

HyWays

European Hydrogen Energy Roadmap

BACKGROUND DOCUMENT

BACKGROUND DOCUMENT	
<i>Relevant Work Package</i>	WP3
<i>Author (s)</i>	Luke Murray
<i>Author email</i>	luke@navier.ist.utl.pt
<i>Institution</i>	IDMEC – IST
<i>Unique Ref. number</i>	0001
<i>Date released</i>	19 th November 2005
<i>Intended audience</i>	HyWays partners, Member State stakeholders, and external reviewers
<i>Purpose of document</i>	It is intended to present not only the decisions which have been taken on scenarios and assumptions for wider scrutiny, but also to present technical “open questions” which have yet to be resolved, and suggested actions are presented in this document. It is envisaged that the procedural review components of this document will contribute to the HyWays “toolbox”.

HyWays

European Hydrogen Energy Roadmap

PHASE I

WP3 BACKGROUND DOCUMENT

Framework for Socio-Economic Analysis

Compiled by IDMEC -IST

Executive Summary

This WP3 Background Document collates the procedures, assumptions, and results of HyWays Phase 1. The aim of this is to facilitate a forthcoming review of the Phase 1 technical decisions and operational experiences with the aim of ensuring that lessons learned are implemented and carried through, thus ensuring increased efficiency in Phase 2. HyWays is a large and highly complex undertaking, and as such, periodic situation assessments are seen as an integral part of ensuring the project's ultimate success.

This document presents summaries of a full spectrum of HyWays assumptions and Phase 1 findings. Specifically, these include:

- Modelling framework assumptions
- HyWays scope and scenarios
- Ad hoc task force findings
- Model interface experiences
- Transition Analysis and modelling interface experiences
- Preliminary hydrogen system transition storylines for the 6 Phase 1 Member States

The document is a product of inputs from each of the technical institutes involved, ad hoc task force leaders, and Member State representatives. It is intended to present not only the decisions which have been taken on scenarios and assumptions for wider scrutiny, but also to present technical "open questions" which have yet to be resolved, and suggested actions are presented in this document. It is envisaged that the procedural review components of this document will contribute to the HyWays "toolbox".

Contents

1. Introduction to the Background Document.....	5
2. Assumptions for the Modeling Framework	6
2.1 Scenario Overview	6
2.2 The HyWays Scoping and Policy Framework Report	9
2.3 Scope of the Roadmap.....	9
2.4 Policy Framework Assumptions (not covered in Section 2.1)	10
2.5 Ad hoc Task Force Results	11
2.5.1 Automotive Data	11
2.5.2 Refuelling Station Infrastructure Development.....	11
2.5.3 Energy Scenarios and Prices	12
2.5.4 Taxation.....	15
2.6 Summary of Model Interfaces	16
2.7 Interaction between Transition Analysis and Models	18
3. Rationale for Chain Choice	20
3.1 Synthesis of WP1 and WP2 Reports.....	20
3.2 Summarized Profiling Reports.....	22
3.2.1 Greece (high penetration only).....	22
3.2.2 Italy (high penetration only)	23
3.2.3 Netherlands (high penetration only)	26
3.2.4 Norway	31
3.2.5 Germany.....	33
3.2.6. France	34
4. Annexes.....	38
Annex 1: Scenario Overview.....	38
Annex 2: “H2 Technology Bounds”	50

1. Introduction to the Background Document

Work Package 3 of the HyWays Project assesses the energy system(s), and economic and environmental impacts of the integration of hydrogen markets in the EU. Hydrogen energy chains, selected by Member State representative stakeholders and comprising all segments from production to end-use, are analysed with the use of four quantitative models.

The Background Document summarizes the Assumptions for the Modelling Framework (Section 2) and the Rationale for the Choice of Energy Chains by individual Member States (Section 3).

This document is designed to communicate the main assumptions and developments to date arising from HyWays Phase I to HyWays partners, Member State stakeholders, and external reviewers, for discussion in the near future (*MS Workshops set V, end of HyWays Phase I*). The document also reports systematically on issues that are open for discussion in the mid-term (HyWays, Phase II). These comments are gathered under the heading “Open Questions” in each section. The Background Document is not intended for wider public dissemination and is delivered in conjunction with WP3 deliverables (D3.6-D3.10).

2. Assumptions for the Modeling Framework

2.1 Scenario Overview

A detailed description of the modelling scenarios developed for HyWays Phase I is provided in the document “Overview of Scenario Assumptions” (Annex 1). The summary table below synthesizes these scenarios and updates the principal modifications to the baseline and hydrogen penetration scenarios (as documented in the initial Scoping Report) that have been carried out for the later runs of the MARKAL model in Phase I.

Table 1. Summary of HyWays Phase I Scenario Assumptions (as of July 2005)

1. Baseline Scenario (BAS)		
	Overview	Sources of detailed information
Energy and Transport Demand	<p>Background and assumptions extracted from PRIMES study, using development over time of population size, household patterns and GDP growth as basis for calculation of development of energy demand.</p> <p>Development of transport demand according to PRIMES and modification proposed by Task Force on passenger car techno-economic developments.</p>	<ul style="list-style-type: none"> - “European Energy and Transport Trends to 2030” (PRIMES study) - HyWays Scoping report - HyWays Task Forces (see section 2.5)
Fuel Prices	<p>Assumptions from PRIMES study, extrapolated to 2050, with gas price coupling according to Task Force, no coal price coupling.</p>	<ul style="list-style-type: none"> - PRIMES study - HyWays Task Forces (see section 2.5)
RES (electricity and heat)	<p>Renewable energy targets for 2010 for each MS extracted from Renewables Directive, and extrapolated to 2020 as</p>	<ul style="list-style-type: none"> - Technical Annex to HyWays Scoping report (Renewable targets for 2010 and 2020)

	lower bound.	- EU Renewables Directive
CO₂ Emissions	EU-wide reductions are assumed through “Contraction and Convergence” principle: Global CO ₂ emissions are linearly reduced by 25% in 2050 relative to 1990 emission level.	- Technical Annex to HyWays Scoping report (Policy Framework) - UNEP (2001) United Nations Environmental Program, Climate Change 2001: Mitigation, Working Group III, 3rd Report.
Nuclear	On the scale of the EU there is no growth in capacity, i.e. possible increase in some countries balanced by phase-out in others	

2. Hydrogen Scenarios

	Transport rates	Stationary rates	MS-specific rates
High penetration (H2H)	Market introduction in 2013 with increasing penetration speed to almost 75% in 2050	Market introduction in 2020 period, close to saturation at 10% in 2050	France: mobile, stationary Greece: stationary Italy: stationary
Low penetration (H2L)	Market introduction in 2016 with increasing penetration speed to a little over 40% in 2050	Market introduction in 2020 period	France: mobile Italy: mobile, stationary

3. Alternative Hydrogen Scenarios

	Overview
Baseline with low cost for H2 cars (BLC)	Use of cost decrease without fixed penetration of mobile applications
High penetration with low cost reductions for H2 cars (L2H)	High penetration rates but relatively low cost reduction potential, leaving costs of fuel cell car higher than that of gasoline car
Low penetration with low cost	Like previous scenario with low penetration rates

reductions for H2 cars (L2L)	
4. Alternative Fuel Price Scenarios	
	Overview
Oil price trends	Oil price trends are presumably instrumental in competitiveness of hydrogen technologies, therefore three different price paths are considered, increasing from 2010 onwards to 50, 70 and 100 \$/barrel
Coal and gas price coupling	The production mix for hydrogen depends on the relative prices of different source fuels, and hence coupling of a source fuel price (coal or natural gas) to the oil price may decrease in attractiveness. The following are considered: no, limited, and strong coupling for coal; weak and strong coupling for gas

The principal modifications to the general assumptions of the three central scenarios (plus alternative scenarios) result from the work of Task Forces on transport demand, fuel prices and vehicle industry learning curves (see Section 2.3). The MS-specific penetration rates and boundaries are also modified, full details of these are documented in the Report “H2 Technology Bounds” (Annex 2).

In addition to some general indications of these MS-specific preferences in the HyWays profiling reports, there are several documents produced internally by MS representatives which describe the detailed calculations of penetration rates and hydrogen production bounds (e.g. renewable energy potential for France).

Open Questions

How do penetration rates and production bounds relate to story-lines?

Raised: Institutes meeting, July 18th 2005, London.

Summary: It has been pointed out that the importance of MS-specific end-use and production bounds has been underestimated and should reflect the will of the political and market actors. Qualitative “story-lines” on the development of infrastructure are underway (see Section 3), and more emphasis should be placed on their consistency with penetration rates and production bounds in the future.

Follow-up: In Phase II the MARKAL team will try to convey the importance of this relationship, and the qualitative MS profiling and Actor Analysis be used to address it more closely.

2.2 *The HyWays Scoping and Policy Framework Report*

The HyWays Scoping and Policy Framework Report was published at the outset of the modelling work (October 2004). Its purpose is to provide the partners a basis for discussion. The report contains the following issues:

- scope of the roadmap
- baseline scenario
- initial penetration rates for the stationary and transport sectors
- EU-wide policies under consideration in HyWays

The baseline scenario and penetration rates have been under development since October 2004 and the latest versions are summarised in previous Section 2.1. Section 2.2 summarises the *scope* of the HyWays roadmap and the issues pertaining to the Policy Framework which are relevant to WP3 assumptions and are not covered in Section 2.1 above.

2.3 *Scope of the Roadmap*

2.3.1 Timeframe (present to 2050)

- **2005-2010:** Short-term – Entry Vector
- **2010- 2030:** Medium.-term - Transition
- **2030-2050:** Long-term - Vision

2.3.2 Geographical Coverage

- **Phase I** - country analysis (current participating 6 MS)
- **Phase II** – country analysis (4-6 new MS) + phase I MS results (6 countries) + harmonization of EU-wide roadmap to all remaining EU countries
- **Regarding European hydrogen developments** versus developments in other areas in the world. HyWays assumes learning curves based on the cumulative production of hydrogen technology within Europe only. However, it is acknowledged that prices might decrease faster as the technology is applied in other areas of the world. As a result in

HyWays, it is assumed that developments outside the EU are in line with developments within it.

2.4 Policy Framework Assumptions *(not covered in Section 2.1)*

2.4.1 Baseline Scenario

- **Relevant policy assumptions** derived from PRIMES:
 - Electricity and gas markets are fully liberalised by 2010.
 - Energy efficiency policies at the Member States and the EU level will continue.
 - Ongoing infrastructure projects in some Member States involving the introduction of natural gas will continue.
 - ACEA/KAMA/JAMA negotiated agreements: The 1998 voluntary agreement between the EC and the European automobile industry commits industry to reduce the average CO₂ emissions for all new cars to 140 g/km by 2008.

- **Additional policy assumptions** used in baseline scenario:
 - Bio fuels Directive (2001): targets for bio fuel consumption in EU starting from 2% of total gasoline and diesel consumption for transport purposes in 2005, reaching almost 6% in 2010.
 - Carbon emission trading: globally tradable carbon emission entitlements are assumed from 2010 onwards.
 - Actions relating to the EU White Paper on Transport - the principal measures proposed in the White Paper are pricing (e.g. harmonising of EU fuel taxes, application of polluter pays principle), revitalising alternative modes of transport (railways, waterborne transport, public urban transport) and targeted investment in the trans-European network.
 - Actions related to the EU Green Paper on Security of Supply: in particular, reducing dependence on oil from the current level of 98% by using alternative fuels and improving the energy efficiency of modes of transport, expansion of natural-gas use, maintaining a minimum coal production platform, on-going dialogue with external suppliers, strategic partnership with Russia, development of oil and gas resources, strengthening the supply networks, development of less polluting energy sources and energy saving schemes.

2.4.2 Hydrogen Scenarios

In the hydrogen scenarios no extra policies / policy targets are added to the baseline scenario, hence the results show the direct impact of hydrogen systems (costs, CO₂ and local emissions, security of supply, industrial competitiveness, employment, real consumption and welfare). The interaction of the policy measures in use in the development of hydrogen energy systems is very complex and will be analysed during the project in the light of results. Prior assumptions on the policy measures which provide conditions for the development of hydrogen energy systems is not practical for modelling purposes, since this introduction would alter the analysis of the effects of introducing hydrogen.

