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the European Hydrogen Roadmap

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HYWAYS

the European Hydrogen Roadmap

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Summary

Hydrogen is an energy carrier with zero carbon content. Just like electricity, hydrogen can be produced from all energy resources, such as biomass, wind and solar energy, nuclear energy and clean fossil fuels[1]. It can be converted to power and heat with high efficiency and zero emissions, especially when used in fuel cells. It improves security of supply due to the decoupling of demand and resources, allowing each European member state to choose its own energy sources. The possibility of taking the frontrunner position in the worldwide market for hydrogen technologies provides new economic opportunities and strengthens European competitiveness. Despite these promising prospects, the introduction of hydrogen into the energy system does not happen autonomously. Substantial barriers have to be overcome, ranging from economic and technological to institutional barriers. The HyWays Roadmap and Action Plan for hydrogen in Europe provide a strategy to overcome these barriers.

MS-visions

The vision on how hydrogen could be introduced in the energy system played a major role in the HyWays project. Over 50 member state (MS) workshops were conducted with key stakeholders, during which inputs for the models were collected. In addition, market scenarios for hydrogen end-use applications, as provided by the HyWays partners, and outcomes of the analysis were discussed, leading to further refinement of the MS-visions. Each country outlined its own preferences. As a result, it was concluded that Europe will need a portfolio of hydrogen energy chains. According to the stakeholders, hydrogen production in the early phase (up to 2020) will rely mainly on existing by-product, steam methane reforming and electrolysis (both onsite) to satisfy early demand. As the energy system evolves until 2050, stakeholders expect the production portfolio to broaden, with centralized electrolysis and thermo-chemistry from renewable feedstocks (solar, wind, biomass) and CO_2-free or -lean sources (coal and natural gas with CCS and nuclear).

Main challenges

The introduction of hydrogen into the energy system faces two major barriers:

- *Cost reduction.* The cost of hydrogen end-use applications, especially for road transport, need to be reduced considerably to become competitive. A substantial increase in R&D investments is needed together with well balanced distribution of deployment to ensure that the economic break-even point is reached as soon as possible at minimum cumulative costs.
- *Policy support.* Hydrogen is generally not on the agenda of the ministries responsible for the reduction of greenhouse gasses and other pollutants, nor in ministries dealing with security of supply. As a result, the required deployment support schemes for hydrogen end-use technologies and infrastructure build-up are lacking.

Main conclusions from the HyWays project

- *Emission reduction.* If hydrogen is introduced into the energy system, the cost to reduce one unit of CO_2 decreases by 4% in 2030 and 15% in 2050, implying that hydrogen is a cost-effective option for the reduction of CO_2. A cash flow analysis shows however that a substantial period of time is required to pay back the initial investments (start-up costs). Total well-to-wheel reduction of CO_2 emissions will amount to 190 – 410 Mton per year in

[1] Using hydrogen production options equipped with carbon capture and storage (CCS) and state-of-the-art pollutant emission reduction technology.

2050.[2] About 85% of the reduction in emissions is related to road transport, reducing CO_2 emission from road transport by about 50% in 2050. Furthermore, the introduction of hydrogen in road transport contributes to a noticeable improvement of air quality in the short to medium term. This holds specifically for the most polluted areas such a city centres where the sense of urgency is greatest.

- *Security of supply.* Like electricity, hydrogen decouples energy demand from resources. The resulting diversification of the energy system leads to a substantial improvement in security of supply. The total oil consumption of road transport could be decreased by around 40% by the year 2050 as compared to today if 80% of the conventional vehicles were replaced by hydrogen vehicles. Based on the long-term visions as developed by the member states that participated in the HyWays project, about 100 Mtoe of oil is substituted due to the introduction of hydrogen in transport. For the direct production of hydrogen, so excluding hydrogen produced by means of electrolysis, about 33 Mtoe of coal and natural gas and 13 Mtoe of biomass will be needed in 2050. According to these visions, about 45% of the hydrogen is produced by means of electrolysis from renewable, sustainable and nuclear energy. Equally important is the fact that several pathways exist that can produce hydrogen at comparable price levels and in sufficient amounts. This range of production options ensures a relatively stable hydrogen production price. At oil prices over \$50 – \$60 per barrel equivalent, hydrogen does become cost competitive as a fuel.
- *Sustainable use of fossil fuels.* Use of hydrogen for electricity production from fossil fuels in large centralized plants will contribute to achieving a significant reduction of CO_2 emissions if combined with CO_2 capture and storage processes.
- *Contribution to targets for renewable energy and energy savings.* The introduction of hydrogen into the energy system offers the opportunity to increase the share of renewable energy. Hydrogen could also act as a temporary energy storage option and might thus facilitate the large-scale introduction of intermittent resources such as wind energy. Further research is needed to quantify the relevance of this function taking into account national and regional aspects. Hydrogen produced from biomass allows for substantial efficiency gains compared to biofuels (and conventional fuels) when used in fuel cell and hybrid vehicles, thus contributing to energy conservation goals. The efficiency gain over biofuels is specifically important since the potential for biomass is limited and strong competition exists (e.g. power sector, feedstocks/synthetic materials, food).
- *Impact on economic growth and employment.* The transition to hydrogen offers an economic opportunity if Europe is able to strengthen its position as a car manufacturer and energy equipment manufacturer. Substantial shifts in employment are observed between sectors, highlighting the need for education and training programmes. The shift to the production of dedicated propulsion systems will contribute to maintaining high skilled labour in Europe rather than outsourcing these to countries where labour costs are low. Assuming that the import/export shares of vehicles in Europe remain the same, the overall impact on economic growth will be slightly positive (around +0.01% per year). This situation changes considerably if Europe is not able to maintain its position as major car manufacturer in which case there will be a substantial negative impact on welfare in Europe. The major benefit for economic growth is a strong decrease in vulnerability of the economy to shocks and structural high oil prices. Studies from the IEA and European Central Bank, for example, indicate that the (temporary) impact on GDP growth of prices shocks or structural high oil prices amounts to -0.2% to -0.4% of GDP growth.
- *End-use applications.* In the time frame until 2050, the main markets for hydrogen end-use applications are passenger transport, light duty vehicles and city busses. About half of the transport sector is expected to make a fuel shift towards hydrogen. Heavy duty transport (trucks) and long distance coaches are expected to switch to alternative fuels (e.g. biofuels). The penetration of hydrogen in the residential and tertiary sector is expected to be limited to remote areas and specific niches where a hydrogen infrastructure is already present.

[2] For the 10 countries analysed in HyWays.

- *Cost of end-use applications and infrastructure build-up*. The costs per kilometre driven for mass-produced cars are comparable to conventional vehicles, provided that the necessary cost reductions are obtained. A substantial period of time is needed before the initial investments are paid back. Total cumulative investments for infrastructure build-up amount to about € 60 billion for the period up to 2030. This is only about 1% of the societal costs for meeting the 450 ppm CO_2 target in Europe.

Table S.1 *Summary of the deployment phases targets and main actions*[3] *outlined in the Roadmap and Action Plan*

	2010	2015	2020	2030	2050
Phases	**Technology development with focus on cost reduction** **Pre-commercial technology refinement & market preparation**	**Start of commercialisation**	**HFP Snapshot 2020** **materialisation of first impacts** • New hydrogen supply capacities partially based on low carbon sources • improvement in local air quality • More than 5% of new car sales H_2 &FC	**HyWays Snapshot 2030** **Hydrogen & FC are competitive** • Creation of new jobs and safeguarding existing jobs (net employment effect of 200,000 – 300,000 labour years) • Shift towards carbon-free hydrogen supply • More than 20% of new car sales H_2 & FC	**H_2 & FC dominant technologies high impact** • 80% of light duty vehicles & city buses fuelled with CO_2 free hydrogen • reaching more than 80% CO_2 reduction in passenger car transport • In stationary end-use applications, hydrogen is used in remote locations and island grids
Targets	**LHPs facilitate initial fleet of a few 1,000 vehicles by 2015** • PPP "Lighthouse Projects" • Increase R&D budgets to 80 M€/year • Financial support for large scale demonstration projects		Vehicles: **2.5 million of fleet** Cost **H_2: 4 €/kg (50 €/barrel)** **FC: 100 €/ kW** **Tank: 10 €/kWh**	Vehicles: **25 million of fleet** Cost **H_2: 3 €/kg (50 €/barrel)** **FC: 50 €/ kW** **Tank: 5 €/kWh**	
Required Policy Support Actions	**Develop H_2 specific support framework** • Create / support early markets • Implement performance monitoring framework • Long term security for investing stakeholders • Education and training programmes • Harmonisation of regulations codes and standards	**H_2 specific support framework** • In place before 2015 at MS level • Deployment supports, e.g. tax incentives of 180 M€/year • Public procurement • Planning and execution of strategic development of hydrogen infrastructure		**Gradual switch from hydrogen specific support to generic support of sustainability (2020 →)**	**Incentives provided through general support schemes for sustainability**
	2010	2015	2020	2030	2050

A pdf-version of the Action Plan, the Member States' Vision Report, an executive summary, the Roadmap and various background reports are available for download at www.HyWays.de.

[3] The targets and actions for the time period up to 2020 have been developed together with the European Hydrogen and Fuel Cell Technology Platform (HFP), see (HFP, 2005a) and (HFP, 2007) and are used as starting point for further targets and actions outlined in this Roadmap and the HyWays Action Plan.

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1. Introduction to the Roadmap

This chapter briefly introduces the HyWays project, by outlining the aim and approach of the project and sketching the context.

1.1 History and context

The success of the European Union is that it brings together diverse economies linking their skills, knowledge and technologies and harnesses them for common purpose. The HyWays project - the European Hydrogen Energy Roadmap is an example of the power of collective representative European research in the face of the challenges posed by the need for more sustainable energy solutions in today's world. The project explores and plans for the potential that the integration of hydrogen technologies into the energy system have to contribute to the challenges of ensuring that Europe's peoples and economies have a secure, environmentally sustainable and economically competitive supply of energy services for generations to come.

The integration of hydrogen into the energy system has the potential to impact directly on the key drivers of European energy policy. Improved system energy efficiency and emission reductions mean that hydrogen has the potential to reduce local and global emissions promoting environmental sustainability. Moreover hydrogen enables the economy to be flexible and rely on a diverse range of primary energy sources ensuring security of supply options are kept open; in particular hydrogen can favour the use of higher shares of renewable sources in the energy sector. The development of market leading hydrogen technologies and the employment they bring with them means that the integration of hydrogen can contribute significantly to on-going European economic competitiveness.

In short, hydrogen technologies have the potential to offer enhanced sustainability benefits in terms of cost-competitiveness, low well-to-tank carbon content, high energy efficiency and flexible reliance on diverse primary energy resources. However, hydrogen is a very innovative energy technology that is not compatible with all existing fuelling and propulsion systems. Fuelling infrastructure and vehicle fleets will have to be built up in parallel from zero, requiring diligent planning and governmental support.

1.2 Background and objectives

The inherent nature of an innovative technology, which can be disruptive, explains the need for the European Hydrogen Energy Roadmap and an Action Plan. The early studies of HyNet gained impetus for more detailed work through the High Level Group and the Hydrogen and Fuel Cell Technology Platform (HFP), culminating in an important milestone at European level of a target of 10 to 20% sustainable hydrogen production by 2015 as set by the Implementation Plan and backed by industry. The HyWays project sets out to produce a roadmap for Europe, that clearly demonstrates the advantages and problems posed by this very innovative energy technology option, alongside the timings and expected costs. An Action Plan accompanying the Roadmap details the conditions, including measures and their timelines, necessary to overcome the initial barriers in order to facilitate the deployment of hydrogen technologies. The Action Plan addresses politicians and policy makers at a national and European level and is designed to inform decision makers with respect to governmental support during the initial phase.

The objective of HyWays, an integrated project co-funded by research institutes, industry and the European Commission under the 6th Framework Programme, is to develop a validated and well-accepted roadmap for the introduction of hydrogen in the energy system in Europe. The HyWays project combines technology databases and socio-/ techno-/ economic analyses to evaluate selected stakeholder scenarios for future sustainable hydrogen energy systems. Scenarios are based on member states (MS) visions for the introduction of hydrogen technologies with extensive interaction between science and stakeholders involving over 50 workshops. For each country the theoretical economic optimum choice is calculated and evaluated by the member states on an iterative basis. A multinational approach covering, at that time, 80% of the EU land area and over 70% of the population ensures a wide diversity in terms of feedstocks, regional & infrastructure-related conditions and preferences.

1.3 Methodology

The HyWays project compiles all pivotal technological and socio-economic aspects related to a future hydrogen infrastructure build-up and provides a number of scenarios under different assumptions. It shows the consequences of the introduction of hydrogen as a fuel and indicates the financial effort necessary to reach the break-even point.

The HyWays project differs from other road mapping exercises as it integrates stakeholder preferences, obtained from multiple member state workshops, with extensive modelling in an iterative way covering both technological and socio-economic aspects, Figure 1.1. This approach enables qualitative data to be incorporated in a systematic and structured manner with quantitative infrastructure analysis, thus adding significantly to the common quantitative modelling approach adopted by other roadmaps.

The stakeholder validation process, which takes into account country specific conditions, is a key element of the road mapping process.

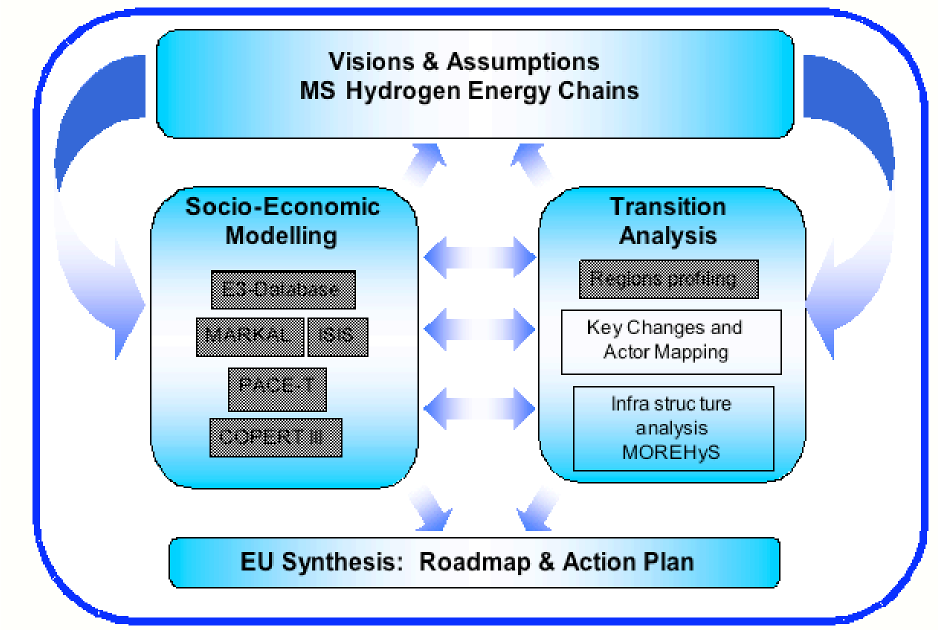

Figure 1.1 *Schematic representation of the HyWays process*

In the HyWays project the Roadmap is based primarily on country-specific analyses of ten member states (MS) (six in HyWays phase I and four in HyWays phase II). The countries selected (Finland, France, Germany, Greece, Italy, the Netherlands, Norway, Poland, Spain and the United Kingdom) ensure a large coverage, both in land and population, and represent the diversity and geographical spread of Europe, increasing the confidence in the validity of the synthesis at European level.

1.4 Transition phases: from demonstration towards mass markets

In 2006, major stakeholders from automotive industry and the energy sector published a common position paper on the next steps for the development of a hydrogen infrastructure for road transport in Europe. Hydrogen-based vehicle rollout is considered to happen in three phases: (i) a currently ongoing phase focussing on technology development and cost reduction followed by (ii) a pre-commercial phase from 2010 to approximately 2015 comprised of technology refinement and market preparation and (iii) after 2015 a commercialisation phase of hydrogen vehicles which is expected to start with a continuous ramp-up of production leading to a mass market within ten years.

1.5 Milestones

The HFP Deployment Strategy published in 2005 proposed commercialization targets for the transport sector in 2020. According to this *'Snapshot 2020'* sales of 0.4 to 1.8 million vehicles per year within the EU are considered to be a realistic goal. The vehicle penetration scenarios calculated in HyWays are in good agreement with the HFP *Snapshot 2020*. Based on various assumptions on future technology development as well as on several levels of policy support, these scenarios have been extrapolated to create a '*Snapshot 2030*', and a further outlook to 2050.

1.6 Alternatives

Considering the interaction of hydrogen technologies with competing / alternative options, in terms of hydrogen from biomass, competing demands do exist. This holds true for stationary applications, the food and chemical industries, transportation and other biofuel applications. Furthermore, technical synergies with biomass to liquids processes exist. In the analysis, the competing use of biomass for other energy uses has been taken into account. However, due to the aim and focus of the project, an in-depth analysis of the role of biomass, specifically for non-transport related purposes, has not been performed. Therefore the resulting indication is to be considered as only qualitatively.

