HyWays

A European Roadmap

Assumptions, visions and robust conclusions from project Phase I

Acknowledgement/Preface

HyWays is an integrated project, co-funded by research institutes, industry, national agencies and by the European Commission (EC) under the 6th Framework Programme [contract N° 502596].

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1. Towards a European roadmap for the introduction of hydrogen

1.1 The aim of this publication

The aim of this report is to introduce the *HyWays 'Hydrogen Roadmap'* project, and to *describe the key assumptions* that were used in the generation of the project results. HyWays has recently reached the end of Phase I of the project. This report presents the *key assumptions and robust results generated in the first phase* of HyWays. These results are preliminary and subject to changes, and therefore *no validated roadmap can be presented at this time.* Nevertheless some robust conclusions can be drawn at this stage of the project. Finally, this publication aims at inviting *feedback* from the readers – both on the underlying key assumptions as well as on presentation of the first results. The process for passing on feedback is explained in Section 5.

1.2 The aim of HyWays

HyWays aims to develop a validated and well-accepted roadmap for the introduction of hydrogen in the energy system. The main characteristic of this Roadmap is that it reflects real life conditions by taking into account not only technological but also country specific institutional, geographic and socio/economic barriers and opportunities. Both stationary and mobile applications are addressed, including possible synergies ('spill over effects') between these applications. HyWays will systematically describe the future steps to be taken for large-scale introduction of hydrogen as an energy carrier in the power market and transport sector and as a storage medium for renewable energy. An action plan for the support of the introduction of hydrogen technologies will be derived from this Roadmap.

1.3 The HyWays process in brief

The implementation of advanced, highly innovative technologies such as hydrogen applications is not just a matter of achieving the right payback time. A transition towards a sustainable energy system involves changes on various levels. Therefore, the assessment framework includes the use of a well-balanced set of models addressing impacts on micro, meso and macro level, an actor analysis as well as an analysis of a hydrogen infrastructure build up.

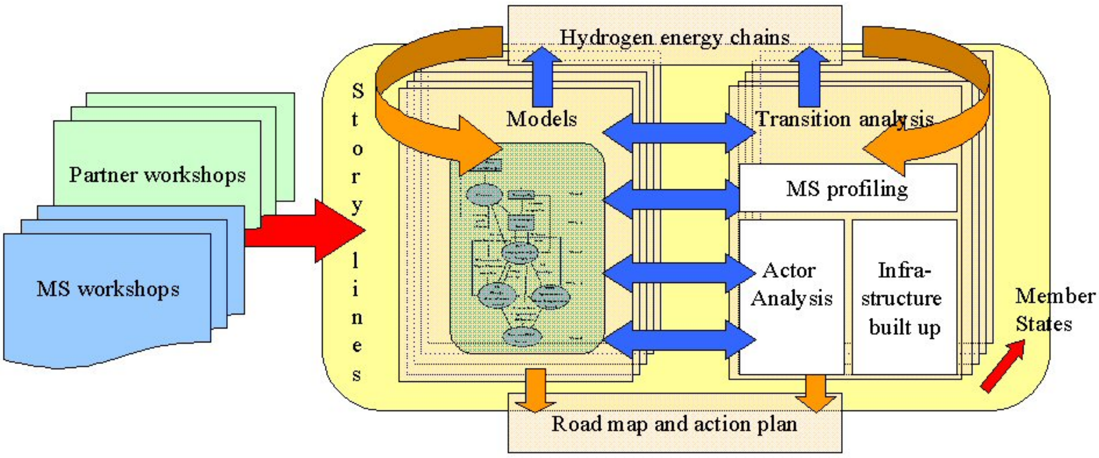

Figure 1.1 *Schematic representation of the HyWays process*

HyWays comprises two phases of 18 months each. In the first phase, an analysis of the introduction of hydrogen is performed for six countries (France, Germany, Greece, Italy, the Netherlands, and Norway). In the second phase, the analysis is carried out for another four countries (Finland, Poland, Spain, and United Kingdom).

Workshops: validation and acceptance of HyWays

Validation workshops both within the consortium and with wider stakeholder groups in the participating countries play a crucial role in the HyWays process. The workshops serve as a platform to discuss and develop the methodology, collect the required input for the scientific analysis as well as for first order validation of results. The goal of the national stakeholder workshops is twofold:

- To collect information on stakeholder preferences and other country specific conditions. This information is used to modify the results of the scientific analysis in order to turn the ‘optimal’ pathways, from a strict techno-economic optimisation point of view, into realistic pathways that reflect real life conditions.
- To validate the results of HyWays and to give these stakeholders a say in the process of selecting energy chains and developing realistic and preferable pathways, thus improving the quality as well as the acceptance of the HyWays results.

2. Scenario outline

To evaluate the possible role of hydrogen in future society, one has to make assumptions about how this society will develop in time. By and large, this means that the energy system has to be parameterised, indicating against which socio-economic background the introduction of hydrogen will take place. HyWays aims at providing a roadmap for the development of hydrogen in the European Union and does not intend to develop new energy scenarios. Therefore, it was decided to use an existing and well-accepted European outlook is as reference. The HyWays consortium has selected the “European Energy and Transport: Trends to 2030” (Energy Trends 2030) to serve as a basis for the development of the baseline scenario (include reference). In this chapter, the general assumptions, the extension from 2030 to 2050 as well as some modifications on the development of energy demand are discussed. It should be noted that although the timeframe is extended up to 2050, the most reliable indications coming from HyWays will bear on 2030. Beyond that, the outcomes should be viewed as indicative only, because of increasing uncertainties in long-term projections.

2.1 Implications and usability of Energy Trends 2030 scenario

The Energy Trends 2030 scenario is based on assumptions about key driving parameters for energy use in the European Union. These include estimates of the drivers that determine demand, most notably the Gross Domestic Product (GDP), and demographic characteristics such as population size and household composition. With these parameters, the demand for end-use of energy is determined, specifying for example the impact that GDP growth has on the energy demand of industry.

2.2 Development of energy prices

While GDP serves as main driver on the demand side of the energy system, the prices of fuels, more specifically the price differences between fuels, are an important driver for the development of the supply side of the energy system. As shown in Figure 2.1, the projections are substantially below today’s values. Nevertheless the consortium has decided to stick to these projections, but perform extensive analysis of the impact of such assumptions on the competitiveness of hydrogen.

There is some freedom in the choice of energy price projections beyond 2030, as the Energy Trends 2030 projections do not extend into this period. For the oil price, a slight increase of the trend prior to 2030 is assumed, leading to a level of 50 $/boe (barrel of oil equivalent) in 2050. A decreased coupling is assumed for the price of natural gas, from a factor 1 in 2020 through 0.67 in 2030 to a level of 0.5 by 2050. Thus, as the oil price increases by 1 $, the gas price in 2020 shows as strong an increase, but by 2050 the increase is reduced to 0.50 $. This leads to a price of 34.9 €/boe in 2050. This assumption of a diverging price increase is based on increasing disparity between oil and gas reserves. The coal price is assumed to remain at the 2020-2030 level of 7 €/boe.

The projections of energy prices from the Energy Trends 2030 scenario have evoked quite some discussion. A number of HyWays partners as well as other stakeholders have the opinion that the oil price projections are unrealistically low, not reflecting recent market development. To account for such (conceivable) criticism, an extensive sensitivity analysis is part of the HyWays approach, see section 2.6.

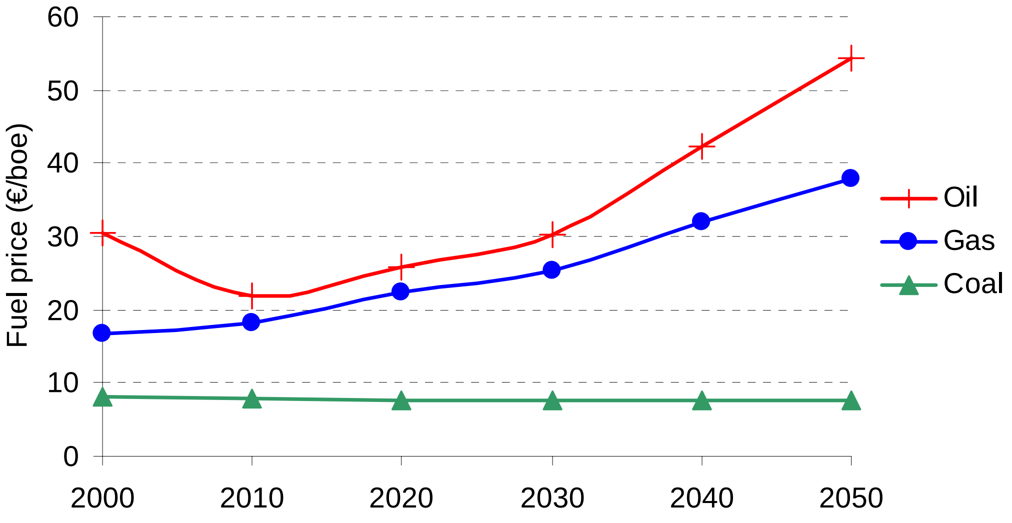

Figure 2.1 *Fuel price projections in € per barrel of oil equivalent (boe) based on (EC, 2003)*

2.3 HyWays assumption for demand for passenger car transport

Developments in the passenger car market play an essential role for the possibilities for hydrogen cars, and hence are crucial for the HyWays roadmap. It is foreseen that this market will have the highest volume effects for hydrogen applications in the next fifty years. Therefore, a realistic estimate of growth in the transport sector that is accepted by the various stakeholders is crucial. The consortium decided to deviate from the Energy Trends 2030-based numbers, particularly for the passenger cars, as the growth there is considered too high. Alternatively it is assumed that average car ownership and usage in all member states becomes comparable to levels in present-day Germany. The resulting HyWays specific assumptions are compared to the extrapolations from the original Energy Trends 2030 in Figure 2.2.

