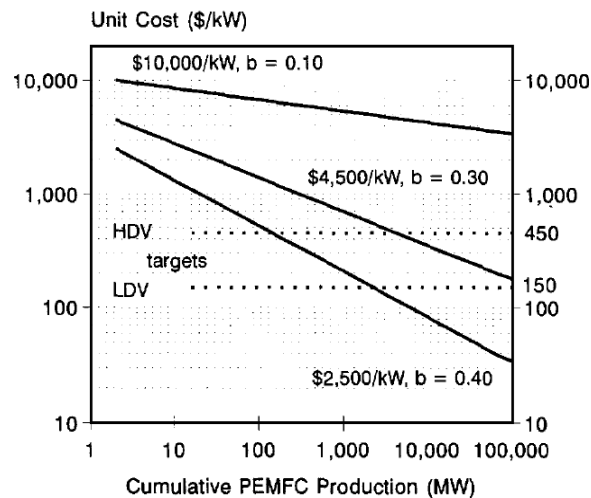


Figure 25 - PEM FC learning curve, example 2

Hypothetical learning curves for PEM fuel cell (Rogner, 1998)

CONCLUSIONS

Literature data show that at the moment there is not a clear understanding of PEM today and future production costs. More in general this is not a certainty because of a wide range of possible results come out from varying future scenario of mass production and technology improving most due to uncertainty about past and present industrial costs which make widely variable learning curve starting point and experience index as well. In most optimistic technology development cases, aim of automotive industry could be achieved or overcome.

From this point it is worth to underline the importance of public research and policy support.

TAX

Cost evaluation in literature doesn't consider profit margin as well as tax. However it is almost clear that tax influence H_2 price and from this point of view can promote, delay or stop a H_2 specific pathway.

For an international use of hydrogen as energy carrier, harmonized tax system can help. Because of H_2 seem to meet environmental needs, tax rate should be lower than tax on conventional fuels. Moreover H_2 tax regime could discriminate between H_2 pathways.

HYDROGEN UNIT COST CONCLUSIONS

Best way to express hydrogen cost as an energy carrier is linked to the energy content of the gas (Euro/GJ) related to LHV. However today is frequently used the cost of a single volume (Nm³), especially for merchant gas.

Hydrogen unit cost depends on several factors.

- **Feedstock and fuel prices:** they can heavily affect H₂ production cost. For example regarding steam reforming bigger the plant capacity is, higher the weight of feed and fuel price on H₂ centralized production unit cost can be.
- **Production process:** central and on-site production process show very different unit costs.
- **Purity:** in specific application as power generation by fuel cell, hydrogen needs a certain purity level (generally not needed when used as chemical plants). Purity can have an effect on final cost.
- **CO₂ capture and storage:** H₂ pathways are often related to fossil fuels and CO₂ emissions as well. Even though at the moment the cost of sequestration is uncertain, it seems to be capable of influencing the final H₂ unit cost.
- **Natural state** of hydrogen produced transported and dispensed (liquid or gaseous). Gaseous H₂ need to be compressed otherwise to be liquefied and then stored on site. Both these transport route need a dedicated part of the plant which increase costs.
- **Scaling of production:** mass production of the gas can be realized on-site or centralized. Final unit cost will be related to the scaling up process.
- **Capacity used:** rate of use of the capacity production plant as well as that of refuelling station can determinate a decrease or increase of final unit H₂ cost.
- **Amortisation period:** this is an important element in evaluating unit cost of centralized or on-site production facility as well that of transport system (pipeline or trailer) and a special influence have in particular on refuelling station cost.
- **Tax and fiscal policy:** cost evaluation in literature doesn't consider profit margin as well as tax (which are related to prices and not to cost). However it is almost clear that tax influence H₂ price and from this point of view can promote, delay or stop a H₂ specific pathway.

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Deliverable 7.1.

Work Plan Competitiveness

Appendix B

The Competitiveness of Alternative Hydrogen Pathways

By Anders Chr. Hansen – Roskilde University

14.11.2005

The Competitiveness of Alternative Hydrogen Pathways

By Anders Chr. Hansen, Roskilde University

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Introduction

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.

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. (2004b), 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. (2004a) 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. (2004b), 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.

Hydrogen Pathways

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. (2004a), and the European investment requirements by the Joint Research Centre of the EU Commission (2004).

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 26. 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.)

Market Competitiveness

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.

Tank-to-Wheel, Vehicle Related Costs

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 15 Assumptions 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.

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 H₂ 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 H₂ 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.

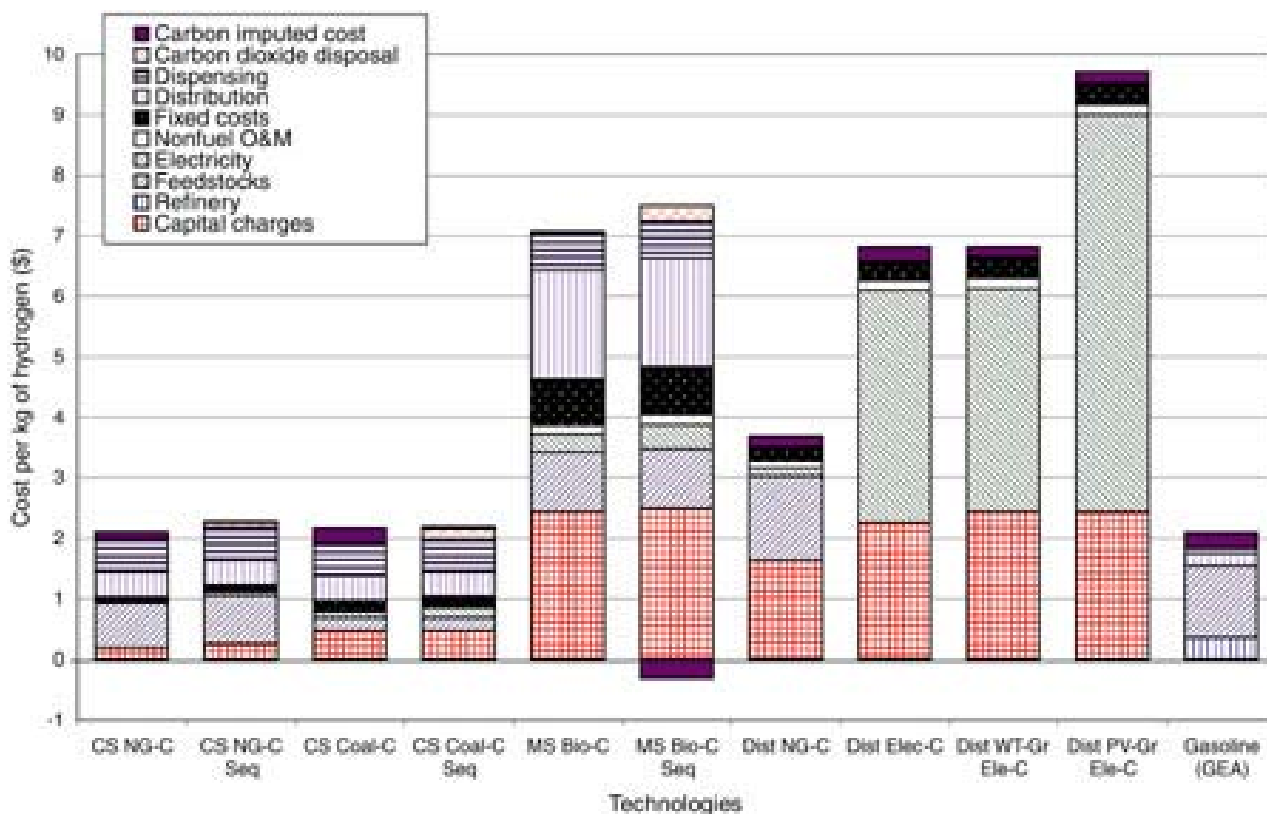
The aspects of H₂ FC vehicle costs are treated in more detail in Chernav'ska and Lanfranconi (2005).

Well-to-Tank, the Hydrogen Costs

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 27. 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 H₂ 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.

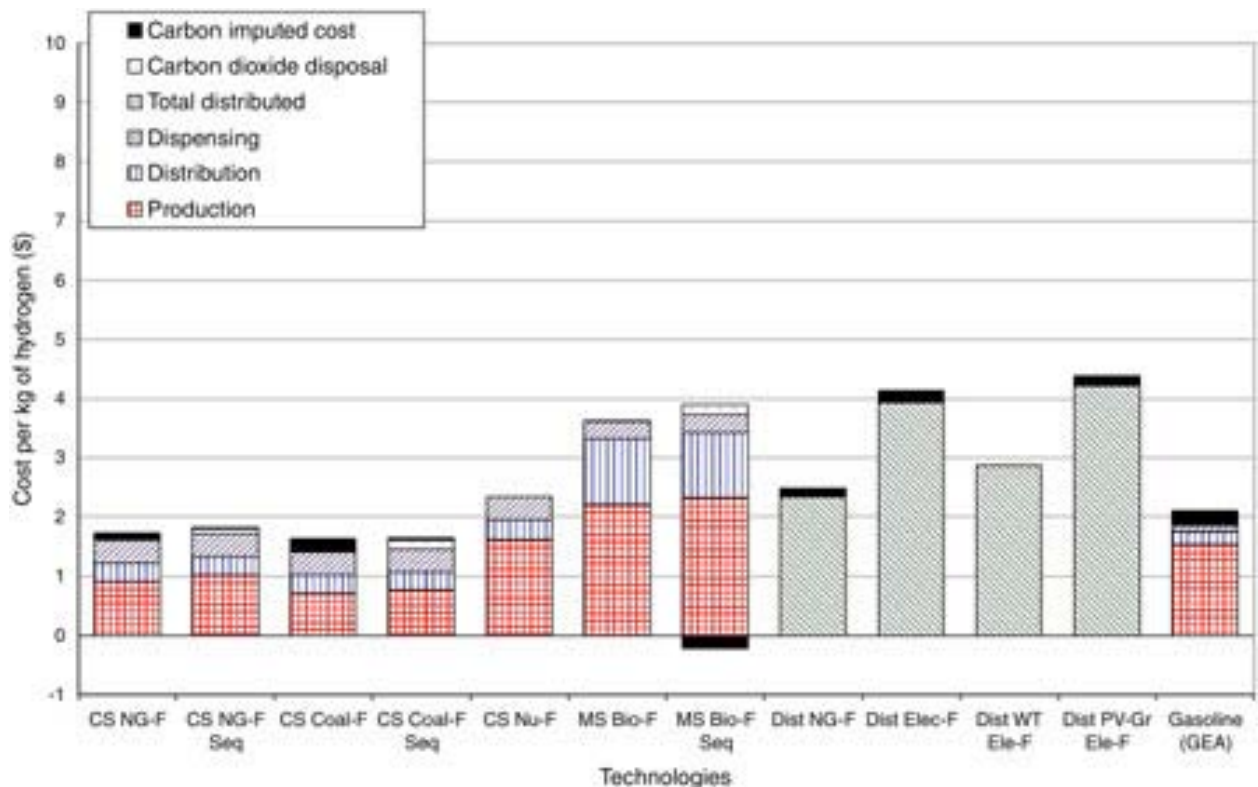
The results rely on the assumption that carbon capturing and sequestration in a central station is very inexpensive (10 \$/tCO₂ or 0.07 \$/kg H₂ for coal and 0.19 \$/kg H₂ for NG). This estimate is disputed by Anderson and Newell (2004) who finds \$200 to \$250 per ton carbon (that is, about \$55-\$68 per ton CO₂) 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 28. Unit Cost Estimates for "Future Technologies" in the US.



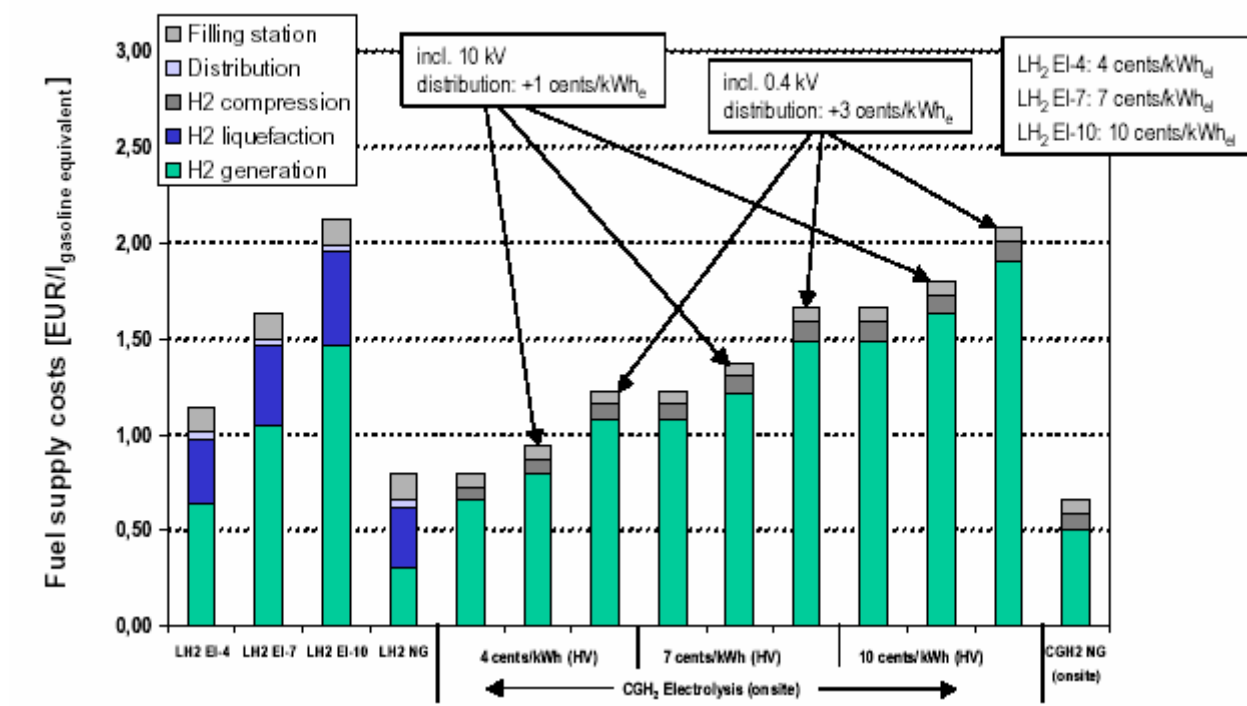
Source: National Academy of Science (2004)

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 29

Fuel supply cost per liter gasoline equivalent:



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 electrolyzers. 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. (2004b) 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.