In a similar manner the development and deployment of drive train technologies, i.e. a broader portfolio including hybrids and battery electric vehicles, can help to cut the costs of a large part of the components used in fuel cell vehicles. In the long term, hydrogen and fuel cell vehicles provide one of the most promising options.

For the stationary use of hydrogen HyWays has assessed its use mainly in fuel cells for CHP which can become a relevant option for remote supply of electricity and heat as well as in complex energy infrastructures for use in stationary appliances and transport and combined with energy storage. In terms of combined heat and power (CHP) and power production there is a broad portfolio of competing technologies that have already been established and others that are being established. Fuel cells promise higher efficiencies at comparable unit sizes. Fuel cells also allow for small CHP units for residential use. The technological synergies are likely to have spill-over effects between different applications and sectors.

1.7 Concurrent initiatives

During the course of the project HyWays has been active in links and interaction with other EU and non-EU activities and has communicated with various HFP-bodies. The HLG Vision 2050 report provided long-term goals to HyWays. In turn HyWays has made inputs to the on-going SET (Strategic Energy Technology)-Plan by EC and has been liaising, through the HyWays-IPHE Project, with the U.S. road mapping activities being undertaken by the Department of Energy, the National Renewable Energy Laboratory and Argonne Laboratory. HyWays has also maintained close cooperation and exchange of information with the EC-funded projects NaturalHy, StorHy, HyLights, Roads2HyCom and with MS/regional initiatives such as HyFrance, NorWays and the Dutch Transition Platform. With NaturalHy joint analysis was carried out on combined natural gas and hydrogen transport and distribution pathways for specific case studies.

HyWays has taken into account the EU 20% Renewable Energy Target for 2020 which will lay the foundation for increasing RES use for hydrogen production, and the EU biofuel target of 10% by 2020, which can partly be met by biomass-to-hydrogen conversion.

In the transition to a hydrogen economy, the public perception of safety is a critical issue, as with any other innovation. Although the public view on hydrogen is – besides some misunderstandings – in general positive, an early large accident in the public environment could change this quickly. As the new hydrogen applications cover new operational domains, like high pressures or cryogenic temperatures, the successful and safe usage in industrial environments might not be translated directly to all these cases. Therefore research especially for a better understanding of all involved phenomena, performance of mitigation and simulation technologies is required. Due to evident limitations of the HyWays project the issues regarding safety were not included. Instead these aspects are addressed by the European Network of Excellence HySafe at least on a technical level. A sufficient information exchange between HyWays and HySafe was arranged with the HyWays coordinator being a member of the HySafe coordination committee.

1.8 Other HyWays reports

The HyWays project makes the case for a transition to hydrogen, showing that with the right policy actions, the introduction of these technologies could have economic, social and environmental benefits. This document summarizes the technical and socio-economic analyses and examines the implications for research priorities and future targets and concludes with a summary of the Action Plan. A number of reports have been published within the context of the HyWays project:

- A Flyer on main results and key actions and recommendations;
- An Executive Summary of the Roadmap and Action Plan;
- The HyWays Roadmap – this report;
- An Action Plan;
- A Member States' Vision Report on the Introduction of Hydrogen in the European Energy System;
- Various background reports.

These documents are available for download at the HyWays web site: www.HyWays.de. For further detailed information on the issues addressed by HyWays please refer to the full background reports on the website.

2. Hydrogen end-use applications

In this chapter, the deployment scenarios for hydrogen end-use applications as well as expected technological progress are described. Niche market applications such as hydrogen powered consumer electronics may play a role, specifically in the area of public acceptance, in the introduction of hydrogen in the energy system, see also (HyWays, 2007a). In this chapter, only early markets, as part of the main markets for road transport and stationary end-use applications are described. The impact of niche market applications on total energy demand is only a fraction of the total energy demand in road transport and the residential and service sector and therefore not taken into account in the scenarios of the development of total hydrogen demand. Industrial hydrogen demand as a chemical product, e.g. for oil refining, oil production from non-conventional resources, steel industry and biofuels production, was not considered by HyWays, but may contribute in the medium term to an increased need for clean hydrogen production routes.

2.1 Hydrogen vehicles

At present hydrogen powered vehicles with PEM (Polymer Electrolyte Membrane) fuel cell drive trains and somewhat less with internal combustion engines are being demonstrated in ongoing projects worldwide. Different classes such as passenger cars (small to luxury) as well as delivery vans or public transport buses are deployed in the relevant demonstration programmes. Due to very high range requirements of 2,000 km and more, long distance trucks and coaches are not considered within the current or planned hydrogen vehicle research and development programmes. For these typical operation profiles of ‘long distance constant speed travelling’, diesel engines can already be operated in best efficiency modes, leaving not much improvement for potential energy savings on a well-to-wheel base. Hence for the scope of the HyWays project only light duty vehicles (cars, commercial vehicles up to 3.5 tons) and public transport buses have been considered as relevant applications. Niche applications such as local operated trucks (e.g. garbage trucks) or scooters fuelled with hydrogen can likely play a role in urban transport but in general (national level, EU-level) the impact of these niche applications on energy consumption is negligible. This approach of focusing primarily on light duty vehicles and public transport buses is in line with the WETO-H_2 study (EC, 2006).

While fuel cells are a key driver for the introduction of hydrogen as a new vehicle fuel, all hydrogen related technologies which have been analysed in the CONCAWE/EUCAR/JRC Well-to-Wheels Study (2006) have been considered in HyWays. Since economic optimisation models such as MARKAL always choose the cheapest solution regardless consumer preferences the technological choice as well as the distribution of small, middle and large sized cars had to be given as exogenous border condition. Based on current trends in technology development and activities of automobile manufacturers the split shown in Figure 2.1 for the different drive train technologies has been used for modelling the vehicle hydrogen demand over time.

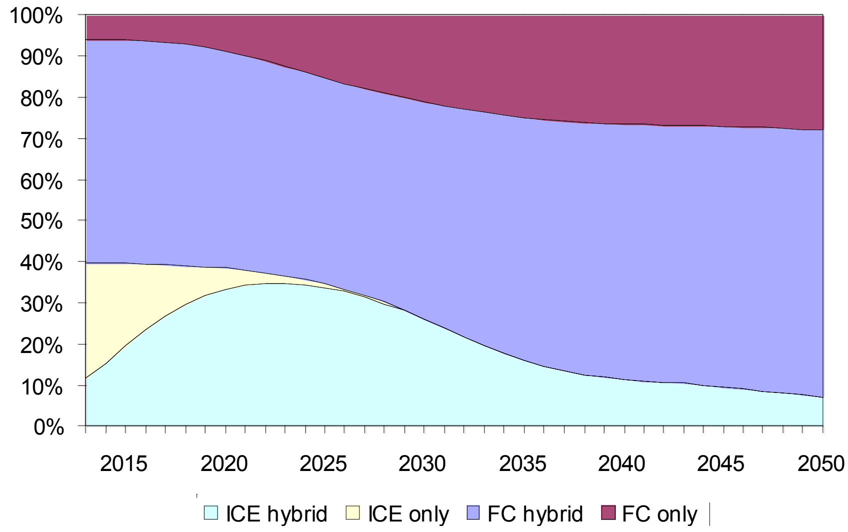

Figure 2.1 *Distribution of various hydrogen fuelled vehicles: fuel cell vehicles and hydrogen ICE vehicles (hybridised and pure)*[4]

Concerning onboard-storage technologies both compressed as well as liquid hydrogen technologies have been considered. In order to assess vehicle-infrastructure interactions two sensitivity scenarios – one without any restrictions and one with a minimum bound of liquid demand – have examined the economic impact of these storage technologies in the frame of the infrastructure analysis (see section 3.3 and 4.1). However, the 'technological toolbox' applied in HyWays can be seen as robust since all feasible hydrogen pathways are considered and even a new onboard storage technology requires for example either a liquid or compressed supply regime.

2.2 Learning curves hydrogen vehicles

In order to reach the deployment targets of the *Snapshot 2020* and *Snapshot 2030* it is necessary to analyse and forecast whether the related cost targets can be met at the required milestones. Since the economical competitiveness, which is determined to a large extent by the retail price development, is strongly influencing the market penetration of fuel cell and hydrogen ICE vehicles, a credible approach was required to assess the future price development beyond the 2030 time frame.

Baseline for the current cost data of key components such as fuel cells or hydrogen storage tanks is the well accepted CONCAWE/JRC/EUCAR Well-to-Wheels Study (2006). Since these data are based on an initial commercialisation with annual production volumes in the order of 100,000 units, the learning curve concept is applied to model the further cost estimate of hydrogen vehicles. A learning curve describes technological progress as a function of accumulating experience with that specific technology. Quite often, the technological progress analysed within a learning curve is parameterised as a cost reduction due to an increase in the accumulated production. Such an estimate is based on historical statistics in the cumulative output. The essential parameter to be estimated in this formalism is the so-called progress ratio (PR). For example, a technology with a progress ratio of 0.8 will see that the unit price will be reduced by 20 percent with each doubling of the cumulative output. The progress ratio is estimated from available historical data or can be derived from the statistics on learning curves of related technologies. It is important to note that learning curves do not represent a physical

[4] Based on current trends and strategic documents such as the HFP SRA (HFP, 2005b) & DS (HFP, 2005a), the HyWays Consortium has elaborated a working hypothesis on the development of the distribution of fuel cell vehicles and hydrogen ICE vehicles (hybridised and pure).

law. They are an empirical phenomenon with significant uncertainties surrounding both the estimation of specific progress ratios and their extrapolation for long-term forecasts of the cost reduction of technologies.

In order to minimise the uncertainties in the price scenarios for fuel cell and hydrogen technologies in HyWays, the fuel cell and hydrogen ICE powered cars are split into different components with different progress ratios. Two different scenarios for the progress ratios were selected (see Table 2.1) in order to specifically handle the uncertainties associated with fuel cells and other key components.

Table 2.1 *Progress ratios of hydrogen and fuel cell technology components*

Component	Fast learning (low PR)		Modest learning (high PR)	
	initial phase	10 years after market entrance	initial phase	10 years after market entrance
Hydrogen Tank*	0.85		0.85	0.98
Electric Motor & Controller	0.90			
Li-Ion Battery	0.90			
FC System	0.80	0.90	0.82	0.92
H_2-ICE**	1.00		1.00	

* In the first ten years after market introduction the PR is the same for both scenarios, after 10 years the learning effects are lower in the case of the modest learning scenario.
** The CONCAWE/JRC/EUCAR WTW-Study assumes the same production cost for gasoline and hydrogen engines.

The progress ratios are based on the research activities of the automotive partners in HyWays, derived from different comparable technologies[5], taking into account scientific publications concerning the learning curve approach, especially those dealing with fuel cell technology (Junginger and Faaij, 2003; Tsuchiya, 2002). Comparing the HyWays approach with current research work of the IEA (IEA, 2005), it was found that in HyWays, both scenarios for technological learning lead to lower cost for fuel cell cars.[6]

The calculation of the vehicle price is based on the assumptions in Table 2.1. Figure 2.2 shows the projected price development for compact class hydrogen-powered cars over the cumulated total production volume. The prices for a cumulative production of 100,000 units reflect the specifications from the CONCAWE/JRC/EUCAR study for the year 2010.

[5] Historical examples for PR: Ford Model T 0.85; photovoltaics 0.82; laser diode 0.75 initially, 0.80 thereafter.
[6] The methodology used in the IEA-study deviates from the HyWays approach. Despite the fact that in the IEA-study the progress ratios have lower values – implying that costs as a function of the cumulative number of vehicles build reduce more quickly in the IEA study – the total costs of the vehicles remain higher.

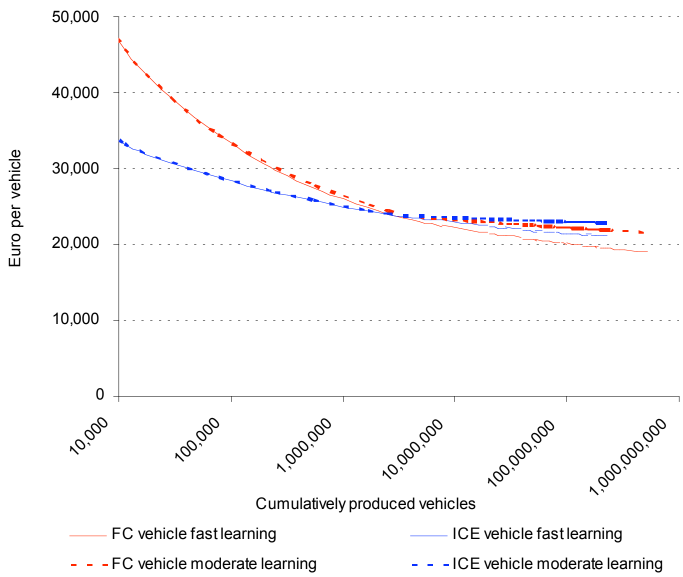

Figure 2.2 *Cost reduction of hydrogen cars (only the compact class cars are shown) for the two progress ratio scenarios for 2010*

It also needs to be stated that the learning curve concept cannot be used for a backward calculation down to the current number of up to 100 vehicles per manufacturer deployed in the actual demonstration projects world wide. For modelling reasons a figure of 10,000 hydrogen and fuel cell vehicles has been assumed as initial population, when the mass market rollout will take place. The initial fleet of these 10,000 vehicles is expected to result from European funded large scale demonstration projects to be initiated by the proposed 'Joint Technology Initiative' (JTI) on fuel cells and hydrogen. A first implementation plan (HFP, 2007) for this JTI has set a target of at least some thousands vehicles to be in operation after the successful completion of the large scale demonstration projects by 2015/16, hence confirming the approach of bridging from today's few demonstration vehicles towards first serial production by a public-private partnership. The planned time frame of this public-private-partnership until 2015 guarantees the required planning security mainly for the industrial stakeholders to undertake both the development of two more vehicle generations that are necessary to meet the minimum performance for mass-market rollout as well as to invest in appropriate production facilities. As a result the combination of research, development and deployment support from both industry and public bodies allows a relatively fast decrease in production cost for fuel cells and key hydrogen components that facilitates entrance to first niche markets. Subsequently, learning effects further decrease the cost as displayed in Figure 2.2 and pave the way for competitiveness of hydrogen vehicles in mainstream markets.

2.3 Hydrogen penetration rates

HyWays has not performed a simulation, in a sense that the penetration rate is a function of the cost-effectiveness of the hydrogen technology. The aim of HyWays was to build a roadmap for the introduction of hydrogen in the energy system. Consequently, the penetration of hydrogen applications was the starting point, not the result of the exercise. This back casting type of approach is a common way in roadmap building.[7] Based on the deployment scenarios, HyWays

[7] By using a back casting approach and taking hydrogen deployment as starting point, a number of complex methodological problems could be avoided (specifically with respect of purchase behaviour) that are in general part of a simulation approach. If the policy framework was taken as a starting point, modelling its effect would have to be oversimplified by translating it into economic impacts only. The (limited rationality of) purchase behaviour and oversimplification of policy framework would lead to a very large uncertainty in the development of the penetration rates, ignoring the fact that the (hydrogen specific) policy framework specifically in the early phase (so

has explored the consequences of hydrogen entering the energy system with respect to, economics, environmental benefits and employment as well as build up of a hydrogen infrastructure and consequences for the energy sector. As a final step, a policy framework to enable the hydrogen transition was developed with a specific focus on how to initiate the transition.

In this paragraph, a description is given of the penetration rates for hydrogen end-use application for the transport sector and the residential and commercial sector. Firstly a brief description of the main drivers that influence the deployment of hydrogen end-use applications is given. Next, deployment scenarios for road transport and stationary end-use applications are given.

2.3.1 Deployment of hydrogen end-use applications

In general, the market share of a specific technology depends on its cost effectiveness. The cost-effectiveness of hydrogen end-use applications are determined by both the fixed costs (investment costs for the end-use application and infrastructure build-up) and the variable costs (costs to produce one unit of H_2). Even though the development of energy prices has an effect on the variable costs, the cost-effectiveness is primarily determined by the cost-reduction of the end-use application as well as the costs for build-up of the hydrogen infrastructure. A higher oil price has an impact not only on the gap between the costs of conventional fuel and hydrogen but also on the portfolio of hydrogen production options. Cost-effectiveness is however only one of the factors that determines the deployment pace.

The non-cost related factors become important specifically after a particular threshold in cost-effectiveness is reached. Several other factors, such as build-up of production capacity, replacement rate (determined by the lifespan of an option) as well as purchase behaviour, determine the pace at which a new technology can enter the energy system. Sometimes, various technologies co-exist within the same market and changes take place only gradually. In other cases, the conventional option is rapidly replaced with the new option as soon as a threshold level in costs or cost-effectiveness is reached, showing a kind of binary introduction behaviour. In general, products which are subject to trends show a more abrupt market introduction behaviour in case a product with new features is introduced. In case of such a "binary introduction behaviour", the direct effect of e.g. high oil prices on the deployment rate is limited.

Since the cost reduction of the end-use application is considered to be the key factor that determines the cost-effectiveness of the introduction of hydrogen into the energy system, the learning capability (expressed in terms of the progress ratio, see section 2.2) is taken as a discrimination factor for the development of the deployment scenarios for hydrogen end-use applications. The impact of energy prices is investigated by means of a sensitivity analysis, see section 3.4.4.

