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SNAPSHOTS OF HYDROGEN UPTAKE IN THE FUTURE

A COMPARISON STUDY

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The European Commission is supporting the Coordination Action “HyLights” and the Integrated Project “Roads2HyCom” in the field of Hydrogen and Fuel Cells. The two projects support the Commission in the monitoring and coordination of ongoing activities of the HFP, and provide input to the HFP for the planning and preparation of future research and demonstration activities within an integrated EU strategy.

The two projects are complementary and are working in close coordination. HyLights focuses on the preparation of the large scale demonstration for transport applications, while Roads2HyCom focuses on identifying opportunities for research activities relative to the needs of industrial stakeholders and Hydrogen Communities that could contribute to the early adoption of hydrogen as a universal energy vector.

Further information on the projects and their partners is available on the project web-sites www.roads2hy.com and www.hylights.org

PREFACE

This study in the framework of the ‘Roads2Hycom’ project of the EU presents a comparison of hydrogen scenario, pathway, roadmap and R&D studies aiming to find common snapshots of hydrogen energy systems in time. This study provides a first step in defining technology pathways for hydrogen uptake in the future as described in the work programme of the 'Roads2Hycom' project. This project is registered at ECN under project number 7.7710.

ABSTRACT

This research addresses scenario, roadmap and pathways studies and R&D plans envisaging hydrogen as a future energy carrier. By comparing the results of the various hydrogen studies an overview of possible hydrogen chains can be given. These snapshots and developments of hydrogen uptake and hydrogen chains in time (2010-2050), describe the common foreseen hydrogen technologies in the future.

The study reviews the IEA energy technology analysis called ‘Prospects for hydrogen and fuel cells’, the ‘World Energy Technology Outlook 2050: WETO-H2’, the results of Phase I of the European roadmap project HyWays (‘Assumptions, visions and robust conclusions from project Phase I’), the United States Department of Energy’s ‘National Hydrogen Energy Roadmap’ and ‘Hydrogen posture plan’, the Hydrogen and fuel cell technology platforms (HFP) ‘Deployment Strategy’, ‘Strategic Research Agenda’ and ‘Implementation Plan’ and Japan’s ‘Strategic Technology Roadmap (Energy Sector)’.

All reviewed studies (except the R&D plans) foresee the main application - 75% or more - of hydrogen is in the transport sector. In the transport sector almost all hydrogen will be used by fuel cell vehicles. Hydrogen internal combustion engine cars will have a bigger share in the starting years, but eventually the share becomes limited. By 2050 between 30% and 75% of the passenger car vehicles will be hydrogen fuelled vehicles. Stationary use of FCs is foreseen in CHP applications, but these are mainly run on syngas and/or natural gas instead of hydrogen.

The analysis shows hydrogen does not enter the energy mix unless there is a stringent climate policy, the oil and gas prices are high, and there is adequate progress in technological learning. Most studies indicate that hydrogen introduction into the energy mix starts with the use of by-product hydrogen. In the short term dedicated hydrogen production starts with decentralised production of hydrogen. This will either be done by reforming of natural gas (steam methane reforming, SMR), by electrolysis of water, or a combination of both. After 2020 production of hydrogen will become more centralised, but will still strongly depend on fossil fuels, mostly natural gas. Carbon dioxide capture and storage (CCS) is mentioned by most studies as a viable option to reduce CO2 emissions by that time. From 2030 and beyond, the production still largely depends on fossil fuels, but renewable energy use for hydrogen production is envisaged and increasing by that time in most studies. Wind electricity combined with electrolysis and biomass gasification with CCS are the most mentioned options for renewable hydrogen production. The outline for 2050 differs strongly between studies. The IEA indicates 80% of the hydrogen will be produced centralised by steam reforming of natural gas and coal gasification, both with CCS. On the other hand, the hydrogen scenario in the WETO-H2 study forecasts a share of about 50% for renewables, especially biomass gasification, and about 40% of nuclear energy for electrolysis. The total hydrogen demand in Europe in 2050 will vary between 2.1 and 5.3 EJ/yr.

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Summary

A lot has been said and written about the future of hydrogen and the role of hydrogen as an energy carrier in the future energy system. Numerous scenario studies have taken hydrogen into account. Several roadmaps have been written, outlining future steps towards hydrogen commercialisation. R&D plans have been set up to set targets and key areas of research. When reading all these documents the question arises what the similarities and differences are between these studies for future use of hydrogen as an energy carrier?