2.5 Ad hoc Task Force Results

Ad hoc Task Forces were created to tackle specific issues in the modelling framework. Where issues were found to be sufficiently important or controversial to merit in-depth discussions. The results of these Task Forces are summarized below.

2.5.1 Automotive Data

a. Task Force Participants: Stefan Berger (Opel), Holger Braess (BMW), Gerard Martinus (ECN), Hans Weidner (Opel), Martin Wietschel (FhG-ISI), Jörg Wind (DC)

b. Objectives of Task Force: An analysis of costs, agreement on price development, and confirmation of numbers development for hydrogen vehicles.

c. Results to Date: The development of hydrogen vehicle numbers were confirmed and different price scenarios were developed and agreed.

d. Reference Documents: All documents available in the documentation of the WP3 meetings and workshops.

2.5.2 Refuelling Station Infrastructure Development

a. Task Force Participants: Gerard Martinus (ECN), Ulrich Büniger (LBST), Jörg Wind (DC); Stefan Huggenberger, Philippe Mulard (TOTAL), Enrique Giron (Repsol), Vaso Tsatsami (BP), Holger Braess and Hans-Christian Wagner (BMW Group)

b. Objectives of Task Force: The size and number of service stations that will be needed to distribute hydrogen for its use in the transport sector is an important issue. This will determine the

infrastructure investment necessary and to a large extent the way the hydrogen will be distributed.

There are a number of factors that have to be taken into account when performing an analysis on infrastructure, these include: the range of the automobiles, the predicted volume of cars, the population distribution, etc. The best starting point for these studies is the lengthy experience with conventional fuels.

c. Results to Date: The first approach was to establish two sizes of service stations. One large station with sufficient capacity and fuel for 2,000 cars, and one small station in the 500-car capacity range. The cost of these stations was calculated and introduced in the models. The results of this approach were unsatisfactory. The economic models predicted a much greater number of service stations than expected and an even greater number than the number of actual conventional filling stations. When analysed, the results showed a preference for the small stations, with a significant increase in the number of these stations as the levels of hydrogen fuelled vehicles increased. With conventional filling stations the trend is to reduce the number of stations and increase their size, despite the increase in the fuel consumption.

As a result a further approach was taken using the first as a reference. The models were altered in such a way that the small service station would be the choice for the first years of the analysis (following the HyNet infrastructure analysis), and by 2030, large car filling stations would be used, thus assuming that refueling stations would grow in size. The results demonstrated that the number of cars per filling station remained at approximately 500 for 2020 and 1,000 for 2030. After that, the maximum number of filling stations was set to the actual number of conventional filling stations and it was assumed that the conventional filling stations would also serve hydrogen, rather than having two sets of filling stations, and that the utilization is likely to be similar to current actual values.

d. Reference Documents: WP1/2 WTW Data Collection, Task Force “H2 Station Development”, Holger Braess, BMW, Telcon, 23rd March
Hydrogen Motorway Filling Stations, Jaco Reijerkerk, BEng.
Hydrogen fuelling-station Capacity for Norway, Bellona, 07.04.05, Isak Okjvold

2.5.3 Energy Scenarios and Prices

a. Task Force Participants: The Task Force participants were mostly from the energy and process but also the automobile industry and were represented by Air Products (UK), bp (UK), Hydrogenics (B), Norsk Hydro (N), Repsol (E), Total (F), Vattenfall Europe (D), BMW (D) and

Daimler Chrysler (D) in several telephone conferences, moderated by the institute partners LBST, ECN and FhG-ISI. TF-co-ordinator was Ulrich Büniger.

b. Objectives of Task Force: After discussions had ignited on the rapidly increasing oil price and the expected impact on future energy markets, a consensus among the HyWays partners about the final assumptions on energy prices and suitable reference/hydrogen scenarios should be developed for the 2nd modelling run in Phase I. Specific issues were the modelling assumptions on absolute and relative energy prices (e.g. gas versus oil) and the difference between and tasks of scenario and sensitivity analysis. The TF was used to also discuss further general energy related topics (e.g. dynamics of energy mix).

c. Results to Date: The results reached in 2 telephone conferences on 23 March and 29 April and tentatively presented at the “Reality Check Workshop/3rd General Assembly“ on 18/19 April are presented in brief below:

- **H₂ penetration rates:** Taken from Scoping Report to be accepted/adapted by each MS
- **H₂ pathway bounds:** MS-spec. assumptions from 1st model run to be updated (Phase II)
- **H₂ share from renewables:** at least 20% electricity from renewables after 2020
- **CO₂ reduction goal:** feasibility/impact of 35% by 2050 to be discussed (Phase II)
- **Role of nuclear energy:** frozen to current levels for European average
- **H₂ scenarios and sensitivity analysis:** The following tentative structure was decided to specifically address the oil price discussion.

Table 3. Energy Price Variations & Car Price Variations

		Energy price (= oil price) variations		
		Scenario type	Modified PRIMES	Cheapest H ₂ enters
Car price variations	High H ₂ car price (= 2050 normal car price?)	Baseline	Baseline cheapest	Baseline renewable
		HyWays high	HyWays cheapest H ₂	HyWays renewable H ₂
		HyWays low		

	Low H ₂ car price (= 2030 normal car price?)		HyWays cheapest H ₂	HyWays renewable H ₂
--	--	--	--------------------------------	---------------------------------

(yellow: HyWays scenarios, introduction of hydrogen with penetration rates; blue: HyWays sensitivity analysis, introduction of hydrogen on economic grounds, by variation of car and energy prices)

- **Oil price:** For the reference HyWays scenarios (yellow) it was agreed to choose the low oil prices assumed by PRIMES, in order to avoid endless discussions on non-hydrogen energy issues. To consider the many concerns about rapidly increasing oil prices it was decided to avoid specific oil price assumptions, and instead to carry out sensitivity analysis to identify the break-even of a) cheapest H₂ alternative, and b) cheapest renewable H₂ alternative.
 - **CCS:** Starting year for CCS (all together, conventional + hydrogen): 2020; limitation in 2020-2025: 25 GW of installed plants (all together, conventional + hydrogen); after 2025: no limitations (only sequestration potential may limit the installation of new plants)
 - **Biofuels:** Upper bound of 15% potential for vehicle fuels based on a biomass feedstock potential independent from the fuel (domestic and import, all types of fuels in total on the basis of biomass). MS can set individual bounds.
 - **Coal:** Coal-to-Liquid with and without CCS will be included in MARKAL. Coal price: In the scenario with higher oil and gas prices it is assumed, that the coal price will remain constant until 2030 (original PRIMES assumption) and then increase in 1/3 ratio to the oil price (e.g. oil price increase by 1\$, coal price will increase by 0.33\$)
 - **Natural gas:** deviating from the oil-to-gas price ratio fixed to 100% by energy contents as in the past (PRIMES assumed a gas-from-oil price decoupling by 2020) HyWays bases its assumptions on the results from Cascade Mints: the relative oil/gas price ratio decreases from 1 (today) to 0.67 in 2030 (partial decoupling). HyWays assumes, that the ratio decreases further to 0.50 in the period from 2030 to 2050.
 - **By-product:** It was decided to link both price and CO₂-emissions of by-product hydrogen directly to natural gas. The available potentials depend on MS-specific inputs.
- d. Open Questions:** A yet unanswered question to ECN concerned if PET coke is considered by MARKAL as a cheap alternative to lignite or hard coal.

e. Next Steps: No further steps were decided. The TF could be re-established if new discussions on energy specific issues or the scenario structure should be raised in Phase II.

f. Reference Documents: Presentation by U. Büniger to HyWays 3rd General Assembly, 18/19 April 2005, GE/Garching. Conclusions compiled by moderated Task Force “Energy Scenarios and Prices” moderated by U. Büniger and M. Wietschel on “Main assumptions from the 1st model run and new assumptions for the 2nd model run, Version 5, 11 May 2005.

2.5.4 Taxation

a. Task Force Participants: Member State Representatives with additional comments from Attendees of the 6th Industry-Modeller meeting.

b. Objectives of Task Force: The Task Force was set up in response to a question that arose at the above meeting, namely whether taxation could be included into the fuel prices used in the MARKAL model. Two possible models were proposed. An indirect approach where it is assumed that taxation within Europe would lead to a harmonised position. This was the current status used within MARKAL and as a result taxes were excluded from the modelling process within MARKAL. A direct approach which required an overview of taxes to be provided for each member state. This would have meant compiling information for all fuels (diesel, gasoline LPG etc.) and also data on taxes for purchase, registration and possession of a vehicle. The aim of the task force was to decide on which approach would be the most desirable and practical to achieve.

c. Results to Date: Information and opinions were received from the Task Force members and presented to the HyWays consortium at the GA in Munich in May 2005. The conclusions were as follows: there was differing opinions on whether and when fuel tax harmonisation would occur within European MS. Information on the current status of fuel and vehicle taxes could be compiled by the ms reps. However it was not possible to predict future tax changes (up to 2050) which would be needed for the modelling. Therefore the conclusion was to keep the indirect approach for the MARKAL model runs, but to incorporate elements of this discussion into Work Package 4.

d. Open Questions: The method of interaction with WP4 was not fully established.

e. Next Steps: Discuss with WP4 group whether any additional work is required.

f. Reference Documents: The presentation given at the GA in Munich can be downloaded from the HyWays website.

2.6 Summary of Model Interfaces

The assumptions on the model linkages (both with E3 database and among models) were prepared and documented in detail prior to modelling work in Deliverable 3.2. An updated summary of the final report is found below.

The assumptions on the model linkages (both with E3 database and among models) were prepared and documented in detail prior to modelling work in Deliverable 3.2. An updated summary of the final report is found below.

Introduction: Within HyWays five different models have been used to analyse the HyWays scenarios. The models are working with the same scenario assumptions as described above for the World and European scale as well as with MS specific assumptions. Between the five models linkages have been established to ensure coherence of the data.

Model Framework: The model framework is divided in four different layers: the world & EU scenario, the EU scenario, the MS scenario and the model specific scenario layer.

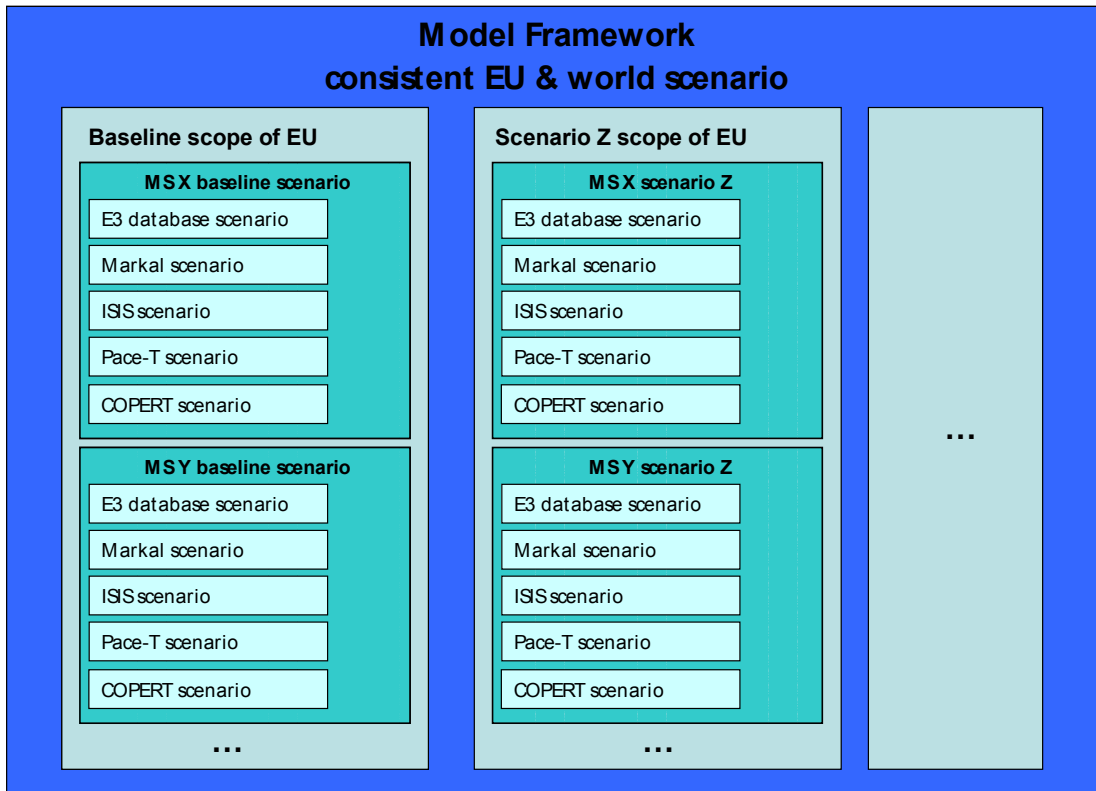
Consistent EU & World Scenario: Within the EU & world scenario assumptions for the overall development for Europe and the world are defined. For detailed information refer to D 3.1.