Significant barriers have to be overcome to enable hydrogen to reach the commercialisation phase. The implementation of hydrogen-specific support schemes in the early phase of the transition is essential to overcome these barriers, see also the HyWays Action Plan (HyWays, 2007a). Large scale demonstration projects have to be facilitated. Next, early markets have to be created. The resulting deployment, together with R&D support, have to bring down the cost of the hydrogen technology. Without the support of a policy framework, the deployment of hydrogen technologies will be seriously hampered or might not occur at all. Therefore, the characteristics and intensity of the policy support framework for hydrogen are, next to the learning capability, seen as the second discriminating factor when deriving scenarios for the

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initiating deployment) plays a crucial role. Within HyWays, there has been a specific focus on the characteristics of the policy framework in the early transition phase, see (HyWays, 2007a).

introduction of hydrogen in the energy system. A brief outline of the policy support scenarios is given in the next paragraph.

2.3.2 Road transport

Since fuel cell and hydrogen ICE vehicles are still in the development phase and large scale research, development and deployment programmes to be performed by the JTI are not yet started, a precise forecast of the market development of fuel cell and hydrogen ICE vehicles cannot be made today. Instead, HyWays proposes a set of four scenarios, determined by the two factors of policy support and technical learning that finally summarize the challenges of the JTI regarding road transport as formulated by the Implementation Plan (HFP, 2007):

- Development of competitive hydrogen vehicles (performance, reliability, cost)
- Build-up of industrial production capacities
- Establishment of a refuelling infrastructure
- Supporting elements for market deployment and industrial investments.

In the above-mentioned challenges, the development of fuel cell components and hydrogen storage technologies is crucial. Especially the transition from today's production volumes towards a pre-commercial fleet of some thousand vehicles requires close collaboration and feedback between research on fuel cell system components and fuel cell stacks as well as electric drive system components on the one side and the technical validation of integrated systems under demonstration programmes on the other side. In this context an assessment of technical achievements and cost reductions needs demonstration vehicles during the latter phases of the JTI demonstration programmes (2010 to 2015).

For a mass-market rollout around 2015 the achievement of the following 'quality gates' has been adopted from the Strategic Research Agenda (HFP, 2005b): Based on a successful technology development and validation during the first phase of large scale demonstrations inaugurated by the JTI by 2009 and a consecutive four year period of series development, the market introduction could commence in 2013 in the optimistic case. More conservative scenarios assume a delayed start of the JTI, based on relatively modest policy support and / or slower technical progress than anticipated in the actual planning (compared to the Implementation Plan (HFP, 2007)). Then commercial readiness of the fuel cell technology would not be achieved before 2010. Hence, the process of serial development could start by 2011 for example, leading to an earliest mass-market rollout by 2016, if assuming a more conservative 5 year period for a full development cycle is.

For the scenarios defined by 'fast technical learning' and 'high' or 'very high policy support' it has been assumed that mass production of hydrogen and fuel cell vehicles will begin by 2013, led by a group of 5 first movers which increase their capacities each by a new plant of 100,000 units per year anticipating an increase in plant utilization from 5% to 90% respectively in the first three years.

In the more conservative scenarios (modest technical learning) the hypothetic start of mass production has been shifted to 2016 and the number of first movers reduced to 4 which will ramp-up their plant utilization rate from 5% to 90% within a five year time frame (maximum production capacity of each of the four plants 100,000 units per year). After reaching full utilisation of the production capacities of the first movers after 3 (high/ very high policy support in combination with fast learning) respectively 5 years (modest learning in combination with high or modest policy support) it was assumed that followers are entering the market in a similar way and the first movers are doubling their production capacities. Based on these hypothetic quantitative scenarios an S-Curve[8] was calibrated for each scenario to the generic

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[8] A modified Makeham Curve was used, applying a time shift of t_0 (start year of mass production) while the other parameters have been calculated according to a 'best fit approach' with the hypothetic absolute production volumes for each year and scenario

production volumes and used to extrapolate penetration shares until 2050 as displayed in Figure 2.3.

The policy support framework
The rationale behind the scenario building parameter of 'policy support' was to describe the potential support from governments and the European Commission without introducing a subset of further parameters pretending pseudo-accuracy. The differences between the policy support levels are related to the type (general, technology specific), timing as well as the intensity of policy support framework.

The level of '*very high policy support*' represents a context with high deployment support where public bodies act and create early markets, whilst assuming that the JTI for fuel cells and hydrogen starts operation by 2008. Within the '*very high policy support*' scenario context, policy instruments are implemented before potential barriers hamper the deployment and cost reduction. The development of both costs and deployment of hydrogen technologies are carefully monitored. Additional R&D funds are made available in case the cost reduction deviates from the optimal pathway, ensuring an optimal balance between learning by doing (deployment) and learning by searching. As a result, the break-even point where hydrogen can compete with conventional technologies is reached a minimum costs and highest pace.

Similar support but with some delay or lower effectiveness is characterising the '*high policy support'* scenarios. In the 'very high policy support' scenario, an optimal timing as well as support level with respect to the implementation of policy instruments is assumed. In the 'high policy support scenarios, policy instruments are implemented when or just after specific technological and market barriers are encountered. In contrast, the specification of '*modest policy support*' characterizes a policy system, where action is only initiated after problems become clearly visible. Subsequently little specific and targeted support actions for hydrogen and fuel cells are introduced. Within the '*modest policy support*' scenario, the focus is on policy instruments that stimulate sustainability rather than a specific technology (such as hydrogen).

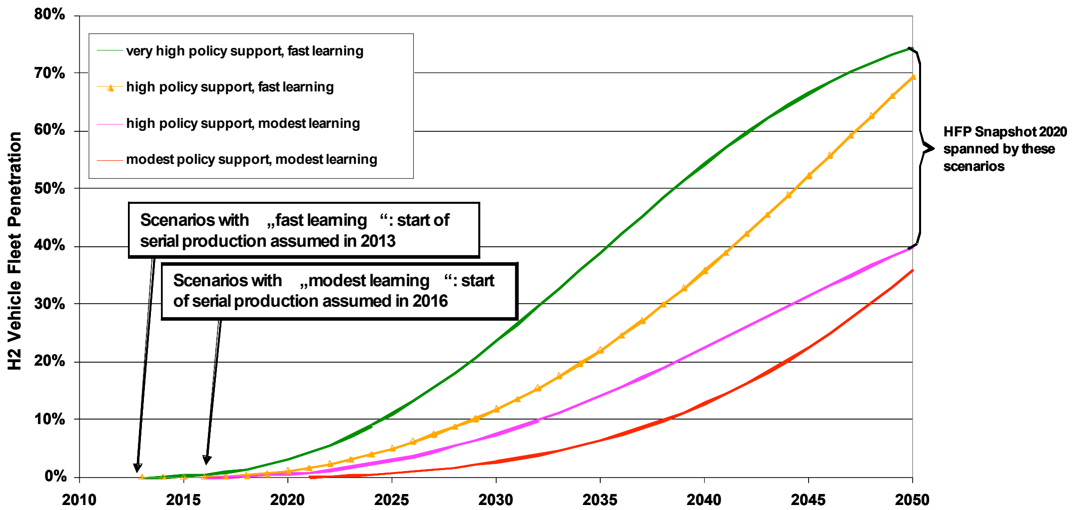

Figure 2.3 *Development of the penetration rate of hydrogen vehicles for passenger transport*

* The scenario 'high policy support, fast learning' has been chosen for target setting since it combines ambitious but realistic targets (see section 5.2).

From this perspective it is recommended to adjust the hydrogen substitution target of the European Commission (EC, 2001) for 2020. Based on the results of HyWays and the 'Deployment Strategy' (HFP, 2005a) of the European Hydrogen and Fuel Cell Technology Platform which, in conjunction with the '*Snapshot 2020*' (see section 1.5), developed, a maximum penetration target for hydrogen and fuel cell passenger cars by 2020 in the range of 1

– 3% of the total passenger car fleet, corresponding with sales of 0.4 – 1.8 million vehicles per year, seems appropriate.

In addition to passenger cars these penetration curves are also applied for other light duty vehicles and public transport buses (see section 2.1.). The importance of each category can be illustrated by the current fleet data (ACEA) for EU15: passenger cars 193 million, light commercial vehicles 23 million, buses and coaches 0.53 million out of which a quarter are used in public transport. The future demand for transportation follows the *Energy Trends 2030* scenario (EC, 2003a), see section 3.1.

2.3.3 Stationary end-use applications

In addition to using hydrogen as transport fuel, hydrogen can be used as a medium for energy storage to remedy the mismatch between energy demand and supply in a renewable electricity system mainly based on intermittent resources such as wind energy. Hydrogen produced locally or centrally during periods of excess electricity can provide back-up power via local CHP or central power units in periods of limited supply. In the short term energy storage will play a vital role in the implementation of large shares of locally available renewable energy into island energy systems and other stand-alone and weak grid situations.

Hydrogen can be used as an energy carrier for the production of heat and power in domestic and commercial CHP units much the same way as natural gas is used today. The drivers for future large hydrogen deployment in the stationary and end-user sectors are:

- Achievement of a better energy mix and security of the primary energy supply.
- Reduction of greenhouse gas (CO_2) emissions to meet the Kyoto and future post-Kyoto commitments.
- Reduction of atmospheric pollutant emissions in urban and/or in heavily populated areas.
- Increase of the renewable sources share for hydrogen production in the long term.
- Identification of the most efficient hydrogen chains both in terms of economy and energy (resource utilisation).
- Promotion of industrial competitiveness in high technology innovative sectors.

However, the use of hydrogen in domestic and commercial CHP is not as obvious as the use of hydrogen for transport. Compared to the direct use of electricity or the direct production of electricity from hydrocarbons, the production of hydrogen for subsequent electricity production introduces extra energy losses. It will be difficult to compensate these losses even if the heat which is released during the production of electricity at the end user is used efficiently.

Unlike transport applications for which biomass based fuels and CO_2-free or –lean electricity are the only sustainable alternatives to hydrogen, many alternatives to hydrogen exist to supply sustainable heat and power to the residential and commercial sector. Alternatives are the use of electricity produced centrally or locally from renewable resources, and the use of "renewable heat" produced locally by means of solar collectors or heat pumps, or supplied centrally through a biomass fired district heating system. In addition, the heat demand in houses and buildings can largely be reduced through improved insulation. In case of new housing development, heat demand for space heating can even be avoided by careful design.

As the future role of stationary hydrogen has not been assessed in the same detail and the same level of consequence as for transport, no sound forecast or its market potential can be made today. Instead, within HyWays a high and low penetration scenario has been used to explore the potential of domestic and commercial hydrogen CHP. The scenarios are shown in Table 2.2. The penetration rates are low compared to the penetration rates for transport. In addition to the considerations above, reasons for this are:

- Islands and remote areas represent only a small part of the energy demand in the member states.

- Unless existing natural gas pipelines can be used for hydrogen transport and distribution, a dedicated hydrogen pipeline infrastructure is required for the supply of hydrogen to the residential and commercial sector. Applications are mainly limited to new districts as replacement of the existing (low pressure) distribution grid is costly.

Table 2.2 *Development of the penetration rates for stationary hydrogen end-use applications in the residential and commercial sector*

Total share in residential sector [%]	2010	2020	2030	2040	2050
High penetration	-	1	4	8	10
Low penetration	-	0.1	0.5	2	5

Total share in commercial sector [%]	2010	2020	2030	2040	2050
High penetration	-	0.3	1.3	2.7	3.3
Low penetration	-	>0	0.2	0.7	1.7

Hydrogen can also be seen as an energy carrier to be used in combination with large scale electricity production. To this end, large centralised production plants can provide both sustainable electricity and hydrogen, using fossil fuels in a sustainable way through CO_2 capture and storage (CCS) and state-of-the-art pollutant emission reduction technology, see also section 3.3.5.

2.4 Portfolio analysis

A major goal of the HyWays technical analysis was to identify the selection of hydrogen supply chains (= pathways) to understand the variations from country to country as well as overlaps or differences for Europe. The selection process was a cornerstone of the vision development in each of the 10 countries.

Although some countries have decided in favour of rather specific pathways such as high-temperature electrolysis from nuclear electricity and heat (ES, FR), in-situ gasification of hardcoal (PL) and solar thermal high temperature conversion (IT) some hydrogen pathways were selected by a majority of the 10 countries. This selection was used for in-depth hydrogen pathways analyses the results of which have been condensed into one single graph for the year 2030, see Figure 2.4. For clarification a set of assumptions has been collected in the textbox at the end of this chapter.

The following most relevant conclusions have been drawn from this portfolio graph:

- Variations of specific WTW GHG emissions and hydrogen supply costs between countries (size of shaded boxes) are in an acceptable range. The differences are based on variations in assumptions for feedstocks and infrastructure.
- The specific pathways costs (0.018 –0.024 €/km) for the majority of the hydrogen energy chains are in the order of the diesel and gasoline reference costs (0.020 –0.022 €/km). The U.S. DoE goal of 2 –3 $/gge for hydrogen supply by 2010/2015 (0.020 –0.022 €/km) is seen as overly optimistic even for 2030.
- Replacing ICEs by FCs will render the operation of hydrogen vehicles competitive with untaxed gasoline/diesel cars irrespective of the hydrogen supply source. Assuming a 50% advantage of FCs versus ICEs (GHG emissions and costs) also ICEs have a GHG advantage over gasoline and diesel reference cars (except onsite SMR), but a cost advantage only if hydrogen is exempted from tax.
- Sensitivity analysis shows that both rising oil prices beyond 50 €/bbl and an internalization of external costs (here 0.9 €/pkm) is to the advantage of hydrogen. A failure of CCS (safe CO_2 storage) would shift the economic advantage towards other non-CCS pathways. In

general and specifically for the case of CCS failure, see also section 3.4.3, further study is needed in order to assess in more detail the role of hydrogen as an energy storage option for intermittent resources.

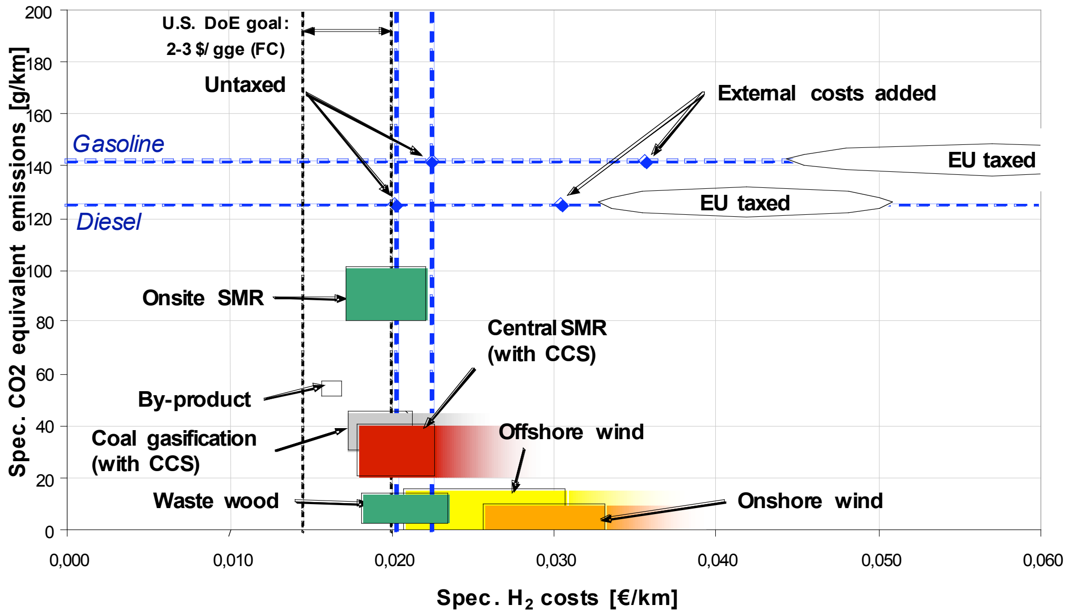

Figure 2.4 *Portfolio analysis of hydrogen production pathways as selected in the member state workshops*

Assumptions for portfolio presentation of hydrogen pathways analysis

The portfolio graph shows specific well-to-wheel emissions on the *y*-axis and specific well-to-wheel costs on the *x*-axis. Although the specific hydrogen costs consider vehicle fuel efficiency they exclude additional vehicle costs for the hydrogen vehicle.

All fossil pathways consider carbon capture and storage (CCS) except onsite SMR For correct comparison only pathways with compressed hydrogen (CGH_2) have been selected.

For reference gasoline/diesel ICEs and the U.S. DoE H_2 cost goal (FS) are included.

Bandwidths (= coloured boxes) represent variations across all 10 countries. Shaded areas indicate uncertainty (additional costs (or failure) of CCS and for intermittent renewable electricity storage).

Reference year is 2030, which has an impact on energy prices and technology/cost learning. The only exception is vehicle performance with reference year 2010 [CONCAWE, EUCAR, JRC study].

All vehicles are hybridized (= Volkswagen Golf class, > 2010), gasoline and diesel internal combustion engines (ICE) for the reference and hydrogen fuel cells (FC, 2.6 $l_{gasoline\ equivalent}$/100 km) for all other pathways (CONCAWE/EUCAR/JRC, 2006). The use of FCs versus ICEs approximately halves specific GHG emissions and costs.