Comparing Natural Gas Steam Reforming with Electrolysis

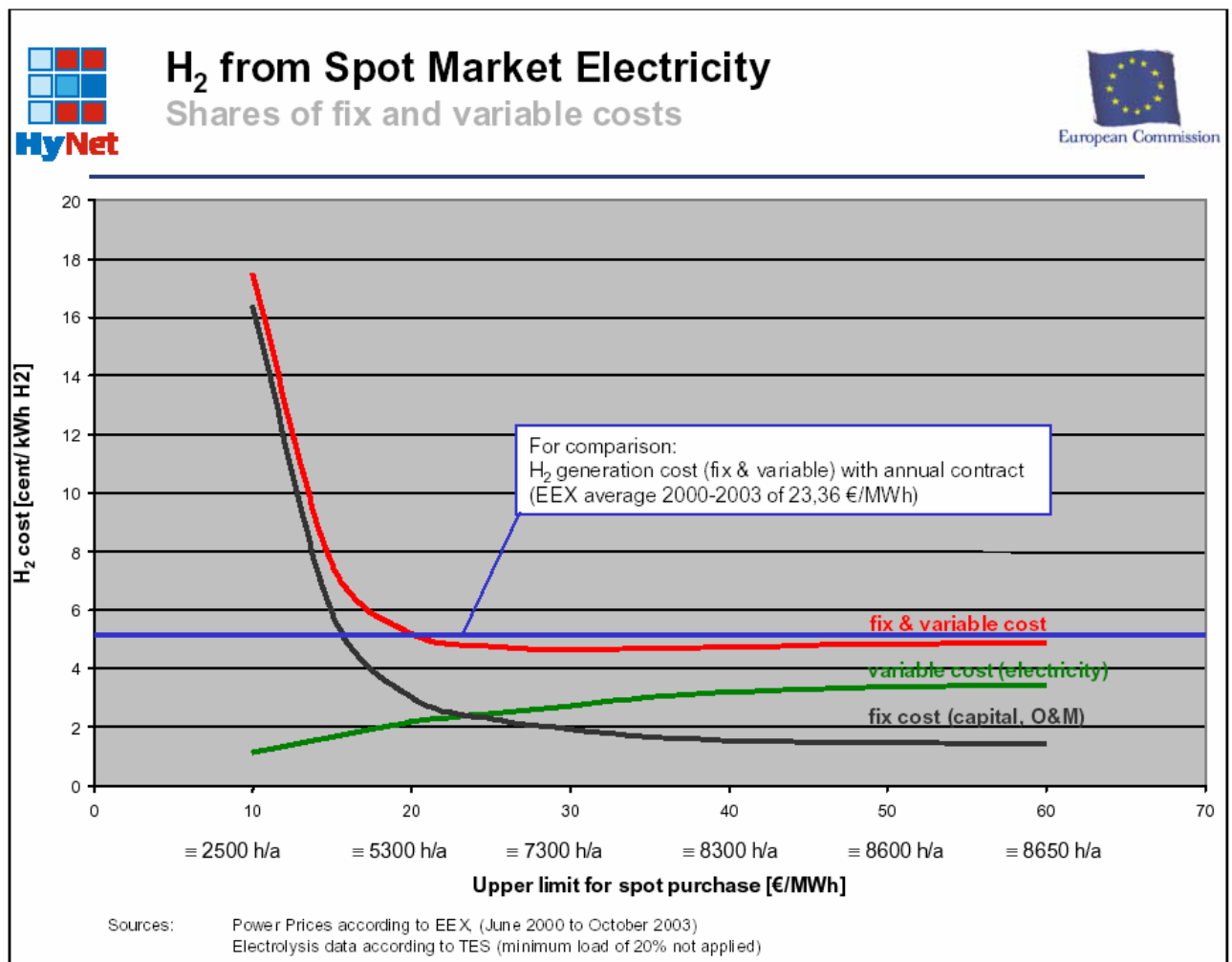
The studies use different assumptions of oil and gas prices and discount rates/capital charges. Crude oil is assumed to cost 25-30 \$/bbl, but this is hardly a realistic prediction for the future decades. This would be of no importance for the relative prices of oil and natural gas if natural gas was 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 H₂ costs.

Figure 30. 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 electrolyzers are restricted to operate in that period, the considerable capital costs of electrolyzers 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.

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 challenged 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 H₂ 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 US\$/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.

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 Nm³/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 H₂. Two alternative concepts include a natural gas steam reformer or an electrolyser.

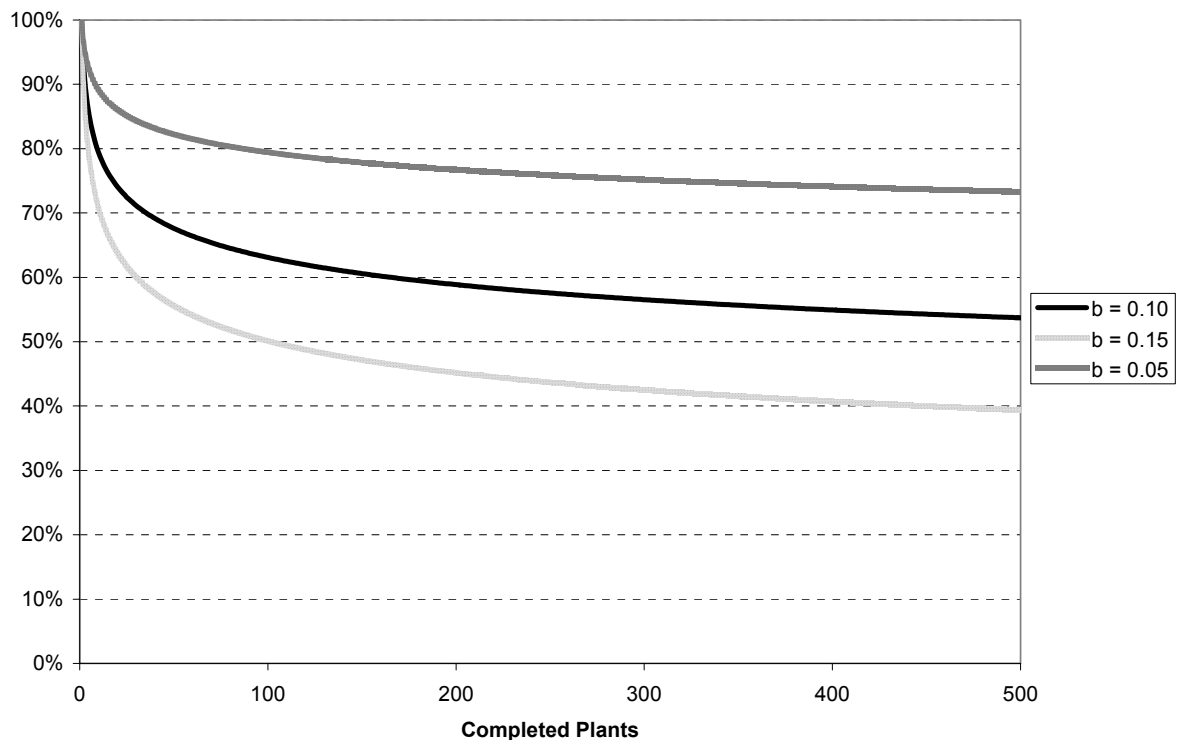
Dynamic Economies of Scale

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:

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

where a is the investment for the 1st 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 31. 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.

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.

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.

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.
- 2) 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 plays 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.

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*.

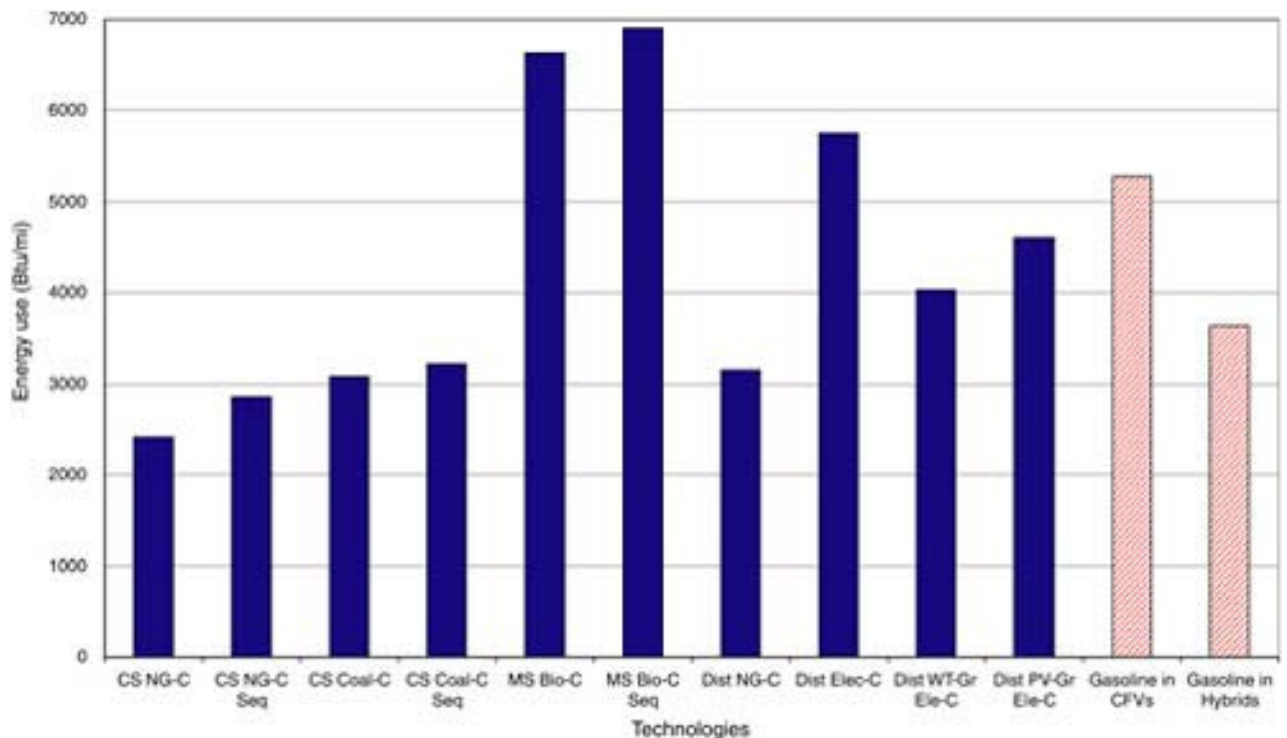
However, it can be argued that occupation and transport safety is at risk the more explosive and chemically reactive the fuel is. Hydrogen carriers such as fossil energy based fuels, methanol, and ammonia are generally perceived to be less demanding for additional security technology compared to the technology used today. In particular, storing of ammonia in sodium 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.

Efficiency

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

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

Figure 32. WtW Energy Consumption per Vehicle Mile of Alternative Hydrogen Pathways (Present Technology).



Source: National Academy of Science (2004).