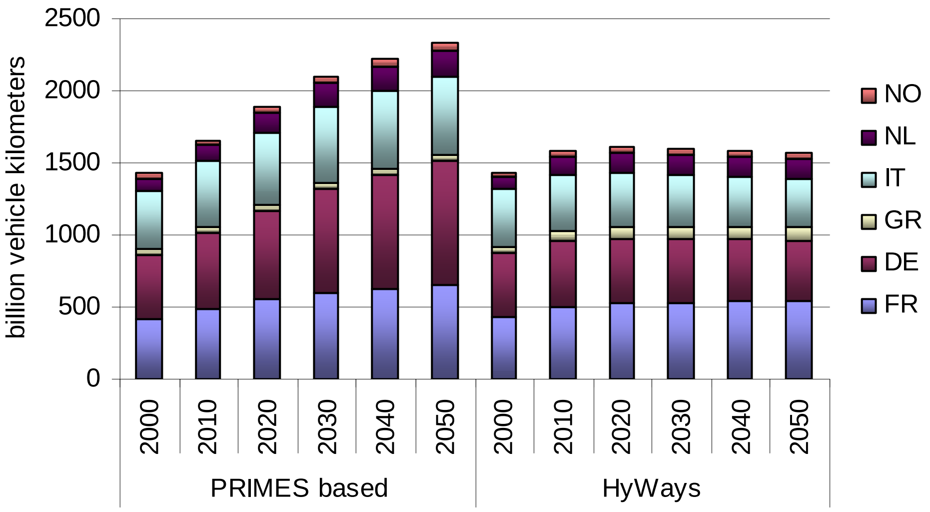

Figure 2.2 *Projections for passenger car stock in the six current HyWays countries: HyWays specific assumptions (right) and Energy Trends 2030 scenario assumptions (left)*

2.4 Policies and policy instruments

The economic and political background against which the role of hydrogen is assessed will play a key role in the evaluation of the effects of hydrogen. The objective of the Energy Trends 2030 scenario is to deliver a “business-as-usual” scenario to serve as benchmark for policy-oriented scenarios, like a climate change or energy efficiency scenario. It was not meant to serve as the most likely development of future energy consumption, but intended to show the consequences of developments in case no new policy measures would be implemented. Thus, the standard Energy Trends 2030 scenario is relatively poor in policies. It takes into account only those policies that were in place or in the process of being implemented by the end of 2001. This implies that in this baseline scenario important drivers for hydrogen, such as a climate change policy, are lacking.

A first addition to the policy framework of the Energy Trends 2030 scenario is to extend it to policies agreed on by the end of 2004. Furthermore, while in the Energy Trends 2030 scenario the implementation was restricted to actual national policy instruments in place, the HyWays baseline scenario assumes that these policies also include the targets set by the EU, most particularly on renewable resources and climate change policies. This leaves open by which actual instruments these targets are implemented. For renewables, the targets are based on official publications by the EU. The targets amount to 22% of all electricity produced in the EU15 region in 2010 and 27.6% from 2020 onwards coming from renewable energy systems. For the period 2030 to 2050 it is assumed that the minimum share of renewable energy remains constant.

Within HyWays it is not the aim to do a full assessment of the policies that are favourable for the introduction of hydrogen into the energy system. If hydrogen scenarios relatively rich in environmental policies would be compared to a baseline like Energy Trends 2030, which is rather poor in such policies, an assessment would be given of the combined value added of hydrogen and environmental policies, rather than of the value added of hydrogen only. Therefore, contrary to the Energy Trends 2030 approach, the HyWays baseline needs to include major drivers for a hydrogen economy, such as limitations on greenhouse gas emissions, policies to promote renewable energy sources or increased fuel prices.

As a baseline assumption, therefore, the HyWays baseline scenario assumes that the EU will adopt a policy on the emission of greenhouse gases beyond 2012. There is still much uncertainty about the actual policy to be implemented in the post-Kyoto era, but the clear aim is a maximum of 2ºC rise in global average temperature by the end of the century. According to recent projections of the IPCC (UNEP, 2001) this may be achievable if a 35 % reduction target of CO_2-emissions in the EU-region by 2050 is adopted, under the assumption of long-term global equality with respect to CO_2-emission rights. In HyWays, this CO_2 emission target is set for Europe as a whole, as well as across the various sectors. Since the free market assumption induces the reduction of emissions through the most cost-effective option, setting the target at such an overall level implies the effectuation of an emission-trading scheme, with trading between sectors and between countries.

As transport is one of the sectors closely looked at in this project, policies on emission from the transport sector can be crucial in assessing the benefits of hydrogen. In particular, care should be taken that current proposed legislation that aims at improving emission characteristics for cars are properly included. Therefore, in the assessment of emissions, two new EURO legislations (V and VI) have been incorporated for cars. These put limits on pollutant emission levels (EURO V), and on fuel consumption (for both). In addition, limits on the SO_2-content of fuels as required by a specific Directive have also been implemented. The fuel consumption limits are assumed to be a result of Voluntary Agreements between car manufacturers and EC, as reaction to the Kyoto protocol and other possible future initiatives to counteract climate changes. It is assumed that the two new legislations will come in force starting respectively on 2010 and 2015.

2.5 Four hydrogen scenarios

In contrast to the "business-as-usual" worldview provided by the baseline scenario, additional assumptions are made in order to build a framework for the hydrogen roadmap. Deployment rates of hydrogen end use applications as well as the learning rate of fuel cells were considered to be important drivers for the introduction of hydrogen. These drivers form the axes of the hydrogen scenarios in HyWays.

		Deployment rate of hydrogen based end use applications	
		high	moderate
learning rate	high	scenario 1	scenario 2
	moderate	scenario 3	scenario 4

An approach is chosen where the driver for the onset of the hydrogen economy is provided by the deployment of end-use technologies, with a focus on mobile and stationary applications. While portable applications may play a crucial role for kick-starting the hydrogen economy, its impact on hydrogen demand will be limited and therefore a qualitative treatment of these applications is considered to be sufficient in HyWays.

Two sets of penetration rates are assumed for the hydrogen consumption technologies, one reflecting an optimistic view on the opportunities for these technologies ("high"), and one reflecting a less optimistic view ("moderate"). In the baseline, no hydrogen technologies manage to make inroads into the market. Assumptions are also made about the cost decreases that result from the deployment (through 'learning-by-doing'). Again, an optimistic view with high cost decrease and a less optimistic view are chosen. The resulting impact on costs is determined by means of by a learning curve approach, see section 3.2.

Combining the two sets of penetration rates and the two sets of cost decrease assumptions results in four scenarios in which the future role of hydrogen technologies can be assessed. The chapter on deployment of hydrogen technologies will deal with the assumptions on a more quantitative level.

2.6 Sensitivity analysis

The introduction of hydrogen will to a large extent be determined by the techno-economic assumptions concerning hydrogen technologies and their competitors, be it production, distribution or consumption. Assessing the impact of variations in the costs of end-use technologies, most notably the hydrogen passenger car, is already covered by means of the differences in learning rate in the standard hydrogen scenarios (see previous section).

The view on oil price developments and the driving forces has changed significantly over the last three yeas. The IEA now also reckons with oil prices exceeding 50 $/barrel in the long term if the investments in oil production capacity in the Middle East region are not significantly increased (IEA, 2005). On top of that, it is expected that in 2007 an update of the Energy Trends 2030 scenario will be published with significantly higher oil prices (58 $/barrel in 2030). For this reason, assessing the sensitivity of the model outcomes to the oil price level is an essential part of the HyWays project.

- The sensitivity analysis for other drivers, besides deployment rate and technology learning, are assessed on a model specific basis. Effects of fossil fuel price variations as well as variations in the overall CO_2 emission target, which have a direct impact on the relative competitiveness of individual technologies, are best assessed using a bottom-up modelling of the energy system like MARKAL (Seebregts, 2001). The variations will provide insight into the robustness of findings related to the production mix for hydrogen. The analysis will focus on the impact of early price shocks, e.g. increases in oil-price to 50$ or higher in the year 2010 and beyond.
- Effects of different shares of import and export of hydrogen related technologies on the Member State level and effects of funding mechanisms for additional costs of the introduction of hydrogen on the economic sectors and the employment market can be analysed best by a model such as ISIS (Walz, 2001).
- Effects of different substitution elasticities (e.g. between transport demand and other consumption) are best assessed by a hybrid macro-economic model such as PACE-T (Böhringer, 2002). Effects of different technological parameters (e.g. different car costs) can also be assessed with this type of model.

3. Deployment of hydrogen technologies and technology progress

3.1 Deployment of hydrogen technologies

Based on still existing uncertainties on technical level a secure market development forecast for mobile and stationary hydrogen and fuel cell applications cannot be given at a reasonable probability. Crucial sub-systems such as fuel cell stacks or hydrogen storage systems but also key components like catalysts and membrane-electrode-assemblies have already achieved significant progress but require further breakthroughs on their way towards mass commercialisation so that a more evolutionary based forecast is not within the scope of this work. Considering the key findings of the HFP Deployment Strategy and the Strategic Research Agenda[1], HyWays introduces a set of two different penetration rates reflecting either a very optimistic or a more conservative development that has been adapted to the specific needs for both mobile and stationary applications.

3.1.1 Mobile Applications

At present hydrogen powered vehicles with PEM (Polymer Electrolyte Membrane) fuel cell power trains and somewhat less often with internal combustion engines are being demonstrated in ongoing projects worldwide. As outlined in the Deployment Strategy[2] the following four steps concerning the introduction of fuel cell powered vehicles have been assumed:

• Today until 2010:	Demonstration of fuel cell powered vehicles in captive fleets
• >2010:	Series production of fuel cell powered vehicles for fleets (1st generation on-board hydrogen storage)
• > 2020:	Series production of fuel cell powered vehicles in broad application (2nd generation hydrogen on-board storage and low-cost high-temperature fuel cell systems)
• >2030 - 2040:	Fuel cells become dominant technology in transport

In the above-mentioned steps the development of fuel cell components and hydrogen storage technologies is crucial. Especially the transition from step 2 to 3 requires close collaboration and feedback between basic research on components and fuel cell stacks on the one side and the technical validation of integrated systems under demonstration programmes that allow an organic growth in dependency of the technical and economical progress. In this context to prove that cost reductions for critical sub-systems such as fuel cell stacks or hydrogen storage tanks are feasible more and more units need to be demonstrated, for example in large scale demonstration projects such as Lighthouse Projects in the 2010 to 2015 time frame. For a mass-market rollout around 2015 the achievement of the following “quality gates” has been adopted from the Strategic Research Agenda:

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[1] European Hydrogen & Fuel Cell Technology Platform: Deployment Strategy Foundation Report and Strategic Research Agenda Foundation Report (August 2005) can be downloaded at https://www.hfpeurope.org/hfp/keydocs

[2] Deployment Strategy Foundation Report, chapter 2.4.1

Table 3.1 *Comparison of the current status with 2015 SRA targets for fuel cell systems for passenger cars*[3]

		Current Status	2015 Target
Power density	liter/ kW	3.0	1.5
Cycle Efficiency (NEDC)	-	37%	> 40%
Specific cost	€/ kW	> 4,000	< 100 (> 150,000 units/ a)

In terms of barriers not only technical issues need to be resolved, but also industry development cycles in terms of timing need to be considered. For a high penetration scenario it has been assumed that mass production of hydrogen and fuel cell vehicles will start in 2013, led by a group of 5 first movers who increase their capacities each by a new plant of 100,000 units per year with an assumed plant utilization of 5%, 50%, and 90% respectively in the first three years. In the low penetration scenario the hypothetic start of mass production has been shifted to 2016 and the number of first movers reduced to 4 who are ramping up their plant utilization rate from 5% to 90% over a five years time frame (maximum production capacity of each of the four plants 100,000 units per year). After reaching a full utilisation of the production capacities of the first movers after 3 (high penetration) respectively 5 years (low penetration) 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[4] was calibrated to the generic production volumes and used to extrapolate penetration shares until 2050 as displayed for both scenarios in the table below.