Oil price for reference fuels: 50 €/bbl, exchange rate € 1 = 1.00 US$ (CONCAWE/EUCAR/JRC, 2006)]. EU bandwidth used for fuel taxes on gasoline and diesel fuels (2005, PL least, NL highest).

Except for some limited cases, dedicated hydrogen production from wind energy was not considered by HyWays. Bulk hydrogen storage is possibly required in order to compensate for intermittent wind energy in large amounts, but is not taken into account in the hydrogen pathways analysis.

3. Infrastructure build-up and hydrogen production mix

In this chapter, the results for the build-up of a hydrogen infrastructure and hydrogen production mix for Europe are presented. First, a brief description is given of the scenario assumptions and policy framework. Next, various aspects of infrastructure build-up, such as regional demand development, fuelling station sizes and locations are described. Finally, the production mix to meet the hydrogen demand is presented.

3.1 Scenario context

In order to minimise discussions on key scenario parameters, the HyWays consortium decided to base the analysis on a well accepted scenario which was developed on behalf of the EC. The development of energy demands is based on the *Energy Trends 2030* scenario (EC, 2003a), which was extrapolated to 2050. As the transport demand given by the *Energy Trends 2030* scenario was considered to be unrealistically high it was modified. For 2030, the demand for passenger cars in HyWays is 20% lower than in the *Energy Trends 2030* scenario.[9] Also freight demand was modified, resulting in a reduced demand growth of +16% over the period 2000 – 2030.

In the first phase of the HyWays project, also the rather low energy prices of the *Energy Trends 2030 scenario* were used. In HyWays Phase II, an updated energy price projection towards higher energy prices was used based on the *WETO-H_2* study (EC, 2006), see Figure 3.1.

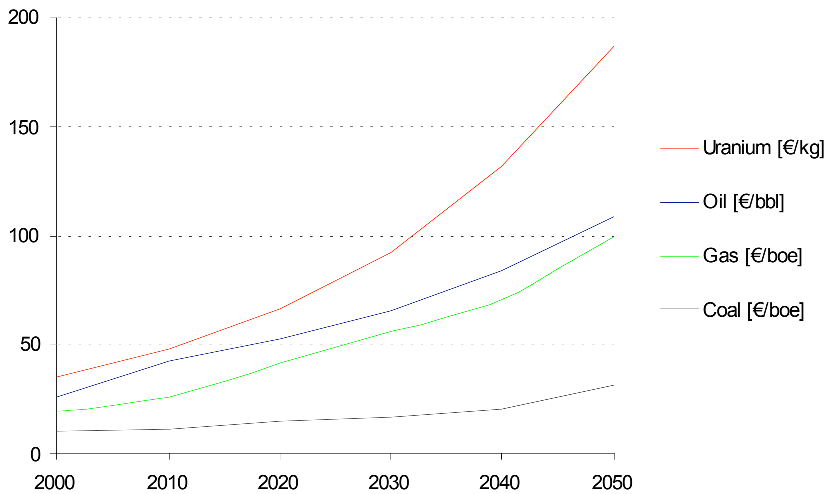

Figure 3.1 *Development of the energy prices in the HyWays baseline scenario (EC, 2006)*

It is assumed that both the natural gas and coal prices are (partially) coupled to the development of the oil price. By means of a sensitivity analysis, the impact of energy prices on final outcomes is assessed. As part of the sensitivity analysis, energy prices were varied as well as the relative price differences. The price of biomass is expected to increase slowly from about 5 €/GJ in 2010 to about 8 €/GJ in 2030.[10] Upper and lower values for energy prices as used in the sensitivity analysis are given in Table 3.1. Along with those assumptions concerning primary energy prices, the European electricity market is described as a single market and regional/national specificities are not taken into account. It is assumed that markets do function

[9] In the *Energy Trends 2030* scenario (EC, 2003a), the demand for passenger cars increases by +23% in the period 2000 – 2030.

[10] All prices in $€_{2000}$.

optimally. This implies, for example, that electricity prices are determined by fuel costs and the total costs of the power plant (construction costs, decommissioning costs, operational costs). Impacts of market imperfections, such as (partial) monopolistic or oligopolistic market situations as well as hidden subsidies by governments, are not taken into account.

Table 3.1 *Lower and upper values for energy prices used in the sensitivity analysis*[10]

		2020		2050	
		Low	High	Low	High
Oil	[€/bbl]	26	81	54	217
Natural gas	[€/boe]	22	68	38	204
Coal	[€/boe]	8	30	8	86
Uranium	[€/kg]	27	66	27	187

Besides on energy prices, further sensitivity analyses were performed on the availability of CCS and for an ambitious CO_2 emission reduction target for 2050, see section 3.4.2 and 3.4.3. The impact of deployment speed as well as technological progress is dealt with by analysing multiple scenarios, see section 2.2 and 2.3.

3.2 Assumptions for the policy framework

In the baseline scenario, a CO_2 reduction target and a target for renewable energy are implemented. For CO_2 emissions, a moderate emissions reduction target of -35% for 2050 (compared to 1990) was implemented. Deliberately, a rather conservative CO_2 emission target was chosen. Current EU ambition is to reduce greenhouse gas emissions by at least 50% over the period 1990 – 2050 (G8 Summit, 2007). However, if the introduction of hydrogen already would bring value added under these ‘mild’ constraints, one can expect that the value added is even higher with more ambitious reduction targets. As a sensitivity case, a CO_2 reduction scenario of -80% has been analysed.

The targets for renewable electricity are in line with the EC ambitions for 2010 and 2020. After 2020, a minimum share of renewable electricity is set to 28% of the total electricity consumption. For transport fuels, the EC target for a minimum share of 10% of alternative motor fuels has been implemented. Additionally constraints for domestic energy resources have been taken into account. The constraints are taken from accepted national or international studies. Biomass potentials are based on (EEA, 2006). For wind energy, several studies show long-term potentials between 600 – 3,000 GW for EU15 (EWEA, 2006; Hoogwijk, 2004; DLR, 2004; Weindorf, 2006). No constraints for wind energy have been implemented in the model, but model results are checked subsequently for consistency and plausibility. One important additional limitation is the assumption of limited storage capacities for CO_2. Country specific potentials are based on (Martinus, 2005). It is assumed that for EU15, total nuclear capacity is restricted to 130 GW.

3.3 Infrastructure analysis

The essence of the infrastructure analysis task was to create regional hydrogen demand and supply build-up scenarios over time by considering the available local resources as well as national policies and stakeholder interests. The purpose is to evaluate different infrastructure options in economic terms and to derive recommendations for introducing hydrogen as a transportation fuel in the next decades. Unlike the other tasks, for the infrastructure analysis special focus was put on the early phase of infrastructure build-up until 2030.

3.3.1 Pathway selection through member state workshops

The pathways analysed in the infrastructure analysis are based upon the portfolio of hydrogen production pathways as selected by the stakeholders at the various workshops at member state level. Out of a common set of hydrogen production pathways, the stakeholders selected a number of pathways which, to their opinion, would fit best in their current and future energy system. Next, the selected pathways were further refined, in order to ensure that they match well with the country specific conditions. A more comprehensive description of the outcomes of the pathway selection process can be found in (HyWays, 2007). This report also includes an overview of the production pathways selected per member state.

3.3.2 Regional demand development for road transport

The regional demand development and infrastructure build-up for road transport is classified into three phases:

- **Infrastructure Phase I**: early start-up phase with very low hydrogen penetration (demonstration phase). A few large-scale first user centres are situated accross Europe. Technology options are selected case-by-case.
- **Infrastructure Phase II**: early commercialisation phase with three to six early user centres per country (10,000 – 500,000 hydrogen vehicles EU-wide). Possibly also a network of transit roads for commuters in and out of early user centres and between them (considered by various deployment scenarios, focus on private cars or captive fleets).
- **Infrastructure Phase III**: full commercialisation phase characterised by the extension of existing user centres, the development of new hydrogen regions and the installation of a dense local and long-distance road network until 2030.

These phases are defined by the number of hydrogen cars on European roads rather than by calendar years. A connection to the calendar years is established through the hydrogen vehicle market penetration curves introduced in section 2.3.2. For the demand development and infrastructure build-up, HyWays focussed on Phases II (10,000 vehicles, 2010 – 2015) and III (3 sub-phases: 500,000 vehicles, 2015 – 2020, 4 million vehicles 2020 – 2030 and 16 million vehicles, 2025 – 2035).

In the first snapshot (Infrastructure Phase II, 2010 – 2015), hydrogen use for local traffic and stationary applications is restricted to the ‘early user centres’. In each country, three to six areas or agglomerations have been selected based on the qualitative evaluation of a list of regional indicators, namely local pollution, cars per household, size of cars, possibility for stationary use, availability of experts, existing demo-projects, favourable hydrogen production portfolio (renewable energy sources, by-product hydrogen), customer base, regional political commitment and stakeholder consensus. The early user centres identified by the stakeholders are typically population centres, but also some less densely populated areas and islands have been considered.

For early long-distance traffic, a few ‘hydrogen corridors’ will be established which mainly serve to connect the early user centres and to permit daily commuting in their vicinity. In total, about 25,000 km of early corridors (highways) will be required to connect the European user centres and allow commuting within and linking individual countries. Early user centres and early hydrogen corridors of the 10 HyWays countries are depicted in Figure 3.2

Figure 3.2 *Early user centres of the 10 HyWays countries selected by the stakeholders from each country on the basis of regional indicator*

The transition phase (Phase III) will be characterised by a demand growth by area and intensity in the highly populated centres and further deployment of new, less densely populated centres. Besides population density in the regions and their surroundings, also purchasing power and vehicle population are considered important for the regional demand development. New hydrogen corridors will be required to link these regions and a total length of about 70,000 km may be envisaged. By the end of Phase III, approximately 16 million hydrogen vehicles will be on European roads and 85 – 100% of the population will have local access to hydrogen fuelling stations. Stationary use of hydrogen will be more restricted to dense areas and possibly remote areas with stranded renewable energy sources.

3.3.3 Fuelling station sizes and locations

The hydrogen refuelling stations will be sited in those areas where hydrogen cars are primarily driven. Therefore, the station locations will follow the regional pattern of the hydrogen cars deployment.

In a first phase (2010 – 2015) a limited number (400) of small (single-dispenser) H_2 stations will be set up to cover the early user centres. They will serve around 10,000 cars in total. In addition, 500 mostly small hydrogen stations are required to cover the motorways linking the user centres (hydrogen corridors). As the demand spreads spatially and reaches new regions (2015 – 2025) the utilisation of previously built hydrogen stations will increase and some will be upgraded to more dispensers. New, bigger stations (up to 4 dispensers) will also be built during this period. At this time the number of hydrogen refuelling stations will grow to between 13,000 and 20,000, serving up to 10 million hydrogen vehicles across Europe. For the massive rollout of hydrogen (post 2025), the same patterns as today's conventional refuelling network will gradually be reached: large stations (up to 10 dispensers), high utilisation and extensive spatial coverage.

It is foreseen that many hydrogen stations will be placed on already existing conventional refuelling stations, because there the basic infrastructure is already in place and because hydrogen retailers is expected to be linked to today’s petrol retailing players. For a given region where the hydrogen demand starts to develop (Infrastructure Phase I-II), there is no need to have as many hydrogen refuelling stations as there are conventional refuelling stations today. It is possible to maintain sufficient accessibility for the customer with only 5 to 20% of today's number of stations. This will allow the highest efficiency for hydrogen retailing and, by maximising station utilisation, will drive the hydrogen costs down. When economic conditions are improved (massive rollout of hydrogen) spatial coverage may increase to reach today's number of fuelling stations.

In the early phases, the fuel retailer will thus have to choose on which conventional station a hydrogen dispensing equipment will be placed. Criteria include economic potential (place the hydrogen station on an already high sales station to reach as many customers as possible and optimise return on investment), space for additional equipment (choose a station where space is available) and accessibility. Such large, high sales stations are usually found on cities' arterial/ring roads and suburbs rather than in the city centres; those stations could retail hydrogen first. A network of motorway refuelling stations dispensing hydrogen with a distance of 60 – 80 km between two adjacent stations will also be required to link the areas where hydrogen cars are used.

The hydrogen station locations will influence the technical solution chosen for hydrogen retailing:

- Stations in remote locations with a constant, small throughput are best suited for onsite production.
- Larger stations in rural areas, e.g. along main motorways, may also receive liquid hydrogen by trucks.
- Large stations located at the city borders may receive liquid hydrogen by trucks or gaseous hydrogen from a pipeline.
- Motorway stations with a very seasonal demand are not suitable for onsite solutions due to part load and peaking capacity issues.

3.3.4 Infrastructure build-up

The production and supply side for road transport was mainly analyzed using the MOREHyS model (Ball et al, 2007). Figure 3.3 shows the average specific hydrogen costs (including feedstock, production, transport and refuelling), and the cumulated investment in hydrogen infrastructure aggregated for all ten countries for the base case scenario.

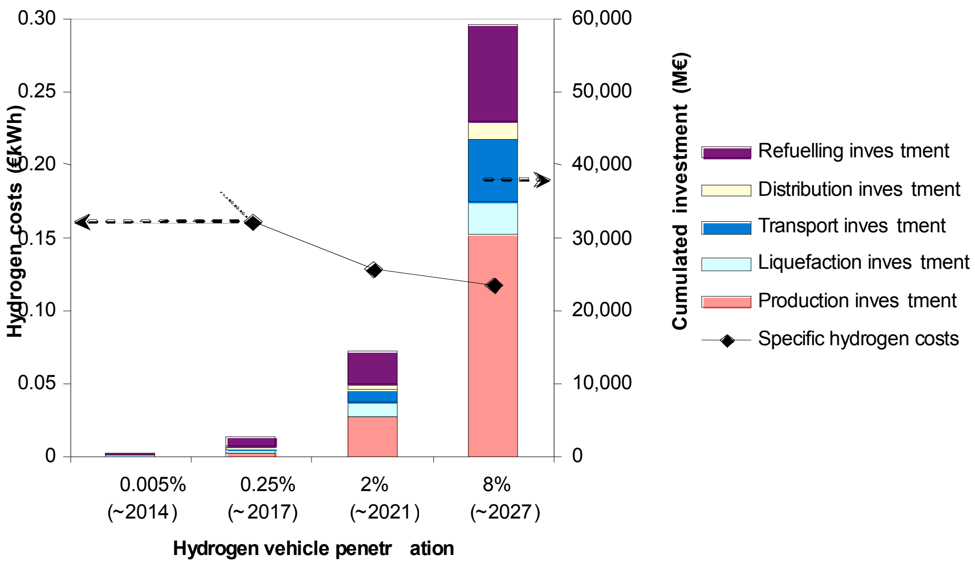

Figure 3.3 *Aggregated total hydrogen costs (base case scenario with country-specific feedstock bounds and 20% LH_2 demand at pump of filling station*

The specific hydrogen costs in the first time snapshot are high due to the required overcapacity of the supply infrastructure and high technology investments because of the early phase of technology learning. However, the cash flow analysis (see section 4.1) shows that the total economic impact of the first time snapshot is small compared to later phases due to the comparatively little turnover. It can be concluded that a gradual build-up of the infrastructure with an initial concentration on agreed user centres efficiently diminishes the often cited chicken-and-egg problem. In order to make hydrogen an attractive fuel and facilitate its deployment among the users, hydrogen supply along an early road network may be required, but this also keeps the total initial investment in infrastructure comparatively small.

Due to the fact that the transport and logistics of hydrogen for use as a chemical is a common and widely spread business which has been in place for some decades most of the populated areas as well as main transit roads can already be reached by some kind of hydrogen supply network.

These supply networks are based on four different concepts. As of today all of them are in use and also considered within the HyWays project. Subsequently these methods are described and their general characteristics pointed out with respect to an infrastructure build-up.

1. Trailers with compressed gaseous hydrogen (bundle or tube, carrying between 3,700 Nm^3 and 7,000 Nm^3 of H_2). CGH_2 trailers are used for a flexible supply of small and medium CGH_2 demand.
2. Trailer/container with liquefied hydrogen (carrying between 40,000 l (equivalent to 31,500 Nm^3) and 50,000l (equivalent to 39,000 Nm^3) of H_2. LH_2 trailers/containers are used for a flexible supply of a medium and large CGH_2 and LH_2 demand.
3. Pipelines with gaseous hydrogen (either hydrogen enriched gas or pure hydrogen). Pipelines are used for the supply of a high and continuous demand of H_2.
4. Onsite supply/onsite hydrogen production (either by reforming or electrolysis). Onsite production methods are used in areas with a lacking centralised production and supply scheme.

Long-term hydrogen costs of 0.11 – 0.16 €/kWh (3.6 – 5.4 €/kg) or 1.1 – 1.6 €/litre diesel equivalent) can be achieved. In such a full commercialization phase H_2 costs at the filling station in comparison to oil-based fuels seems to be no relevant barrier for H_2 as long as the crude oil price stay beyond 50 $/bbl or 60 $/bbl. Among others, this depends on the countries analysed, because a relevant variation of costs is observed between countries (depending on availability of feedstock, stakeholder selection of hydrogen pathways, car and population density).