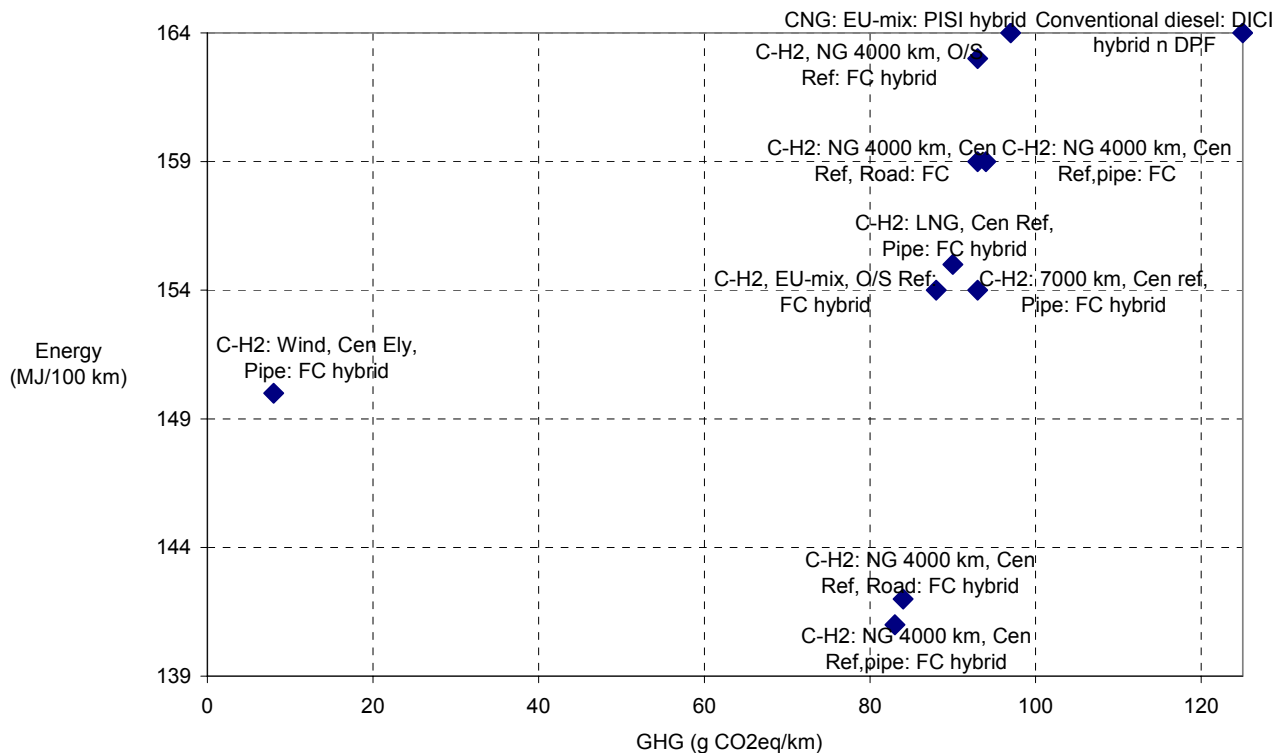
The results shown in the figure, indicates that fossil fuel based hydrogen pathways are considerably more energy efficient than the conventional gasoline fuel pathway (“Gasoline in CFVs”), but only marginally more energy efficient than the GHEV-pathway. Moreover, the present stage of electricity based 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 H₂FC technology in transport. One is to develop low cost methods of electrolysis.

Figure 33. Estimated Energy Consumption and GHG Emissions for the Top Ten Alternative Fuel Pathway/Powertrain Combinations.



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, is 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.

Environment

Environmental Pressure of Fossil Fuel Based Pathways

Automotive transport consumes 47% of world oil supply and contributes with 21% of global CO₂ 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, SO₂ 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.

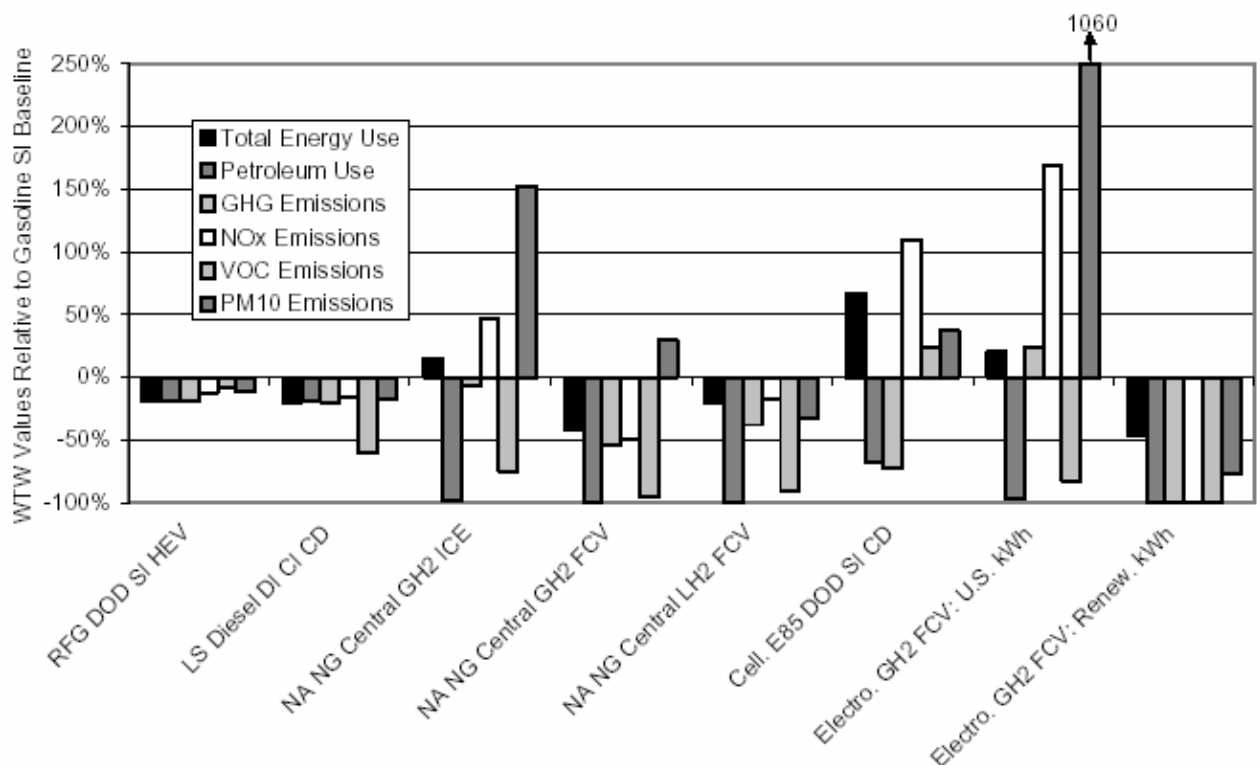
A useful measure to analyse and compare the environmental performance of each pathway is the environmental pressure per kilometre associated with each pathway.

Urban and Regional Air Pollutants

The competitiveness of the NG O/S H₂FCVs 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 34 Well-to-Wheels Energy Use and Emissions for Selected Pathways



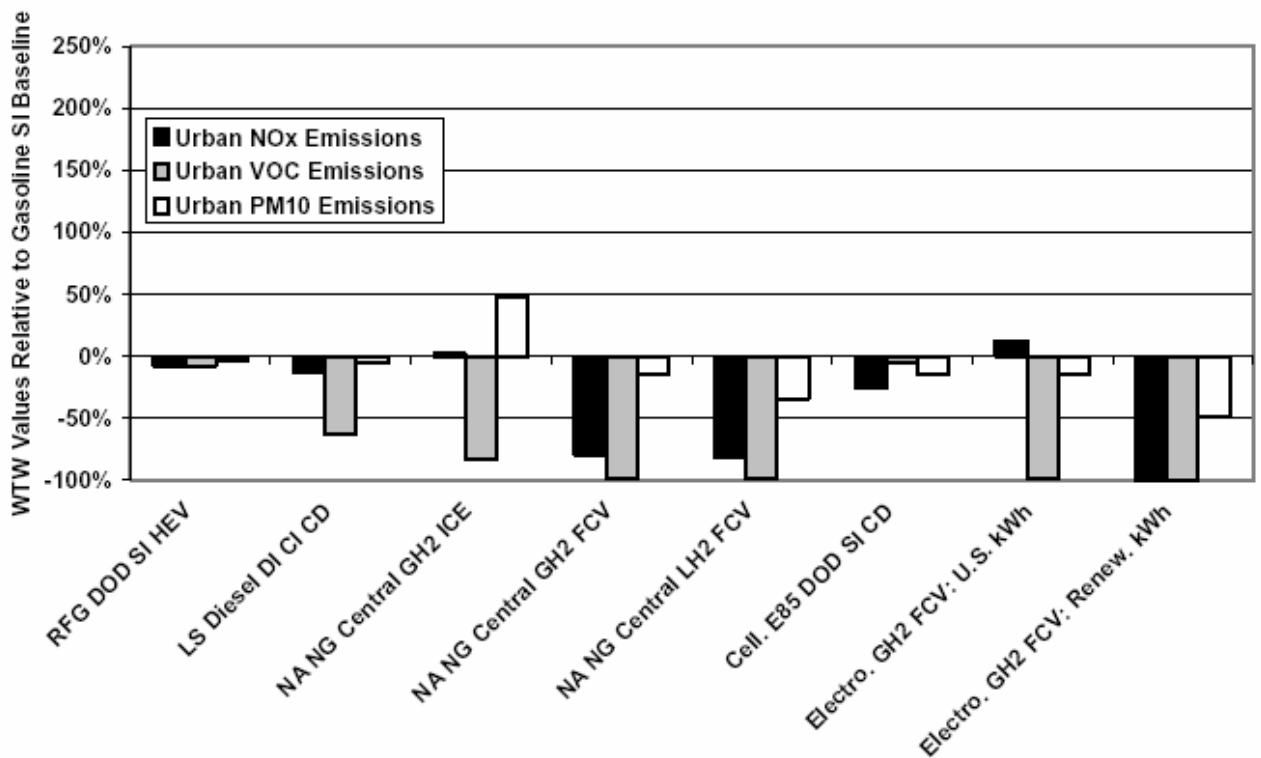
Source: Brinkman, Wang et al. (2005)

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 35. 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.

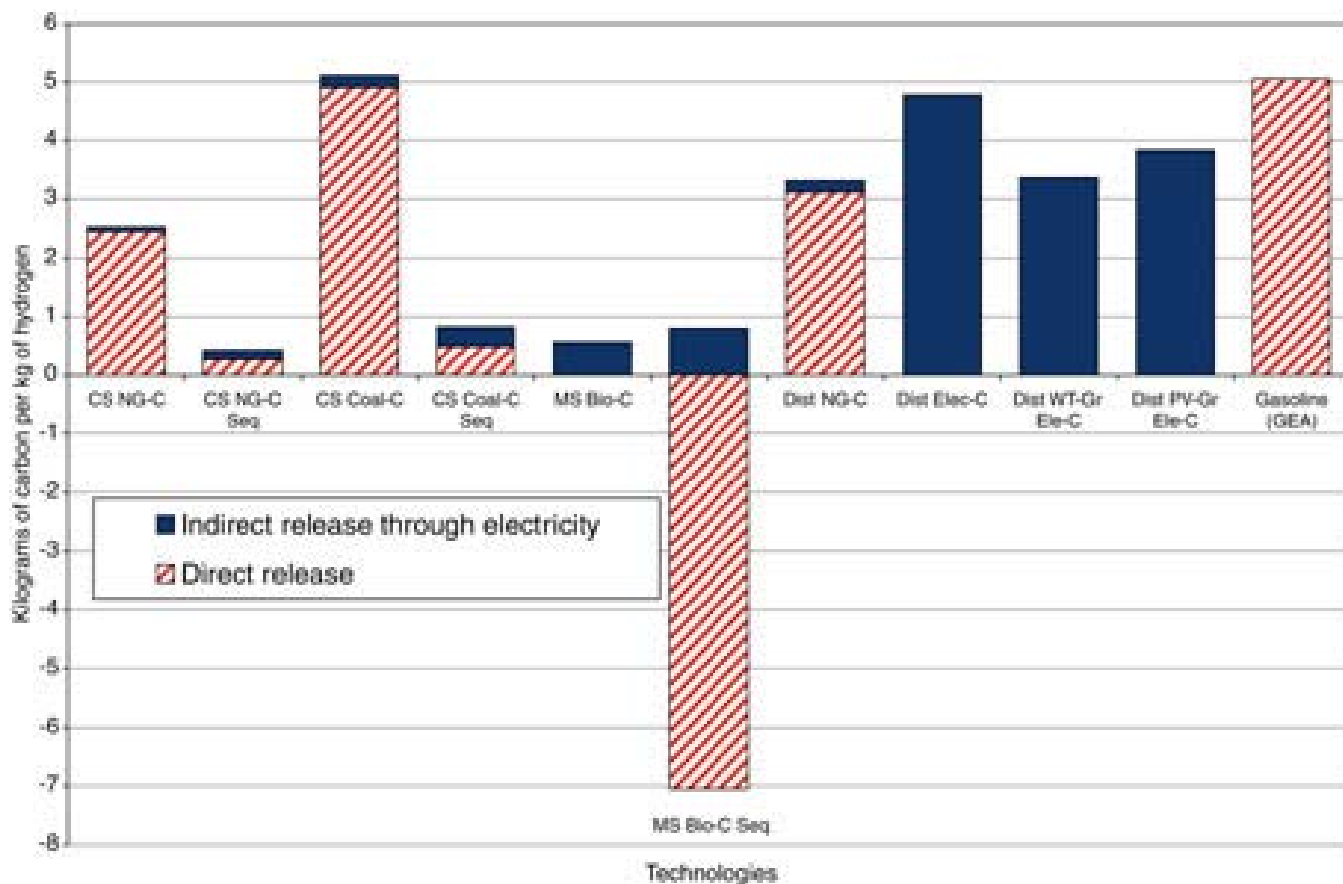
A full lifecycle account of environmental impacts of the hydrogen and fuel cell technologies should include the impacts of vehicle and fuel cell stack manufacturing as well. Full life cycle accounts would add local and regional pollutants as SO₂, CO, benzene, benzo(a)pyrene, and palladium to the pollutants 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.