Table 3.2 *Scenarios for the potential development of hydrogen vehicles, share in vehicle stock*

Total share of fleet	2010	2020	2030	2040	2050
High Penetration	-*	3.3%	23.7%	54.4%	74.5%
Low Penetration	-*	0.7%	7.6%	22.6%	40.0%

* Demonstration vehicles and fleets only

In addition to passenger cars these penetration curves are also applied for commercial light duty vehicles and public transport buses. Long haulage heavy duty trucks and coaches have not been considered for relevant hydrogen penetration rates due to the requirements for extremely long ranges and the fact that the internal combustion engines of these vehicles are usually operated in a higher efficiency range.

In the "Biofuels Directive"[5] the European Commission has set indicative targets for hydrogen that demand a fuel market share of 2% in 2015 and 5% in 2020 of 5% respectively. A comparison with the HyWays "High Penetration Scenario" shows clearly that these EC targets for hydrogen cannot be met even under best conditions. An earlier start for mass production than 2013 is hard to argue not only based on technical facts but also concerning the incomplete legal framework. A decision on mass production of hydrogen vehicles is awaiting the formal ECE type approval for hydrogen and fuel cell vehicles. Although draft directives are about to be submitted to the Commission and the European Parliament[6], an approval of such directives takes approximately two years. The 2013 introduction year thus allows for a five year period

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[3] Strategic Research Agenda Foundation Report chapter 2.4.3.1

[4] 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 (high, low)

[5] Proposal for a directive, COM(2001) 547 final, 7.11.2001

[6] Reiner Würster, LBST, October 16th 2005.

from final acceptance of safety standards to market introduction of mass produced hydrogen vehicles. From this perspective it is recommended for the European Hydrogen Roadmap to adjust the hydrogen substitution target for 2020. Based on the discussions in HyWays and the findings of HyNet[7] a maximum penetration target for hydrogen and fuel cell passenger cars in 2020 of 3 % of the total passenger car fleet seems appropriate.

3.1.2 Stationary Applications

Small and medium-sized hydrogen fuelled Combined Heat-and-Power (micro-CHP) systems are expected to evolve from a possible precursory major mass-market application for natural gas based fuel cells. Initially the natural gas based systems not only will serve as a precursor to hydrogen fuel cell systems, but also as a direct competitor. This is especially the case as the infrastructure for gas-based systems in many countries is well developed, while hydrogen grids need to be build up. A second barrier might be technological characteristics of hydrogen-fuelled systems, which might be less suited for micro-CHP applications than natural gas fuel cell systems. Finally, existing heating systems, such as the condensing boiler combined with a solar thermal water heater, have high theoretical efficiencies. Moreover, the energy efficiency of the power sector also will increase in the future and the CO_2-emission coefficient may go down severely due to the introduction of CCS or renewables, leading to an erosion of the value added of micro-CHP. These are the major reasons why the penetration of hydrogen fuelled systems for stationary end-use is assumed to see a moderate development, as compared to the mobile applications. The penetration rates for the households and commercial buildings are given in Table 3.1 and Table 3.2, respectively.

Table 3.1 *Scenarios for the potential development of stationary hydrogen applications in the residential sector*

Total share of households	2010	2020	2030	2040	2050
High penetration	-	1%	4%	8%	10%
Low penetration	-	0.1%	0.5%	2%	5%

Table 3.2 *Scenarios for the possible development of stationary hydrogen applications in the commercial and services sector*

Total share of commercial demand	2010	2020	2030	2040	2050
High penetration	-	0.3%	1.3%	2.7%	3.3%
Low penetration	-	>0%	0.2%	0.7%	1.7%

In the longer term, fossil reserves become more and more scarce, creating opportunities for hydrogen fuelled systems. However, even if a relative cheap production technology for hydrogen from non-fossil fuels becomes available, the hydrogen will have to compete with direct application of electricity, which in particular for residential and commercial applications will prove a hard task, particularly in urbanised areas with relative high demand densities. This is the major reason for the expected limited penetration in the longer term, and for the difference between residential and commercial penetration, as the latter is even more concentrated in urbanised areas than the former.

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[7] In June 2004 HyNet presented a 1st order European hydrogen roadmap which for the hydrogen vehicle build-up resulted in a bandwidth of 1–5% and a mean of 2.5% of all passenger cars by 2020 (http://www.hynet.info/publications/docs/HYNET-Roadmap_Executive_Report_JUN2004.pdf)

For larger-scale fuel cell systems, an exception to the above-sketched scenario could lay in a co-production facility of hydrogen for transport and electricity. Already to date, plans are being developed for building such a facility, where the electricity is generated from hydrogen by means of a fuel cell because of the higher efficiency. A second exception could occur in the presence of existing hydrogen pipeline infrastructure close to urban areas, or admixture of hydrogen in the natural gas grid. There, early introduction in the stationary sector could be followed by substantial take-up of hydrogen technologies in that area. It would particularly be interesting if the hydrogen were surplus hydrogen, for example from chlorine production, and hence relatively cheap.

3.2 Investment costs of hydrogen vehicles

One major influence on the results of the analysis is the assumption concerning the future cost developments of technologies. The learning curve concept is applied to the 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 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 (see table below, and (Tsuchiya, 2002)). Two different scenarios for the progress ratios were selected (see Table 3.3) in order to specifically handle the uncertainties associated with fuel cells.

Table 3.3 *Progress ratios of H_2-technology components for a fuel cell car (figures from HyWays automobile industry partners)*

Component	Low PR (fast cost reduction)		High PR (low cost reduction)	
	Initial phase	After 10 years	Initial phase	After 10 year
Alternative fuel tank	0.85		0.85	0.93
Electric motor	0.90		0.90	0.98
Li-Ion battery	0.90		0.90	0.98
FC system	0.80	0.90	0.82	0.92
H2-ICE[a]	1.00		1.00	

[a] The 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, and taken from the specifications of other research projects. Comparing the HyWays approach with current research work of the IEA (Gielen, 2005), the following difference could be identified: in HyWays, both progress ratio scenarios lead to lower cost for fuel cell cars compared to the IEA scenarios.

The calculation of the vehicle price is based on the assumptions in Table 3.3. Figure 3.1shows the projected price development for hydrogen-powered cars. The starting price for the gasoline car as well as the fuel cell car corresponds to specifications from (EUCAR, 2004) for the year 2010.

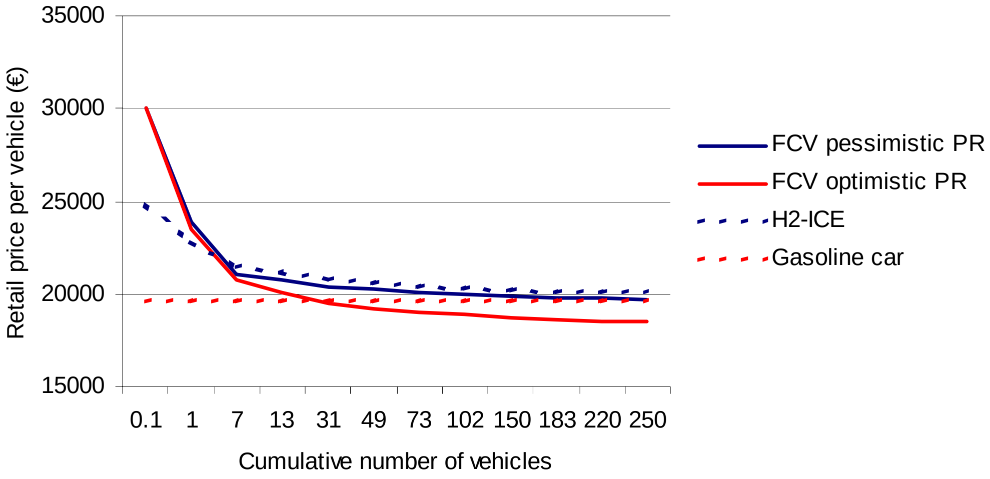


Figure 3.1 *Cost reduction of hydrogen cars (only the medium class cars are shown) for the two progress ratio scenarios and as a reference the gasoline car figure for 2010*

In the next phase of HyWays, research will focus on cluster learning effects. Economies of scale in the production process can be utilised for the production of “new” components such as fuel cell membranes and stacks, especially for PEM fuel cells used in transport applications, small scale CHP and early markets. (This effect is mentioned among others in (HFP, 2004)). However, it has to be investigated if these effects will have a significant influence on the cost forecast for fuel cells.

4. Robust results from Phase 1

The aim of HyWays is to devise a well-accepted and fully validated roadmap for the introduction of hydrogen into the energy system. This implies a very strong involvement of stakeholders on many levels. A drawback of the desire to involve all relevant stakeholders is the time-consuming process of such efforts as well as the number of iterations needed in order to produce the final results. In this phase of the projects, few validated results are available. Nevertheless, some robust conclusions were drawn from the interactions with the various stakeholder groups. These will be highlighted in this chapter. Both the model extensions as well as more detailed model results will be covered in HyWays publications to be published towards the end of the project.