Assuming that 20% of all hydrogen demand will be in liquid form, initially hydrogen delivered by LH_2 trucks has the highest share (more than 40%), see Figure 3.4. In later phases, the supply of gaseous hydrogen will gradually be dominated by pipeline transport and distribution. Pipelines for medium and large fuelling stations may become relevant once a significant market penetration of hydrogen vehicles has been achieved, but these are mostly used for local distribution in highly populated areas and for large-scale interregional energy transport. Along with the appearance of decentralised, regional production, CGH_2 truck distribution is a solution for the transition phase towards the use of pipelines. Onsite supply methods at the fuelling station from natural gas/biogas or electricity are considered over the whole period studied in areas where there is too little demand for more centralised schemes.

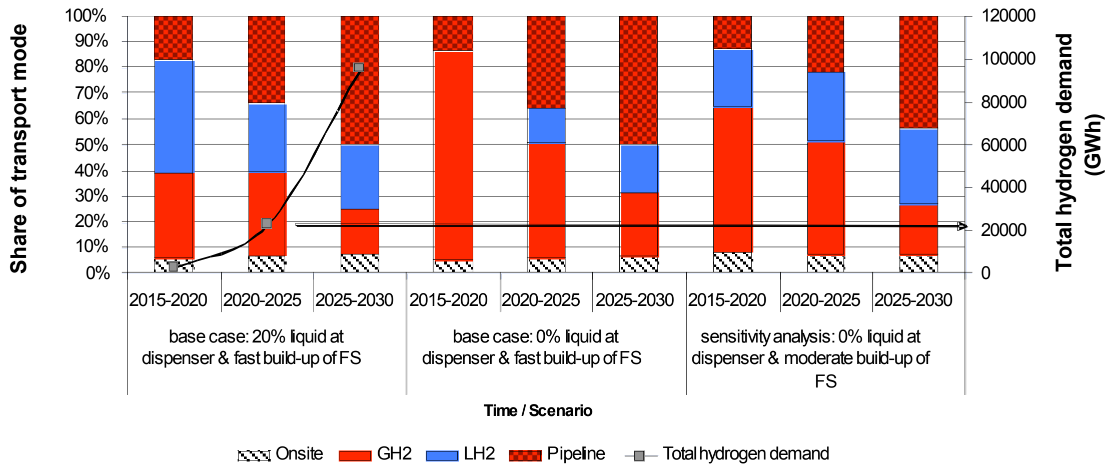

Figure 3.4 *Hydrogen transport modes*

In those less populated and remote areas, onsite supply and LH_2 transport remain the most economic choice even in later phases. in densely populated areas, practical problems such as space requirements may hinder the application of onsite technologies due to space limitations. Very low initial utilisation leads to very high specific investments for onsite supply schemes compared to central plants with higher utilisation.

Therefore, more than half of the hydrogen required may come from central production despite the high contribution of transport costs, combined with inter-regional transport in all phases. This proves that the consideration of larger regions and the interconnections between them will be important when aiming at an economically optimised build-up of hydrogen refuelling infrastructure. Well planned and distributed siting of the production plants is essential to minimise transport costs. If liquid hydrogen is not demanded at the pump (Figure 3.4, centre), gaseous trailer transport and distribution in combination with decentralised production units may be favourable at the beginning. Liquid hydrogen as transport option will become relevant at later stages when demand rises. However this may change if existing free liquefier capacity could be used.

To study the sensitivity to the fuelling station number and utilisation, a scenario with a moderate fuelling station build-up has been analysed. Here it was assumed that the fuelling stations have a higher initial utilisation and that less fuelling stations be required to satisfy the user, resulting in less dispersed and cheaper infrastructure. In such a scenario, liquid hydrogen delivery may play a relevant role already at the early stages (Figure 3.4, right).

3.3.5 Combined production of hydrogen and electricity

Next to the option to produce hydrogen through electricity with electrolysers, other direct links between hydrogen and electricity production in the power sector exist. A rapid build-up of wind power but also photovoltaic and solar thermal power electricity generating capacity is expected. Despite clear advantages (renewable, CO_2-free), the inherent characteristics of wind- and solar-generated electricity as an intermittent source lead to challenges with load levelling when capacity grows. Here, hydrogen could become one of the solutions, as it offers the opportunity to store and transport the energy. The relevance of hydrogen for energy storage needs to be analysed in further detail.

Use of hydrogen for electric energy production from fossil fuels in large centralized plants will positively contribute to achieve important reductions of CO_2 emissions if combined with CO_2 capture and storage processes. Such plants, see Figure 3.5, will also help to increase diversification of resources since a variety of fossil feedstocks, including resources such as coal and waste that otherwise cause major impacts on the environment, as well as biomass can be used as fuel.

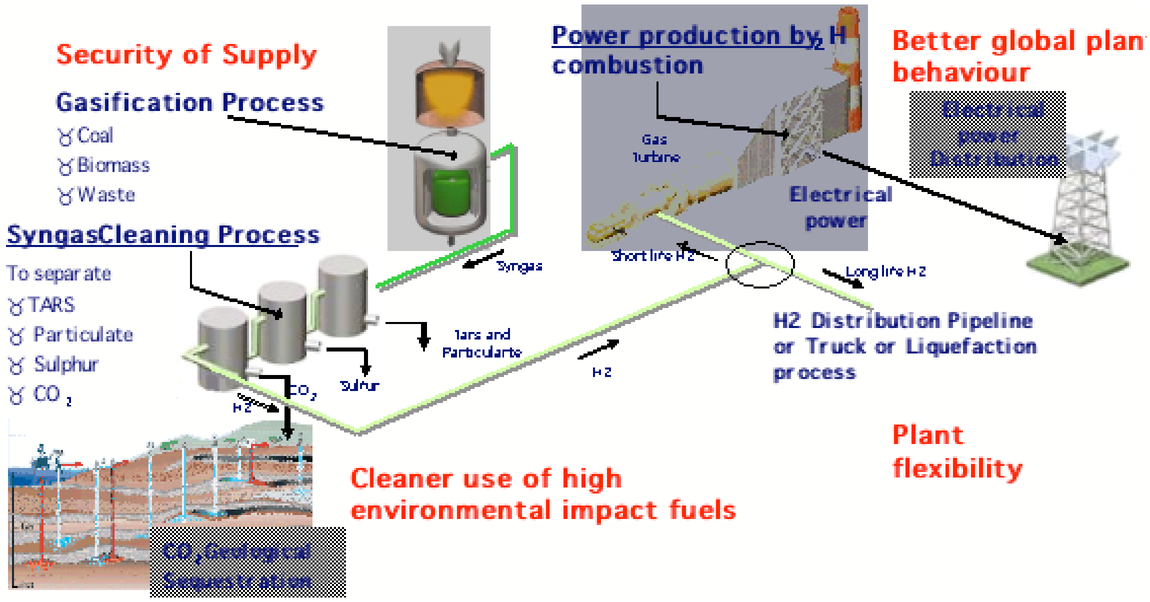

Figure 3.5 *Combined production of hydrogen and electricity*

Nowadays different processes (steam reforming, autothermal reforming, partial oxidation) are available and their technologies are commercially mature for hydrogen production from natural gas. These processes have to be combined with CO_2 capture and storage (CCS). A power plant that combines electricity and hydrogen production can be more efficient in comparison to retrofitted CO_2 separation systems.

Conceptually these plants could be designed to deliver only hydrogen, only electricity through combined cycle plants or a mix of both. They offer a way to use fossil fuels without paying tribute to climate change. At the same time energy supply security is improved, as a result of the diversification of (fossil) feedstock options.

The main risk lies in the potential failure of permanent underground storage of CO_2. This requires that special attention be paid to demonstrate economic and technical feasibility of such processes and the availability of sites to sequester virtually all CO_2 produced. CCS technologies extends the time available to develop a full and durable solution for a sustainable power and fuel provision.

The use of hydrogen in electricity production will broaden the sectors where such a carrier can be used in a sustainable way. It will provide the opportunity to utilise the advantages offered by hydrogen as demonstrated in the transport sector, enabling the power sector to diversify its feedstocks with very low CO_2 emissions.

3.4 Hydrogen production mix

In this section, the hydrogen production mix is described. First, results are given based on the visions developed by the 10 member states that have participated in HyWays. Next, a sensitivity analysis is carried out to identify the effect of key parameters. All results presented in this paragraph are based on the scenario 'high policy support, high technological learning'. The production mix refers to the demand for both transport and stationary end-use applications.

3.4.1 MS-visions

The hydrogen production mix is based on the inputs generated by over 50 workshops conducted in the 10 member states that participated in HyWays. In a first step, the stakeholders have selected the hydrogen energy chains that in their opinion could play a major role in their country, see also (HyWays, 2007). In this selection process, both stakeholder preferences and country specific conditions, such as availability of resources and the potential to sequester CO_2 as well as the characteristics of the current and future energy system, were taken into account. The stakeholders were given the ability to set minimum and maximum shares for (some of) the hydrogen energy chains.[11] As a result, a rather diversified hydrogen production mix has been found for the 10 member states, see Figure 3.6, reflecting the inhomogeneous conditions in Europe quite well. In Figure 3.6, the resulting hydrogen production mix is given. Interactions with other parts of the energy system with respect to constraints in resource availability (e.g. biomass) and the restriction on total capacity of nuclear energy have been taken into account, see also section 3.1.

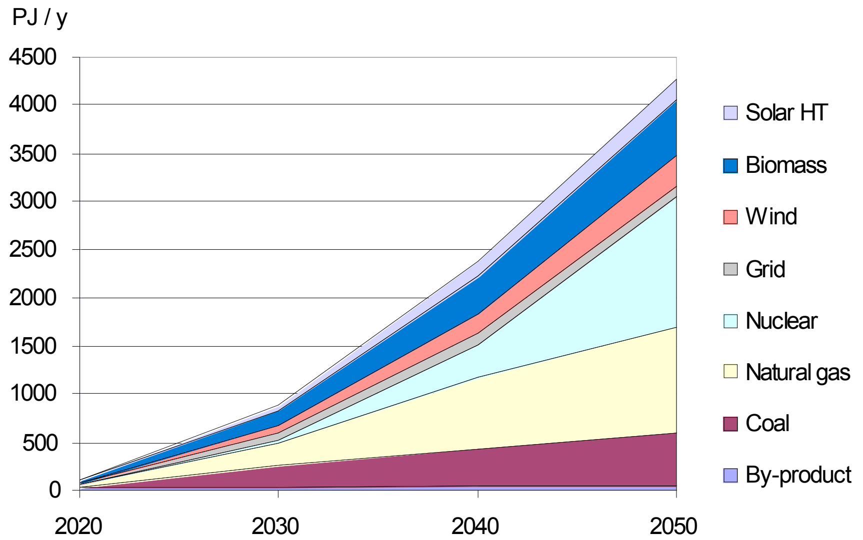

Figure 3.6 *Hydrogen production mix for the 10 HyWays countries based on the visions developed in the MS workshops*

Natural gas, biomass and wind energy based pathways have been selected by all member states participating in HyWays. Nuclear energy based pathways were selected in France, Finland, Spain, Poland and the UK. For Finland, France and Norway, coal (and lignite) based hydrogen pathways were excluded.

HyWays has considered hydrogen produced from both on- and offshore wind energy.[12] Given the constraints imposed by the member state visions on the development of a future hydrogen system in their country, the share of renewable resources in the production mix is about 1/3 by 2050. Natural gas, coal mainly equipped with CCS and (after 2030) nuclear energy based pathways play a significant role in the hydrogen production mix.

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[11] The MARKAL model that is used to calculate the hydrogen production mix is a so-called optimisation model that determines the least-cost solution. In case of no constraints, such as limitation in resource availability, are implemented, the energy chain with lowest cost will obtain the full market share.

[12] Even though all production options that produce electricity (including wind energy) are connected to the electricity grid, ‘grid electricity’ as such is a concept that is non-existent in the models. A change in electricity demand, i.e. due to the introduction of electricity based hydrogen production pathways, causes a change in the power sector. In case of an increase in electricity demand, the model responds by building additional capacity in the power sector. The impact on emissions from the introduction of hydrogen into the energy system is therefore determined by the emissions origination from the additional capacity in the power sector needed to meet the additional demand. The characteristics of the additional capacity may deviate strongly from the average characteristics of the power sector at that point in time. Calculation of the impact of hydrogen based on the average characteristics of the power sector (grid electricity) is therefore misleading.

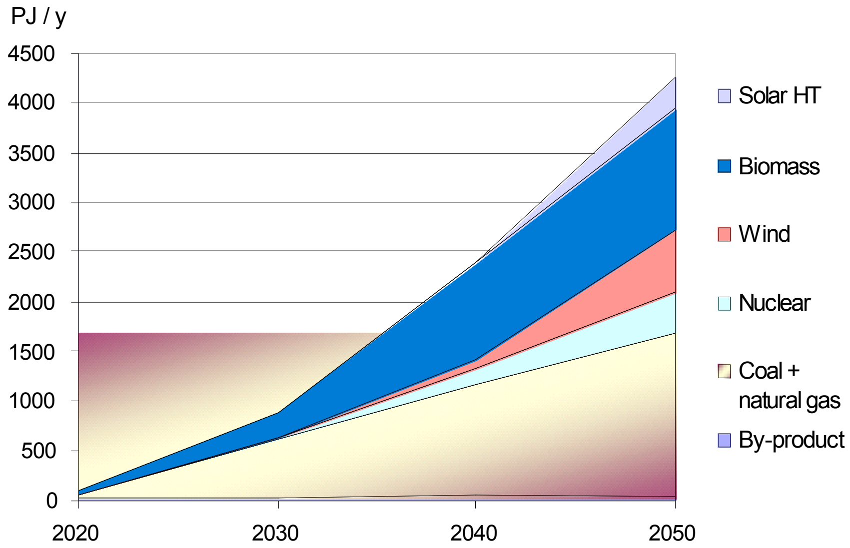

Figure 3.7 *Least-cost solution for the hydrogen production mix for the 10 HyWays countries based on the hydrogen pathways selected by the stakeholders*

As a next step, the least-cost solution was calculated based on the pathways selected by the member states but ignoring the minimum and maximum shares that were set by the stakeholders on some of the pathways, though taking into account constraints on resources (see section 3.1). The results are shown in Figure 3.7. A sensitivity analysis on energy prices did show that the share of coal vs. natural gas is very sensitive to changes in the relative price of these energy carriers. Therefore, the natural gas and coal based pathways are not shown separately. In comparison to Figure 3.6, the share of renewables in the hydrogen production mix in 2050 is substantially higher and the share of nuclear energy is substantially lower. Wind energy enters somewhat later in the production mix but reaches a higher share in 2050. This can be explained by the fact that first the price of wind electricity has to drop sufficiently, due to technological learning, before the technology becomes cost competitive as a source for hydrogen production. As soon as it reaches this phase, the market share increased rapidly.

3.4.2 -80% CO_2 reduction target

The results shown in section 3.4.1 are based on a CO_2 emission reduction target of -35% over the period 1990 – 2050, see also section 3.2. Within the sensitivity analysis, also the impact of a -80% reduction target is explored, see Figure 3.8. When compared to Figure 3.7, the share of natural gas + coal and nuclear energy based pathways in 2050 is about the same. However, in this scenario, there is a strong competition for biomass. Most of the biomass resources are used in parts of the energy system which have limited to no (renewable) alternatives. Examples are the use of feedstocks in industry and the need to switch to biofuels for the part of the transport sector that does not change to hydrogen, such as heavy duty trucks and long distant coaches. After 2040, the hydrogen production pathways based on wind electricity become cost competitive and take over the role of biomass. Before 2040, the reduced availability of biomass for hydrogen production is compensated for by an increase in the share of ‘coal + natural gas’ based pathways.

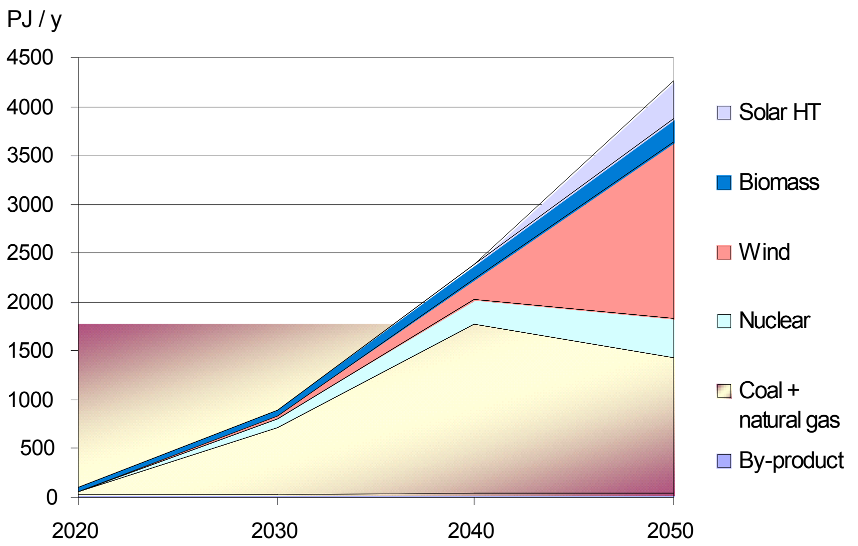

Figure 3.8 *Hydrogen production mix for the 10 HyWays countries at a -80% CO_2-emission reduction scenario*

3.4.3 Failure of CCS

Carbon capture and storage (CCS) is a key technology for hydrogen production pathways based on fossil fuels. The technology has not yet proven its capability at very large scale. Given the significant role it does play in a number of the scenarios, the impact of a failure of CCS is investigated as part of the sensitivity analysis. A potential failure of CCS not only has an influence on the hydrogen production pathways, it also influences the power sector to a large extent. Since a CO_2 emission constraint of -35% has to be met by 2050, the share of nuclear energy and biomass in the power sector increases severely whilst the share of fossil fuel decreases considerably. Given the constraints on total biomass availability and total capacity of nuclear energy[13], this strongly influences the contribution of nuclear and biomass based pathways for the production of hydrogen.