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 CO₂ emissions associated with the current technologies. They are compared with the equivalent amount of gasoline in the figure below.

Figure 36. Unit Carbon Dioxide Emissions by Current Hydrogen Technologies



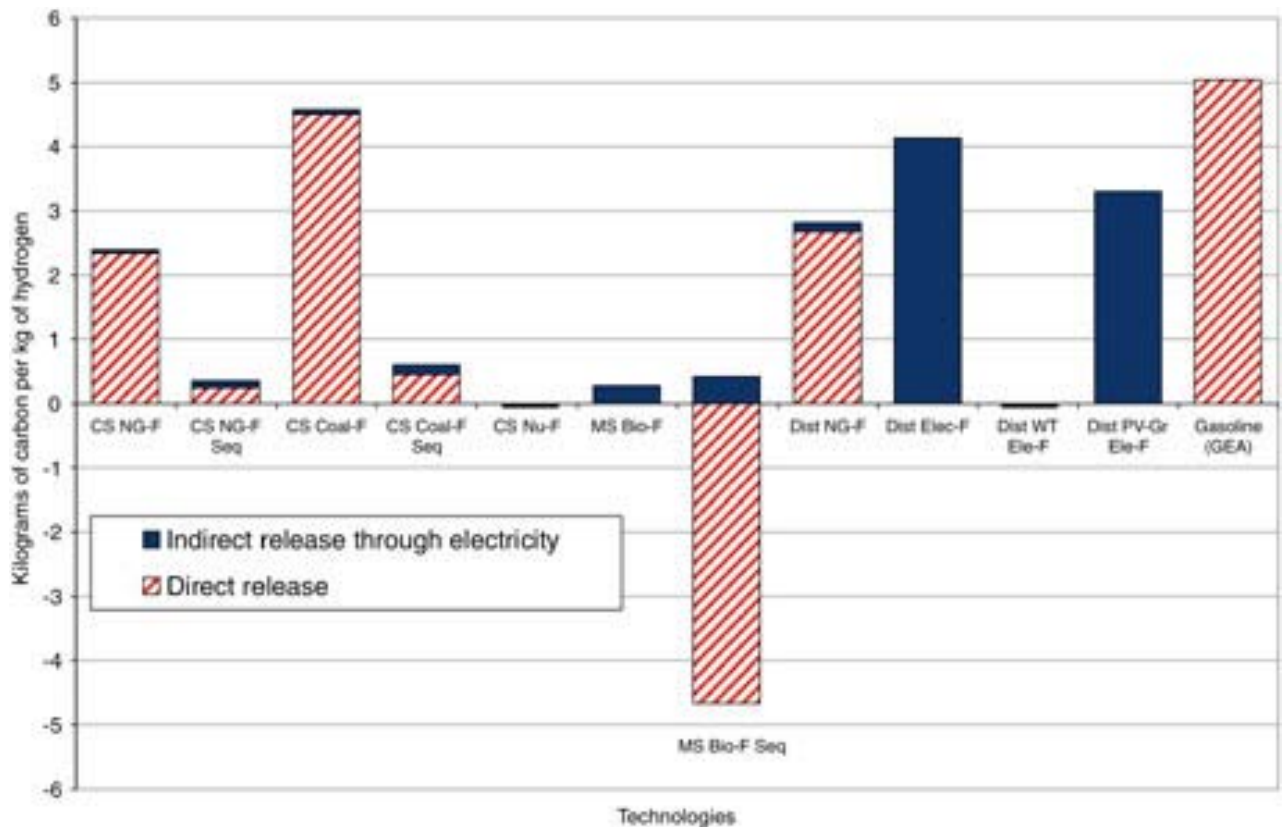
Source: National Academy of Science (2004).

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 CO₂ as gasoline combusted in HEVs do. Since even wind power and PV is backed up by grid electricity, their CO₂ emissions are significant too.

Distributed gas reforming to H₂ will result in about 30%, but not dramatically lower CO₂ 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 H₂FCVs based on-site natural gas reforming could even lead to higher CO₂ emissions.

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

Figure 37. Unit Carbon Emissions by Future Hydrogen Technologies.



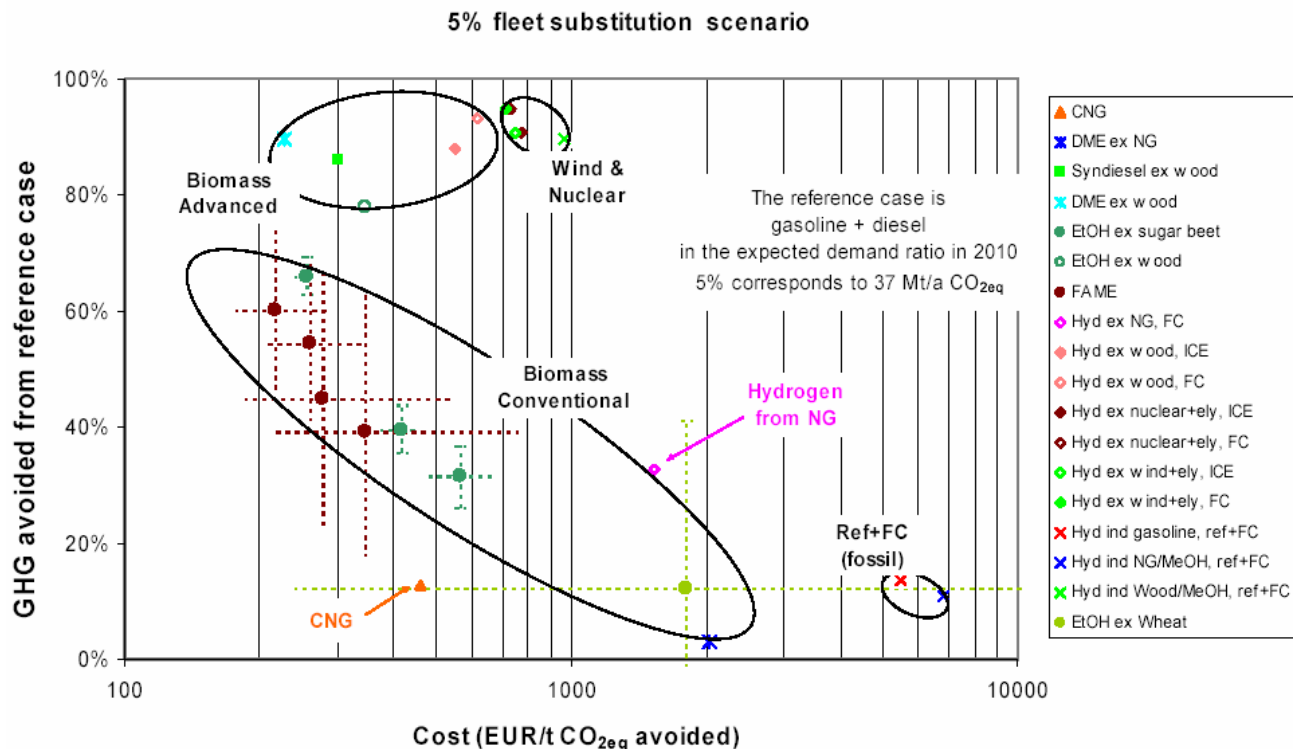
Source: National Academy of Science (2004).

The most important expectations of the competitive position with respect to CO₂ 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.

CO₂ Reduction Cost

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

Figure 38. 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 tCO₂ avoided exceeding those involved in energy efficiency programmes and low CO₂ 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 CO₂ 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.

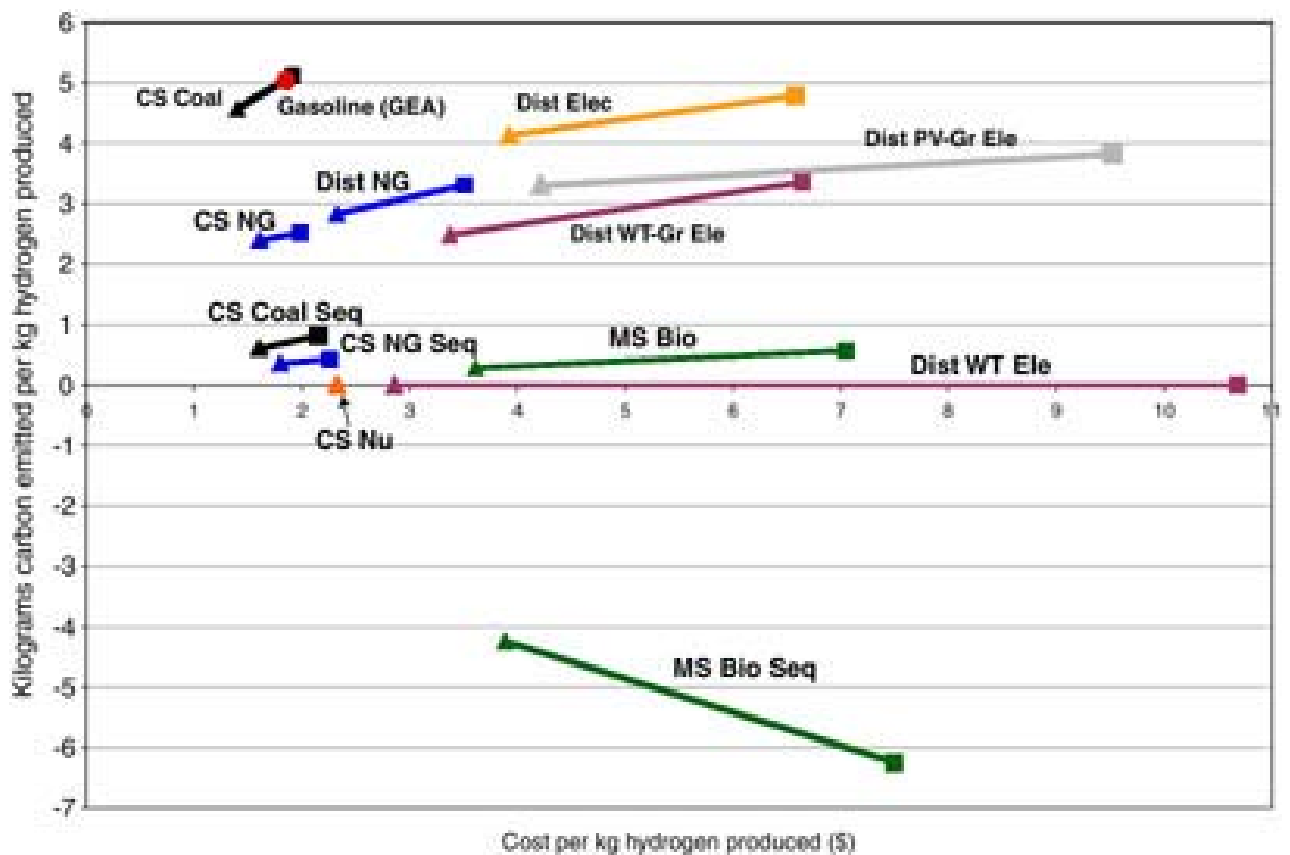
Nevertheless, the study indicates that biofuel based pathways could be the closest “competitor” to hydrogen pathways for the near future. Thus, the competitiveness of the

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 fixing hydrogen in hydrogen carriers in the form of liquids (such as methanol) or solids (such as ammonia fixated in sodium 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 CO₂ emissions by similar technologies are reported by the National Academy of Science (2004) as well.

Figure 39. 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* CO₂ 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.

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.