4.1 Energy chains selected

The definition and description of the hydrogen production, distribution, and consumption technologies in the E3-database (Agator, 2003) stand at the basis of the selection of country specific chains. The database provides a means of accessing all known techno-economical characteristics of hydrogen technologies, as well as a tool for energy chain analysis. In such an analysis, the energy efficiency, greenhouse gas emissions and costs for a particular chain are determined, from production to consumption of hydrogen.

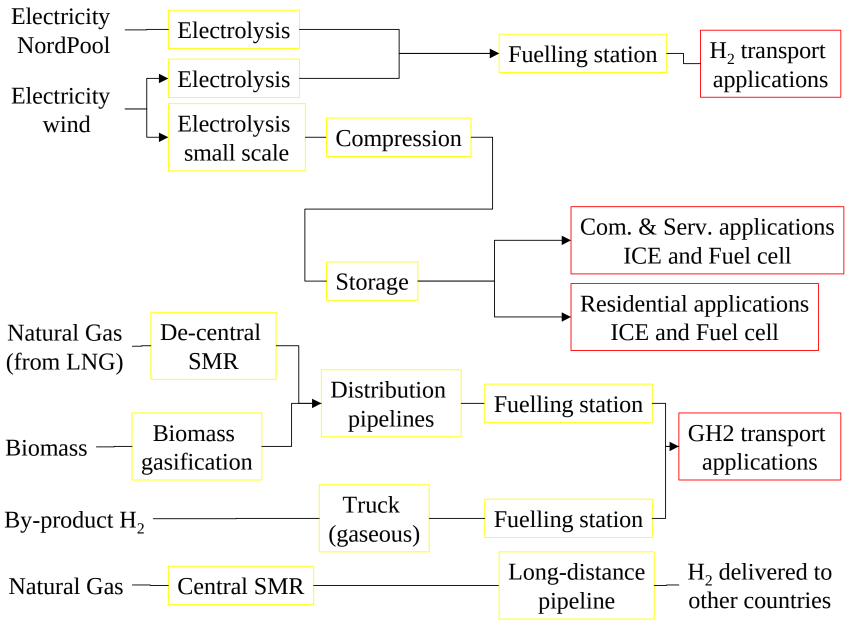


Figure 4.1 *Example of hydrogen source-to-user and well-to-wheel chains (Norway)*

The chain selection process for the six countries participating in Phase I combined the specific socio-political landscape of a country with the availability of information in the E3-database. The selection indicates that the countries share the view on the importance of transport applications. The use of hydrogen in the built environment for combined heat and power is viewed as relevant, albeit to a lesser extent in terms of size of hydrogen demand. A similar consensus can be observed on the choice of distribution options, with a main role for pipeline transport, and a limited role for trucks carrying liquefied hydrogen. In Italy, like in the US, for power production technologies in which hydrogen is temporarily produced, it is considered as an intermediate energy vector in the power sector. In the other countries this is still open for discussion.

The major distinction between the countries is in the selection of the production options, although even there the differences between the Member States are limited. All countries foresee a role for the production from natural gas, biomass, and electrolysis, from the grid or from wind. Coal is also viewed as a possible option for hydrogen production, particularly through coal gasification, or in the case of Greece, lignite gasification. This holds especially for countries where coal already today plays a significant role in the electricity production.

The necessity to be able to provide some techno-economical parameterisation for the technology prohibits the selection of new production options. This means that inevitably a certain “conservative” bias has been introduced in HyWays. It is important to keep in mind that new production options investigated among others in other FP6 Integrated Projects that are carried out in parallel to HyWays may in time change the outlook for hydrogen.

4.2 The impact of hydrogen on the energy system

4.2.1 Hydrogen production

Until 2030, hydrogen production from fossil fuels with carbon capture and storage (CCS) is expected to be the most important production source in Europe, with renewable hydrogen slowly being phased in. This is explained by the maturity of fossil fuel based technologies, assumptions on the availability of feedstocks and consequently the cost of hydrogen produced, as well as uncertainty about allocation of renewables to different energy sectors. At the same time, the baseline sees a drive towards low-carbon fuels, or carbon capture technologies, due to the strong carbon policy assumed. These conclusions hold even in the most extreme sensitivity run for the crude oil price, running at 200 $/barrel in 2050, with both natural gas and coal price assumed to follow the oil price.

Although the overall trends clearly indicate a continued dominance of fossil resources in the timeframe considered, in some cases benefits from local production and use may be advantageous to the use of renewable resources. This is most apparent for the use of biomass in rather small-scale gasification units, connected to local networks. To a lesser extent this also holds for intermittent resources, like wind power. In the first phase of HyWays, the consequences on electricity prices of intermittent resources have not been taken into account. It is foreseen that further analysis will be carried out on the costs of and conditions for production of hydrogen from renewable energy sources. Some countries clearly see a window of opportunity for the production of hydrogen from such resources, due to side benefits other than simple cost-competitiveness. Moreover, in some countries there is likely to be a political will to stimulate the use of renewables in a local setting. At the European level, the result is a limited but growing contribution from renewable resources.

4.2.2 Benefits of the hydrogen economy

There are three potential benefits from the introduction of hydrogen in the energy system: reduced emissions (environment), reduced dependence on critical imports of fossil fuels (security of supply), and economic growth opportunities for industry (economic stability). The impacts on the emissions are rather straightforwardly evaluated, as emissions are covered by a number of the models used in HyWays. Power production with CCS plays an important role in attaining the CO_2-emission reduction target. Some important CCS technologies have hydrogen as an intermediate product, and the use of such technologies may facilitate the large-scale introduction of hydrogen as an energy vector.

The energy system analysis shows that there is no direct effect on Security of Supply (SoS) when comparing the introduction of hydrogen to the baseline projections because the baseline already assumes that more diversification of energy sources will occur due to rather strict emission targets. However, the introduction of hydrogen eases the strong dependence on biomass in the transport sector induced in the baseline due to the CO_2-target. Hence, introducing hydrogen leads to a more robust projection of an increased SoS.

4.3 Impact on Industry and Economy

4.3.1 Economic analysis of hydrogen fuel cell vehicles compared with conventional vehicles

Four major drivers influence the cost-competitiveness of hydrogen cars compared with conventional vehicles: the crude oil price, hydrogen price (infrastructure costs), internalisation of CO_2-emissions and hydrogen drive system costs. Figure 4.2 shows the influence and the range of uncertainty of different drivers on the economy of fuel cell vehicles (FCVs).

The cost assumptions for the hydrogen drive system are dominant, followed by the variation of crude oil price, hydrogen feedstock and production technology, and then the internalisation of CO_2 emissions. Whereas the infrastructure costs for a hydrogen-based energy system can be estimated on the basis of today's technologies, it is more difficult to estimate the future development of hydrogen drive system costs. The main challenge to hydrogen use in the transport sector is to reach a price level for FCVs near the prices of conventional vehicles. Dependent on the other drivers, the target is between 0 and 1500 Euro of additional cost compared to conventional vehicles. It is important to notice that the calculations are based on the assumption that FCVs are perfect substitutes for conventional cars.

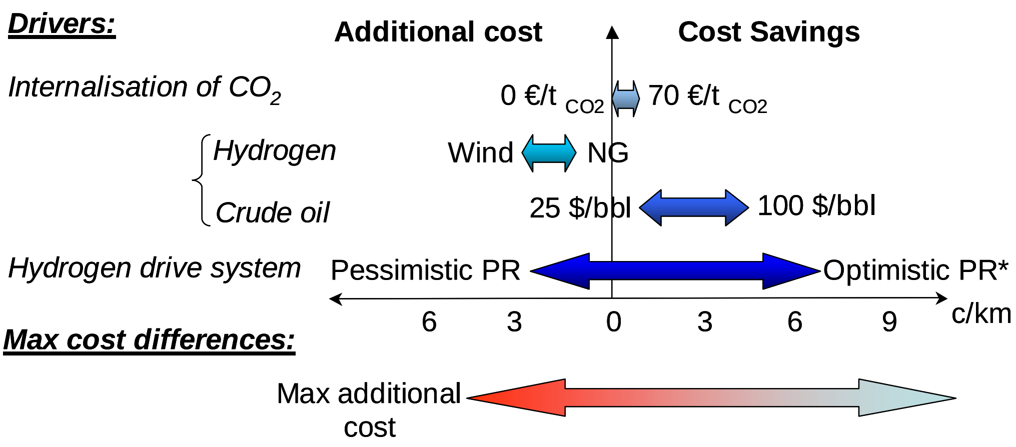
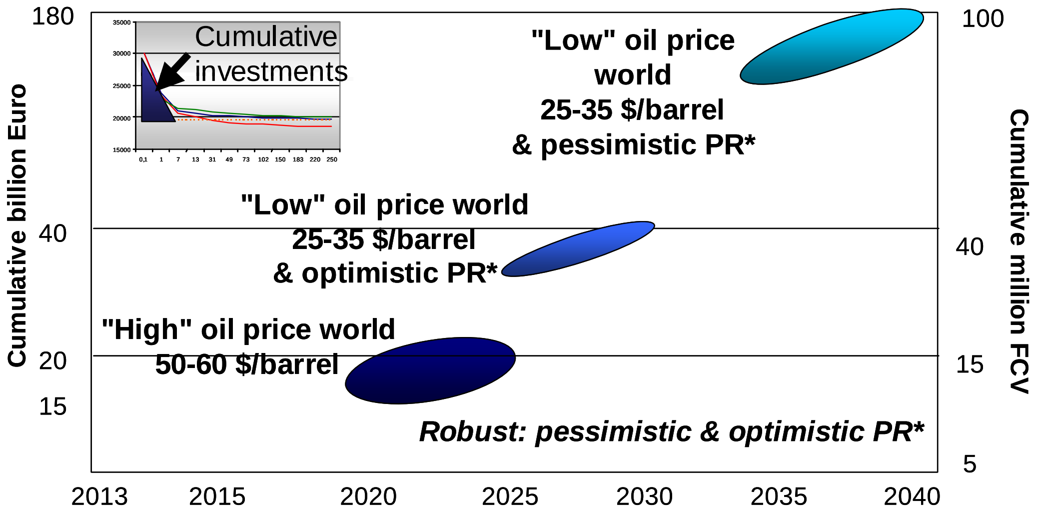


Figure 4.2 *Specific additional cost and savings of a FCV compared with a conventional vehicle (PR: progress ratio for fuel cell cars: describes the speed of cost reduction over the cumulative output, for assumed values see Chapter 3)*

In order to reach cost-competitiveness of fuel cell vehicles investments in both research, demonstration and development as well as in large-scale deployment are needed. Figure 4.3 shows the cumulative additional investments (additional compared with conventional vehicles) required until cost-competitiveness of FCVs for different scenarios. All cases analysed show that FCVs will reach this cost-competitiveness but with a wide range of cumulative cost. The important factors in reaching cost-competitiveness are the potential for cost reductions of fuel cells, given as the *progress ratio* (PR), and the oil price. For low oil prices around 30 $/barrel the break-even point depends strongly on the value of the progress ratio, and the investments show variations by a factor six. For high oil prices of 50 $/barrel or higher, the impact of the magnitude of the progress ratio is substantially smaller[8], varying only by a factor two. The uncertainty in cumulative costs between positive and unfavourable circumstances for hydrogen-fuelled vehicles can be as big as a factor ten.