EU Scenario Scopes: The EU scenario gives the scope of the MS specific scenarios. For detailed information refer also to D 3.1.

MS Specific Scenarios Within the EU Scope: The MS specific scenario is defined within the EU scenario and describes the MS specific situation and development, which are not yet considered in the EU scenario. For detailed information refer to D 3.3.

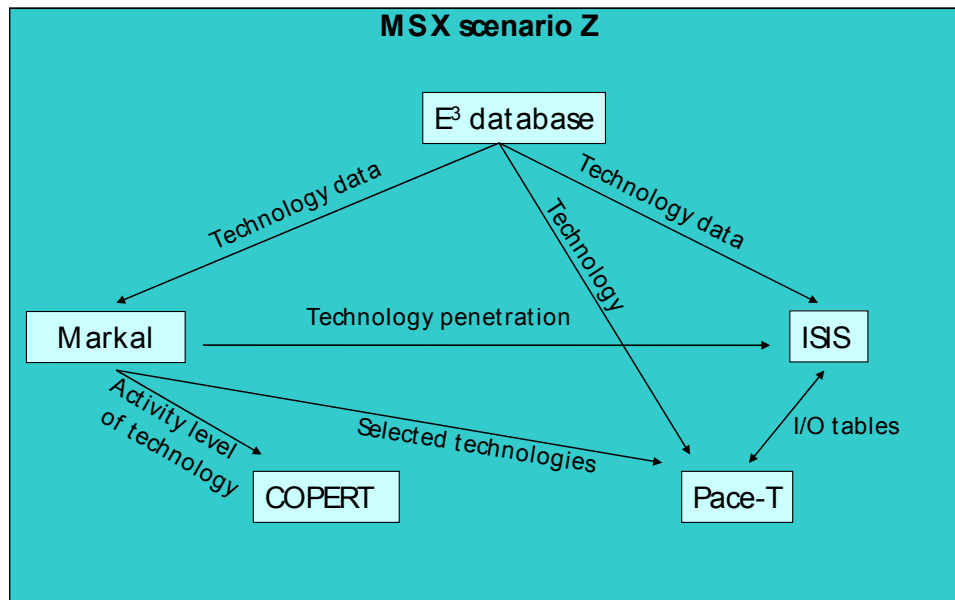
Model Specific Scenarios: Each model needs some specific assumptions. The model specific assumptions do not necessarily affect the other models and therefore will be covered by sensitivity analysis from the single models.

Figure 1. The model Framework Illustrated Schematically



Model linkage: Within each scenario the models have been linked as shown in figure 2 below

Figure 2. Linkages between Model Scenarios



Sensitivity Analysis: The sensitivity analysis of each model has been carried based on the research question of each model and are therefore has not been followed by the other models.

2.7 Interaction between Transition Analysis and Models

Transition Analysis is the collective term for the processes of Member State Profiling, Infrastructure Analysis (IA), and Actor Analysis (AA). These processes focus on qualitative socio-economic and geographical infrastructural elements which are not captured in the main computational models.

MS Profiling reports aim to outline the main issues that are discussed by national stakeholders regarding the present potential, the identified drivers and barriers, and the future vision for hydrogen energy at the national level in a structured way that aids ongoing discussion and provides information which could be used for purposes of comparison. Interaction with models is indirect in that they serve as a source of information and guidance for Member States in selecting their hydrogen chains, as well as acting as a repository of background information for Actor Analysis and Infrastructure Analysis. The structure of the MS Profiling Reports is being revised and improved for Phase 2.

The purpose of Infrastructure Analysis is to address the temporal development of a hydrogen production, transport and distribution infrastructure both at a national and EU level (also including

trans-boundary flows). This is done by taking into account the spatial distribution of both demand and hydrogen feedstock, which is not accounted for elsewhere in the HyWays toolbox. The aim is to develop robust scenarios for hydrogen infrastructure development, which can be proposed and validated by the MS through an iterative interaction process. As IA is part of Transition Analysis, consistency with both Member State Profiling and Actor Analysis is necessary. A feedback loop with MARKAL is also foreseen. IA can contribute to the definition of the shares of utilisation of selected hydrogen energy chains, which constitute an important input to MARKAL. On the other hand, input from MARKAL should be used for all relevant data on the energy system as a whole, such as energy prices and competing use of hydrogen feedstock.

Actor Analysis and its practical application, the Key Changes and Actor Mapping (KCAM) tool, aims to highlight priority requirements for hydrogen chains selected by Member States in a qualitative, structured and systematic manner. Phase 1 focused on the development of the KCAM methodology, the construction of a flexible Access-based tool, and gathering industry input in the formulation of generic system development requirements. Interaction with other models has been limited in Phase 1. In Phase 2 there will be a significantly increased, although indirect, interaction with other models; following the finalization of the methodology and development of the KCAM tool MS representatives will be able to iteratively manipulate qualitative information relating to distinct hydrogen chain elements and use this resource as an additional basis for consideration when selecting chain structures and setting penetration targets and boundaries.

Interactions between Infrastructure Analysis and Actor Analysis are focused on the exchange of MS specific information concerning drivers and barriers for infrastructure development. Examples include geographical hydrogen system development prospects, hydrogen demand and production loci, and political priorities concerning all of the above.

3. Rationale for Chain Choice

3.1 *Synthesis of WP1 and WP2 Reports*

Within the framework of the HyWays Project, the final WP1 / WP2 report presents the energy chains selected for the timeframe up to 2020 by the six involved Member States: France, Greece, Germany, Italy, Norway and the Netherlands.

The objectives of WP1/ WP2 are to propose a set of chains for each MS whose data and hypothesis will be transmitted to WP3 and to calculate for each chain: energy efficiencies, GHG emissions, and levelised costs.

The chains (H₂ production, infrastructure of supply and end use technologies) are selected with consideration of the timeframe, specificities of each country (politic, geographic, etc.) and the existing and projected available technologies and related infrastructure.

In this Section:

- **Selected chains** are presented and described through schemes including the processes used and their links
- **Data** is compiled for the six countries in a synthesis table to underline the common choices and differences
- **Results** are obtained for each MS regarding the different ways of calculation and presentation. At this time results are temporary and need to be improved.

The simulation of the energy chains is realized with the use of the E3 database tool developed by LBST (Germany). Most of the data used was derived from the EUCAR/CONCAWE/JRC study or the GEMIS database. Moreover some data has been specifically adapted or created by MS's. Creating a dataset that feeds into the MARKAL database.

The first results are temporary. However after the WP3 feedback some data and hypothesis were modified or completed and a harmonization of the results was considered.

Where end uses are concerned: All the MS use a vehicle as transport application and the stationary approach depends on the country.

The table below summarizes the chain choices made by each of the Member States.

Table 4. View of the Energy Chains studied by the 6 Member States

		France	Germany	Greece	Italy	Norway	Netherlands
Feedstock	NG	×	×	×	×	×	×
	Electricity	×	×	×	×	×	×
	Biomass	×	×	-	×	×	×
	Waste	-	-	-	×	-	-
	Coal	-	×	×	×	-	×
	By-product	-	×	-	-	×	-
H₂ Production	SMR	Central	×	×	×	×	×
		Onsite	-	×	-	×	×
	Electrolysis from mix electr.	Central	×	×	-	-	-
		Onsite	×	×	-	×	×
	Electrolysis from onshore wind power	Central	-	-	×	-	×
		Onsite	-	×	×	×	×
	Electrolysis from offshore wind power	Central	-	×	-	-	-
		Onsite	×	-	-	-	-
	Gasification of residual wood	×	-	-	×	×	-
	Gasification of waste wood	-	×	-	-	-	-
	Gasification of farmed wood	-	×	-	-	-	-
	Gasification of hard coal	-	×	×	×	-	×
Gasification of municipal waste	-	-	-	×	-	-	
Gasification of biomass	-	-	-	-	-	×	
Distribution	Filling-station	×	×	×	×	×	×
	CHP (FC)	×	×	-	×	-	×
	CHP (ICE)	×	-	×	-	×	-
	Heating boiler	-	-	-	-	-	-
	CCGT	-	×	-	×	-	-

Cells with “-“: not applicable

3.2 Summarized MS Storylines

This section gives an overview of a hydrogen energy implementation storylines for six Member States, as well as reasoning for selection of the hydrogen energy chains. Following general considerations on hydrogen energy implementation, follows a chronological description of how hydrogen energy demand are expected to develop over the years, and how this demand is to be met by production (different chains), where production plants could be located (regional chain distribution), and how infrastructure could develop. The storyline is based on stakeholder inputs and discussions conducted in connection with the MS workshops.

3.2.1 Greece (high penetration only)

The storyline development for hydrogen production in Greece is based on the extended utilisation of Renewable Energy Sources, being the most important options for the hydrogen economy in 2050. RES utilisation will play a significant role in the development of the first applications, while a niche market is foreseen in the remote islands and in areas with important environmental protection goals. Taking into account the highly populated areas in Greece, namely Athens region having almost the half of the Greek population and the relevant hydrogen demand for both transport and stationary applications and under the light of the significant RES utilisation policy, the electricity transmission interconnected grid will be used linking the high RES potential locations with the high hydrogen demand areas, where electrolysers will be installed.

Utilisation of Lignite, which is the only domestic fossil fuel energy source, is also foreseen contributing with a small share of the total hydrogen production. However, the mean for the hydrogen economy transition will be the utilisation of Natural gas, undertaking the most significant role for hydrogen production in the medium term period. Mixing H₂ in natural gas pipelines is foreseen in the early stages of hydrogen utilisation. Solar technologies for hydrogen production are selected as the Greek wild card. In general, the hydrogen economy is aimed to be based on terms of sustainability and environmental friendly methods, favouring the local energy sources.

a. In the Short Term (up to 2015) Development of hydrogen applications in Greek island based on wind parks and electrolysers technological scheme supporting local hydrogen supply. Transport applications cases are considered for that period.

b. In the Medium Term (up to 2020) The main option for hydrogen production will be natural gas reforming based on central production schemes, reaching 82% of the total production. Solid fuels

utilization will be located in the existing lignite mines areas, in the north part of Greece and in the center of Peloponnesse mainly for the supply of local demand.

c. In the Medium Term (up to 2030) This period is characterised by the increased development of decentralized schemes and upgrade of RES share on hydrogen production with a share of 40%. Natural gas has the significant role representing 42% of the total production.

d. In the Long Term (2050 and beyond) The majority of hydrogen production will be based on RES and a share of domestic solid fuels gasification will be also present. Decentralised options are expected to reach 56% of the total production, while RES will contribute to 75% to the Greek hydrogen demand.