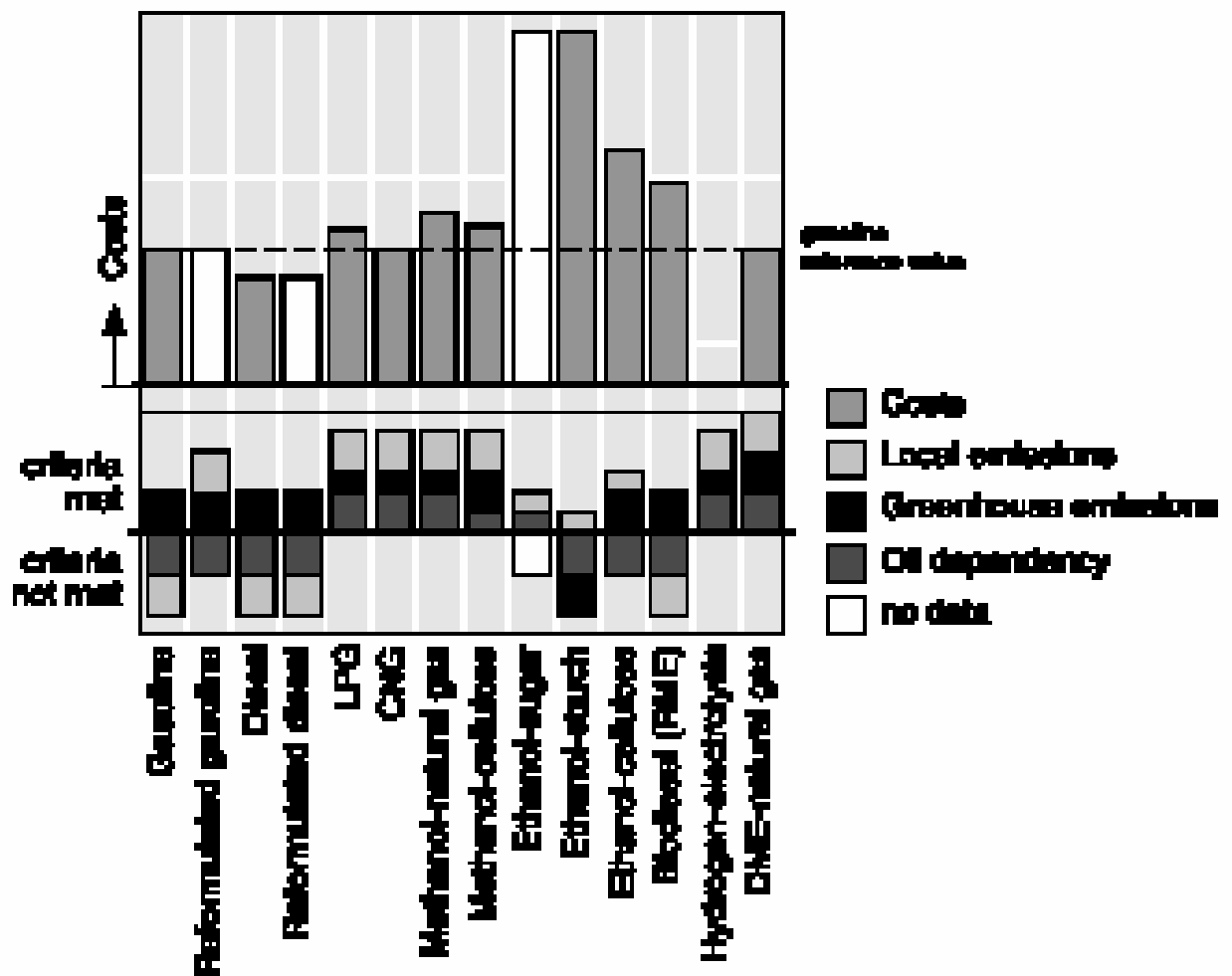
In this paper, both of these approaches are applied.

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 extent outdated, the following result of an IEA study of alternative fuels could serve as a reasonable suggestion of such a balance.

Figure 40. Long Term WtW Performance for Alternative Fuels



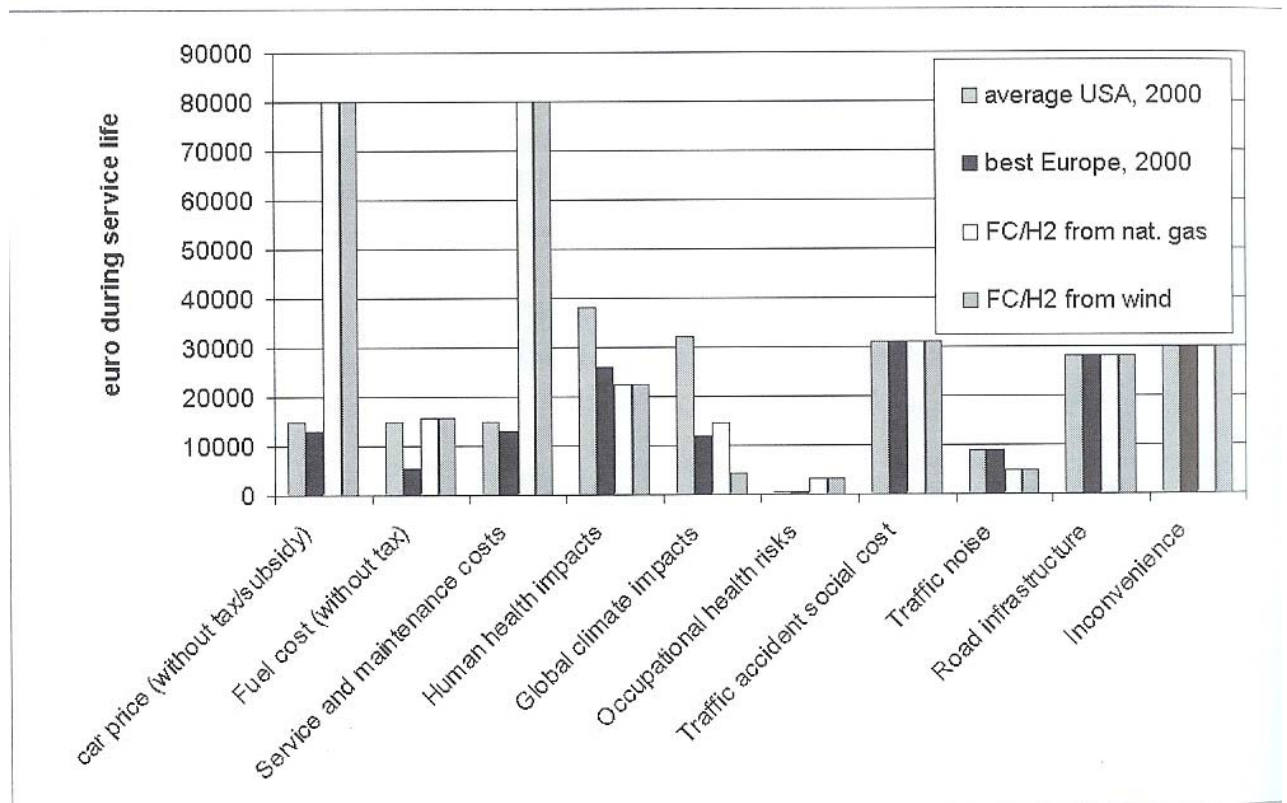
Source: International Energy Agency (IEA) (2000)

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 41. Life Cycle Private and Social Costs of Alternative Pathways.



Source: Sorensen (2005).

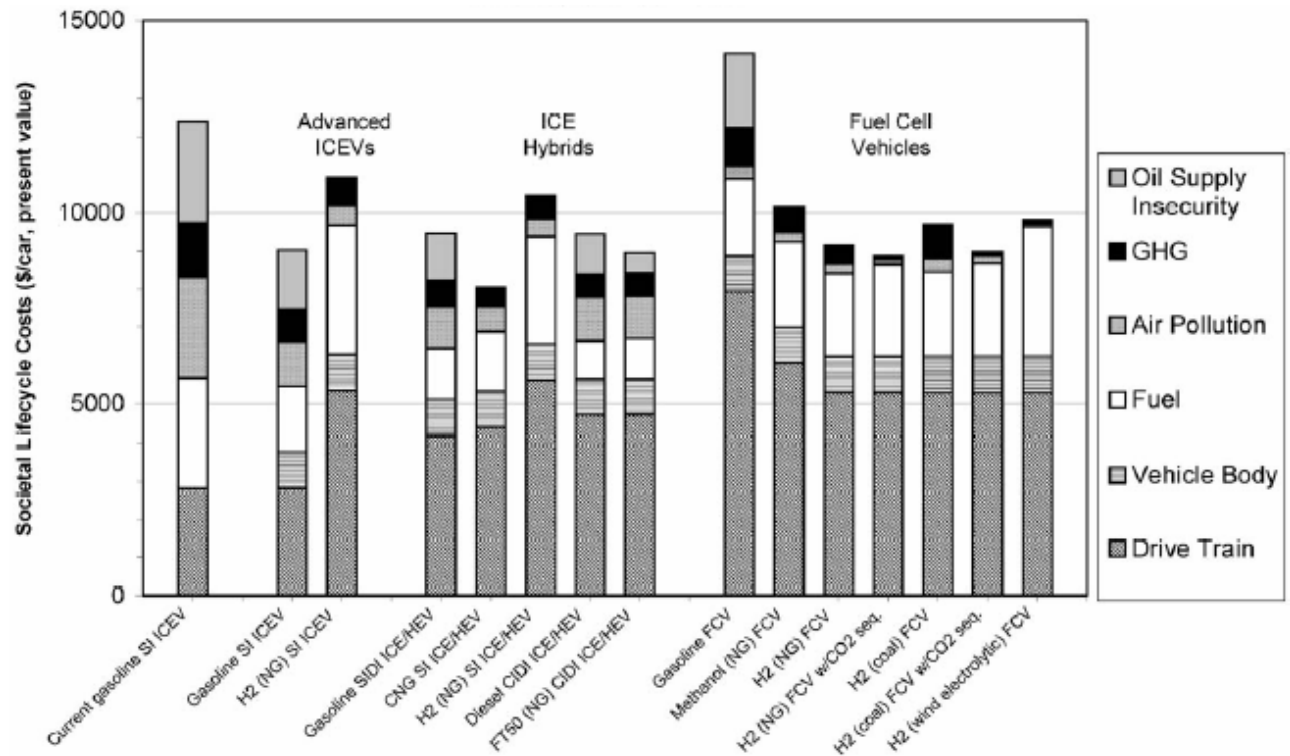
The two petro-fuel pathways included in the study are an average American car (Toyota Camry) and the best performing (mileage) European technology (Lupo). The hydrogen pathways include natural gas based and wind power based H₂, both used in a Daimler Chrysler FCV. The estimates indicate that the presently (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 negligible.

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. (2004a) compares pathways through three main types of drive configurations: ICEV (Current gasoline, advanced gasoline, and H₂ (NG)), HEV (Gasoline, CNG, H₂, diesel, and FT50), and FCV (Gasoline, methanol (NG), H₂ (NG), H₂ (NG with CCS), H₂ (coal), H₂ (coal with CCS), and H₂ (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 ExterneE figures adjusted to a Southern California context. The following figure shows the results.

Figure 42. Societal Lifecycle Costs of Alternative Fuel/Enginge Configurations of Cars.



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

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 H₂FCVs (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. (2004b) 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 H₂HEVs) come out as the lowest cost option. If they are monetised with very high values, FCVs are the low cost options.

Competitiveness Research in Zero Regio

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.

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 be 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.

H₂ 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 H₂ price at the pump is defined as

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

$$P_{\text{kgH}_2} / (E_{\text{HFC}} * e_{\text{kgH}_2}) \leq P_{\text{IG}} / (E_{\text{GV}} * e_{\text{IG}}) \Leftrightarrow$$

$$P_{\text{kgH}_2} \leq P_{\text{IG}} * (E_{\text{HFC}} / E_{\text{GV}}) * (e_{\text{kgH}_2} / e_{\text{IG}}),$$

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_{kgH_2} = The price at pump of a kg of hydrogen (net of taxes and subsidies) (€)

P_{IG} = 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_{kgH_2} = 120.1 MJ/kg H₂

e_{IG} = 34.2 MJ/l gasoline

The gasoline equivalent H₂ 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 H₂ 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 16. 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 Environmental 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 \$/kg¹⁷. It is optimistically assumed that this cost can

¹⁷ At a 6.50 \$/MMbtu HHV natural gas price

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 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.

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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Deliverable 7.1.

Work Plan Competitiveness

Appendix C

Start and End Data for Technological and Economic Issues in the Assessment Framework for ZERO REGIO Project

By Liliya Chernyavs'ka and Cristian Lanfranconi – IEFE Università Bocconi

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I. H2 PRODUCTION

1.

DESCRIPTION OF THE H2 PRODUCTION PLANT	
	To cross with an X
Steam Methane Reforming:	
Catalytic Partial Oxidation (SCT-POx)	
Chlorine -Soda - H2 by-product	
Notes:	

Note for Chlorine Soda Plant: any required data has to be specifically related to hydrogen part of the plant.

2.

PERFORMANCE	Operational characteristics	
H2 production (Nm3/h and Nm3/y)	Nm3/h	Nm3/y
H2 Purity (%)		
Energy efficiency ¹⁸ of the H2 production process		
	Theoretical yield	
	Real yield	
Outlet H2 pressure before compression (bar)		
Notes:		

PERFORMANCE	H2 Compressor characteristics
-------------	-------------------------------

¹⁸ Energy efficiency = (Energy content of H₂/ energy content of inlet feed and fuel) on Low Heating Value basis

PERFORMANCE		H2 Compressor characteristics	
Energy efficiency of H ₂ compression process			
	Power (kW)		
	Inlet pressure (bar)		
	Outlet pressure (bar)		
	Nominal Capacity (Nm ³ H ₂ /h)		
	Real Capacity (Nm ³ H ₂ /h)		
	Compressor cost (Euro)		
	Theoretical yield		
	Real yield		
Expected compressor lifetime (years)		hours	years

PERFORMANCE		Technical maturity		
Development stage of the production technologies		Prototype		
		First of kind		
		Second of kind		
		... of kind		
		Fully commercial ¹⁹		
		Other (specify)		
Planning and realization time to build the H ₂ production facilities				
		Total n° of months required		
Reliability				
		Reasons	Total n°	Average n°/y
	Failure mode when starting up			
	Failure mode during operation			
	Number of major repairs per H ₂ production facility			
Availability (calculated on annual basis = 8760 h)		% h/y		
		Foreseen operation use		
		In regular use		
		Not in operation because of operational schedule		
		Not in operation because of schedule maintenance		

¹⁹ Fully commercial means economical and competitive (with mature technology)

PERFORMANCE	Technical maturity	
	Not in operation because of repairs of parts of the H2 production facilities	
	Not in operation because of unavailability of the feedstock, the filling station or the vehicles (specify)	
	Other (Non-technical reasons)	
Durability		h/d/w/m/y
	Lifetime of the H2 production facility	
Notes:		

3.