* **PR** = **P**rogress **R**atio describes the speed of cost reduction over the cumulative output

Figure 4.3 *Accumulated additional investments in hydrogen vehicles and number of cars until cost-competitiveness of FVC is reached (without externalities and interest rate, from the beginning of mass production (€ 10,000 more for a fuel cell car), worldwide)*

To put the investment costs required to reach cost-competitiveness for FCV into perspective, a comparison can be made with the global investment of 16 trillion USD that would be required for the overall energy supply system until 2030 according to the IEA World Energy Outlook Reference Scenario (IEA, 2004). Alternatively, the number can be compared to the 1 billion US$ which is typically necessary to bring one new car type into the market, and which besides R&D expenditures includes costs for marketing, construction of plants, etcetera.

From the economic viewpoint, CO_2 reduction is not a major driver for the introduction of hydrogen. As compared to for example the price of hydrogen production and transport, the impact of carbon prices is relatively small. They could play a relevant role in decision-making of consumers only if FCVs are nearly cost-competitive. Having said this, if hydrogen fuel cell cars enter the market due to their competitiveness, this would lead to a significant CO_2 reduction (up to

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[8] Conclusions hold for similar variations in progress ratio for the two oil price ranges. The potential for cost reduction is essential, in that with cost reductions the oil price should be considerably higher than 50 $/barrel to reach cost-competitiveness.

a factor of 10 for every vehicle substituted). In this case, it is a win-win situation for the economy and environment. The benefits are even higher as not only CO_2 emissions but also other local air emissions and noise will be reduced by the introduction of hydrogen vehicles.

4.3.2 Impacts of a hydrogen economy on employment

The structure of the investments necessary for a transition to a hydrogen economy is clearly dominated by the expenditures for hydrogen vehicles (see Figure 4.4). If a hydrogen vehicle is imported in a country, not only the hydrogen drive system will be imported, but the whole vehicle. Therefore the structure of the domestic vehicle industry sector turns out to be one of the key factors for the employment analysis, but also for GDP and welfare development.

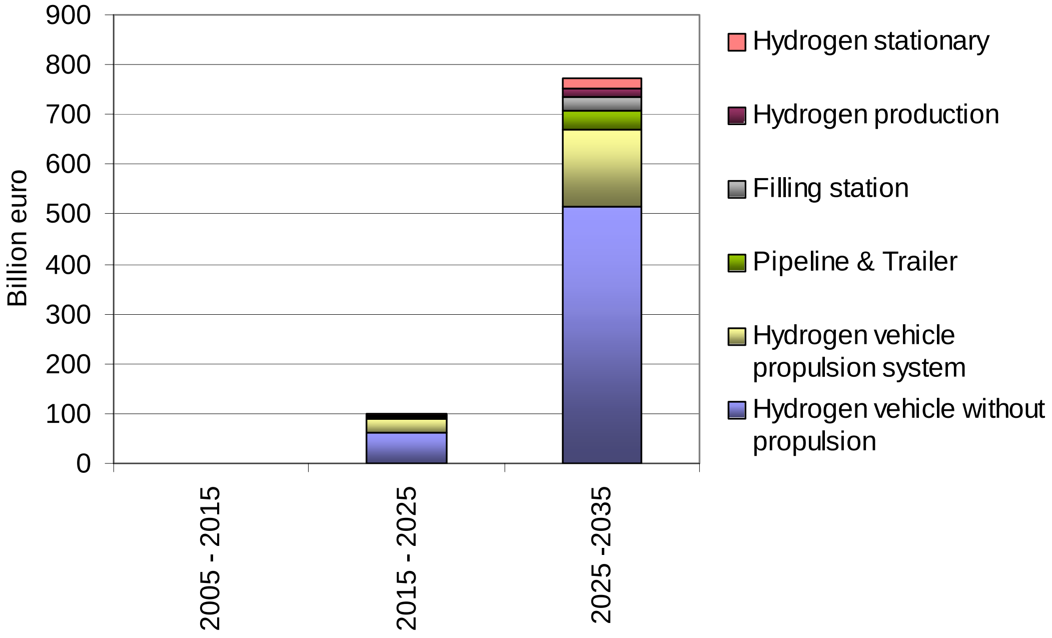


Figure 4.4 *Structure of the investments in a hydrogen economy of the six HyWays countries (cumulative investments for a ten-year period, hydrogen high penetration scenario)*

Four import/export scenarios have been analysed so far. Every scenario tells a story of a possible future for the competitiveness of the hydrogen technologies produced within the EU. The “Structural identity” scenario is based on today’s technology imports and exports, in which the EU and the six countries have a good market position. A lead market analysis shows that other regions of the world, namely USA and Japan, are also in a very strong position to become a lead market for hydrogen. This is expressed by the “Today’s potential” scenario where the EU export falls back compared to the structural identity scenario. The “Pessimistic” scenario shows what would happen if other regions of the world take over the leading position and Europe has to import hydrogen vehicles. In the “Optimistic” scenario, great efforts will be undertaken which result in increased EU exports of hydrogen vehicle and technologies.

The analysis shows that the transition to a hydrogen based energy system has the largest employment effects on the automotive industry and to a lesser extent on the plant and equipment sector. Whether the impact is negative or positive depends strongly on Europe’s efforts to consolidate or improve its current position in the car market. This holds even stronger for the current car manufacturing countries, which therefore face the dilemma: should they invest in a risky new technology, losing possibly many billions of R&D investments, or not, at the possible expense of even higher losses in GDP and jobs.

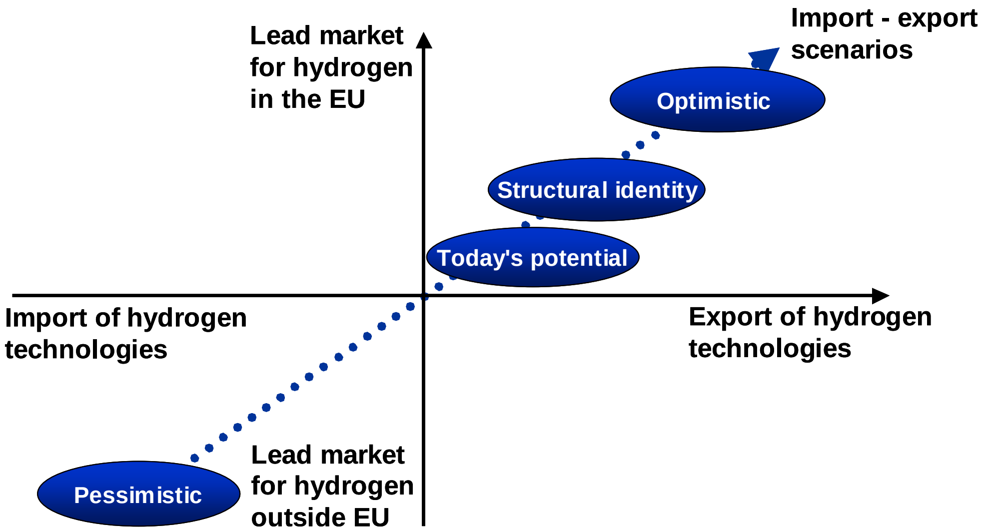


Figure 4.5 *The classification of the four hydrogen import/export scenarios for the economic analysis*

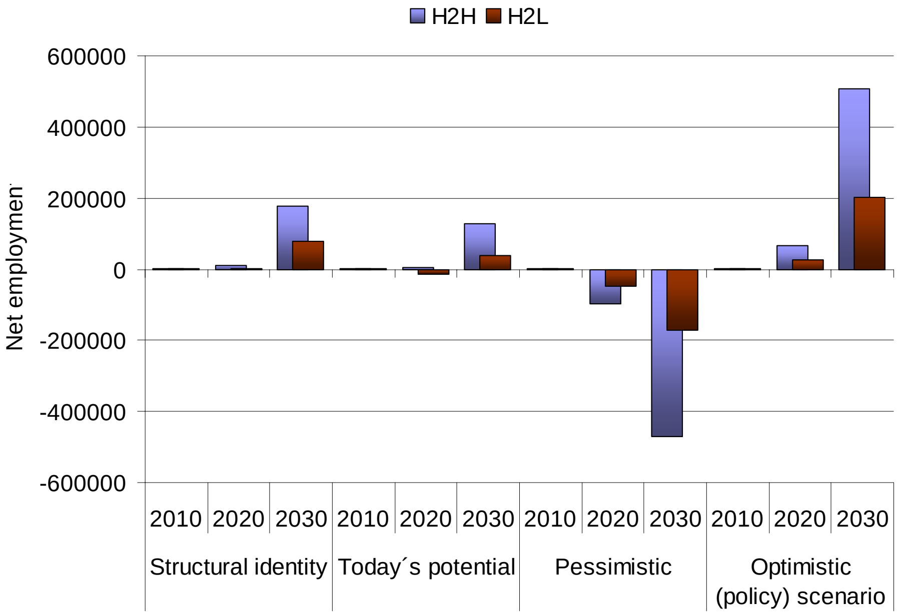


Figure 4.6 *Net employment effects for the “hydrogen high penetration (H2H)” and “hydrogen low penetration (H2L)” scenarios with high learning rates for hydrogen passenger cars for the years 2010-2030. Shown are the net employment effects for the six HyWays Phase I countries in four import/export scenarios*

The replacement of conventional vehicles by FCVs induces a sectoral employment shift away from the traditional car manufacturing. This shift requires considerable training of the work-force. Because of the required gradual build-up of manufacturing capacity and hence skilled labour force, preparing for expected mass production by 2015 necessitates political early action.