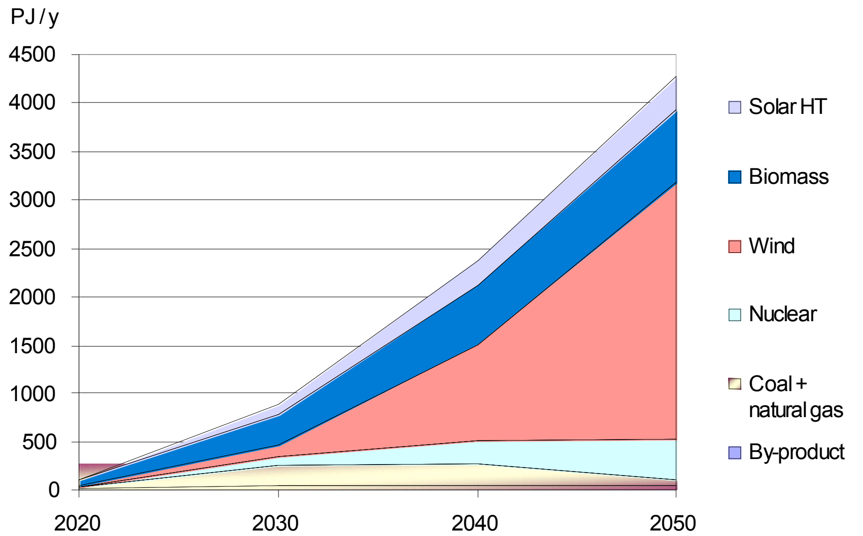

Figure 3.9 *Hydrogen production mix in a scenario where failure of CCS is assumed*

[13] It is assumed that the total nuclear capacity is limited. In a number of scenarios, such as "failure of CCS" and "-80% CO_2 emission reduction", the demand for low carbon production technologies in the power sector is very high. The model results show that in this case, nuclear power is utilised (close) to its full potential in the power sector and is not to hardly available in order to meet the additional electricity demand due to the introduction of hydrogen (via electrolysis based pathways).

In Figure 3.9, the hydrogen production mix in case of a failure of CCS is shown. Since most biomass resources and the nuclear capacity are utilised by the power sector, hydrogen production from wind energy does become the preferred option. Due to the CO_2 emission reduction constraint, fossil fuel based pathways - in this case without CCS - do play a marginal role. The total amount of wind capacity needed to meet the hydrogen demand is very large. Also in the power sector, wind energy is applied. For hydrogen production, about 220 GWe of wind energy is needed in this scenario. This is substantial, but within the range that is considered potentially feasible for 2050 (EWEA, 2006; Hoogwijk, 2004; DLR, 2004; Weindorf, 2006). It should be noted that we are dealing here with a very extreme case. In reality, one can expect that in an extreme scenario like this, the baseline development will be influenced significantly (e.g. decrease in energy demand or an increase in nuclear capacity[14]). The sensitivity analysis shows that in case of a failure of CCS, the energy system can still meet the reduction target, but only by utilising potentials of carbon free sources to its maximum.

3.4.4 Impact of energy prices

In the baseline scenario, the oil price does increase to about 110 $/bbl in 2050, see section 3.1.[15] In a sensitivity analysis, the oil price was varied. Renewable energy based pathways then become competitive after 2030, suppressing the fossil fuel based pathways. For both 2030 and 2050, the hydrogen production mix strongly resembles the production mix as found for the case where a failure of CCS was assumed, see section 3.4.3. Again, nuclear energy and biomass are used to almost their full potential in other parts of the energy system. Due to the high energy prices, wind energy has become cost competitive as a hydrogen production option by 2030, i.e. before the hydrogen demand starts increasing rapidly, gaining a dominant market share in the long term hydrogen production mix. In the case of very low energy prices for fossil fuels, the hydrogen production mix is dominated by fossil fuel based hydrogen production pathways, with renewables slowly growing in the long term. Sensitivity analysis has been carried out on different future electricity mixes for Europe. Depending on the way electricity will be produced the level of competitiveness of hydrogen may vary. In an established hydrogen energy market intermittent renewable energy overcapacity can be used to produce hydrogen.

3.5 Impact on CO_2 emissions

The impact of hydrogen on CO_2 emission is determined by both the penetration rate of hydrogen end-use applications, see section 2.3, and the way hydrogen is produced, see section 3.3.5.

Road transport

Within road transport, passenger cars, light duty vehicles and city buses gradually shift to hydrogen. In the scenarios with high learning, about 50% of the demand in road transport in 2050 is covered by hydrogen transport options, see Figure 3.10. The emissions shown in Figure 3.10 include emissions during the production process for hydrogen as well as petrol and diesel. In the baseline scenario, the demand for transport increases substantially (EC, 2003a), explaining the increase in CO_2 emissions until 2020. It needs to be emphasised that the development of the CO_2 emission in the baseline scenario strongly depends on the scenario assumptions. Specifically the development of the oil price and CO_2 emission reduction targets and targets for (minimum shares) of alternative motor fuels are key parameters, see also section 3.1 and 3.2. By 2050, total CO_2 emissions are 10% below the emission level in 1990 in the baseline scenario. As a result of the introduction of hydrogen, total CO_2 emissions from road transport for the 10 member states analysed in HyWays decrease impressively by about 350 Mton by 2050 ('high learning scenario'), reducing emissions by 55% – 60% compared to the

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[14] Total increase of nuclear capacity is restricted.

[15] Prices of natural gas and coal are assumed to be coupled to the oil price.

baseline scenario. This is about twice as high as the overall CO_2 emission reduction constraint. In the scenario with modest policy support and modest learning, total CO_2 emission in 2050 decrease by slightly over 30%.

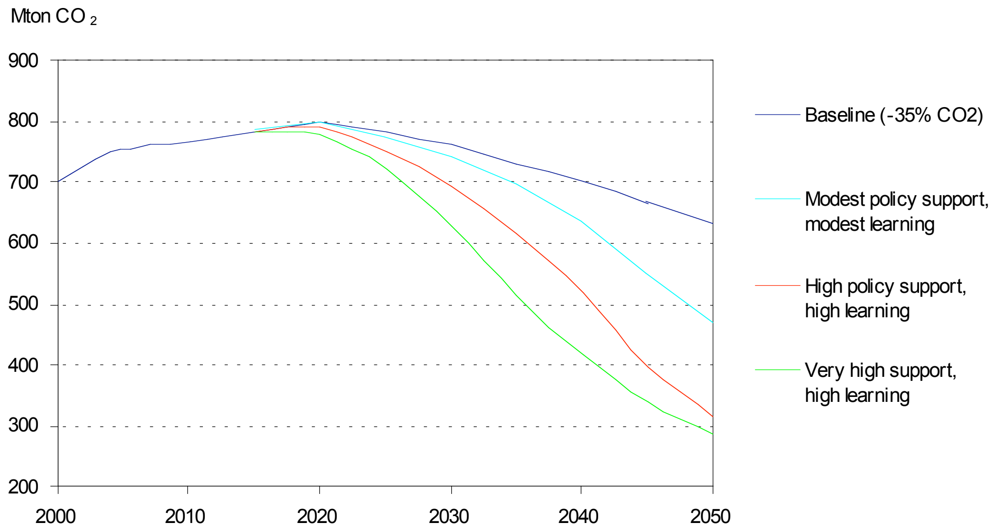

Figure 3.10 *Development of total CO_2 emission for road transport for the 10 member states analysed in HyWays*[16]

Stationary end-use applications

For stationary end-use applications, two penetration scenarios are assumed, see 2.3.3. In stationary end-use applications, hydrogen can play a relevant role in niche markets and remote areas. The penetration in the remaining part of the residential and tertiary sector is slow, a.o. due to the very low replacement rate of the existing infrastructure. The total impact on CO_2 emissions as a result of the introduction of hydrogen in stationary end-use applications amounts to 25 – 50 Mton per year in 2050.

3.6 Impacts on non-CO_2 emissions

The large deployment of the use of hydrogen in the transport sector (cars, light duty vehicles and city buses) has a significant impact on the reduction of atmospheric pollutant emissions. Emission reduction of pollutants is one of the main drivers for the first introduction of hydrogen in such market. A detailed description of the methodology used to quantify the impact on non-CO_2 emissions is given in (Mattucci, 2007).

In the baseline scenario, local pollutant emissions are generally decreasing due to more severe legislations on exhaust emissions of vehicles. Two new EURO legislations (V and VI) have been added for cars and light duty vehicles to consider that more stringent requirements on vehicle emissions can be imposed by the European Commission. Legislation reduces the acceptable levels on pollutant emissions (EURO V, EURO VI) and imposes limitations in fuel consumption (EURO VI) as result of voluntary agreements between car manufacturers and the EC, Kyoto protocol and post-Kyoto initiatives to counteract climate changes. The new regulations are assumed to be in place by 2010 and 2015 respectively. No pollutant emissions have been considered for hydrogen internal combustion (ICE) vehicles due to the lack of information on the specific emissions of NO_x from these vehicles. This latter assumption is not critical, considering that for road transport the main share will be taken by fuel cell vehicles, whose emissions are zero. Moreover, by means of specific devices (catalysts) NO_x emissions for hydrogen fuelled ICE vehicles can be minimised.

[16] The baseline figures for road transport (light and heavy duty vehicles) are based on the EC-study *Energy Trends 2030* (EC, 2003a) with some modifications on the growth rate, see section 3.1.

The impact of an introduction of hydrogen in road transport has been assessed for three domains; urban, extra-urban and highway. Therefore, specifically the impact in heavily polluted areas is taken into account, since highest concentration and therefore highest impact on health occurs in densely populated areas, such as the urban ones. Projections of emission levels are made for all pollutants (CO, NO_x, PM, VOC, etc.) as well as for fuel consumption and CO_2 and other greenhouse gas emissions at the point of use.

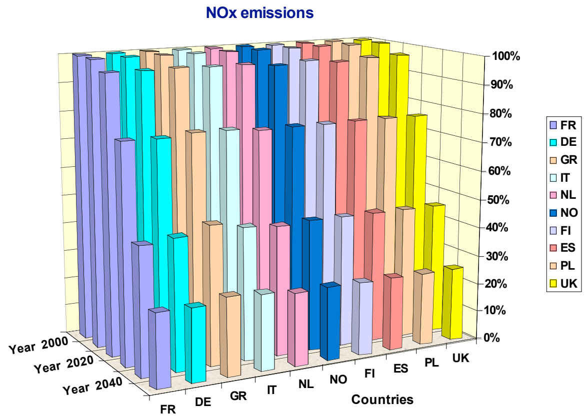

Figure 3.11 *Impact on NO_x emissions as a result of the introduction of hydrogen in road transport*

An indication of the environmental effects of hydrogen deployment for each of the 10 member states is given in Figure 3.11, which shows the total NO_x emissions for the high policy support scenario. Similar trends are found for other pollutants. The data are normalised with respect to the baseline and show similar trend for all the member states with a reduction of more than 70% by 2050. The results are averaged per country. On local level, higher reductions can be achieved if also non-technical measures, such as limitation of city centre access for non-zero emission vehicles, are taken into account.

4. Economic impacts

In this chapter, the economic effects of the introduction of hydrogen into the energy system are presented. First, results of a cash flow analysis is presented, followed by an analysis of impacts on employment and a section on cost-effectiveness of hydrogen as a CO_2 emission reduction option. The chapter concludes with a description of the impact on economic growth.

4.1 Cash flow analysis - additional costs and savings through hydrogen

Hydrogen production and supply as well as hydrogen vehicles will in early phases be substantially more expensive than conventional fuels and vehicles they replace. On the other hand, conventional transportation fuels are very sensitive to increasing fossil fuel prices, which hydrogen is primarily not, and moreover hydrogen vehicles consume less fuel. Furthermore, due to technology learning, the costs of fuel cell vehicles will gradually decrease to a level comparable to conventional vehicles (see section 2.2). Therefore the initial additional costs for hydrogen infrastructure and vehicles are expected to turn into savings. This is investigated and confirmed by a cash flow analysis comparing the expenses for hydrogen production and supply and vehicles with the savings gained from replacing conventional fuel and conventional vehicles over time. The penetration and infrastructure scenarios explained in section 3.3 are the basis for the cash flow analysis, as well as the assumption that each hydrogen vehicle substitutes a conventional vehicle.

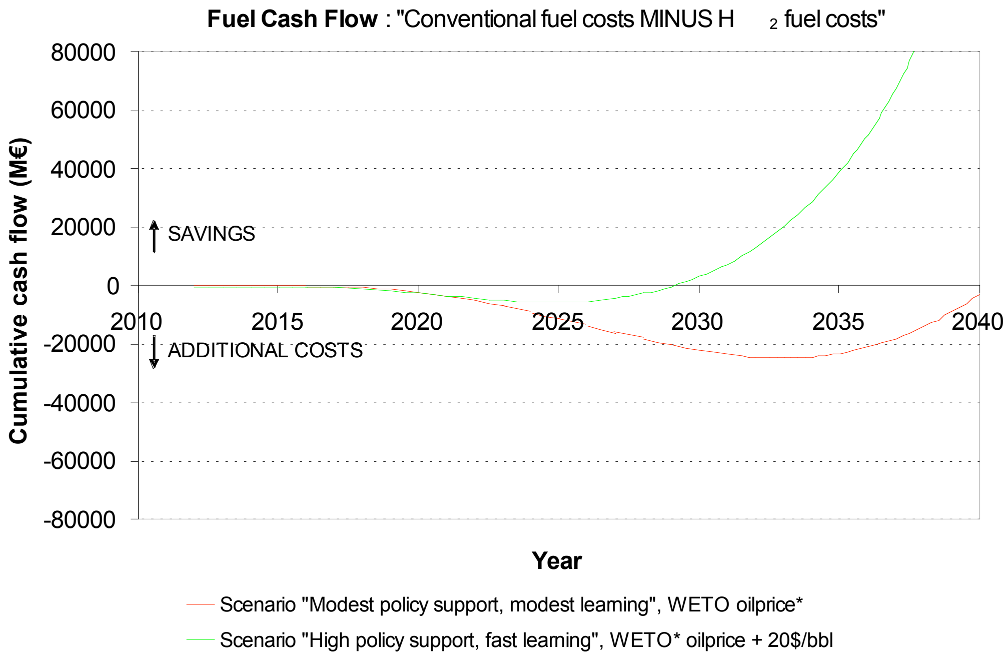

Figure 4.1 *Fuel cash flow (total costs of hydrogen for an increasing vehicle fleet versus costs saved on conventional transportation fuels)*[17]

Figure 4.1 shows the cumulative fuel cash flow for all hydrogen used as transportation fuel in comparison to the use of conventional fuel (the zero line represents the cash flow for using conventional fuel). Two extreme scenarios are shown; one with modest policy support modest learning, and WETO oil prices, and one with high policy support, fast learning, and higher oil prices (WETO + 20 $/bbl), see also Figure 3.1. These extreme scenarios give the bandwidth for

[17] Assumptions on the development of the oil price are given in Section 3.1.

the other calculated scenarios. Depending on penetration scenario and oil price development, the break-even is reached between 2025 and 2035 and the costs will be reimbursed between 2030 and 2040. At the point where the curves are horizontal (2025/2033), the hydrogen fuel costs per km break even with conventional fuel. At the point where the values turn positive (2028/2040), the initial additional costs for hydrogen have been balanced and from this point on, hydrogen leads to savings. Furthermore it can be seen that the high specific hydrogen costs in the early phase do not cause high economic losses; in fact the period after 2020 is the most costly with still significantly higher costs for hydrogen than for conventional fuels despite the already high vehicle penetration.