SAFETY AND REGULATIONS		Codes, standards and regulations					
Existence of standards, codes and regulations on production facility design							
					Did you adopt these standards and regulations?		
		Yes	No	Specify main codes of standards and regulations and developer organization	Yes	No	Your reasons/comments/suggestions
	Worldwide standards and regulations						
	Country standards and regulations						
	Preliminary standards and regulations						
	Standard and regulations being discussed						
	Lack of standards and regulations						
	Own standards and regulations						

SAFETY AND REGULATIONS		Codes, standards and regulations					
Existence of codes and standards, codes and regulations on fuel specifications							
					Did you adopt these standards and regulations?		
		Yes	No	Specify standards and regulations and developer organization	Yes	No	Your reasons/comments/suggestions
	Worldwide standards and regulations						
	Country standards and regulations						
	Preliminary standards and regulations						
	Standard and regulations being discussed						
	Lack of standards and regulations						
	Own standards and regulations						
Notes:							

SAFETY AND REGULATIONS		Permits and licenses	
Imposed safety measures on production process			Specify main safety standards
		Imposed by regulation	
		Adopted by you but not imposed	
		Own suggestions	
Time to obtain permits			
		Time from first talks to formal apply of permits (w/m/y)	
		Time from formal apply to approval (w/m/y)	
		Working time for the whole process (Man-hours)	
Notes:			

4.

ECONOMICS		Costs for operator	
Investment			
	Capital costs for H ₂ production facilities		Euro
		Land	
		Plant and equipment	
		Interest allowed during construction	
		Other financial costs	
		Total capital costs	
		Labour cost during construction	
Notes:			

ECONOMICS		Costs for operator					
Depreciation					% (depreciation rate)	N° years	Annual cost (Euro)
	Depreciation plan						
Notes:							

ECONOMICS		Costs for operator					
Net raw materials		Unit of measurement	Price range (min & max) for single unit (Euro/Unit)	Unit/ Nm ³ H ₂	Annual amount (Units)		Annual cost (Euro)
	Natural gas (NG) (feed)	Nm ³					
	Catalysts & Chemicals						
	Total raw materials						
Notes:							

ECONOMICS		Costs for operator					
Utilities							
	Electricity	kWh					
	Cooling water	m ³					
	Boiler feed water	kg					
	Fuel gas	Nm ³					
	Total utilities						
		Total raw material + Utilities					
Notes:							

ECONOMICS		Costs for operator					
Labour costs							
				N° Man*hours	Cost (Euro/Man*hour)		Annual cost (Euro)
	Operating labour						
	Operating supervision						
	Total labour and supervision costs						

ECONOMICS		Costs for operator					
Maintenance costs							
Materials							Annual cost (Euro)
	Costs of materials for scheduled maintenance						
	Costs of materials for repairs						
	Costs of materials for configuration changes						
Labour							Annual cost (Euro)
	Labour costs of scheduled maintenance			N° Man*hours	Cost (Euro/Man*hour)		
	Labour costs of repairs						
	Labour costs of configuration changes						
	Total maintenance costs						

ECONOMICS	Costs for operator
Notes:	

ECONOMICS		Costs for operator					
Other costs							
							Annual cost (Euro)
	Overheads						
	Running royalty						
	Research and development costs						
	Insurance expenses						
	Commercial expenses						
	Others not mentioned above						
	Total other costs						
Notes:							

5.

PUBBLIC SUPPORT FOR H2 TECNOLOGY DEVELOPMENT		Year(s)	Euro
Input from national support programs			
Input from EU support programs			
Input from other sources			
Direct financial subsidies			
	Grant from other institution		
	Own investment		
Notes:			

II. ON ROAD H2 TRANSPORT

1.

DESCRIPTION OF THE H2 TRANSPORT PATHWAY	
	Cross with an X
Compressed H2 delivered by truck	
Liquid H2 by delivered by truck	
Notes:	

2.

TRUCK TRANSPORT PERFORMANCE	General data		
	Unit of measurement	Compressed H2	Liquid H2
Total mass of H2 delivered in one year	Kg/y		
Total mass of the truck in outward journey	kg		
Total mass of H ₂ transported in one journey	kg		
Total mass of the truck in return	kg		
Total mass of H ₂ delivered in a journey	kg		
Delivery H ₂ pressure (gaseous H ₂)	bar		
Delivery H ₂ temperature (Liquid H ₂)	°C		
Boil off	(% (Nm ³ /m ³ /h)		
Fuel cost (gasoil)	Euro/MJ		
Average distance in outward journey	km		
Total hours of H ₂ transport 1 one year.	h		
Total number of annual journey (one way)	N°		
Total distance in a year	km		
Expected lifetime of the truck (years)	y		
Notes:			

TRUCK TRANSPORT PERFORMANCE		Technical maturity	
Reliability		Total n°	Average n°/y
	Failure mode during operation		
	Number of major repairs per H ₂ transport technology		
Availability (calculated on annual basis = 8760 h)		% h/y	
	Foreseen operation use		
	In regular use		
	Not in operation because of operational schedule		
	Not in operation because of schedule maintenance		
	Not in operation because of repairs of parts of the H ₂ transport technology		
	Not in operation because of unavailability of H ₂ , the filling station or the vehicles (specify)		
	Other (Non-technical reasons)		
Durability			
		h/d/w/m/y	km
	Lifetime of the H ₂ transport facility		
Notes:			

3.

SAFETY AND REGULATIONS	Codes, standards and regulations			
Existence of standards, codes and regulations on compressed H ₂ transport			Did you adopt these standards and regulations?	

SAFETY AND REGULATIONS		Codes, standards and regulations					
		Yes	No	Specify standards and regulations	Yes	No	Your reasons/comments/suggestions
	Worldwide standards and regulations						
	Country standards and regulations						
	Preliminary standards and regulations						
	Standard and regulations being discussed						
	Lack of standards and regulations						
	Own standards and regulations						
Existence of codes and standards on Liquid H2 transport					Did you adopt these standards and regulations?		
		Yes	No	Specify standards and regulations	Yes	No	Your reasons/comments/suggestions
	Worldwide standards and regulations						
	Country standards and regulations						
	Preliminary standards and regulations						
	Standard being discussed						
	Lack of standards and regulations						
	Own standards and regulations						
Notes:							

SAFETY AND REGULATIONS		Permits and licenses	
		Compressed H ₂	Liquid H ₂
Safety measures for gaseous H2 transport			
	Imposed by regulation		
	Adopted by you but not imposed		
	Own suggestions		

SAFETY AND REGULATIONS	Permits and licenses
Notes:	

4.

TRUCK TRANSPORT ECONOMICS		Cost for the deliverer			
Investment					
		Euro/truck	N° of trucks	Compressed H ₂	Liquid H ₂
	Capital costs for trucks				
Notes:					

ECONOMICS		Costs for operator					
Depreciation for on road compressed gaseous H ₂ transport					% (depreciation rate)	N° years	Annual cost (Euro)
	Depreciation plan						
Depreciation for on road Liquid H ₂ transport					% (depreciation rate)	N° years	Annual cost (Euro)
	Depreciation plan						
Notes:							

TRUCK TRANSPORT ECONOMICS		Cost for the deliverer				
Compressed H ₂ labour costs						
				Man*hours	COST (Euro/Man*hour)	Annual cost (Euro)
	Operating labour					
	Operating supervision					
	Total labour and supervision costs					
Liquid H ₂ labour costs						

TRUCK TRANSPORT ECONOMICS		Cost for the deliverer					
				Man*hours	COST (Euro/Man*hour)		Annual cost (Euro)
	Operating labour						
	Operating supervision						
	Total labour and supervision costs						
Notes:							

TRUCK TRANSPORT ECONOMICS		Cost for the deliverer					
Compressed H ₂ maintenance costs							
Materials							Annual cost (Euro)
	Costs of materials for scheduled maintenance						
	Costs of materials for repairs						
	Costs of materials for configuration changes						
Labour				N° Man*hours	COST (Euro/Man*hour)		Annual cost (Euro)
	Labour costs of scheduled maintenance						
	Labour costs of repairs						
	Labour costs of configuration changes						
	Total maintenance costs (materials+labour)						
Liquid H ₂ maintenance costs							
Materials							Annual cost (Euro)
	Costs of materials for scheduled maintenance						
	Costs of materials for repairs						
	Costs of materials for configuration changes						
Labour				N° Man*hours	COST (Euro/Man*hour)		Annual cost (Euro)

TRUCK TRANSPORT ECONOMICS		Cost for the deliverer					
	Labour costs of scheduled maintenance						
	Labour costs of repairs						
	Labour costs of configuration changes						
	Total maintenance costs						
Notes:							

TRUCK TRANSPORT ECONOMICS		Cost for the deliverer					
Other costs				Compressed H ₂		Liquid H ₂	
					Annual cost (Euro)		Annual cost (Euro)
	Overheads						
	Research & Development costs						
	Insurance expenses						
	Commercial expenses						
	Others not mentioned above						
	Total other costs						
Notes:							

5.

PUBLIC SUPPORT		Year(s) Gaseous H ₂	Year(s) Liquid H ₂	Compressed H ₂	Liquid H ₂
				Euro	Euro
	Input from national support programs				
	Input from EU support programs				
	Input from other sources				
	Direct financial subsidies				
	Grant from other institution				
	Own investment				

III. H2 PIPELINES

1.

PERFORMANCE	Operational characteristics	
H ₂ delivery flow rate Nm ³ /h and Nm ³ /y (pipeline capacity)	Nm ³ /h	Nm ³ /y
H ₂ delivery distance (km)		
H ₂ pressure inlet and outlet (bar)	bar	bar
Compressor size (kW)		
Compressor Number		
H ₂ flow into pipeline (Nm ³ /h)		
H ₂ flow out pipeline (Nm ³ /h)		
Notes:		

PERFORMANCE	Technical maturity	
Development stage of the compressor technology		
	Prototype	
	First of kind	
	Second of kind	
	... of kind	
	Fully commercial	
Other (specify)		
Notes:		

PERFORMANCE	Technical maturity		
Planning and realization time to build the H ₂ piping system			
	Total n° of months required		
Reliability			
	Failure mode when starting up	Reasons	Total n°

PERFORMANCE		Technical maturity		
	Failure mode during operation			
	Number of major repairs per pipe system			
Availability (calculated on annual basis = 8760 h)			% h/y	
		Foreseen operation use		
		In regular use		
		Not in operation because of operational schedule		
		Not in operation because of schedule maintenance		
		Not in operation because of repairs of parts of the H ₂ piping facilities		
		Not in operation because of unavailability of H ₂ , the filling station, vehicles or electricity		
		Other (Non-technical reasons)		
Durability			h/d/w/m/y	
		Lifetime of the H ₂ pipeline system		
Notes:				

2.

SAFETY AND REGULATIONS		Codes, standards and regulations					
Existence of standards, codes and regulation on compressed H ₂ transport facility						Did you adopt these standards and regulations?	
		Yes	No	Specify standards and regulations	Yes	No	Your reasons/comments/suggestions
	Worldwide standards and regulations						

SAFETY AND REGULATIONS		Codes, standards and regulations					
	Country standards and regulations						
	Preliminary standards and regulations						
	Standard and regulations being discussed						
	Lack of standards and regulations						
	Own standards and regulations						
Notes:							

SAFETY AND REGULATIONS		Permits and licenses	
Imposed safety measures on piping process			Specify main safety standards and regulations
	Imposed by regulation		
	Adopted by you but not imposed		
	Own suggestions		
Time to obtain permits			
	Time from first talks to formal apply of permits (w/m/y)		
	Time from formal apply to approval (w/m/y)		
	Working time for the whole process (Man-hours)		
Notes:			

3.