The production and maintenance of hydrogen and fuel cell technologies and related services offer economic growth opportunities for industry. It is important to develop a strong position for European industry compared to U.S. and Japanese competition among others to maximise the economic benefits for Europe.

4.3.3 Impacts of a hydrogen economy on welfare and GDP development

The impact of the transition to a hydrogen based energy system on overall welfare is quite small, as the change in GDP. Figure 4.7 shows the impact of the high-penetration scenario on GDP in the HyWays Phase I countries (again given as percentage deviations from the baseline scenario). The difference between countries is mainly due to differences in H_2 production costs and car-class dependent penetration rates. Whether the impact on welfare is positive or negative depends strongly on the cost reduction potential of FCVs. GDP changes take place in those periods where actual resources from the transport sector (lower overall costs of hydrogen cars) are released for use in other sectors. This means that GDP increases are broadly proportional to the car cost differences and to the penetration rates (which are both rising over time).

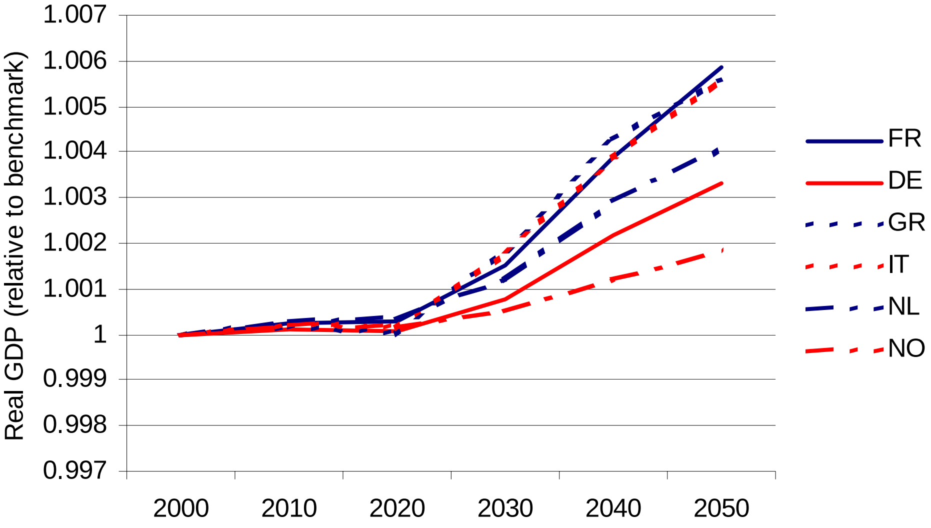


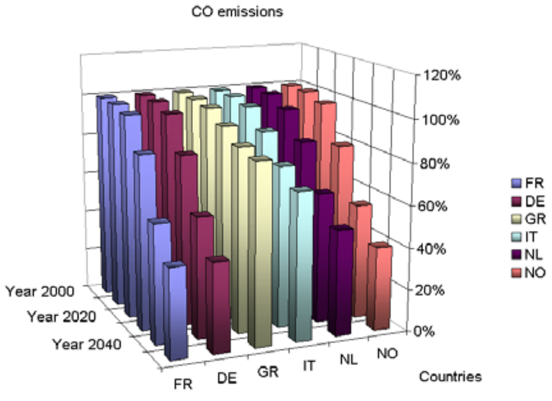
Figure 4.7 *Real GDP (structural identity scenario)*

4.4 Impact on emissions

The introduction of hydrogen technologies for mobile and stationary applications has the obvious advantage of reducing end-of-pipe emissions. Particularly for fuel cell technologies in the transport sector, emissions can be substantially reduced. At local level the benefits are very relevant for the air quality, especially in urban areas, as combustion of hydrogen results in no exhaust emission of pollutants when used in a fuel cell, and only few when used in an internal combustion engine (ICE). Therefore the emissions of local pollutants are considerably lower in the hydrogen penetration scenarios than in the baseline. The emissions have been calculated using the COPERT III model (Ntziachristos, 2000), as the road transport sector is the one where hydrogen has the largest deployment, using furthermore the TREMOVE database (EC, 2005) for projections of the fleet composition to 2050.

For hydrogen vehicles zero emission of pollutants from the tailpipe has been assumed. The assumption is mainly based on the predominant share in the long term of fuel cell vehicles, and the fact that these have zero pollutant emissions from the tailpipe. Lack of information was an additional reason to ignore specific emissions from hydrogen ICE such as NO_x-emissions. While future additional information on such emissions may render a more complete analysis feasible, this would not change the results much.

Calculated emission levels for CO, NO_x and Particulate Matter (PM) in the high hydrogen penetration scenario are shown in Figure 4.8, Figure 4.9, and Figure 4.10, respectively, for all six countries, and for the periods from 2000 to 2050. As the figures illustrate, there are important positive environmental effects for all of these pollutants, when compared to reference scenario. In most of the case the reductions are higher than 50%, except for CO-emissions in Italy and Greece due to a relatively high share of two wheelers. For PM the reduction is even higher due to the large share of diesel cars in the reference scenario, which amplifies the positive effects of hydrogen.



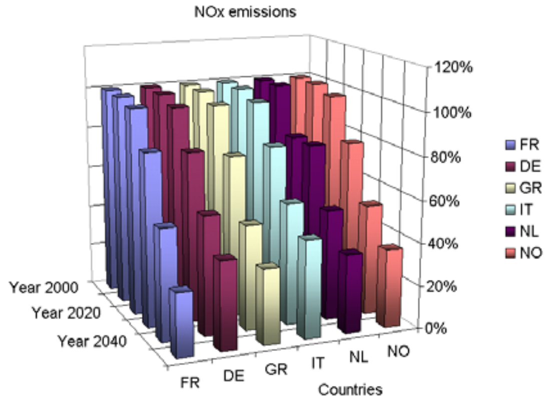


Figure 4.8 *Development of CO emissions normalised to reference scenario for the period 2000 - 2050*

Figure 4.9 *Development of NO_x emissions normalised to reference scenario for the period 2000 - 2050*

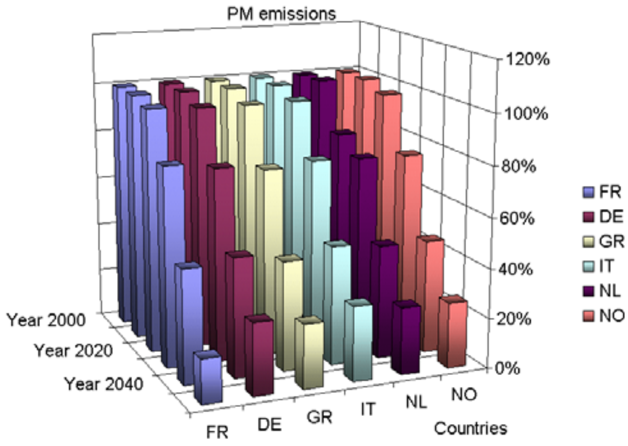


Figure 4.10 *Development of the PM emissions normalised to reference scenario for the period 2000-2050*

A major advantage of hydrogen use is the impact on local emissions, particularly due to the assumed high penetration of FCV. Aside from the reduction of conventional fuel consumption and CO_2 emissions, which are in line with the MARKAL results, emissions in urban areas with large population density are substantially reduced, indicating possible benefits on health.

The above results include also emissions from trucks and two-wheelers, where it is currently assumed that hydrogen will not contribute. The effects could be more substantial if further analysis would show that such vehicles actually do show potential for update of hydrogen technologies.

5. Development of MS-specific end-visions

The development of member state specific end-visions on the development of the energy system as well as the future role of hydrogen is an important step in the HyWays process. By means of these end-visions, stakeholder preferences with respect to e.g. the source for hydrogen production as well as views on the development of hydrogen demand can be taken into account. These end-visions for example set the boundary conditions for the analysis on infrastructure build-up and are also of key relevance in the discussion of the selection of MS-specific energy chains. In this chapter, a brief overview of the most important elements of these end-visions is given for the countries assessed in Phase I of HyWays.

5.1 German Vision of Hydrogen Chains

The German HyWays stakeholders have developed a national vision of the deployment of hydrogen energy for the next decades. This national vision takes into account: a wide variety of relevant H_2 sources from fossil to renewable feedstocks, as well as the different scales of production from onsite to centralised production. In this vision CO_2-reducing or CO_2-free sources should play an important role especially in a long-term view.

The most promising application sector for hydrogen is seen in transport with a focus on cars and regional vehicle fleets using hydrogen in fuel cells, and in the transition phase also in internal combustion engines. For stationary applications the potential to use hydrogen is also envisioned, but to a lower extent. The key drivers for a hydrogen economy – energy supply security and international competitiveness – put less pressure on industry and politics than the transport sector. In the transition phase to a wider use of hydrogen energy starting after 2010, industrial by-product hydrogen can significantly contribute. Additionally hydrogen will be produced by on-site steam methane reforming (SMR) and electrolysis. Demand centres in densely populated areas will arise and for hydrogen transport liquid or compressed hydrogen trucks will play a relevant role.

After 2020 the growth in hydrogen demand is expected to broaden the range of options for local and central hydrogen production. Another H_2 supply option with growing importance is electrolysis from renewables and grid mix electricity. Depending on the hydrogen penetration rate and the feasibility of CCS (economy, security) natural gas (NG) and coal can contribute to secure higher amounts of GHG emission free hydrogen (centralized). For hydrogen transportation pipelines will play a relevant role at this stage. But also on-site steam methane reforming (SMR) and electrolysis production will be important, especially for the supply in rural areas with warranted demand profiles.

After 2030, hydrogen already plays a major role in supplying vehicles and a remarkable role for stationary applications. Provided, CCS is already established at industrial scale, central hydrogen production schemes based on fossil fuels could dominate in Germany either from SMR, or coal gasification - depending on long-term price developments of the energy carriers. Although the end-use competition for the merits of renewable resources between different sectors (transport, electricity, heat) will grow, the share of renewable hydrogen will increase. Main renewable H_2 supply chains are wind (on- and off-shore) via grid electricity and central or de-central electrolysis as well de-central biomass gasification. New renewable resources (geothermal) might fit the growing hydrogen demand with the help of new storage systems. The import of hydrogen (e.g. from Norway via a European pipeline network) may become another option. The transport of hydrogen will be by pipeline or liquid hydrogen truck depending on the hydrogen demand and location of the end use.