3.2.2 Italy (high penetration only)

Hydrogen production will be from both fossil fuel and renewable sources. The trend will be to increase the share of renewable sources in production, aiming at a target of not less than 33% of the total hydrogen production over the long term. When combined with economic and efficiency factors, the hydrogen economy will help achieve Italian national environmental and security of supply goals. Centralized and decentralized systems will allow independence from the primary source hydrogen and will be utilised for traction and stationary applications. In the early penetration phase decentralized Steam Methane Reforming (SMR) will most likely dominate hydrogen production systems as it will be the most economic production method (with no CCS). However, over the long-run all Italian hydrogen production from fossil fuels will be centralized with CCS, mainly owing to environmental constraints. Hydrogen production from renewable sources will focus around biomass, wind and solar. With wind and solar taking a significant role only in the long-term. All these systems will be decentralized with no CCS, even in the case of biomass. The location of hydrogen production plants will take into account economic and environmental criteria. In particular the fossil plants will be located considering the geography of hydrogen demand and the potential to dispose of captured CO₂. Location considerations imply that production plants will be built in the Italian macro-regions. There will be some regional variations depending on the primary energy sources to be used (i.e. with renewable sources, biomass plants will be in the north, while wind plants will most likely have higher shares in the south).

The main option for hydrogen transport will be through pipelines. The main pipeline will rely on the centralised production plants and will deliver the fuel to the most important centres of use (typically metropolitan areas). Hydrogen transport by truck will be viable in the first phase of

deployment, where the lack of wide pipeline networks make this choice possible (although safety limitations may apply).

Viable storage systems are required for hydrogen for two reasons:

- Significant shares are produced by renewable sources whose availability fluctuates in different patterns to the demand for hydrogen.
- Some hydrogen applications are related to locations (mainly islands) where pipeline connection with the main network is neither economically affordable or available.

Hydrogen will be used for the following sectors: centralised electricity production, transport and residential. Centralized electricity production will operate with fossil fuels, using hydrogen or hydrogen enriched natural gas as used normally in high efficiency combined cycle plants. This enables meeting economic and environmental targets, reducing the number of production sites and decreasing the infrastructure for CO₂ disposal. In addition, the use of coal as fossil source alternative to natural gas will give the chance to have another clean source for energy production, while also the security supply will increase.

At the present time Italian legislation is already giving incentives to the use of hydrogen for electricity production, because it is considered an eligible source to have tradable green certificates regardless of the feedstock used to produce the hydrogen.

The transport sector will rely on hydrogen production from fossil and renewable sources (with 40% from centralized and decentralized plants). Road transport will be a lead market for hydrogen systems, with the first applications likely to start in the main cities. The environmental benefits of hydrogen (low atmospheric and noise pollutants at the point of use) make hydrogen vehicles viable for cities. While the reduced distance will make the cost of the filling infrastructures less critical. Public transport, captive car fleets and goods delivery will lead the deployment of hydrogen vehicles. Incentives, environmental laws and regulations will be necessary for the initial take up of the technologies. As vehicle applications for hydrogen become competitive filling infrastructures will be deployed along highways and main roads, creating the conditions for the private consumer to buy hydrogen cars. This is likely to happen between 2020 and 2030, after one million hydrogen vehicles are on the road. By 2050 the hydrogen vehicle fleet will have nearly a 50% share of total and this is expected to increase further with time. In behind the cars, will be other vehicles (such as road and non road including: trains, ships and ferries, fork-lift, etc). These can be developed to use hydrogen and each will have their market. The residential sector will rely on hydrogen applications particularly Combined Heat and Power

capable of achieving very high overall efficiencies. Distributed generation will interest the commercial and industrial sectors where the investment can have a viable payback and at the start and this will be followed by applications in new housing estates, with affordable new infrastructure deployment. For existing housing there will be a lack of interest to switch to hydrogen, as most households already use natural gas.

a. In the Short Term (up to 2010) The production of hydrogen will be less than 100 kton and will be provided mainly from fossil sources in distributed plants. The production cost will range between 3 and 5 €/ kg. Hydrogen for electric energy production will be used in high efficiency combined cycle plant. Methane fuel cells will begin to interest a niche market for distributed generation, for small and medium power applications (PEFC up to 250 kW, SOFC up to 500 kW, MCFC for higher size up to 5 MW). The market will mainly interest UPS where the higher cost can be afforded (telecommunications, hospitals, computer servers, etc.). Hydrogen will be transported by trucks both in liquid and compressed forms, even if many filling stations are producing hydrogen on-site through small SMRs and Electrolysers. The most diffused storage systems will be based on pressure vessels (350-700 bars) or cryogenic tanks. The hydrogen price to the end user will be mainly driven by the production cost and be higher for electrolytic production. IFC vehicles will cover a very limited niche of the total market, with ICE vehicles having a higher share among the hydrogen vehicles. The main applications will be related to fleets normally used in urban areas (captive fleets, LDVs and public transport). Urban buses will be the first hydrogen vehicles and their introduction will be pushed by Local Administrations to reduce the urban pollution. In any case these bus fleets will be the basis to improve the hydrogen vehicle performances to make them competitive for a wider automotive market. The hydrogen will be stored in compressed form in the vehicles (350-700 bars) and this allows ranges of 250-350 km. The filling stations will be mainly located in the urban areas. The hydrogen demand in the road transport will be some tens of thousands of tons. Urban rail vehicles (metro, tram, etc.) will be required to be more and more independent from the electric line, especially for safety reasons and to allow the APU to supply energy for longer periods of time. New prototypes of hybrid traction rail vehicles will be developed based on FC (100-500kW) and energy storage. Watercraft applications will mainly be used for leisure and in protected and touristy areas (e.g. Venice) with onboard hydrogen storage. While the reduction of the size and weight of the FC makes them viable for special aircraft.

b. In the Medium Term (up to 2030) Over the medium term the fossil share of hydrogen production will be reduced to three quarters of the total, focusing on centralized plants with CCS. This implies higher production costs (20-30%). At the same time there will be a considerable increase of the renewable sources (biomass, RSU and wind), including solar demonstration

plants of significant size (dozens of MW). For electric Energy Production hydrogen will be used widely in hydrogen-air combined cycles with CCS. At the same time there is a boost of small and medium size distributed generation plants. Hydrogen will be delivered through short-to-medium range pipelines (10-50 km) from the centralized production plants. New storage technologies will be available and absorbing/adsorbing materials will cover a storage share of about 10%. The hydrogen fleet will be quite large with millions of vehicles and several hundreds of new vehicles per year. The new FC vehicles will increase their range up to similar levels as conventional cars. As hydrogen vehicle performance becomes equivalent to conventional vehicle performance and costs competitive the market will become self-sustaining. As the above systems will be industrialised, with an increase in maximum power. trains will also be designed using such technologies. Power size will increase and enable the application of HFC systems on bigger vessels, with the use of onboard reforming. HFC systems on air transport will be used as backup for more conventional technologies (such as Li batteries, super capacitors, etc.)

c. In the Long Term (2050 and beyond) Over the long term hydrogen production will emerge from a number of sources both fossil and renewable, with solar having a considerable share. The renewable production will be about one third of the total, which will be a level of several millions of tons. For electric energy production new advanced cycles will be available (hydrogen/oxygen) and hybrid cycles will emerge (high temperature FC coupled with turbo-gas systems). Road Transport through hydrogen vehicles will become the preferred choice of the consumers and get a very high share of the market. While with rail transport the series production of rail vehicles will be based on new technologies, with a complete revamping of old trams and metro systems and the dismantling of electric lines. Waterborne transport systems will adopt as wide a use of HFC technologies (up to sizes of 15 MW) as possible. Air transport will also adopt HFC systems as they will become competitive and will substitute other systems.

3.2.3 Netherlands (high penetration only)

Introduction

The basic end-vision for the Netherlands emerged from the first two stakeholder workshops. The MS representative with the help of ECN then produced a tentative detailed regionalisation which specifies types of production plants and distribution to end use options in different parts of the country. This was then presented in the final stakeholder workshop as a *possible* introduction path for hydrogen in the Netherlands

- Natural gas will play a dominant role (also after 2030)

- Decentralised SMR will be the on-site hydrogen production technology in this timeframe
- Pipeline infrastructure is necessary to achieve further objectives of introducing hydrogen (CCS, renewable hydrogen)
- Mixing H₂ in natural gas pipelines enables quick growth of H₂ volume
- Hydrogen pipeline infrastructure will grow from existing (industrial) hydrogen infrastructure
- Additional hydrogen to feed pipelines initially produced by expanded SMR capacity in the Rijnmond (Rotterdam) area (with CCS)
- Biomass gasification and coal gasification with carbon capture will provide hydrogen with low carbon emissions
- (Surplus) electricity from wind will be a source of renewable hydrogen
- Regional division between Randstad (region in the West containing the largest metropolitan areas) and less populated eastern/northern part
- Hydrogen demand will start in the densely populated areas of the Netherlands
- Pipeline infrastructure develops in Randstad, onsite production dominates in other regions
- Initially also liquid delivery in all regions to fuel stations along motorways
- Pipeline network extended later for hydrogen from coal and biomass gasification in Limburg province and Energy Valley (northern provinces)
- Border areas may be linked up to pipelines from Germany and Belgium, sooner than from Randstad. Consistency check with MS Germany needed.

a. In the Short Term (up to 2010) Mobile applications: Hydrogen demand for cars in 2010 is only 17 ton H₂, i.e. less than the capacity of single small-scale reformer as defined in the E3 database. Yet additional capacity needs to be developed to supply hydrogen to fuel stations. Small reformers will be reasonably affordable and the hydrogen price will be competitive (with petrol and other fuels). Part of the fuel stations will be supplied with liquefied hydrogen. This comes from existing liquefaction units (such as those Air Products currently operates).

For the storyline, assumptions are made about the location of the first fleets and the filling stations in 2010 (e.g. five in all):

- **Filling stations in Rijnmond**, which receive hydrogen from the industrial pipeline
- **Filling stations in Arnhem and Amsterdam** with decentral SMR (small-scale)
- **Filling stations in The Hague and Utrecht** served with liquefied hydrogen from central SMR without CCS

- **Chain distribution:** central SMR (without CCS) 30%, decentral SMR (small-size) 40%, liquefied from central SMR without CCS 30%.

Stationary applications: There is very little demand for stationary applications in 2010. A few experiments in Rijnmond use hydrogen from the industrial pipeline (specific project: retirement home Zwijndrecht), and some by-product hydrogen will be used in a few locations (specific project: AKZO PEMPOWERPLANT).

b. In the Medium Term (up to 2020) In this period H₂ demand will not yet be so large that new central production options can become economically feasible. In other words, it is not possible yet to combine large-scale production with a dedicated pipeline infrastructure. Demand is too small (38 kton H₂ for mobile and 32 kton for stationary). The number of on-site reformers increases. Delivery of liquefied hydrogen starts losing out to onsite.

In 2020 6000 MW installed off-shore wind capacity is planned, with on-shore electrolyzers which use surplus-electricity. Assuming that 10% of capacity is used for electrolysis (80% efficiency) during 2000 hours/year, production is 8 kton hydrogen. *[More study of micro-economics needed.]* This is used in IJmond. Hydrogen production with wind is combined with a new SMR plant in IJmond. The pipeline network extends from here into the northern-Randstad (merging with the network extending from Rijnmond).

According to E3, every filling station retails 120 ton hydrogen, so 333 filling stations are needed. But overcapacity is needed, so let's say there is a need for 500 fuel stations that retail hydrogen.
 E.g. 50 stations in Rijnmond supplied from the industrial pipeline
 150 stations on motorways that receive liquefied hydrogen from central SMR in Rijnmond
 300 stations in built-up areas outside Randstad with decentral SMR (small- or medium-size)

Chain distribution: central SMR (without CCS) 30%, wind 10%, decentral SMR (small-size) 40%, liquefied from central SMR without CCS (existing capacity) 20%.

Stationary applications: In 2020 hydrogen demand is $1\% \times 7.000.000$ households $\times 450$ kg/jr = 31.500 ton H₂. This boils down to a number of (newly built) residential areas with microgrid, that receive hydrogen from the existing pipeline in Rijnmond, or elsewhere from decentral SMR (large-size), or from wind hydrogen (IJmond area), or from mix/extraction in the regional natural gas network (neighbourhoods in Energy Valley, 7.000 households).

Chain distribution: central SMR (without CCS) 40%, decentral SMR (large-size) 30%, wind 10%, mix/extraction 10% (which receives hydrogen from small-size central SMR).

Note: part of stationary is also commercial & services (a.o. glasshouses for agriculture).