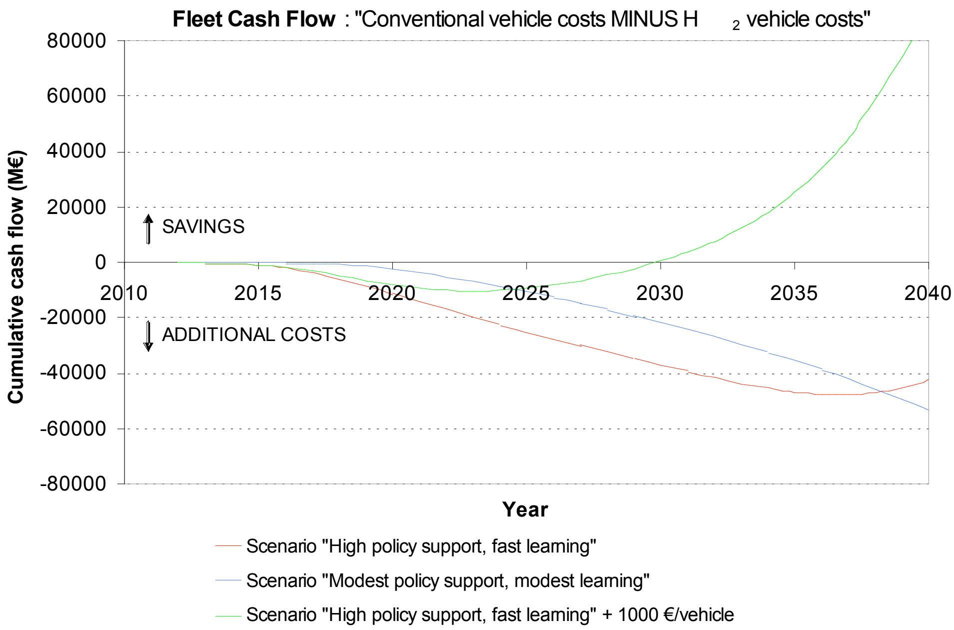

Figure 4.2 *Fleet cash flow (total costs of hydrogen vehicles for an increasing vehicle fleet versus costs saved on conventional vehicles)*

Figure 4.2 shows the cumulative fleet cash flow for all hydrogen vehicles in comparison to the use of conventional vehicles for two extreme scenarios (the zero line represents the cash flow for using conventional vehicles). Both curves are based on the scenario with high policy support and fast technology learning. As a result, hydrogen vehicles break even with conventional vehicles by 2036 (red line). The green curve shows the cash flow under the assumption that the price of a hydrogen vehicle is € 1,000 higher than that of a conventional vehicle. Arguments for such a difference may be the willingness of the user to pay more for a clean and silent vehicle or subsidy measures argued by an internalisation of external costs. The analysis of external cost studies in the transport sector leads to the following conclusions: external costs of the transport sector could be relevant, but the uncertainties about the level of external costs are high. However, hydrogen drive systems have the potential to reduce the external cost in the field of climate change and local air pollution (particles, NO_2, SO_2). Furthermore, hydrogen fuel cell cars will remarkably reduce transport noise in urban areas. Based on the average cost figure of external costs for an average vehicle (see Figure 4.3) the internalisation of external cost will lead to a cost advantage of € 1,000 to € 1,500 per hydrogen vehicle compared to a conventional vehicle.

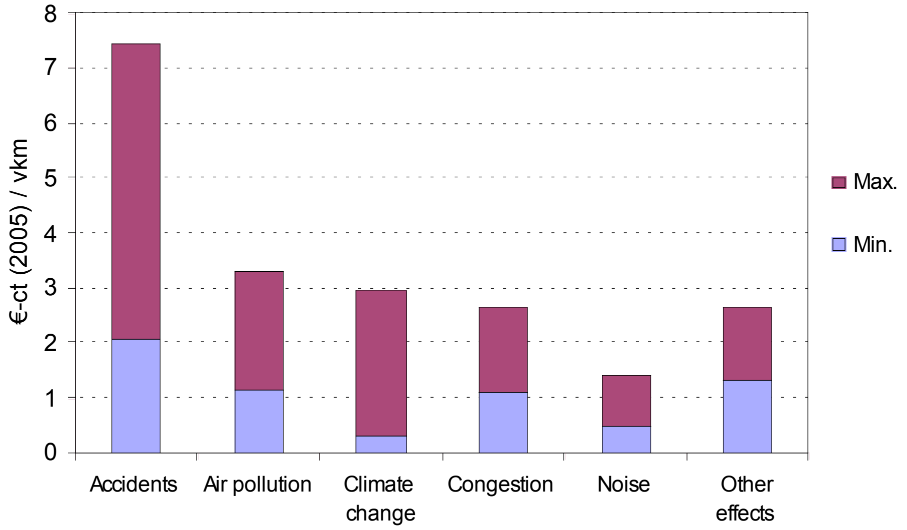

Figure 4.3 *External cost for passenger vehicles in EU15 (Data sources: Nash et al. (2003), Maibach et al., (2004 and 2007a, 2007b), DOT (1997), VTPI (2007); data has been processed to 2005 Euros by average price indices and exchange rates 2005*

Only a very limited number of willingness-to-pay studies for hydrogen vehicles exist. The results of such studies have to be treated very carefully because empirical results show that a relevant discrepancy between willingness-to-pay analyses and real market decisions exist. Nevertheless, based on the study from J.D. Power and Associates (2003) a consumer is willing to pay approximately 600 $ more for a fuel cell vehicle than for a conventional car.

Similarly, today users are willing to pay more for a diesel car than for a gasoline car, and some countries already grant € 1,200 or more for cleaner or more efficient vehicles. With this affirmation, hydrogen cars may break even with conventional cars already by 2023 and the additional costs will be reimbursed as soon as by 2030.

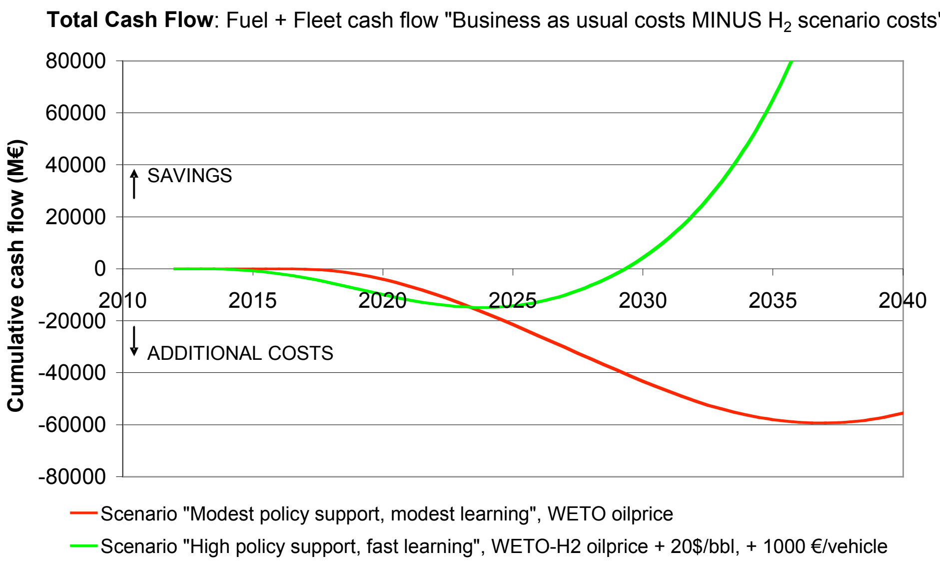

Figure 4.4 *Total cash flow (fuel and fleet cash flow))*[18]

[18] Assumptions on the development of the oil price are given in section 3.1.

The total cash flow being the sum of fuel and fleet cash flow for two extreme scenarios is shown in Figure 4.4. Depending on the framework, hydrogen and vehicles will break even with conventional fuel and vehicles between 2025 and 2035. The savings through hydrogen after reaching the break-even point can be enormous as long as the oil price remains above 50 $/bbl for densely populated countries and 60 – 70 $/bbl for less populated countries, see also Figure 3.1.

A slow market penetration of hydrogen vehicles (modest policy support, modest learning) is unacceptable both from a fuel infrastructure viewpoint (due to the long period of plant underutilisation, no investors will be interested) and the vehicle manufacturer side (too slow pay-back of R&D costs). Higher oil prices lead to increased conventional fuel costs and earlier break-even and back payment of the H_2 fuel infrastructure expenses. A higher H_2 vehicle penetration rate (through policy support) reduces negative cash flow and advances break-even and back payment both for hydrogen infrastructure and vehicles. A surcharge of € 1,000 per hydrogen vehicle accepted by the user or a subsidy helps to diminish the negative fleet cash flow strongly.

4.2 Employment effects

The structure of the investments necessary for the use of hydrogen as an energy vector is clearly dominated by the expenditure on hydrogen vehicles (see the cash flow results in section 4.1). If a hydrogen vehicle is imported, it is very likely that not only the hydrogen drive system will be imported but the whole vehicle instead. Therefore the structure of the domestic vehicle industry turned out to be one of the key factors for the employment analysis, but also for GDP (see section 4.3). A comprehensive description of the analysis on employment effects can be found in (Wietschel et al., 2007).

Three import/export scenarios have been analysed. Each scenario describes a possible future for the competitiveness of hydrogen technologies produced within the EU. The so-called 'Structural Identity Scenario' is based on the assumption that the international competitiveness of domestic hydrogen technologies is mainly influenced by today's competitiveness of industrial sectors producing goods which are very similar to hydrogen technologies. For example, if a country makes and exports conventional cars, this country is likely to do so in the future as well for hydrogen vehicles. These assumptions are weak because today's domestic industry based on conventional technologies does not automatically bring about a leading position for hydrogen technologies in the future. For example, if a country has the current manufacturing capacity to develop conventional internal combustion engines this does not necessarily entail a relevant industry for stack production in the future as technological differences between the products are eminent.

The 'Pessimistic Scenario' shows what could happen if other world regions achieve a leading position and Europe needs to import a larger share of hydrogen vehicles. In this scenario it was assumed that all hydrogen vehicle technology will be imported (see Figure 4.5). In contrast, the 'Optimistic Scenario' assumes that major efforts will be undertaken which result in in-creased EU exports in hydrogen vehicles and technologies.

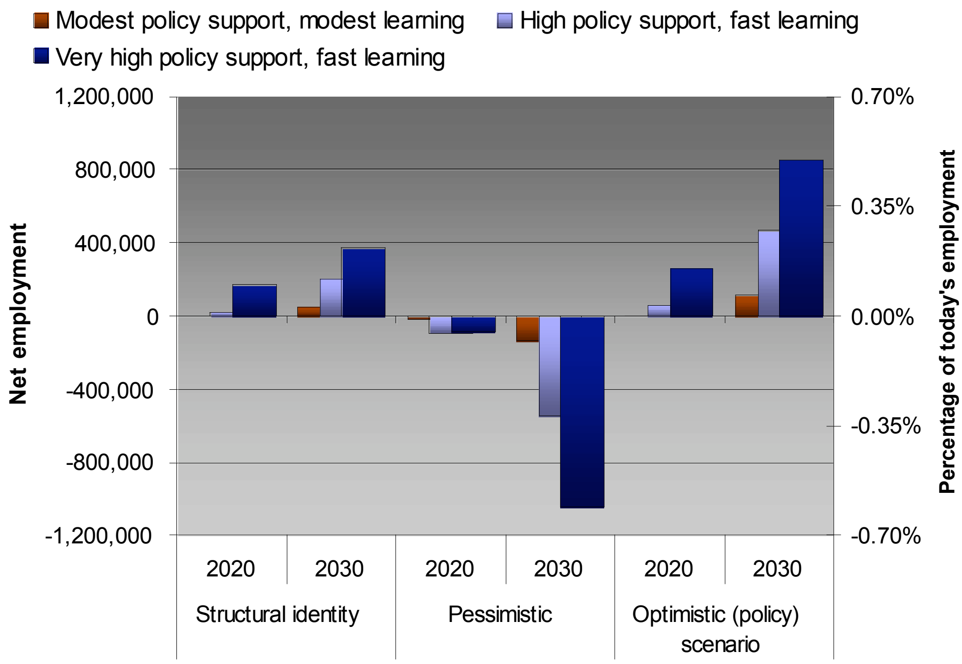

Figure 4.5 *Net employment effects for the ten HyWays countries*

Figure 4.5 shows the employment development for the ten countries analysed. Small gains can be achieved if the import/export shares for H_2 technologies are similar to conventional technologies. This result is mainly influenced by a lower automation and standardisation level for hydrogen technologies in the start-up phase. However, the same level of competitiveness as for conventional technologies must be reached on world markets first. When looking upon the results of the lead market analysis, this will be a challenging task.

The largest direct effects on employment resulting from the transition to an economy incorporating hydrogen energy are seen for the automotive industry, and to a lesser extend for the process and equipment industry. Countries in Europe with high car production intensity will need to face the following dilemma. On one hand, job losses (up to 0.7% in 2030 for the Pessimistic Scenario) could be drastic if these countries were to lose market shares due to late market entry. On the other hand, uncertainties regarding the market success of H_2 cars remain and the potential risk of losing several billion Euro due to investments in premature H_2 infrastructure and H_2 car development. Specifically France, Germany, Spain, the UK and Italy are vulnerable for this dilemma situation. Similar conclusions can be drawn for the process and equipment industry. Mainly Germany, Italy and France are affected here.

Compared with large automotive countries, the economic risks of a hydrogen economy are much smaller for the Netherlands, Norway, Finland, Poland, and Greece, but also promise significant increases in employment if the right strategy should be pursued.

Replacing conventional vehicles by FCVs induces a sectoral employment shift away from traditional automobile manufacturing among others to the fabricated metal, electrical, machinery and rubber/plastic sectors. Preparing for the expected mass production makes early political action essential taking the required gradual build-up of manufacturing capacity and hence a skilled labour force into consideration.

4.3 Impacts on economic growth

HyWays has identified that the overall impact on economic growth (GDP) as a result of the introduction of hydrogen into the energy system will be small. The most important factors determining the impact on economic growth are net changes in the expenditures for transport services (in case of road transport) and changes in the energy bill (hydrogen fuelled micro-CHP in the residential and tertiary sector) and import/export shares in Europe, see also section 4.2. The analysis within HyWays shows that, hydrogen end-use applications do become cost-competitive in time, implying that e.g. a household needs to spend less money for transport needs. These (small) savings can be spent on other activities, leading to small positive impacts on economic growth. The development of cost reduction of the drive train of the hydrogen vehicle has, by far, the strongest impact on expenditures. Besides the fact that net changes in expenditure patterns are small, also the fact that hydrogen is introduced in only part of the energy system explains the relative small GDP impacts.

Assuming no changes in the import/export shares for Europe, see also section 4.2, small positive effects on GDP are found for most countries analysed within HyWays (Jokisch et al., 2007).[19] As a result of the introduction of hydrogen, GDP in 2050 is on average 0.3% higher, corresponding to an average increase in GDP growth of about 0.01% per year. In a worst-case scenario, where hydrogen end-use applications do not reach a full cost-competitive stage, the negative impact on economic growth is very small.

The total cumulative costs to reach the break-even point are in time compensated by the gains when the hydrogen technology becomes cost-competitive in comparison to both the reference technology as well as competing options, see also section 4.1. For the economic impact, the fact that hydrogen technologies become cost-competitive is the key factor. Whether the additional costs are covered directly by the end-user or indirectly through financial schemes is of no consequence with respect to the impacts on GDP, provided that the transaction costs for the support schemes can be ignored. In the end society has to pay to overcome the initial cost hurdle. Total cumulative costs are independent of the way they are financed. Also in the case of a governmental support scheme, society / the end-user will in the end have to pay for the total cumulative costs. A detailed outline of policy instruments for the support of hydrogen is given in the HyWays Action Plan (HyWays, 2007a).

Even though impacts on GDP growth are small, hydrogen is introduced in a sector that is vulnerable to price shocks and high oil prices. Although hydrogen itself is decoupled from the influence of high oil prices that poses a likely benefit, this aspect is not incorporated in the calculation of impact on GDP due to the nature of the models used. Given the current vulnerability of conventional transport to oil price shocks, this effect may even outweigh the economic benefits of the long-term reduction of costs for transport due to the introduction of hydrogen. Transport is a key factor in ensuring economic stability. If alternatives to oil are not introduced at sufficient pace, economic growth may seriously be hampered. Studies indicate that due to price shocks of about 5 –10 $/bbl, GDP growth of oil-importing countries may (temporarily) be reduced by 0.2% –0.4% per year[20] (IMF, 2006; IEA, 2004; Greene, 2005). Structural high oil prices are likely to have impacts on GDP in the same order of magnitude.

The analysis performed by HyWays shows that the impact on GDP growth is small for all cases. The slight decrease in GDP growth in a worst-case scenario is by no means comparable to the potential threat of major disruptions in oil price. It is therefore concluded that hydrogen can play a key role in ensuring economic stability in the transport sector.

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[19] In comparison to a baseline without hydrogen.

[20] Percentage point.

4.4 Cost effectiveness of CO_2 emission reduction

In the baseline scenario, the marginal abatement costs[21] increase to over 100 €/ton of CO_2 in order to meet the -35% CO_2 emission reduction goal. As a result of the introduction of hydrogen into the energy system, the marginal abatement costs decrease by 15% – 30%, see Figure 4.6. This means that, in time, hydrogen does become a cost-effective emission reduction option, lowering the costs of meeting future CO_2 emission reduction targets. Comparable results are found for a -80% CO_2 reduction target implementation by 2050.