5.2 French Vision of Hydrogen Chains

The French stakeholders have thought about an intuitive national vision of hydrogen energy in the period 2010-2050. This national vision takes into account: the political will to promote water electrolysis using the French electricity mix (90% from non-fossil sources, i.e. without CO_2 emission); the potential of renewable energy resources (wind, biomass) which could be mobilized for hydrogen production; the potential of CO_2 storage in sedimentary basins; the geographical distribution in six large areas (groups of regions), depending on the population density.

In the entry phase (by 2010), the early markets would require small quantities of hydrogen produced by steam methane reforming (SMR) or water electrolysis, using the existing infrastructures (pipelines, tube trailer…). In the transition phase (2010-2030), the growth of hydrogen demand would enlarge the range of options for local and central hydrogen production, taking into account the French specificities. The capture and storage of CO_2 issuing from central SMR installations would not be envisaged before 2020 at industrial scale. However, this option would be privileged afterwards, assuming a dissuasive CO_2 taxation. The use of existing natural gas pipelines to transport hydrogen would be envisaged in this transition phase, assuming the extraction of hydrogen from the mix at the point of use.

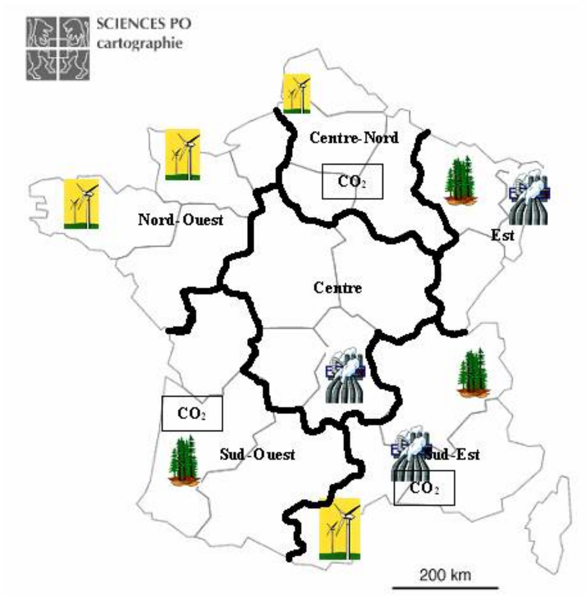


Figure 5.1 *Regionalisation of hydrogen energy chains in France, with indicative location of renewable energy resources which could be mobilized for hydrogen production*

In the vision phase (2030-2050), SMR would be privileged in areas with large population density (Centre-North and South-East of France), when hydrogen demand is high and CO_2 geological storage feasible at large industrial scale. In areas with a lower population density (North-West, East, South-West and Centre), hydrogen would be produced preferably by local or central water electrolysis using the French electricity mix, whereas SMR would be used depending on the economic competitiveness of the process, including CO_2 transport and storage costs. The renewable energy resources would contribute significantly to local hydrogen production in the most favourable regions. In the long term (by 2050), the emergence of innovative high temperature nuclear reactors could allow a massive production of CO_2-free hydrogen.

The transport of hydrogen by pipeline would be progressively the most attractive option for significant quantities of hydrogen delivered, whereas the transport by truck would be preferred for more limited quantities. The hydrogen would then be delivered to the consumers, i.e. the refuelling stations, for hydrogen cars, and the distribution centres, through local hydrogen grids, for the heating needs of individual households, buildings and industry. The refuelling stations would be distributed near urban centres and along mains roads and the distribution centres near urban centres and industrial areas.

5.3 Greek Vision of Hydrogen Chains

The Greek vision for the development of the hydrogen energy market was based on the promotion of the use of domestic energy sources including renewable energy sources (wind, biomass) and domestic lignite utilisation. The vision for 2050 is based on the promotion of the sustainable and CO_2 free production of the hydrogen, supporting the renewable energy sources potentials, the centralised and decentralised hydrogen schemes according to the regional specifications, the non electricity grid connected areas and the achievement of environmental improvement especially in urban areas. The medium for hydrogen production in the transition period will be the utilisation of natural gas with steam methane reforming.

In the entry phase (by 2010) wind energy and electrolysers should be considered as the first applications for the production of hydrogen in local based supply schemes focusing on applications for local supply of hydrogen where the cases of development of demo cases in islands is foreseen as promising option.

In the transition phase (up to 2030), Natural gas will have the primary role in the evolution of the hydrogen market representing a share of more than half of the expected hydrogen production demand for both transport and stationary applications, especially in short and medium time. Centralised Steam Methane Reforming schemes are foreseen as the most economically attractive options where Carbon Sequestration and Storage schemes should be considered in terms of their applicability and viability in large-scale options in national level.

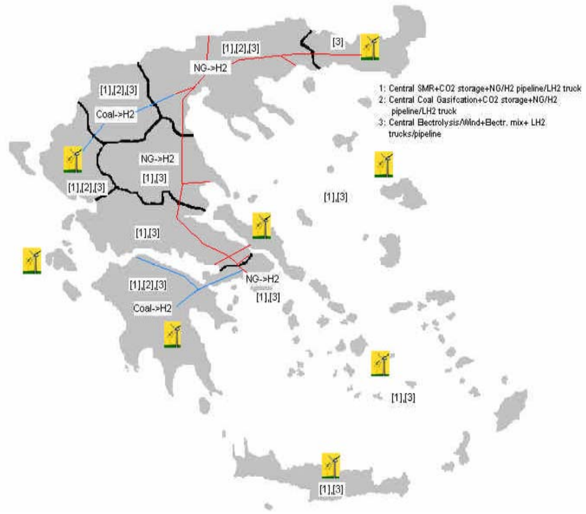


Figure 5.2 *Regionalisation of hydrogen energy chains in Greece*

Lignite gasification for hydrogen production is foreseen to have a limited but continuous contribution to the total hydrogen production, in relation to the market economical characteristics.

The Greek visions promotes the use of Renewable Energy Sources focusing mainly on wind–electrolysis concepts, expecting to achieve a significant position to the hydrogen production with increasing share in the medium – end transition period. In addition, biomass utilisation is proposed to have a relevant increasing share in terms of a quarter of the total hydrogen production based on RES at the end of the time period.

Utilisation of hydrogen - natural gas mixtures in existing natural gas pipelines is expected to be present with a limited role in the early stages of hydrogen utilisation, with separation and supply of hydrogen to end users.

In the vision phase (2030-2050) renewable energy sources is foreseen to undertake the dominant role in the hydrogen production market, presenting a balanced share between centralised and decentralised options. The hydrogen supply infrastructure through the development of pipelines grid will be established taking into account the high population of urban regions. Supportive actions of linking RES electricity production to hydrogen production by electrolysis are foreseen through the use of electricity grid. Hydrogen will be used to transport application followed by stationary applications for households and tertiary sector applications.

5.4 Italian Vision of Hydrogen Chains

The Italian national vision on hydrogen deployment in the future energy market has been outlined through many contacts, meetings and discussions with all the interested stakeholders, where the different points of views have been settled to reach a quite common understanding. To this end the Italian stakeholders are stressing the main drivers are the achievement of a better energy mix and the safety of the primary energy supply, the reduction of the greenhouse gas (CO_2) emissions to meet the Kyoto and future post-Kyoto commitments, the containment of atmospheric pollutant emissions in urban and/or in heavily populated areas, the increase of the renewable sources share for hydrogen production in the long term, the promotion of industrial development in high technology innovative sectors.

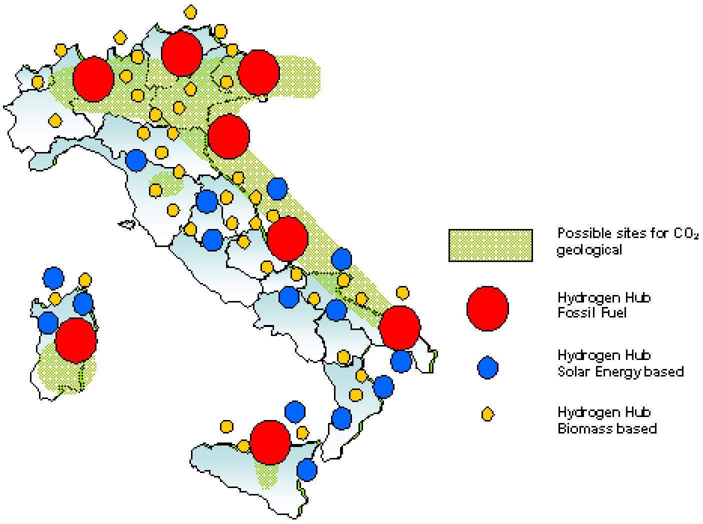


Figure 5.3 *Regionalisation of hydrogen energy chains in Italy*

This requires that the identification of the most effective hydrogen chains both in terms of economy and energy is carried out as one of the preliminary tasks of the national roadmap.

In the short term, i.e. up to 2015, with an hydrogen consumption less than 100 kton, the most important production share is associated to steam methane reforming (SMR) in decentralised plants and the hydrogen is transported by trucks both in liquid and compressed way and where possible mixing the hydrogen in the NG pipelines.

In the medium term (up to 2030) the hydrogen production by fossils will be based both on NG and coal, but in centralized plants where the Carbon Capture and Sequestration can be viable. Such plants that utilize the de-carbonisation technology will allow production of electricity, by a turbo gas fed with a hydrogen rich gas, and hydrogen almost pure stream, for external end user, at the same time. The fossil share will cover about three quarters of the total, as there is a considerable increase of the renewable sources (biomass, urban wastes and wind), while there is the starting of solar demonstration plants of significant size (dozens of MW). The hydrogen is mainly delivered through short-medium range dedicated pipelines (10-50 km) from the centralized production plants, which expand the existing NG pipelines.