Assumption: there is very little by-product hydrogen available in this period, and this will be used for other demand (industry).

c. In the Medium Term (up to 2030) In this period the on-site production technology starts being replaced by central production methods. Hydrogen demand increases tenfold to 460 kton (330 mobile, 160 stationary), over twice the capacity of a coal gasification plant or a central SMR plant. It is assumed that one of both will be built. One chooses for central SMR with CCS that increases capacity in Rijnmond/ Randstad, and a coal gasification plant is built on Moerdijk industrial zone, that will serve Brabant province especially. Also a biomass gasification plant is built in Eemshaven (Groningen province). This will serve filling stations (and households) in the north via pipelines. Onsite SMR stays important. And the off-shore wind parks supply more hydrogen from surplus electricity.

Using the same numbers as above, 2500 hydrogen filling stations are now needed, or 3000 when taking care of necessary overcapacity.

- **1200 stations in Randstad** that receive H₂ from the now extended industrial pipeline (mostly supplied from central SMR now mainly with CCS, and a little with wind generated hydrogen)
- **500 stations on motorways** which receive liquefied hydrogen from central SMR (now mainly with CCS)
- **1000 stations in built-up area outside Randstad** with decentral SMR (medium-size)
- **300 stations in the north** served with H₂ from biomass gasification

Chain distribution mobile: central SMR now with CCS 30%, liquefied from central SMR with CCS 10%, decentral SMR (medium-size) 15%, biomass gasification 10%, wind 5%, coal 30%.

Stationary: demand is now 125 kton, or 280.000 households. Households and companies in Randstad receive hydrogen via pipelines; built-up areas outside Randstad are supplied with decentral SMR; neighbourhoods in the north of the country receive hydrogen from biomass gasification transported by hydrogen pipeline; and via mix/extraction with hydrogen from small-size central SMR.

Chain distribution: central SMR now with CCS 30%, decentral SMR (mediums-size) 15%, biomass gasification 10%, wind 5%, coal 30%, mix/extraction 10%.

d. In the Long Term (2050 and beyond) In this period hydrogen demand for mobile applications more than doubles to over 600 kton. Two coal gasification plants are built. If they are used for enhanced coal bed methane production then these plants will be built in De Peel (Brabant) and Limburg (which is convenient for transport of coal by barges). The capacity for central and decentral SMR remains stable, which means the shares go down. Biomass gasification increases: a second plant will be built shortly after 2030 in Ijmond area, which will serve mainly the northern part of Randstad (and Corus steel mills). Capacity for wind surplus electrolysis also increases.

Chain distribution mobile: central SMR with CCS 20%, liquefied from central SMR with CCS 5%, decentral SMR (medium-size) 5%, biomass gasification 20%, wind 5%, coal 45%.

Stationary demand also more than doubles. Decentral SMR and mixing will have phased out. Chain distribution: central SMR with CCS 20%, biomass gasification 20%, wind 5%, coal 55%.

Conclusions for Regional Development of Hydrogen Infrastructure

- **a central SMR plant with CCS** will come into operation in Rijnmond after 2020, and the existing central SMR will be retrofitted for CCS after 2020. The pipeline network extends from Rijnmond into the Randstad
- **a coal gasification plant** will come into operation on Moerdijk industrial zone after 2020, serving a pipeline network that extends into Brabant province
- **a biomass gasification plant** will come into operation in Eemshaven (Groningen province) after 2020, serving a pipeline network that extends into the northern provinces
- **a central SMR plant without SMR** will come into operation in Ijmond before 2020 (retrofitted for CCS later), as well as wind surplus electrolysis facility (off-shore wind parks with electrolyser on shore), and after 2030 also a biomass gasification plant. The pipeline network extends from there into the northern Randstad.

- **two more coal gasification plants with CCS** will come into operation in Limburg and Brabant (De Peel) provinces after 2020, serving a pipeline network that extends into both provinces
- **pipelines** may also extend into the border areas from Germany (Ruhr area) and Flanders (Antwerp)
- **liquefied hydrogen** will be trucked to fuel stations alongside motorways, but this will phase out after 2030

Open Questions

Many questions still surround the natural gas mixing option. These include: mixing in what part of the network: main pipelines, regional pipelines, distribution pipelines? Is mixing and extracting worth the trouble, and at what percentages so? What are the maximum percentages? Can this option compete on price with decentral SMR or dedicated hydrogen pipelines? Further research will be carried out in interaction with NATURALHY. It has been decided to disregard this option in the second run of the model, even though it still is included in the storyline.

Also to be defined: what demand per fuel station is the tipping point?

3.2.4 Norway

The Norwegian stakeholders have made some thoughts about hydrogen energy infrastructure development and chain distribution in Norway. This takes into account: the potential to develop and utilise water electrolysis using the Norwegian electricity mix (92% from renewable sources, i.e. without CO₂ 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.

Even though the main hydrogen production in Norway 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. However, extensive hydrogen pipeline grids in Norway are not expected due to low population densities and demanding topographical conditions. The transport by truck and production at site would thus be preferred for more limited hydrogen quantities, particularly in

the early phases. 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 niche markets on remote locations including islands.

a. In the Short Term (up to 2010) In the entry phase (up to 2010) hydrogen will probably only be used for demonstration purpose. The hydrogen will most likely be supplied from industrial by-products, by on-site electrolysis, steam methane reforming and biomass/waste utilisation. Some transport of compressed hydrogen by truck to the refuelling stations is likely to be seen. No major pipeline transport of hydrogen is expected. Early uses of hydrogen energy are mainly expected to be in personal and public transport, most likely connected to the 800 km long hydrogen corridor HyNor between Oslo and Stavanger. The stationary use of hydrogen produced by wind powered electrolysis is demonstrated on the remote island Utsira as an example of a possible early niche market. Another interesting project is the Hytec project in Trondheim where both mobile and stationary applications are planned to be demonstrated.

b. In the Medium Term (up to 2030) 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 for use of hydrogen energy in the transport market. Natural gas transported as LNG by ships from the North Sea to local on-shore SMR hydrogen production facilities is foreseen. The population in Norway is widely spread and utilizing the electricity grid for water electrolysis could be a possible production path.

Central production based on fossil fuels is not likely to be present at the large scale in this phase. Capture and storage of CO₂ (CCS) from natural gas reforming facilities is not envisaged before 2020 at industrial scale. However, this option will probably be prioritised afterwards, reflecting increased CO₂ taxation and technology maturity.

c. In the Long Term (2050 and beyond) In the longer term (2030-2050), renewable electricity to power electrolysis based hydrogen production, as well as 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 includes coastal regions where wind and wave energy could become important sources for hydrogen production by water electrolysis. Biomass utilisation will probably mainly be connected to wood waste in forestry regions in mid- and southern Norway, and to municipal waste treatment near large cities. Export of hydrogen from central production facilities to other European countries (e.g. with pipeline to Germany and The Netherlands) could become a viable option by 2050.

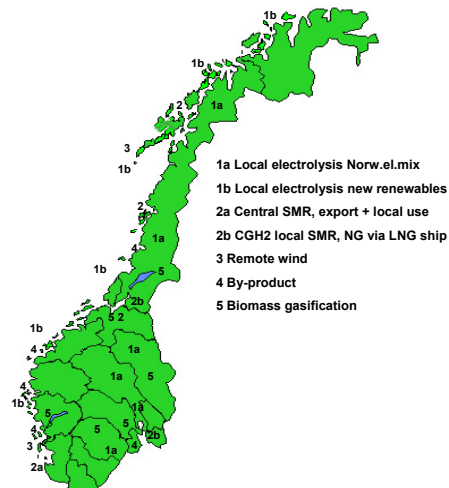


Figure 3: The Regional Distribution of Potential Hydrogen Chains in Norway

3.2.5 Germany

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 H₂ sources from fossil to renewable feedstocks, as well as the different scales of production from onsite to centralised production. In this vision CO₂-reducing or CO₂-free sources should play an important role especially in a long-term view.

a. In the Short to Medium Term (up to 2020) 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 for hydrogen transport and liquid or compressed hydrogen trucks will play a relevant role.

b. In the Medium Term (up to 2030) After 2020 the growth in hydrogen demand is expected to broaden the range of options for local and central hydrogen production. Another H₂ 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.

c. In the Long Term (2030 and beyond) After 2030, hydrogen already plays a major role in supplying vehicles and a significant 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 H₂ 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.

3.2.6. France

The French stakeholders have thought about an intuitive national vision of hydrogen chains 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 CO₂ emission), the potential of renewable energy resources (wind, biomass) which could be mobilized for hydrogen production and the potential of CO₂ storage in sedimentary basins.

Complementary to the national approach, a regional approach has been chosen, dividing the French territory into six large geographical areas (groups of regions), depending on the population density.

These visions, worked out by the French stakeholders, are in line with the orientation of national energy policy. The preferred hydrogen chains represent a compromise taking into account the cost criteria and the need for a substantial reduction of CO₂ emissions, which gives reason to anticipate a future tax on CO₂ emissions.

a. Vision of future hydrogen chains

The French stakeholders have reflected on the possible use of the different hydrogen chains for the time horizons given by the project. Based on the knowledge of experts the potential market shares of the different hydrogen supply chains have been estimated. The following table shows a matrix of the hydrogen supply chains as required by the HyWays project.

Table 5: Future use of hydrogen chains

		Entry	Transition		Vision
No	French Chains for Hydrogen Supply	< 2010	2010-2020	2020-2030	2030-2050
1.a	On-site or central SMR ¹ + CGH ₂ ² or LH ₂ ³ trucks	40	20	0	0
1.b	Central SMR + CGH ₂ pipeline	10	10	0	0
1.c	Central SMR + CO ₂ storage + CGH ₂ pipeline	0	5	30	20
2.a	Central Electrolysis + French Electricity Mix + LH ₂ trucks	0	15	15	10
2.b	Central Electrolysis + French Electricity Mix + CGH ₂ pipeline	0	0	5	10
3	On-site Electrolysis + French Electricity Mix	50	40	30	30
4	Regional Biomass Gasification + CGH ₂ trucks or pipeline	0	5	10	10
5	On-site Electrolysis + dedicated wind electricity	0	5	10	10
6	Central HTE ⁴ or TCC ⁵ + CGH ₂ pipeline	0	0	0	10
	Total	100	100	100	100

- 1) Steam methane reforming
- 2) Compressed gaseous hydrogen
- 3) Liquefied hydrogen
- 4) High temperature electrolysis
- 5) Thermo chemical cycles

As it can be seen from the table, the entry phase (until 2010) presents the first markets for hydrogen energy, particularly to be found within the transportation sector (captive fleets, public transport...). The transition phase covers the time span from 2010 to 2030 preceding the vision phase from 2030 to 2050.

In the entry phase, the early markets would require small quantities of hydrogen produced by steam methane reforming (SMR) (chains 1a and 1b) or water electrolysis (chain 3), 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 new options would be central electrolysis (chains 2a and 2b), biomass gasification (chain 4) and on-site electrolysis based on wind energy (chain 5). The capture and storage of CO₂ issuing

from central SMR installations (chain 1c) would not be envisaged before 2020 at industrial scales. However, this option would be privileged afterwards, assuming a dissuasive CO₂ taxation.

In the vision phase (2030-2050), the development of nuclear high temperature reactors allows for the consideration of CO₂-free and high yield mass production of hydrogen, based on high temperature electrolysis or thermo chemical cycles (chain 6). These long term options will be evaluated during the second phase of the HyWays project.

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 use of existing natural gas pipelines to transport hydrogen is envisaged for the transition phase and will be evaluated during the second phase of the HyWays project.

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 main roads and the distribution centres near urban centres and industrial areas.

b. Regional long term vision

For the long term vision (2030-2050), the French stakeholders have additionally developed a regional approach for the development of hydrogen chains in French areas with different population density, energy resources and infrastructure.

High population density areas

SMR would be favoured in areas with large population density (Centre-North and South-East of France), when hydrogen demand is high and CO₂ geological storage feasible at large industrial scale. The existence of sedimentary basins near Paris and in South-East of France supports this scenario, leading to minimised costs of CO₂ transport.

The alternative production process would be central water electrolysis using the French electricity mix. However, the use of this option would depend on its economic competitiveness compared with SMR (including CO₂ transport and storage).