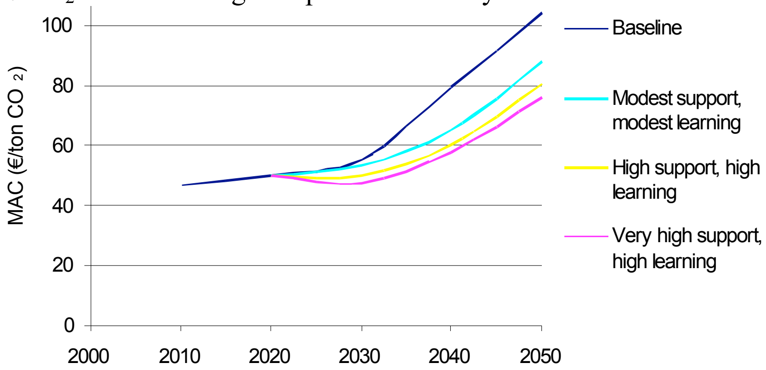

Figure 4.6 *Development of the marginal abatement costs (MAC) for CO_2 reduction for the whole energy system*

The actual benefits with respect to emission reduction is underestimated, since only the benefits with respect to reduction of CO_2 emissions are taken into account. The introduction of hydrogen also reduces emissions of other pollutants (CO, NO_x, PM, VOC, etc.), see section 3.6. The economic benefits may be substantial since they occur in densely populated areas with highest pollution level. Further research on this topic is recommended. It is not possible to predict using marginal abatement costs when the initial costs needed to make hydrogen cost effective will be reimbursed. This question can be answered by means of a cash flow analysis, see section 4.1.

[21] The costs (€) to reduce one additional unit (ton) of CO_2.

5. Implications for research

5.1 Research priorities

For a smooth and successful introduction of hydrogen into the energy system, increased R&D efforts will be required, particularly in the pre-commercial phase up to 2015. A multinational approach covering a wide diversity in terms of feedstocks, regional constraints and infrastructure related preferences and conditions will have to be considered. Hence, the R&D focus should be to overcome current obstacles, and increase the speed of technological development, in the period until hydrogen becomes commercially viable. A summary of the key targets and priorities as well as their timing is given in Table 5.1.

Table 5.1 *Summary of R&D targets and priorities*

Timeline	R&D targets	R&D priorities
→ 2010	Introduce early applications for hydrogen & FC in premium niche markets, to stimulate the market, improve public acceptance, and gain experience (EC, 2003b)	Focus on demos – Component technology development – Cost reduction – 'Lighthouse projects'
2010 – 2015	Same as above (→ 2010), but increased focus on commercial issues and public acceptance	Focus on pre-commercial applications – System integration – Market preparation – Continued cost reduction Development of international regulation, codes and standards
2015 →	HFP *Snapshot 2020*: – H_2: 4 €/kg (@ 50 €/bbl) – FC: 100 €/kW – Tank: 10 €/kWh HyWays *Snapshot 2030*: – H_2: 3 €/kg (@ 50 $/ bbl) – FC: 50 €/kW – Tank: 5 €/kWh H_2 technology is fully competitive by 2030 H_2 technology is fully sustainable by 2050	Focus on commercialization – Switch from modified conventional vehicles to purpose-built vehicles – Verify hydrogen safety and reliability – Build consumer confidence Mass market maturing

Hydrogen technology components will need to be developed, tested through large-scale demonstration projects and integrated in relevant energy systems to a fully commercial level, while creating a market demand.

Focussed R&D will be essential to overcome current barriers and reach key targets described in the HyWays Roadmap and in key documents such as the HFP Implementation Plan. Concerning hydrogen and fuel cell vehicles, key result is the necessity of further cost reductions of hydrogen drive trains. This task can only be facilitated with significant R&D funding, accompanied by well balanced deployment activities in order to ensure a fast feed-back loop from demonstration to R&D.

From a macro-economical point of view, a key issue is to bring down the hydrogen vehicle cost to the levels shown for an accumulated production of 10,000 units (see starting value of Figure 2.3). A prerequisite is the successful deployment of a European fleet of some thousand vehicles within the next 8 – 10 years through a public-private partnership, such as the JTI, and subsequently measures such as public procurement regimes as well as fleet applications. This task has been identified by the European Hydrogen and Fuel Cell Technology Platform and is fully supported by the HyWays analysis.

Important R&D areas considered for mobile and stationary hydrogen and fuel cell applications as well as for the required infrastructure are:

1. ***Obtain significant cost reduction of the H_2 drive train***
   - Improvement of PEM fuel cells (bi-polar plate, membrane, catalyst)
   - Periphery components (air supply, humidification, valves, power and control electronics)
   - Onboard storage (optimisation of currently demonstrated compressed and liquid storage systems, new technologies such as cryo-compressed or chemical metal hydrides)
   - Hydrogen ICE integration (including fuel cell APU and hybridisation)
   - System optimization (trade-off between the single subsystems to get highest performance at lowest cost)
2. ***Obtain significant cost reduction of the hydrogen production chains***
   - Electrolysers, biomass gasification systems, CCS as well as standard components and instruments such as compressors, valves, sensors etc.
3. ***System integration for hydrogen systems***
   - Integration of main components (drive train, onboard storage) and auxiliary equipment (safety equipment, valves, electronics) for hydrogen transport applications
   - Integration of main components (FC and onsite storage) and auxiliary equipment (safety equipment, valves, electronics) for stationary hydrogen applications
   - Integration of renewables and hydrogen in 'island / remote' systems, specifically integration aspects (power conversion and power conditioning) and storage (hydrides, porous adsorbents, compression)
   - Use of current low pressure grid for transport of pure hydrogen
4. ***Assure safe and reliable hydrogen applications***
   - Close current gaps in development of harmonized regulations, codes and standards for hydrogen
   - Build consumer confidence in hydrogen end use
5. ***Comply with long-term sustainability requirements***
   - Hydrogen produced from renewable energy sources, fossil fuel with CCS or nuclear pathways, i.e. without CO_2 emissions and with a closed fuel cycle (generation IV reactors)

Priorities for socio-economic research

Another important area of R&D in the next stages of hydrogen introduction is socio-economics. Sound planning is needed to continue the work which has been initiated by HyWays. HyWays's analysis has proven to be supportive in the following areas:

- To foster mutual learning between and among various levels of stakeholders: member state and country representatives, industry and the research community as well as other regional stakeholders.
- To engage in the parallel use of technical, infrastructural, ecological and socio-economic simulation and modelling tools which before have never been applied simultaneously to cover various aspects of one topical area (need of sound methodological approach, definition of clear interfaces and disciplined cooperation among institute partners) and
- To involve industry in socio-economic modelling and to learn about the use of the methods for providing answers to questions on research priorities for industry and potential of future markets.

The toolbox as developed in HyWays and the outcomes should be made available to a wide group of interested countries and EU Member States. The positive learning within HyWays-IPHE which benchmarks the European against the U.S. DoE modelling results should encourage to extend the international benchmarking towards further World regions in the next phase.

A key finding is that hydrogen is not yet sufficiently high on the agenda of policy makers. These policy makers do play a crucial role in the process of developing and implementing the required policy incentives that enable hydrogen to smoothly enter the energy system under sound economic conditions. Demonstration projects can play a crucial role in raising the awareness of policy makers. In addition, it is of utmost importance to inform the policy makers about the prospects of hydrogen, the initial barriers that have to be overcome as well as on the type, characteristics and support level of the policy framework.

In the end, the tight HyWays budget turned out to be a clear deficiency which affected the opportunity for sufficient discussions between stakeholders. These discussions were intended to provide valuable opportunities for mutual learning across barriers in industry and specifically between participating member states. Hence the involvement of member states and countries should be fostered with a sense for urgency of this issue to build on the harmonised HyWays European Roadmap.

Another specific R&D area is the impact of non-CO_2 effects on the opportunities for hydrogen energy. Internalisation of external costs, the interaction and synergies of hydrogen and the power sector (load management), the short-term relevance of local pollution abatement and other general and difficult to quantify advantages of hydrogen, such as adequacy for decentralised energy supply schemes resulting in improved level of financing of projects, need to be studied in more detail. Furthermore it is recommended that more analysis on the role and place of hydrogen technologies be carried out with regard to their alternatives, e.g. biofuel and non-fuel cell electric vehicles, taking into account national and regional aspects.

Finally, public awareness and acceptability of hydrogen in the public should be assessed and fostered more intensively by further R&D studies, involving experts from marketing. The power of this topic should not be underestimated and become an integral part of the other more techno-economic R&D topics. The results could then further on considered e.g. by the JTI.

5.2 Future targets

When claiming a public-private research, development and deployment programme for hydrogen vehicles and related refuelling stations in the order of 2.5 billion Euro in total over a 10 years time frame, sufficient proof for reaching the deployment goals as well as a monitoring tool for interim milestones are required (HFP, 2007). The HyWays Roadmap highlights two important milestones on the way to the successful commercialisation of hydrogen and fuel cell applications in transport:

- *Snapshot 2020* translates to the ‘take-off’ point of the S-curve where production volumes are increasing substantially and breaking the level of (at least) 100,000 units per year and manufacturer due to almost competitive production cost of fuel cell systems;
- *Snapshot 2030* translates to the growth phase. Hydrogen and fuel cell applications are now fully competitive and hence lead to a booming market where the growth rates reach their maximum.

When comparing these targets with the four scenarios for market penetration (see Figure 2.3) one realises that only the scenarios which combine fast learning with high or very high policy support can meet the targets of the *Snapshot 2020*. If the technical progress will be slower than actually planned but policy support could be sustained on high level, it is likely that the ‘take-off’ point of the market penetration will be postponed by approximately five years. This requires a close monitoring of the next large-scale demonstration and deployment projects in terms of their economical as well as technical performance. While the EC has already recognised this important task and established the HyLights project in order to develop a Monitoring and Assessment Framework, it is necessary to implement these monitoring activities as firm element of the JTI programme activities.

The analysis of the learning cost curves for the three scenarios with respect of the specific system cost of the fuel cell drive train are shown in Figure 5.1. below. A similar analysis was also carried out for liquid and compressed storage system and hydrogen ICE hybrid drive trains.

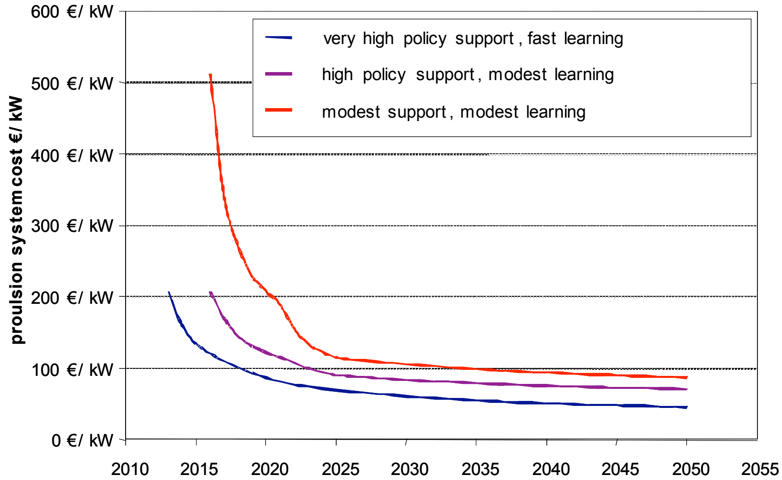

Figure 5.1 *Learning cost curve analysis for fuel cell drive train systems (excluding storage)*

For the course of target setting two considerations have been taken into account. First of all, the socio-economic as well as technical assumptions should be ambitious but still achievable under optimistic real world conditions. In addition, cost targets should be related to optimistic volumes and market conditions that match at least the magnitude of an optimistic but still possible scenario. Hence the HyWays consortium has chosen the second highest market penetration scenario 'high policy support, fast learning' as target setting scenario since it can fulfil the requirement of being ambitious but still realistic. In the case of the *Snapshot 2020* the fuel cell system cost targets of the Deployment Strategy and the Strategic Research Agenda of 100 €/kW are confirmed as displayed in the table below.

Table 5.2 *HyWays cost targets for fuel cell and hydrogen storage systems*

	'Snapshot 2020' (HFP DS & SRA)	'Snapshot 2030'
Fuel cell power train	100 €/kW	50 €/kW
H_2 storage system	10 €/kWh*	5 €/kWh

* Based on SRA: tank cost ≥ 10 times conventional (€ 125) @ 4.2 kg → ≥ 8.9 €/kWh

A comparison with the targets of the DoE Roadmap leads to the first impression of relatively weak cost targets for 2020 and 2030. However, these targets do not imply any scale-up calculations to assumed mass production figures but reflect both the technical progress as well as optimistic sales volumes in the order of at least 400,000 units sold for the EU by 2020. Consequently the approach of the integration of learning effects into the cost targets also simplifies the monitoring and resolves disputes on sensitive scale-up parameters which can dilute the strength of economical targets related to mass production already in an early phase.

The cash flow analysis (see section 4.1) shows that limited additional investment in the 2020 to 2030 time frame could be borne by the industrial and public stakeholders. When meeting the cost targets of the *Snapshot 2030*, hydrogen and fuel cell vehicles will become fully competitive and the cost for the fuel cell drive train will not be higher than for a conventional diesel powertrain. This translates to a retail price of a compact class fuel cell vehicle which was the reference class[22] of the CONCAWE/EUCAR/JRC Study in the order of 20 to 23 k€ by 2030.

[22] The CONCAWE/EUCAR/JRC Study has chosen a VW Golf 1.6 Model 2002 as reference vehicle; the retail price includes 16% VAT but no further taxes.

For a compact class vehicle, it was assessed that a fuel cell of 80 kW was required in order to meet the driving performance of the reference class, correlating to the specific cost targets displayed in Table 5.2. Based on the same assumptions, the *Snapshot 2020* leads to a retail price range of 23 – 26 k€.

In Table 5.3, a summary of the deployment phases, targets and main actions based on the Roadmap and Action Plan is provided. The targets and actions for the time-period up to 2020 have been developed together with European Hydrogen and Fuel Cell Technology Platform, see HFP, 2005a) and (HF,2007), and have served as starting point for the development of further targets and actions as outlined in the HyWays Roadmap and Action Plan. The learning curve concept has also been applied to the production technologies. Based on this and other assumptions such as energy price development and market penetration of hydrogen vehicles the infrastructure analysis (see section 3.3) and the cash flow analysis (section 4.1) show that hydrogen fuel costs at the pump of around 4 €/kg H_2 in 2020 and 3 €/kg H_2 in 2030 can possibly be reached. Also, the figures above lead to a cost-competitiveness with conventional vehicles if the oil price stays beyond 50 €/bbl in the fuel commercialisation phase of hydrogen (see section 4.1). However, strong interdependency between the hydrogen fuel cost targets, the targets of hydrogen propulsion system, and oil price need to be taken into account. E.g. higher hydrogen fuel costs will be acceptable if the oil price rises well beyond 50 $/bbl or if the hydrogen propulsion system would reach lower costs than the technology development targets in Table 5.2. Also other target figures will result if externalities are included (see section 4.1). In such a case higher costs of the hydrogen drive system and/or hydrogen at the pump will become acceptable. Due to this dependency on the oil price, the target figures given in Table 5.3 have to be treated indicatively.

Table 5.3 *Summary of the deployment phases, targets and main actions*[23] *outlined in the Roadmap and Action Plan*

	2010	2015	2020	2030	2050
Phases	**Pre-commercial technology refinement & market preparation** **Technology development with focus on cost reduction**	**Start of commercialisation**	HFP Snapshot 2020 **materialisation of first impacts** • New hydrogen supply capacities partially based on low carbon sources • improvement in local air quality • More than 5% of new car sales H_2 &FC	HyWays Snapshot 2030 **Hydrogen & FC are competitive** • Creation of new jobs and safeguarding existing jobs (net employment effect of 200,000 – 300,000 labour years) • Shift towards carbon-free hydrogen supply • More than 20% of new car sales H_2 & FC	**H_2 & FC dominant technologies high impact** • 80% of light duty vehicles & city buses fuelled with CO_2 free hydrogen • reaching more than 80% CO_2 reduction in passenger car transport • In stationary end-use applications, hydrogen is used in remote locations and island grids
Targets	**LHPs facilitate initial fleet of a few 1,000 vehicles by 2015** • PPP "Lighthouse Projects" • Increase R&D budgets to 80 M€/year • Financial support for large scale demonstration projects		Vehicles: **2.5 million of fleet** Cost **H_2: 4 €/kg (50 €/barrel)** **FC: 100 €/ kW** **Tank: 10 €/kWh**	Vehicles: **25 million of fleet** Cost **H_2: 3 €/kg (50 €/barrel)** **FC: 50 €/ kW** **Tank: 5 €/kWh**	
Required Policy Support Actions	**Develop H_2 specific support framework** • Create / support early markets • Implement performance monitoring framework • Long term security for investing stakeholders • Education and training programmes • Harmonisation of regulations codes and standards	**H_2 specific support framework** • In place before 2015 at MS level • Deployment supports, e.g. tax incentives of 180 M€/year • Public procurement • Planning and execution of strategic development of hydrogen infrastructure		**Gradual switch from hydrogen specific support to generic support of sustainability (2020 →)**	**Incentives provided through general support schemes for sustainability**
	2010	2015	2020	2030	2050

[23] The targets and actions for the time period up to 2020 have been developed together with the European Hydrogen and Fuel Cell Technology Platform (HFP), see (HFP, 2005a) and (HFP, 2007) and are used as starting point for further targets and actions outlined in this Roadmap and the HyWays Action Plan.

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