In the long term (2050 and beyond, i.e. the vision phase) the hydrogen is made by different sources both fossil and renewable, with the solar having a considerable share. The renewable production will reach about one third of the total, which is valuable in several millions of tons. The renewable production will have its main contribution from wind, with the other renewable options not very far. Viable storage systems will be available to filter the large time variations of renewable sources and fit the hydrogen demand. There is a considerable improvement of the infrastructures, with the pipelines that are built to transport hydrogen up to some hundreds of km from the production site. The final use of hydrogen will not differ from the other countries and will consider transport, residential, and localized (large scale) power generation applications.

5.5 Dutch HyWays vision of hydrogen chains

The Dutch stakeholders in HyWays have developed a national vision of hydrogen energy in the period 2010-2050. This vision takes into account: the availability of industrial hydrogen in Rijnmond area (near Rotterdam); the extensive natural gas grid in the country and the important share of natural gas in the current energy mix; the strong logistics and transport capabilities (for import of feedstocks coal and biomass); the (wavering) political will to promote off-shore wind energy; the availability of huge carbon storage locations; the population densities in the country. Natural gas will play a dominant role up to 2030 in the Netherlands and will also be important up to 2050. On-site reforming from natural gas will be the on-site hydrogen production option of choice for this timeframe. Developing pipeline infrastructure is necessary to achieve further objectives of introducing hydrogen (CCS, renewable hydrogen). Pipeline infrastructure will grow from the existing industrial infrastructure in Rijnmond. Hydrogen to feed this pipeline will initially be produced by additional SMR capacity in the Rijnmond area.

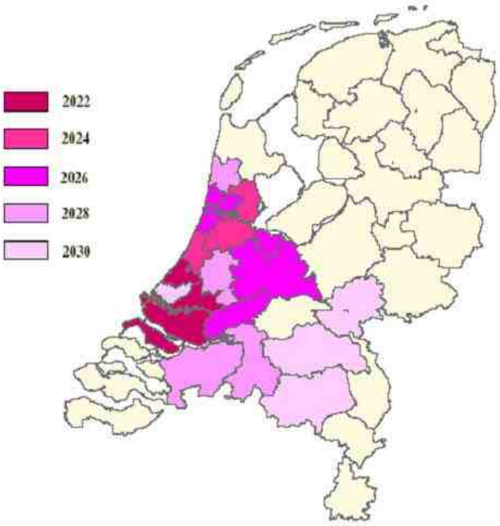


Figure 5.4 *Tentative indicative point in time for profitability to shift from local hydrogen production to pipelines for the Netherlands*

After 2030, biomass gasification and coal gasification with carbon capture will provide hydrogen with low carbon emissions. In the same timeframe, electricity from offshore wind parks will be an important source of renewable hydrogen for the Netherlands. In each case the hydrogen will be distributed via the pipelines.

Hydrogen demand will start in the more densely populated areas, especially for mobility. There will be a regional division between the Randstad (the most densely populated area, containing the main metropolitan areas) and the less populated eastern/northern part of the Netherlands: pipeline infrastructure develops in the Randstad, on-site reforming will dominate in other regions. The fuelling stations will be located near urban centres and along main roads, as well as at industrial areas. Fuelling stations will initially be supplied with on-site reformed hydrogen or liquid hydrogen that is trucked in. Later they will receive hydrogen from pipelines.

5.6 Norwegian Vision of Hydrogen Chains

The Norwegian stakeholders have made some thoughts about a national vision of hydrogen energy in the period 2010-2050. This national vision takes into account: the potential to develop and utilise water electrolysis using the Norwegian electricity mix (92% from renewable sources, i.e. without CO_2 emission); the potential of new renewable energy resources (wind, wave, biomass) which could be mobilized for hydrogen production; the use of Norwegian natural gas for hydrogen production; the use of industrial by-product hydrogen; the regional distribution of chains based on resource availability and population density.

In the entry phase (by 2010), the early energy markets are expected to require small quantities of available hydrogen from industrial by-products or produced by on-site electrolysis, steam methane reforming and biomass utilisation. In the transition phase (2010-2030), the growth of hydrogen demand is expected to expand the range of options for local and regional hydrogen production. Local industrial by-product hydrogen remains an important source. Central production based on fossil fuels is not likely to be present at large scale. Capture and storage of CO_2 (CCS) from natural gas reforming facilities is not envisaged before 2020 at industrial scale. However, this option would be prioritised afterwards, reflecting increased CO_2 taxation and technology maturity.

In the vision phase (2030-2050), renewable electricity to power electrolysis based hydrogen production, and natural gas reforming with CCS is expected to be the dominating sources of hydrogen in Norway. The renewable energy resources would contribute significantly to local hydrogen production in the most favourable regions. This encompasses coastal regions where wind and wave energy would become important sources for hydrogen production by water electrolysis, and biomass utilisation mainly connected to wood waste in southern Norway. Export of hydrogen to other European countries (e.g. Germany and The Netherlands) is part of the Norwegian vision.

Even though the main hydrogen production is envisaged for local and regional use, the transport of hydrogen by pipeline will gradually become a more attractive option for large quantities of hydrogen. Extensive hydrogen pipeline grids in Norway are not expected due to low population density and challenging topographical conditions. The transport by truck would be preferred for more limited hydrogen quantities. The hydrogen would then be delivered to the consumers, i.e. the refuelling stations, for hydrogen cars, buses and trucks. Stationary hydrogen use (for the heating needs of individual households, buildings and industry) is only foreseen at small scale on remote locations.

6. Outlook

This section briefly describes the work currently under way to finalise Phase I, and outline the first steps of Phase II of the HyWays project.

6.1 Current state of affairs and next steps in Phase I

In the first phase of HyWays, the emphasis was on the development and validation of the assessment framework. For each of these member states participating in Phase I, a number of preferred hydrogen pathways have been selected and analysed on various aspects such as costs and benefits, impacts on emissions, energy consumption and impact on fossil and renewable resources. By means of a series of workshops, the results of analysis were discussed within a broad group of stakeholders in order to take into account the stakeholder views as well as to validate the first results.

The following steps are foreseen in the finalisation of Phase I of HyWays:

- Finalisation of the actor analysis. The actor analysis aims to identify critical actors that are involved in the key changes in the energy system resulting from the introduction of hydrogen.
- Identification of open issues not yet covered. The internal and external workshops have revealed a number of issues that have to be tackled in Phase II of the project. Some of these issues defined up until now are:
    - The price gap between hydrogen produced from fossil and renewable resources. A number of factors have to be considered such as the learning curves of renewable resources as well as efficiency and cost development of electrolysers.
    - The development of the demand of goods transported with light, medium and heavy trucks, possibly deviating from the Energy Trends 2030 scenarios.
    - Constraints imposed on the energy system such as the (local and regional) availability of biomass as well as possible limitations of CCS technology, e.g. due to a lack of (local) storage capacity or related to public acceptance.
    - Analysis of the infrastructure build-up. For several reasons, it has not been possible to carry out an assessment of infrastructure build-up and have this validated by the various stakeholders.
- Evaluation of the process as well as contents produced in phase I of the HyWays project. In Phase II, the assessment framework as developed and applied in Phase I will be used again. It is however critical to check if key research questions can be answered and the objectives of the project are met. Possible gaps need to be identified and actions to overcome these flaws have to be taken.
- The development of a common framework to derive a general EU-wide roadmap based on MS-specific analyses, e.g. by identification of the drivers and policy aspects that surpass the developments within the individual MS.

6.2 HyWays Phase II

For six members states, a country specific analysis is performed in HyWays Phase I. In the second phase of HyWays, the process will be repeated for another four member states. The member states to enter into the second phase of HyWays (Finland, Poland, Spain, and United Kngdom) have been selected through a public call for tenders. This call was issued on 6th of August 2005, see www.hyways.de/call. For these additional MS, also a number of workshops will be held where stakeholders are encouraged to deliver input to the process. At the end of Phase II, a final round, including model runs as well as an overall stakeholder workshop, is foreseen in which also minor changes for the MS that have participated in Phase I will be taken into account.

7. Summary

HyWays aims to develop a validated and well-accepted roadmap for the introduction of hydrogen in the European energy system until 2030 and provides an outlook to 2050. In drawing this roadmap, essential assumptions have been made on the penetration of hydrogen technologies, as well as on the driving elements in the system in which the introduction will take place. The results produced in HyWays Phase I are preliminary and subject to changes. Therefore *no validated roadmap can be presented at this time.* Nevertheless some robust conclusions can be drawn at this stage of the project.

- Until 2030, fossil fuels, increasingly with carbon capture and storage (CCS), are expected to be the dominant source for production of hydrogen in Europe, while hydrogen from renewable sources will slowly phase in. In the second phase of HyWays, more attention will be paid to the development of the price gap between fossil fuel based hydrogen and hydrogen produced from renewable resources to identify and discuss the opportunities for an accelerated introducing of renewable hydrogen,
- According to the view developed in the six countries involved in Phase I, hydrogen infrastructure build-up is likely to comprise both central and on-site hydrogen provision,
- The market introduction of Fuel Cell Vehicles hinges to a large extent on the successes in reducing the costs of the hydrogen drive train system. To a lesser extent, the price of hydrogen production and handling, the crude oil price, and the internalisation of environmental damage will determine the penetration of hydrogen in the energy system,
- There is still a large uncertainty with respect to the pace with which hydrogen can enter the market, as well as in the total investments required to bring hydrogen technologies to the market,
- The introduction of hydrogen into the European energy system will cause substantial shifts in employment structure, particularly in the automotive sector. Overall impact may be positive or negative, depending strongly on Europe’s efforts to consolidate or improve its current position in the car market.
- Developing end-visions of the energy system at the country-specific level plays an important role in assessing the future role of hydrogen, as an aid in incorporating socio-political barriers and stimuli for the introduction of hydrogen. The end-visions aim at reflecting views of major stakeholders, and thus create validation of and support for the results of HyWays.

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HYDROGENICS CORPORATION

VATTENFALL

bp

TOTAL

REPSOL YPF

HYDRO

DNV

EDF Electricité de France

Statkraft

acciona Energía

SenterNovem

dena Deutsche Energie Agentur

HELLENIC INSTITUTE OF TRANSPORT

ENEA

cea

ECN Energy research Centre of the Netherlands

IST

IDMEC Pólo INSTITUTO SUPERIOR TÉCNICO

ISI

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ZEW Zentrum für Europäische Wirtschaftsforschung GmbH

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