For the supply of limited quantities, hydrogen could be produced by water electrolysis on-site at refuelling stations and distribution centres, using the French electricity mix or dedicated wind electricity. Moreover hydrogen could be produced by regional biomass gasification and delivered to the point of use by truck or pipeline.

By 2050 the emergence of innovative high temperature nuclear reactors could allow a massive production of CO₂-free hydrogen on a national scale.

Low population density areas

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 CO₂ transport and storage costs.

The renewable energy resources would contribute significantly to local hydrogen production in the most favourable regions. Particularly, water electrolysis based on wind energy in Brittany and Normandy and biomass gasification in East and South-West France have been envisaged.

4. Annexes

Annex 1: Scenario Overview

G.H. Martinus, ECN Policy Studies

Scenario Overview

In the MARKAL model results, three central scenarios are discerned. The baseline scenario provides a view of the future against which the introduction of hydrogen into the energy system may be gauged, and in a way provides a 'business-as-usual' view. Then there are two hydrogen penetration scenarios, which from a modeling perspective lay on top of the baseline. One of these, called the 'HyWays High' scenario, gives an optimistic view of the future of hydrogen. The other one assumes a less pronounced introduction of hydrogen, and is accordingly called the 'HyWays Low' scenario. In this chapter, the key assumptions on the scenarios are described.

BAS: Key Baseline Assumptions

As MARKAL is a demand-driven model, the most relevant inputs defining the scenario are the development over time of the demands for energy services. Such developments are determined to a large extent by macro-economical parameters, such as growth in Gross Domestic Product (GDP, population size and composition). On a somewhat higher level of detail, at the level of technologies satisfying the demand for energy services, the prices of primary fuels becomes quite determining. Finally, policies on technological deployment or effects thereof (e.g., greenhouse gas emissions) will be instrumental in the (technological) build-up of the energy system. On each of these issues, particular choices were made for the baseline, which are discussed below.

Drivers for Demand

In the initial phase of the HyWays project, it was decided that for the macro-economic parameters, a close link to existing European outlooks is preferable, and hence it was decided to use assumptions on these key drivers that are consistent with those in the PRIMES model (EC, 2003). For the annual growth of the per-capita GDP value, a gradually decreasing trend is projected. On the level of the individual Member States (MS) participating in the first phase of HyWays, this is illustrated in the Figure 0.1. Most MS show a slow decrease to a level in the range between 1.5% (Norway) and a little under 2% (1.93%, Netherlands); only Greece remains at a level considerably above the 2% level. In a way, Greece may be viewed as representative of the newer EU members, with relatively high growth (yet low absolute value).

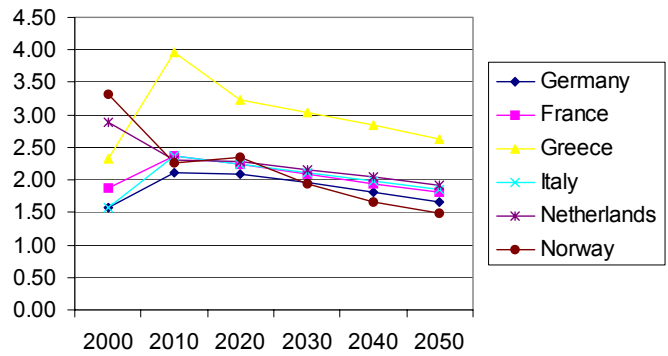


Figure 0.1 Projected growth of GDP per capita for the six ‘Member States’ currently participating in HyWays

In the residential sector, a major driver is the population size, as it is a determining factor in the overall demand for energy services. For this driver, in principle the projection from the UNFCC is used, which are available on the internet (<http://www.un.org/esa/population/unpop.htm>). In practice, the numbers quoted in (EC, 2003) were used, and extrapolated beyond 2030. The resulting projections for the six countries in the first phase of the HyWays project are given in Figure 0.2. Aside from the total population, the population’s composition contributes to the determination of residential demand. The average household size is taken as reflection of this, and is given in Figure 0.3.

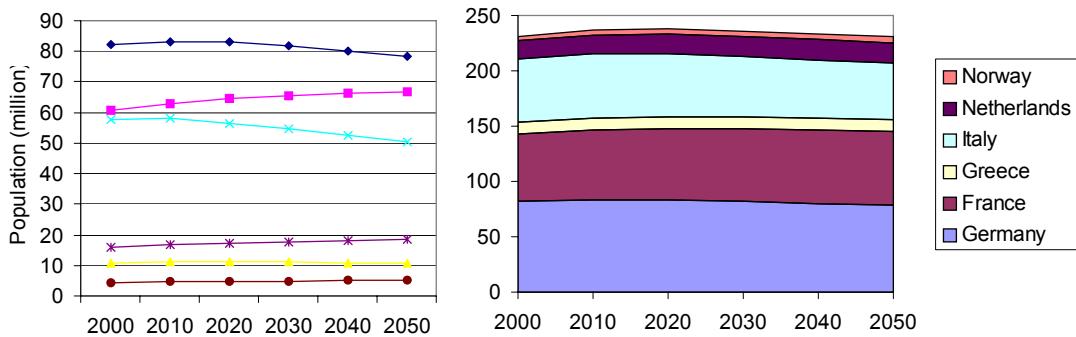


Figure 0.2 Projected population size in the six selected Member States, per country (left) and summed total (right)

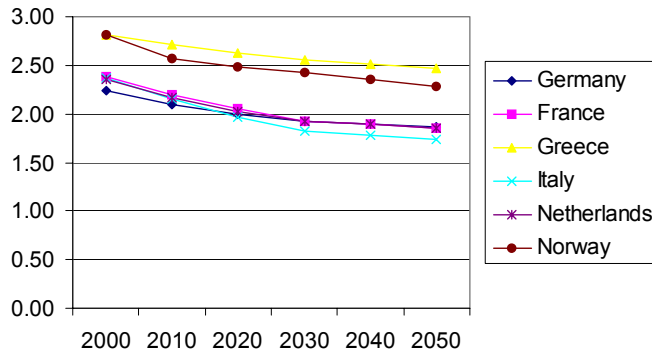


Figure 0.3 Projected average household size in the six selected Member States

Prices of Fossil Fuels

A second group of driving parameters consists of the prices for resources, and in particular the prices of fossil fuels. As mentioned before, the basis for the HyWays assumptions should be that they should exhibit close correspondence with the assumptions underlying recent EU-studies, and in particular the EU Outlook. This is realised by assuming modest growth in the oil price from 2010 onwards, after an initial decrease from 2000 to 2010. With such an assumption, illustrated in Figure 0.4, a close link with the projections given in (EC, 2003) is retained. The figure also shows the assumptions on the two other major classes of fossil fuels, gas and coal. For the gas price a slightly different price projection is used than one directly based on (EC, 2003), as the industrial partners in the project suggested a weakening link between the gas price and the oil price as the latter increases.

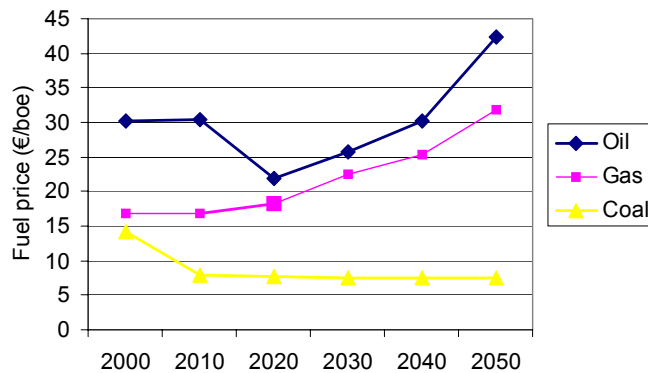


Figure 0.4 Fuel price projections in € per barrel of oil equivalent (boe) based on (EC, 2003), see text for further explanations

Technology oriented policies

RES target

The main policy instrument playing a role for the power sector is the target set for the contribution from renewable resources from 2010 onwards. The EU provides targets at the level of Member States, but for MARKAL are currently implemented as one overall target that will be met. As MARKAL includes Norway (as well as Iceland and Switzerland) in the energy system, the targets are somewhat deviating from those for the EU15. In Table 0.1, the numbers for the contribution from renewable resources in the power sector are given. The numbers are taken from a compilation drawn up by ISI/ Fraunhofer, which in turn is based on the *European Energy and Transport Trends* (EC, 2003).

Table 0.1 Target for the contribution of renewable resources to the power production

[%]	WEU	Germany	Italy	France	Greece	Netherlands	Norway
2010	25.3	12.5	25.0	21.0	20.1	9.0	
2020	30.8	20.2	29.2	23.1	22.3	10.7	99.0
2030	30.8	20.2	29.2	23.1	22.3	10.7	99.0
2040	30.8	20.2	29.2	23.1	22.3	10.7	99.0
2050	30.8	20.2	29.2	23.1	22.3	10.7	99.0

CO₂-emission target

As the EU has clearly committed itself to Kyoto, and currently is working on formulating a post-Kyoto strategy, it is likely that beyond 2012 some policy on the emission of greenhouse gases is adopted. There is however still a large uncertainty as to the actual policy to be implemented in the post-Kyoto era. The only clear aim is a maximum of 2°C rise in global average temperature.

In line with recent projections of the IPCC (UNEP, 2001), such a target may be warranted by reducing global CO₂ emissions 25 percent in 2050 relative to 1990 levels (contracting). Furthermore, distributing the burden of emission reduction enforces a uniform per capita allocation of emission rights across all people in the world by 2100 (convergence). This is realized by linearly adjusting countries emission allocations per capita from 2010 onwards. This is acceptable for industrialized countries with currently high per capita emissions and acceptable for countries with currently low per capita emissions due to the long run uniformity. The resulting target, shown in Figure 0.5, has been agreed upon in the HyWays consortium.

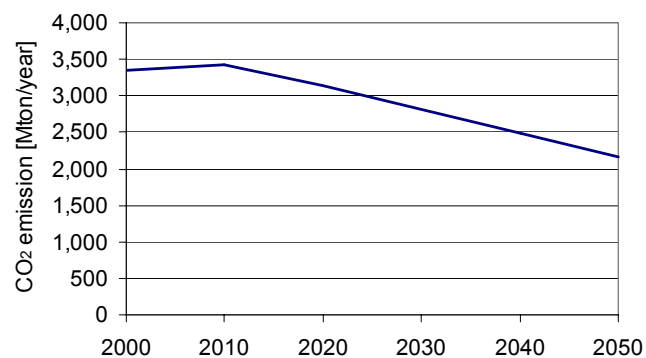


Figure 0.5 CO₂-emission target for the WEU region, reaching a reduction of 35% in 2050, with respect to the 1990 reference value

Nuclear target

As a strong target for CO₂-emissions is assumed, there may be a push towards nuclear energy. Presently, given the relatively low price levels for the fossil resources, such a push seems not very likely. However, to ensure that all scenarios share a common understanding of the socio-political potential of nuclear energy, it was decided to include a representation of policies for nuclear technologies in the baseline assumptions. It is unlikely that a uniform policy on the nuclear option will take shape. Nevertheless, by assuming that the current level of 130 GW nuclear power installations will be an upper bound to the WEU region, some representation of the mixed country-specific policies is drawn up. The upper bound represents contradicting policies, where some countries are striving for a phase-out of nuclear power generation on the long term, while others are likely to remain oriented towards a considerable contribution from nuclear technologies. On the scale of the region as a whole, the trends are assumed to more or less balance out.

H2H: High penetration of hydrogen

End-use applications

The second of the three central scenarios is one where the changes for hydrogen are capitalized upon, and consequently hydrogen takes off to become a major energy carrier. This is primarily driven by a penetration of hydrogen technologies in the transport sector. Substantial technological improvement facilitates the market introduction of both internal combustion engine (ICE) hydrogen cars, as well as fuel cell (FC) cars. The introduction leads to additional cost reduction through 'learning-by-doing'. At the same time, conventional technology sees little improvement,

so that between 2020 and 2030 the FC car becomes cost competitive. Both the penetration rate of hydrogen cars (ICE and FC), as well as the costs of hydrogen cars is given in Figure 0.6.