H2 PIPELINE TRANSPORT ECONOMICS	
Investment	

H2 PIPELINE TRANSPORT ECONOMICS							
			Unit of measurement	N° units	Euro/Unit	Cost (Euro/Nm3)	Annual cost (Euro)
	Land (right of the way)		km				
	Compressor capital cost		kW				
	Pipeline		km				
	Other (specify)						
	Interest allowed during construction						
	Other costs						
	Total capital costs						
	Labour cost during construction						
Notes:							

H2 PIPELINE TRANSPORT ECONOMICS		Costs for operator					
					% (depreciation rate)	N° years	Annual cost (Euro)
Depreciation							
	Depreciation plan						
Notes:							

H ₂ PIPELINE TRANSPORT ECONOMICS							
		Unit of measurement	Price range (min & max) for single unit (Euro/Unit)	Unit/Nm3 H2	Annual amount (Units)		Annual costs (Euro)
Utilities							
	Electric power	kWh					
	Other (specify)						
Notes:							

H ₂ PIPELINE TRANSPORT ECONOMICS							
Compressed H ₂ pipeline system labour costs							
				N° Man*hours	Cost (Euro/Man*hour)		Annual cost (Euro)
		Operating labour					

H ₂ PIPELINE TRANSPORT ECONOMICS						
		Operating supervision				
		Total labour and supervision costs				

H ₂ PIPELINE TRANSPORT ECONOMICS						
Compressed H ₂ pipeline system maintenance costs						
Materials						Annual cost (Euro)
		Costs of materials for scheduled maintenance				
		Costs of materials for repairs				
		Costs of materials for configuration changes				
				N° Man*hours	Cost (Euro/Man*hour)	Annual cost (Euro)
Labour		Labour costs of scheduled maintenance				
		Labour costs of repairs				
		Labour costs of configuration changes				
		Total maintenance costs				
Notes:						

H ₂ PIPELINE TRANSPORT ECONOMICS						
Other costs						
						Annual cost (Euro)
	Overheads					
	Running royalty					
	Research and development costs					
	Insurance expenses					

H₂ PIPELINE TRANSPORT ECONOMICS						
	Commercial expenses					
	Others not mentioned above					
	Total other costs					
Notes:						

4.

PUBLIC SUPPORT			
		Year(s)	Euro
Input from national support programs			
Input from EU support programs			
Input from other sources			
Direct financial subsidies			
	Grant from other institution		
	Own investment		

IV. REFUELLING STATION

Any required data has to be specifically related to hydrogen part of the station.

1.

DESCRIPTION OF THE H2 REFUELLING STATION	
	To cross with an X
Refuelling station in Mantova (Italy)	
Refuelling station in ISH (Germany)	
Notes:	

2.

PERFORMANCE	Operational characteristics			
	Compressed H2		Liquid H2	
	Nm3/h	Nm3/y	Nm3/h	Nm3/y
H2 refuelling station refuelling capacity				
H2 container capacity (Nm3)				
H2 purity (%)				
Expected lifetime of the facilities (years)				
Notes:				

PERFORMANCE	Technical maturity		
		Gaseous H2	Liquid H2
	Development stage of the H2 tank	Prototype	
First of kind			
Second of kind			

PERFORMANCE	Technical maturity		
	... of kind		
	Fully commercial		
	Other (specify)		
Development stage of the H2 refuelling station compressors and pumps	Prototype		
	First of kind		
	Second of kind		
	... of kind		
	Fully commercial		
	Other (specify)		
Development stage of the H2 refuelling station filling equipment	Prototype		
	First of kind		
	Second of kind		
	... of kind		
	Fully commercial		
	Other (specify)		
Planning and realization time to build the H2 refuelling facilities	Total n° of months required		
Notes:			

PERFORMANCE	Technical maturity		
Reliability, (only hydrogen part of the station)	Total n°	Average n°/y	
	Technology fails when starting up		
	Technology fails during operation		
	Number of major repairs per H ₂ refuelling facility		
Availability (calculated on annual basis = 8760 h), (only hydrogen part of the station)		% h/y	
	Foreseen operation use		
	In regular use		
	Not in operation because of operational schedule		
	Not in operation because of schedule maintenance		
	Not in operation because of repairs of parts of the H ₂ refuelling facilities		

PERFORMANCE	Technical maturity	
	Not in operation because of unavailability of H ₂ , power or the vehicles (specify)	
Notes:		

3.

SAFETY AND REGULATIONS	Safety characteristics and features				
		Gaseous H ₂		Liquid H ₂	
		bar		bar	°C
Refuelling and technology related	Max pressures in refuelling process				
	Min/Max temperatures in refuelling process				
Notes:					

SAFETY AND REGULATIONS	Codes, standards and regulations					
Existence of standards, codes and regulations for compressed H ₂ refueling station design (only hydrogen part of the station)				Did you adopt these standards and regulations?		
	Yes	No	Specify standards and regulations	Yes	No	Your reasons/comments/suggestions
			Worldwide standards and regulations			
			Country standards and regulations			
			Preliminary standards and regulations			
			Standard and regulations being discussed			
			Lack of standards and regulations			
			Own standards and regulations			

SAFETY AND REGULATIONS		Codes, standards and regulations					
Existence of standards, codes and regulations for Liquid H2 refueling station design (only hydrogen part of the station)					Did you adopt these standards and regulations?		
		Yes	No	Specify standards and regulations	Yes	No	Your reasons/comments/suggestions
	Worldwide standards and regulations						
	Country standards and regulations						
	Preliminary standards and regulations						
	Standard and regulations being discussed						
	Lack of standards and regulations						
	Own standards and regulations						
Notes:							

SAFETY AND REGULATIONS		Codes, standards and regulations					
Existence of standards, codes and regulations for compressed H2 fuel specifications					Did you adopt these standards and regulations?		
		Yes	No	Specify standards and regulations	Yes	No	Your reasons/comments/suggestions
	Worldwide standards and regulations						
	Country standards and regulations						
	Preliminary standards and regulations						
	Standard and regulations being discussed						
	Lack of standards and regulations						
	Own standards and regulations						

SAFETY AND REGULATIONS		Codes, standards and regulations					
Existence of standards, codes and regulations for Liquid H2 fuel specifications					Did you adopt these standards and regulations?		
		Yes	No	Specify standards and regulations	Yes	No	Your reasons/comments/suggestions
	Worldwide standards and regulations						
	Country standards and regulations						
	Preliminary standards and regulations						
	Standard and regulations being discussed						
	Lack of standards and regulations						
	Own standards and regulations						
Notes:							

SAFETY AND REGULATIONS		Permits and licenses		
		Specify main safety standards		
		Gaseous H2	Liquid H2	
Safety measures for refueling stations (only hydrogen part of the station)				
	Imposed by regulation			
	Adopted by you but not imposed			
	Own suggestions			
Time to obtain permits		Gaseous H2	Liquid H2	
	Time from first talks to formal apply of permits (w/m/y)			
	Time from formal apply to approval (w/m/y)			
	Working time for the whole process (Man-hours)			
Notes:				

4.

ECONOMICS		Costs for operator		
Investment		Units ²⁰	Quantity	Euro
Capital costs for H2 refuelling facilities				
	Conventional station land			
	Land (H2 part of the station)			
	Liquid H2 container			
	Gaseous H2 Container			
	Liquid and gaseous H2 container			
	Liquid H2 pump			
	Gaseous H2 pump			
	Vaporizer			
	Gaseous H2 dispenser			
	Liquid H2 dispenser			
	Other equipments			
	Interest allowed during construction			
	Others not mentioned above			
	Total capital costs			
	Labour cost during construction			

Notes:

ECONOMICS		Costs for operator				
Depreciation for H2 refuelling facility				% (depreciation rate)	N° years	Annual cost (Euro)
	Depreciation plan					

Notes:

²⁰ The units necessary for comparisons to be agreed with the partners.

ECONOMICS		Costs for operator					
Utilities							
		Unit of measurement	Price range (min & max) for single unit (Euro/Unit)	Unit/ Nm3 H2	Annual amount (Units)		Annual cost (Euro)
	Electric power	kWh					
	Fuel gas	Nm3					
	Other						
	Total utilities						
Notes:							

ECONOMICS		Costs for operator					
Maintenance costs							
Materials							Annual cost (Euro)
	Costs of materials for scheduled maintenance						
	Costs of materials for repairs						
	Costs of materials for configuration changes						
Labour				N° Man*hours	Cost (Euro/Man*hour)		Annual cost (Euro)
	Labour costs of scheduled maintenance						
	Labour costs of repairs						
	Labour costs of configuration changes						
	Total maintenance costs						
Notes:							

ECONOMICS		Costs for operator					
Other costs							
							Annual cost (Euro)
	Overheads						
	Running royalty						

ECONOMICS		Costs for operator					
	Research and development costs						
	Insurance expenses						
	Commercial expenses						
	Others not mentioned above						
	Total other costs						
Notes.							

5.

PUBLIC SUPPORT FOR H2 TECHNOLOGY DEVELOPMENT			
		Year(s)	Euro
Input from national support programs			
Input from EU support programs			
Input from other sources			
Direct financial subsidies			
	Grant from other institution		
	Own investment		
Notes:			

V. PEM FUEL CELL VEHICLES

1.

H2 PEM FUEL CELL VEHICLE	
	To cross with an X
FIAT	
Daimler Chrysler	
Notes:	

This tables are to be filled for all PEM FC vehicle into ZERO REGIO project if their present some technical modification and/or economic variation.

2.

VEHICLE PERFORMANCE	Operational characteristics		
	H2 consumption	Nm3 H2/100km	
		g H2/100 km	
		kg H2/100 km	
	H2 required Purity	%	
	Range	km	
	Max speed	km/h	
	Acceleration 0-100 km/h	Sec	
	Filling time	Min.	
Durability	Expected lifetime of the FC vehicle	km	
Notes:			

VEHICLE PERFORMANCE	Technical maturity
---------------------	--------------------

VEHICLE PERFORMANCE		Technical maturity		
Development stage of the technologies (related to your overall production of PEM Fuel Cell Vehicle)		Prototype		
		First of kind		
		Second of kind		
		... of kind		
		Fully commercial ²¹		
		Other (specify)		
Planning and realization time to fabricate the H2 PEMFC vehicle		Total n° Man hours required		
Reliability				
		Reasons	Total n°	Average n°/y
	Failure mode when starting up			
	Failure mode during operation			
	Number of major repairs per H2 PEMFC vehicle			
Availability (calculated on annual basis = 8760 h)			h/y	
		Foreseen operation use		
		Foreseen hours of operation		
		Realised hours of regular use		
		Not in operation because of operational schedule <note>		
		Not in operation because of scheduled maintenance of vehicle		
		Not in operation because of unscheduled repairs of vehicle.		
		Not in operation because of unavailability of the feedstock, the filling station or other (specify)		
		Other (Non-technical reasons)		
Notes:				

3.

²¹ Fully commercial means ready for mass production and sell

VEHICLE GENERAL SPECIFICATIONS		Vehicle Data		
Vehicle Specifications	Vehicle Manufacturer			
	Model			
	Number of FC vehicles realized for EU Zero Regio project			
Vehicle Dimensions		Unit of measurement		
	Length	m		
	Width	m		
	Height	m		
	Wheelbase	m		
	Gross Vehicle Weight Rating	kg		
Passenger Seating				
	Maximum number of passengers	n°		
Fuel				
	Fuel type(s)			
	Fuel state	Gas or liquid		
	Necessary Additives			
Fuel Cell		Unit of measurement		
	Manufacturer/ Model Number			
	Type	PEM, SOFC, etc.		
	Number of units			
	Cell current density	A/cm2		
	Voltage of fuel cell	V		
	Total rated power	kW		
		Fuel cell placement in the vehicle		
	Expected lifetime of fuel cell stack	hours		
	Weight of fuel cell stack	kg		
	Working temperature range	Min/max (°C)		
		Yes	No	Details and comments
Hybrid				

VEHICLE GENERAL SPECIFICATIONS		Vehicle Data			
	Full power from fuel cell				
	Hybrid configuration				
		Breaking energy recovery			
		Battery			
		Manufacturer			
		Nominal package voltage (V)			
		Total capacity (Ah)			
		Total energy (kWh)			
		Placement in the vehicle			
Fuel Storage System					
		Storage system (gas or liquid)			
		Number of containers			
		Total capacity	Nm3		
		Weight of a single container	kg		
		Total Useful Amount of Fuel	kg		
		Tank manufacturer			
		Location of tanks	roof, under floor, etc.		
		Maximum filling pressure	bar		
		Burst pressure (gaseous H ₂)	bar		
	Working temperature range				
	Maximum admissible leakage	Nm3/l/h			
	Maximum Working Pressure (Gaseous H ₂)	bar			
	Time to fill storage system	minutes			
Propulsion Electric Motor(s)					
		Manufacturer/ Model Number			
		Type			
		Nominal output power	kW		
		Peak output power	kW		
		Rated speed	rpm		
		Rated torque	Nm		
		Maximum current	amps		
	Minimum voltage	V_DC			

VEHICLE GENERAL SPECIFICATIONS		Vehicle Data	
		Location of motors	hub mounted, between torque coupler and final drive, etc
Safety equipment			
			YES/NO
	Safety of FC vehicle - Leakage detection system.		Specify
		How calibrate (% of LFL of H2)?	
		How many sensors?	
		Where located?	
		Are they active when vehicle is off?	
		Prevention of gas accumulation on board	
		Check of gas release	
		Behaviour during fire – safety valves	
		Fire detection and suppression system	
	Safety related to vehicle collisions		
		Prevention of fuel leaks following breaking	
		Containment of gas into container (cut off valves)	
		Fastener for H ₂ containers and components	
	Electric device safety (fuel cells):		
		Isolation of electric components	
		Prevention of sparks and electric discharges	
		Electromagnetic compatibility	
Notes			

4.