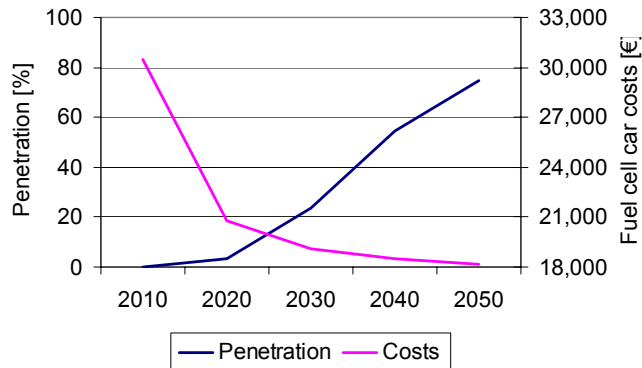
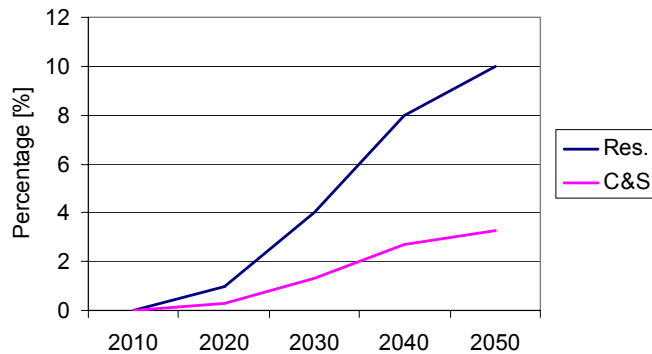


Figure 0.6 High penetration rate for automotive hydrogen technologies, and associated cost projection for a hydrogen powered fuel cell car (H2H scenario)

Aside from the transport sector, opportunities for hydrogen in the built environment appear. In the residential and commercial sectors, hydrogen is used as feedstock for de-central combined heat and power (CHP) installations. As this requires a substantial and fine mazed grid, and is in direct competition with electricity, a lesser penetration is foreseen in these sectors. The penetration, in



terms of percentage of households or companies using a hydrogen CHP-installation, is given in Figure 0.7.

Figure 0.7 Percentage of household and companies using a hydrogen fuelled combined heat and power installation in the high penetration scenario (H2H)

The penetration of vehicles, as well as that of CCHP-installations, has been defined on the European level first, providing a guiding value for the Member States. In some cases, individual Member States see somewhat different opportunities for their respective country. In table 0.2, an overview is given for the countries having distinct penetration rates for end-use applications.

Table 0.2 End-use applications with country-specific penetration rates in the high penetration scenario (H2H); see (Contestabile, 2005) for numbers

Country	Transport	Residential	Commerce & Services	Power production
France	*	*	*	
Greece		*	*	
Italy		*	*	*

Production technologies

As mentioned, the hydrogen economy is primarily demand driven, by which is meant that the demand for hydrogen determines the contribution of hydrogen to the energy system. Thus, the production of hydrogen is not a free variable, and at first sight it would seem that there is no reason to set restrictions to specific production options. This particularly would seem so, as MARKAL is an optimising model, generally used to project the most cost-effective way of producing energy carriers.

In reality, the situation is more complex, as there may be several reasons why specific options may experience limitation, be it physical (such as feedstock application) or socio-political (such as acceptance, or willingness to support a specific technology). The Member State representatives were asked to comment on possible limits during and after the definition of the hydrogen pathways, and in particular in reaction to the first round of results. This has led to limits of various level of detail, as can be seen from Section 2.1, where an overview of the country-specific bounds on technologies is given.

The table shows whether a Member State foresees factors limiting the deployment of certain technologies (the column market 'Up'), and also whether there is some minimum in the deployment of a technology, for example due to political demands (the column market 'Low').

Limits may be defined for some specific technologies, or for all hydrogen production technologies. This is indicated in the table through the use of 'Some' and 'All', respectively. The column marked 'By-product' indicates whether the country foresees availability of by-product hydrogen, in which case the potential always serves as a maximal limit.

Table 0.3 Country-specific limits on hydrogen production options

Country	Low	Up	By-product
Germany	Some	None	Yes
France	None	Some	Yes
Greece	None	None	No
Italy	Some	None	No
Netherlands	All	All	Yes
Norway	All	All	Yes

H2L: Low penetration of hydrogen

Between the two penetration scenarios, the only difference in the set-up of the cases is in the end-use applications. The limits on production technologies differ only in absolute value, so that the overview in Section 2.1 also holds for the low penetration case.

End-use applications

The third central scenario is somewhat of an intermediate between the pessimistic baseline view, and the optimistic high penetration scenario. It has a rather modest penetration of hydrogen technologies, again mostly in the automotive sector, as is illustrated in Figure 0.8 and Figure 0.9 furthermore shows that the slower penetration results in a slower cost decrease, and the date by which the FC cars become cost-competitive is delayed by some ten years.

For this particular scenario, some Member States have set additional country-specific penetration rates, as can be seen from comparing Table 0.4 with

Table 0.2.

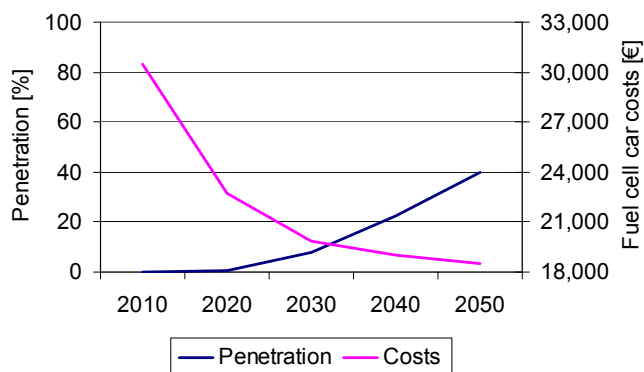


Figure 0.8 Low penetration rate for automotive hydrogen technologies, and associated cost projection for a hydrogen powered fuel cell car in the low penetration scenario (H2L)

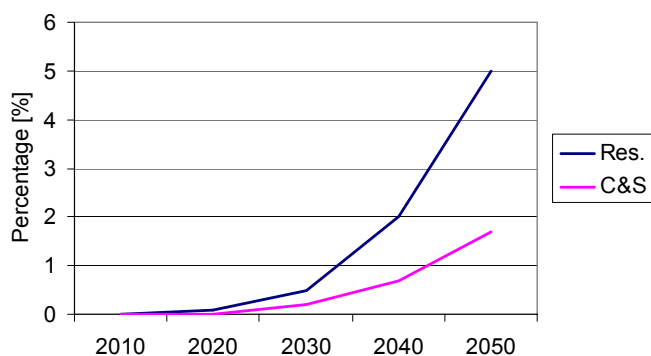


Figure 0.9 Percentage of household and companies using a hydrogen fuelled combined heat and power installation in the low penetration scenario (H2L)

Table 0.4 End-use applications with country-specific penetration rates in the low penetration scenario (H2L); see (Contestabile, 2005) for numbers

Country	Transport	Residential	Commerce & Services	Power production
France	*	*	*	
Greece		*	*	
Italy	*	*	*	*

Alternative scenarios

Aside from the three central cases, a number of alternative scenarios have been defined. Most of these are in principal specific for the MARKAL model, as they are developed to study the dependence of the outcomes on particular model assumptions. A few others will serve as consortium-wide alternatives that are also incorporated in the macro-economic models. One stands out, which is a variation of the baseline, where cost decrease for the hydrogen cars from the HyWays high scenario is assumed. They are discussed here in reverse order.

BLC: baseline with low costs for hydrogen cars

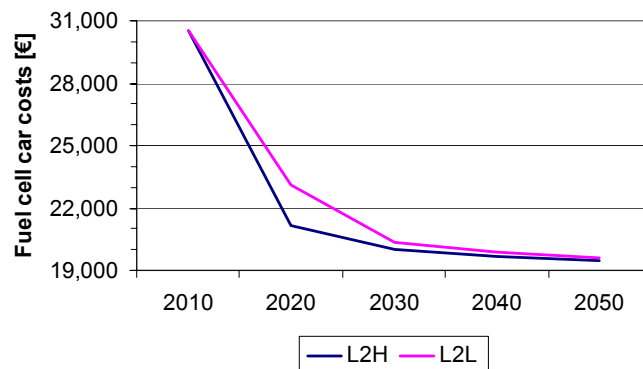
In this scenario, the assumptions on cost decrease of hydrogen cars from the HyWays high scenario are included, without the penetration rates from that scenario. The resulting scenario is rather unrealistic, as the basis for the cost decrease is missing. The penetration rates in a way are a reflection of the willingness to ensure the onset of mass production for hydrogen vehicles. If this aspect is missing, there is no reason why the initial investments needed to get the vehicle ready for market introduction are made. All in all, this scenario is likely to be dropped in the final analysis due to this inherent inconsistency.

L2H: High penetration with small cost decrease

The standard HyWays high scenario takes a rather optimistic view on the possible cost decrease for the hydrogen fuelled cars. An alternative, where the potential reductions are considerably less sizeable, has been developed by car industry to study the impact of technological improvements. The resulting costs are shown as the curve marked 'L2H' in Figure 0.10. The estimation of the potential cost decrease is the only difference between this scenario, and the central case denoted by H2H above.

L2L: Low penetration with small cost decrease

A case very similar to the previous one is the scenario where the low penetration rates are assumed to hold, but the technological progress again leads to less cost improvements than the



central case. Instead, the costs develop according to line marked 'L2L' in Figure 0.10.

Figure 0.10 Hydrogen fuel cell car costs for the L2H and L2L scenarios

Oil price scenarios

The oil price is thought to be a likely candidate for influencing the changes for a hydrogen economy. In particular, knowing that the major contributors to the production of hydrogen are fossil fuel based technologies, a change in oil price may have considerable impact on the shaping of the hydrogen system. Therefore, a number of sensitivity analysis cases are run, with oil prices in 2050 ranging between 50\$/bbl to 100\$/bbl. The 50\$ run might seem superfluous, but as the price developments in the Task Force on Energy Scenarios and Prices are used, it really isn't.

In all sensitivity scenario the coupling of the gas price to the oil price from the baseline is used, i.e. a gradually decreasing coupling of the price increases. For the coal price, two options are investigated. In one case, the coal price is kept constant at the baseline level. In the other set of runs, the oil price is assumed to be coupled to the coal price, through a virtual coal-to-liquid (CtL) process. The latter scheme is implemented by assuming a break-even point for CtL at an oil price of 30\$/bbl, with coal production costs at 7.5\$/boe at this price, leading to a process price differential of 22.5\$/boe for coal.

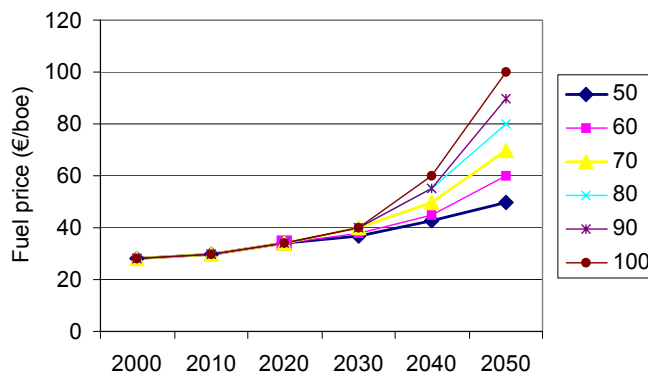


Figure 0.11 Oil price projections in the sensitivity analysis cases

References

UNEP (2001): United Nations Environmental Program, Climate Change 2001: Mitigation, Working Group III, Third Assessment Report. Section 1.3.1.

EC (2003): *European Energy and Transport – Trends to 2030*. Office for Official Publications of the European Communities, Luxembourg.

Annex 2: “H2 Technology Bounds”

Specifying bounds to reflect socio-political and physical limits to the deployment of H₂ production and handling technologies

G.H. Martinus, ECN Policy Studies

Introduction

A major part of the preparatory work for the HyWays runs, and specifically for the MARKAL model, lays in the specification of limits to some or all pathways. Such limits may either stem from the socio-political framework, or from physical restrictions. In the MARKAL model, such limitations can be included in the form of bounds, limiting the penetration of a particular option from either below or above, or both.

In this document, first the role of bounds for hydrogen technologies in MARKAL will be briefly summarized. The aim of the summary is to serve as a background for the specification of the bounds, in the next two sections. Two sets of bounds may be needed, reflecting optional (and indeed utilized) differences in the specifications of the bounds. These differences are due to differing total H₂ production levels stemming from the two sets of penetration rates (high and low). Finally, some reflections on the type of bound (absolute versus relative) are given.

Background on bounds in MARKAL

The hydrogen pathways extend from hydrogen production to consumption, possibly sharing amongst each other certain elements. For example, many of the pathways describing separate production options end up in one specific consumption option, a hydrogen fuel cell passenger car. In such cases, a limitation on the number of fuel cell passenger cars serves as a bound on all pathways involved. At the same time, it does not serve as a limitation of a specific production option involved, particularly as such an option may have other end uses of hydrogen (stationary). Thus, it should be clear that in the end the bounds should basically be defined for technologies, not for pathways, at least for the purpose of serving as MARKAL input.

For the end use technologies, a specification of bounds was given already in the Scoping Report, in the form of penetration rates. These give the rate by which the end use technologies can and will be introduced into the market, reflection both the physical limitations from the built-up of

production facilities, as well as the socio-political willingness to invest in what in the beginning may be non-competitive technologies. The rates are reported on in the scenario overview document.

For the production options, as well as for some selected transport and handling options, for some of the MS involved bounds were provided by the some MS representatives. These bounds may be dependent on the penetration rates of end-use technologies, as these will lead to varying overall hydrogen production levels. If the bound is a reflection of underlying (physical) limitation to a technology, a change in overall production may result in different bounds, as indeed three out of six countries have assumed will occur. Germany, the Netherlands and Norway have specified production bounds depending on the penetration scenario.

Technology bounds for the high penetration scenarios

Production Technology	2020	2030	2040	2050	Unit
Germany					
By-product	P < 6 PJ/y	P < 6 PJ/y	P < 6 PJ/y	P < 6	PJ/y
Biomass gasification ¹⁾	S < 15	S < 15	S < 15	S < 15	%
Wind electrolysis	2.29 < S	14.62 < S	6.29 < S	4.56 < S	%
Electrolysis, central+on-site	5 < S	5 < S	5 < S	5 < S	%
France					
By-product ²⁾	P < 2.2	P < 2.2	P < 2.2	P < 2.2	GNm ³ /y
Biomass gasification ³⁾	P < 4.43	P < 13.3	P < 20.4	P < 34.6	TWh
Wind electrolysis ³⁾	P < 2.33	P < 7	P < 14.73	P < 30.2	TWh
Greece					
Renewable	< 5.2	< 6.5	< 12.3	< 12.3	%
Lignite Gasification	< 0.9	< 1.4	< 1.4	< 1.4	%
Biomass Gasification	< 2.0	< 4.8	< 7.6	< 7.6	%
Italy					
Wind electrolysis ⁴⁾		6.17 < S	12.33 < S	18.5 < S	%
Biomass gasification ⁴⁾		1.67 < S	3.33 < S	5 < S	%
Waste gasification ⁴⁾		3.33 < S	6.67 < S	10 < S	%
Netherlands⁵⁾					
By-product ²⁾	P < 0.005	P < 0.005	P < 0.005	P < 0.005	GNm ³ /y
De-central SMR ⁵⁾	25 < S < 35	10 < S < 20	5 < S < 20	1 < S < 9	%

Wind electricity	5 < S < 15	1 < S < 9	1 < S < 9	1 < S < 9	%
Coal gasification ⁵⁾	0 < S < 5	25 < S < 35	35 < S < 45	40 < S < 50	%
Central SMR+CCS	0 < S < 5	25 < S < 35	25 < S < 30	15 < S < 25	%
Biomass gasification	0 < S < 5	5 < S < 15	10 < S < 20	15 < S < 25	%
Existing central SMR ⁵⁾	35 < S < 45	0 < S < 5	0 < S < 5	0 < S < 5	%
Liquefaction	15 < S < 25	5 < S < 15	2 < S < 12	1 < S < 9	%
Norway					
By-product ²⁾	P < 0.9	P < 0.9	P < 0.9	P < 0.9	GNm ³ /y
On-site mix electrolysis	20 < S < 40	30 < S < 50	30 < S < 50	25 < S < 45	%
On-site wind electrolysis	5 < S < 10	10 < S < 15	10 < S < 20	10 < S < 20	%
Central SMR to export	0 < S < 0	5 < S < 10	5 < S < 10	5 < S < 10	%
Regional SMR from LNG	15 < S < 30	10 < S < 25	10 < S < 20	10 < S < 20	%
Remote wind electrolysis	0 < S < 5	0 < S < 5	0 < S < 5	0 < S < 5	%
Biomass gasification	2 < S < 100	5 < S < 100	5 < S < 90	5 < S < 62	%

¹⁾ Maximum on use of biomass in the transport sector (including hydrogen use).

²⁾ Defined as absolute number in "HyWays - Current potential for by-product hydrogen (updated 27Apr05).doc".

³⁾ Numbers are only given for 2030 and 2050, the numbers in italics are interpolation.

⁴⁾ Numbers are only given for 2050, the numbers in italics are interpolation.

⁵⁾ The Netherlands provides shares for mobile and stationary end-use, separately. Differences occur for the options market with this note. Due to the system definition in MARKAL, such a split does not exist in the model. Because of the dominance of mobile applications, the numbers for mobile application are used in MARKAL to define bounds (and given here). Furthermore, one option concerns handling rather than production (liquefaction). Entries for 2040 are interpolations.

Technology bounds for the low penetration scenarios

Production Technology	2020	2030	2040	2050	Unit
Germany					
By-product	P < 6 PJ/y	P < 6 PJ/y	P < 6 PJ/y	P < 6	PJ/y
Biomass gasification ¹⁾	S < 15	S < 15	S < 15	S < 15	%
Wind electrolysis	10.71 < S	42.12 < S	16.08 < S	9.01 < S	%
Electrolysis, central& on-site	5 < S	5 < S	5 < S	5 < S	%
France					

By-product ²⁾	<i>P < 2.2</i>	<i>P < 2.2</i>	<i>P < 2.2</i>	<i>P < 2.2</i>	GNm ³ /y
Biomass gasification ³⁾	<i>P < 4.43</i>	<i>P < 13.3</i>	<i>P < 20.4</i>	<i>P < 34.6</i>	TWh
Wind electrolysis ³⁾	<i>P < 2.33</i>	<i>P < 7</i>	<i>P < 14.73</i>	<i>P < 30.2</i>	TWh
Greece					
Renewable	< 5.1	< 7.8	< 11.8	< 11.8	%
Lignite Gasification	< 0.9	< 1.4	< 1.0	< 1.0	%
Biomass gasification	< 1.7	< 4.0	< 6.4	< 6.4	%
Italy					
Wind electrolysis ⁴⁾		<i>6.17 < S</i>	<i>12.33 < S</i>	<i>18.5 < S</i>	%
Biomass gasification ⁴⁾		<i>1.67 < S</i>	<i>3.33 < S</i>	<i>5 < S</i>	%
Waste gasification ⁴⁾		<i>3.33 < S</i>	<i>6.67 < S</i>	<i>10 < S</i>	%
Netherlands					
By-product ²⁾	<i>P < 0.005</i>	<i>P < 0.005</i>	<i>P < 0.005</i>	<i>P < 0.005</i>	GNm ³ /y
De-central SMR ^{5,6)}	<i>45 < S < 55</i>	<i>15 < S < 25</i>	<i>10 < S < 20</i>	<i>5 < S < 15</i>	%
Wind electricity	<i>5 < S < 15</i>	<i>5 < S < 15</i>	<i>5 < S < 15</i>	<i>5 < S < 15</i>	%
Coal gasification ⁵⁾	<i>0 < S < 5</i>	<i>10 < S < 25</i>	<i>20 < S < 35</i>	<i>35 < S < 45</i>	%
Central SMR+CCS	<i>0 < S < 5</i>	<i>10 < S < 25</i>	<i>10 < S < 20</i>	<i>5 < S < 15</i>	%
Biomass gasification	<i>0 < S < 5</i>	<i>15 < S < 25</i>	<i>20 < S < 30</i>	<i>25 < S < 35</i>	%
Existing central SMR ^{5,6)}	<i>15 < S < 35</i>	<i>0 < S < 5</i>	<i>0 < S < 5</i>	<i>0 < S < 5</i>	%
Liquefaction	<i>0 < S < 0</i>	<i>0 < S < 0</i>	<i>0 < S < 0</i>	<i>0 < S < 0</i>	%
Norway					
By-product ²⁾	<i>P < 0.9</i>	<i>P < 0.9</i>	<i>P < 0.9</i>	<i>P < 0.9</i>	GNm ³ /y
By-product	<i>50 < S < 100</i>	<i>50 < S < 90</i>		<i>4 < S < 10</i>	%
On-site mix electrolysis	<i>20 < S < 40</i>	<i>25 < S < 45</i>	<i>25 < S < 45</i>	<i>20 < S < 40</i>	%
On-site wind electrolysis	<i>10 < S < 10</i>	<i>10 < S < 20</i>	<i>10 < S < 25</i>	<i>15 < S < 25</i>	%
Central SMR to export	<i>0 < S < 0</i>	<i>5 < S < 10</i>	<i>5 < S < 10</i>	<i>5 < S < 10</i>	%
Regional SMR from LNG	<i>15 < S < 30</i>	<i>10 < S < 25</i>	<i>10 < S < 25</i>	<i>10 < S < 20</i>	%
Remote wind electrolysis	<i>5 < S < 10</i>	<i>0 < S < 5</i>	<i>0 < S < 5</i>	<i>0 < S < 5</i>	%
Biomass gasification	<i>5 < S < 100</i>	<i>10 < S < 100</i>	<i>10 < S < 100</i>	<i>10 < S < 100</i>	%

¹⁾ Maximum on use of biomass in the transport sector (including hydrogen use).

²⁾ Defined as absolute number in "HyWays - Current potential for by-product hydrogen (updated 27Apr05).doc".

³⁾ Numbers are only given for 2030 and 2050, the numbers in italics are interpolation.

⁴⁾ Numbers are only given for 2050, the numbers in italics are interpolation.

⁵⁾ The Netherlands provides shares for mobile and stationary end-use, separately. Differences occur for the options market with this note. Due to the system definition in MARKAL, such a split does not exist in the model. Because of the dominance of mobile applications, the numbers for

mobile application are used in MARKAL to define bounds (and given here). Furthermore, one option concerns handling rather than production (liquefaction). Entries for 2040 are interpolations.
⁶⁾ Accidentally, the bounds for de-central SMR and existing SMR got interchanged in the calculations (as of July 2005)

Absolute versus relative bounds

As is clear from the tables in sections 0 and 0, some bounds are given as absolute numbers, while others are given as relative contributions to overall production. Possibly, some of the relative numbers are actually also based on absolute numbers, and translated into relative numbers by using the overall production information from the first set of runs. In general, absolute numbers could be a reflection of any type of limitation, whereas relative numbers are most likely a reflection of socio-political limits (e.g., the political will to have at least 5% of all hydrogen produced from renewable energy).

Redefining absolute numbers in relative terms is not required for implementation in MARKAL. As a matter of fact, for the input into MARKAL bounds as absolute numbers have a slight preference over relative bounds. Working with relative numbers in MARKAL is non-trivial, as these require defining the overall H₂ production level in such a way that it may be used to determine the relative contribution of each technology. Although in principle such a definition of the bounds is possible, at first instance a definition using the overall H₂ production from the first set of runs was used.

Using information from a previous run in the end leads to the need for an additional iteration, where the overall production of the new run is used for the definition of the bounds. In the current output from the MARKAL model, this has not yet been done. Thus, the actual production levels of individual technologies can be somewhat lower or higher relative production levels, depending on whether the overall production in the second set of runs is higher or lower, respectively, than in the first set.