STACK PEM FUEL CELL COSTS (based on your own knowledge)							
			UNIT OF MEASUREMENT	Euro/m2	g/m2	Euro/g	Euro/kW
	PE Membrane						
	Electrodes						
	Bipolar Plate						
	Platinum Catalysts						
	Peripheral Materials						
	Assembly						
	Total PEM fuel cell costs						
Notes:							

5.

SAFETY AND REGULATIONS	Safety characteristics and features			
			Gaseous H2	Liquid H2
Transport and technology related			bar	bar °C
		Max pressures in FC vehicle		
		Min/Max temperatures in FC vehicle		
Notes:				

SAFETY AND REGULATIONS	Codes, standards and regulations				
Existence of standards, codes and regulations on compressed H2 FC vehicle design				Did you adopt these standards and regulations?	
	Yes	No	Specify standards and regulations	Yes	No
					Your reasons/comments/suggestions

SAFETY AND REGULATIONS		Codes, standards and regulations					
	Worldwide standards and regulations						
	Country standards and regulations						
	Preliminary standards and regulations						
	Standard and regulations being discussed						
	Lack of standards and regulations						
	Own standards and regulations						
Existence of standards, codes and regulations on Liquid H2 FC vehicle design						Did you adopt these standards and regulations?	
		Yes	No	Specify standards and regulations	Yes	No	Your reasons/comments/suggestions
	Worldwide standards and regulations						
	Country standards and regulations						
	Preliminary standards and regulations						
	Standard and regulations being discussed						
	Lack of standards and regulations						
	Own standards and regulations						
Notes:							

SAFETY AND REGULATIONS		Permits and licenses	
		Compressed H2	Liquid H2
Safety measures FC vehicle			
	Imposed by regulation		
	Adopted by you but not imposed		
	Own suggestions		
Time to obtain permits		Compressed H2	Liquid H2
	Time from first talks to formal apply of permits (w/m/y)		

SAFETY AND REGULATIONS		Permits and licenses		
		Time from formal apply to approval (w/m/y)		
		Working time for the whole process (Man-hours)		
Notes:				

6.

ECONOMICS		Costs for operator			
		N° of units	Unit price (Euro/Unit)	Unit/ Vehicle	COST (Euro/Vehicle)
	Basic vehicle				
	Filling connector				
	Hydrogen container				
	Container safety valve				
	Fuel feeding pipes				
	Pressure reducing valves				
	Pressure relief valves				
	Air compressor				
	FC stack price (KW)				
	Cooling system				
	Auxiliaries				
	Inverter				
	Electric motor				
	Safety hydrogen equipment				
	Hybrid configuration				
		Braking energy recovering			
		Battery			
		Battery charger			
	Other (Specify)				
	Total				
Utilities					

ECONOMICS		Costs for operator			
		Unit of measurement	Euro/Unit	N° Unit/vehicle	COST (Euro/Vehicle)
	Electric power required	kWh			
	Heat	MJ			
	Other (Specify)				
	Total utilities				
Labour costs					
		N. operators	Euro/operator year cost	N° hours to realize a PEMFC vehicle	COST (Euro/vehicle)
	Operating labor				
	Operating qualified labor				
	Operating high qualified labor				
	Operating supervision				
	Total labor and supervision costs				
Other costs					
					COST (Euro/MJ H2)
	Overheads				
	Running royalty				
	Research and development costs				
	Insurance expenses				
	Commercial expenses				
	Total other costs				
TOTAL VEHICLE PRODUCTION COST					
Notes:					

7.

MAINTENANCE COSTS	
	Annual cost (Euro)

MAINTENANCE COSTS							
		Expected	First year	Second year	Third year	Average value next years	COST (Euro/Vehicle)
	Costs of materials for scheduled maintenance						
	Costs of materials for repairs						
	Costs of materials for configuration changes						
	Labor costs of repairs						
	Labor costs of scheduled maintenance						
	Labor costs of configuration changes						
	Total maintenance costs						

1

8.

PUBLIC SUPPORT			
		Year(s)	Euro
Input from national support programs			
Input from EU support programs			
Input from other sources			
Direct financial subsidies			
	Grant from other institution		
	Own investment		



Deliverable 7.1.

Work Plan Competitiveness

Appendix D

Test Data for Competitiveness Analysis in the ZERO REGIO Project

By

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PERFORMANCE	Operational characteristics	
Emissions of		
CO ₂		
CO		
SO ₂		
NO _x		
Particle Matter		
Metals and chemicals (please specify)		
Notes:		

3.

ECONOMICS		Costs for operator					
Labour costs							
				N° Man*hours	Cost (Euro/M an*hour)		Quarterly cost (Euro)
	Operating labour						
	Operating supervision						
	Total labour and supervision costs						
ECONOMICS		Costs for operator					
Maintenance costs							
Materials							Quarterly cost (Euro)
	Costs of materials for scheduled maintenance						
	Costs of materials for repairs						
	Costs of materials for configuration changes						
Labour				N° Man*hours	Cost (Euro/M an*hour)		Quarterly cost (Euro)
	Labour costs of scheduled maintenance						
	Labour costs of repairs						
	Labour costs of configuration changes						
	Total maintenance costs						
Notes:							

II. ON ROAD H2 TRANSPORT

1.

DESCRIPTION OF THE H2 TRANSPORT PATHWAY	
	Cross with an X
Compressed H ₂ delivered by truck	
Liquid H ₂ by delivered by truck	
Notes:	

2.

TRUCK TRANSPORT PERFORMANCE	General data		
	Unit of measurement	Compressed H ₂	Liquid H ₂
Total mass of H ₂ loaded	Kg		
Total mass of H ₂ delivered	Kg		
Total distance driven	km		
Total number of transports	Km		
Total hours of H ₂ transport	H		
Fuel consumption (gasoil)	L		
Notes:			

TRUCK TRANSPORT PERFORMANCE	Technical maturity		
		Total n°	Average n°/q
Reliability	Failure mode during operation		
	Number of major repairs per H ₂ transport technology		
Availability (calculated on quarterly basis = 2190h)		Hours	
	Foreseen operation use		
	In regular use		
	Not in operation because of operational schedule		
	Not in operation because of schedule maintenance		
	Not in operation because of repairs of parts of the H ₂ transport technology		
	Not in operation because of unavailability of H ₂ , the filling station or the vehicles (specify)		
	Other (Non-technical reasons)		

TRUCK TRANSPORT PERFORMANCE	Technical maturity
Notes:	

3.

TRUCK TRANSPORT ECONOMICS		Cost for the deliverer				
Compressed H ₂ labour costs						
				Man*hours	COST (Euro/Man*hour)	Quarterly cost (Euro)
	Operating labour					
	Operating supervision					
	Total labour and supervision costs					
Liquid H ₂ labour costs						
				Man*hours	COST (Euro/Man*hour)	Quarterly cost (Euro)
	Operating labour					
	Operating supervision					
	Total labour and supervision costs					
Notes:						

TRUCK TRANSPORT ECONOMICS		Cost for the deliverer				
Compressed H ₂ maintenance costs						
	Materials					Quarterly cost (Euro)
	Costs of materials for scheduled maintenance					
	Costs of materials for repairs					
	Costs of materials for configuration changes					
	Labour			N° Man*hours	COST (Euro/Man*hour)	Quarterly cost (Euro)
	Labour costs of scheduled maintenance					
	Labour costs of repairs					
	Labour costs of configuration changes					
	Total maintenance costs (materials+labour)					

TRUCK TRANSPORT ECONOMICS		Cost for the deliverer					
Liquid H ₂ maintenance costs							
Materials							Quarterly cost (Euro)
	Costs of materials for scheduled maintenance						
	Costs of materials for repairs						
	Costs of materials for configuration changes						
Labour				N° Man*hours	COST (Euro/M an*hour)		Quarterly cost (Euro)
	Labour costs of scheduled maintenance						
	Labour costs of repairs						
	Labour costs of configuration changes						
	Total maintenance costs						
Notes:							

III. H2 PIPELINES

1.

PERFORMANCE	Operational characteristics	
H ₂ delivery flow rate (Nm ³ /h)		
H ₂ delivery distance (km)		
H ₂ flow into pipeline (Nm ³ /h)		
H ₂ flow out pipeline (Nm ³ /h)		
Notes:		

PERFORMANCE	Technical maturity		
Planning and realization time to build the H ₂ piping system			
	Total n° of months required		
Reliability			
	Reasons	Total n°	Average n°/y
	Failure mode when starting up		
	Failure mode during operation		

PERFORMANCE		Technical maturity		
	Number of major repairs per pipe system			
Availability (calculated on Quarterly basis = 8760 h)			% h/y	
		Foreseen operation use		
		In regular use		
		Not in operation because of operational schedule		
		Not in operation because of schedule maintenance		
		Not in operation because of repairs of parts of the H ₂ piping facilities		
		Not in operation because of unavailability of H ₂ , the filling station, vehicles or electricity		
		Other (Non-technical reasons)		
Notes:				

H ₂ PIPELINE TRANSPORT ECONOMICS							
Utilities		Unit of measurement	Price range (Euro/Unit)	Unit/ Nm ³ H ₂	Quarterly amount (Units)		Quarterly costs (Euro)
	Electric power	kWh					
	Other (specify)						
Notes:							

H ₂ PIPELINE TRANSPORT ECONOMICS							
Compressed H ₂ pipeline system labour costs							
				N° Man*hours	Cost (Euro/Man*hour)		Quarterly cost (Euro)
		Operating labour					
		Operating supervision					
		Total labour and supervision costs					

H ₂ PIPELINE TRANSPORT ECONOMICS							
Compressed H ₂ pipeline system maintenance costs							
Materials							Quarterly cost (Euro)
		Costs of materials for scheduled maintenance					
		Costs of materials for repairs					

H₂ PIPELINE TRANSPORT ECONOMICS						
		Costs of materials for configuration changes				
				N° Man*hours	Cost (Euro/Man*hour)	Quarterly cost (Euro)
Labour		Labour costs of scheduled maintenance				
		Labour costs of repairs				
		Labour costs of configuration changes				
		Total maintenance costs				
Notes:						

IV. REFUELLING STATION

Any required data has to be specifically related to hydrogen part of the station.

1.

DESCRIPTION OF THE H2 REFUELLING STATION	
	To cross with an X
Refuelling station in Mantova (Italy)	
Refuelling station in ISH (Germany)	
Notes:	

2.

PERFORMANCE		Technical maturity	
Reliability, (only hydrogen part of the station)		Total n°	
	Technology fails when starting up		
	Technology fails during operation		
	Number of major repairs per H ₂ refuelling facility		
Availability (calculated on Quarterly basis = 2190 h), (only hydrogen part of the station)			hours
		Foreseen operation use	
		In regular use	
		Not in operation because of operational schedule	
		Not in operation because of schedule maintenance	
		Not in operation because of repairs of parts of the H ₂ refuelling facilities	
		Not in operation because of unavailability of H ₂ , power or the vehicles (specify)	
Notes:			

3.

ECONOMICS		Costs for operator			
		Unit of measurement	Price (Euro/Unit)	Quarterly amount (Units)	Quarterly cost (Euro)
Hydrogen	Received amount	Kg			
	Supplied amount	Kg			
Energy Consumption	Electric power	kWh			
	Fuel gas	Nm3			
	Other				

ECONOMICS		Costs for operator					
Maintenance costs							
Materials							Quarterly cost (Euro)
	Costs of materials for scheduled maintenance						
	Costs of materials for repairs						
	Costs of materials for configuration changes						
Labour				N° Man*hours	Cost (Euro/Man*hour)		Quarterly cost (Euro)
	Labour costs of scheduled maintenance						
	Labour costs of repairs						
	Labour costs of configuration changes						
	Total maintenance costs						
Notes:							

V. PEM FUEL CELL VEHICLES

1.

H2 PEM FUEL CELL VEHICLE	
	To cross with an X
FIAT	
Daimler Chrysler	
Other (specify)	
Notes:	

This tables are to be filled for all PEM FC vehicle into ZERO REGIO project if their present some technical modification and/or economic variation.

2.

VEHICLE PERFORMANCE		Operational characteristics		
		H ₂ consumption	Kg	
		Registered boil off	Kg	
		Registered leaks	No	
		Fillings	No	
		Total time spent for filling	Minutes	
		Total distance driven – urban	Km	
		Total distance driven – highway	Km	
Notes:				
Reliability				
		Reasons		Total n°
	Failure mode when starting up			
	Failure mode during operation			
	Number of major repairs per H2 PEMFC vehicle			
Availability (calculated on Quarterly basis = 2190 h)			Hours	
		Realised hours of regular use		
		Not in operation because of operational schedule		
		<note>		
		Not in operation because of scheduled maintenance of vehicle		

VEHICLE PERFORMANCE	Operational characteristics	
	Not in operation because of unscheduled repairs of vehicle.	
	Not in operation because of unavailability of the feedstock, the filling station or other (specify)	
	Other (Non-technical reasons)	
Notes:		

3.

MAINTENANCE COSTS							
		Quarterly cost (Euro)					
					Quantity	Price	COST (Euro/Vehicle)
	Costs of materials for scheduled maintenance						
	Costs of materials for repairs						
	Costs of materials for configuration changes						
	Labor costs of repairs						
	Labor costs of scheduled maintenance						
	Labor costs of configuration changes						
	Total maintenance costs						