The aim of this research is to review and compare the outcomes of R&D plans and of different scenario and roadmap studies, especially focussing on hydrogen. By doing so, the robust technological options for hydrogen production and end-use are evaluated, together with snapshots of the hydrogen energy chain in time that can be formulated based on similarities in the outcomes. Apart from that, critical assumptions which have to be made for hydrogen to enter as an energy carrier can be outlined. This will result in common snapshots for hydrogen energy systems for 2020 to 2050.

The following studies and plans have been reviewed and compared:

- Scenario studies (forecasts based on integrated energy system modelling)
  - IEA energy technology analysis called ‘Prospects for hydrogen and fuel cells’.
  - The ‘World Energy Technology Outlook 2050: WETO-H_2’ study.
- Roadmaps
  - The United States Department of Energy’s ‘National Hydrogen Energy Roadmap’.
- Backcasts[1] and pathways
  - HyWays European roadmap called ‘Assumptions, visions and robust conclusions from project Phase I’[2].
  - The Hydrogen and fuel cell technology platforms (HFP) ‘Deployment Strategy’.
  - Japan’s ‘Strategic Technology Roadmap (Energy Sector)’[3].
  - R&D plans

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[1] Backcast studies start with an end vision and then start to formulate the steps or pathways in order to realise that vision.

[2] Although the project is called a roadmap project, HyWays and does include roadmapping and backcasting activities, it also combines integrated energy system modelling like in the IEA and WETO-H_2 studies, with individual energy chain analyses and more qualitative roadmap activities. The available report (Phase I report) at the moment this report is written fit best in this category.

[3] This report is called a roadmap, but was based on a backcasting methodology and thus is put in this category.

- The United States Department of Energy's 'Hydrogen posture plan'.
- The Hydrogen and fuel cell technology platforms (HFP) 'Strategic Research Agenda'.
- Hydrogen and fuel cell technology platforms (HFP) 'Implementation Plan'.

The analysis shows hydrogen does not enter the energy mix unless there is a stringent climate policy, the oil and gas prices are high, and there is adequate progress in technological learning. Climate policy is mostly expressed in a CO2 price and has to be in the range of 50 €/tCO2 or more (in 2050) in order to make hydrogen an option for introduction into the energy system. This combined with a high oil price of 60 to 100 $/bbl (in 2050) gives hydrogen the necessary push to become competitive. Technological learning (which reduces cost of technology) has to be assumed as well.

Looking at the end-use applications envisaged in all reviewed studies (except the R&D plans), the main foreseen application of hydrogen is in the transport sector. According to these studies, at least 75% or more of all the hydrogen will be used in the transport sector. Main end-use technology in this sector is the fuel cell (FC) vehicle. Hydrogen internal combustion engine cars will have a bigger share in the starting years, but eventually the share becomes limited. By 2050 between 30% and 75% of the passenger car vehicles will be hydrogen fuelled vehicles. Stationary use of FCs is foreseen (up to 400 GW) in the industrial application of combined heat and power (CHP), but these are mainly run on syngas and/or natural gas in stead of hydrogen.

In scenarios in which the conditions are favourable the introduction of hydrogen into the energy mix starts between 2015 and 2020. The shared picture of hydrogen production includes hydrogen coming from by-product hydrogen in the starting years. Early dedicated hydrogen production starts with decentralised production of hydrogen. This will either be done by steam reforming of methane (SMR), electrolysis or a combination of both. After 2020 production of hydrogen will become more centralised, but will still strongly depend on fossil fuels, mostly natural gas. Carbon capture and sequestration (CCS) is mentioned by most studies as a viable option to reduce CO2 emissions. From 2030 and beyond the production still largely depends on fossil fuels, but renewable energy use for hydrogen production is envisaged and increasing by that time in most studies. Wind electricity combined with electrolysis and biomass gasification with CCS are the most mentioned options for renewable hydrogen production. However, the outline for 2050 differs strongly between studies. The IEA indicates 80% of the hydrogen will be produced centralised by steam reforming of natural gas and coal gasification, applying CCS in both cases. On the other hand the WETO-H2 study (the hydrogen case) describes a large role (50%) for renewable (especially biomass gasification) and nuclear energy use for electrolysis (40%) in 2050. Total hydrogen demand in Europe will vary (depending on the study used) between 2.1 and 5.3 EJ/yr. Worldwide demand varies between 12.4 and 39.4 EJ/yr.

The overall picture which arises based on the similarities of all the studies can be seen in the figure below. Based on this figure different 'snapshots' in time can be made. The general conclusion can be that hydrogen needs high CO2, oil and gas prices. Even then it will first be produced from fossil fuels, shifting towards renewable sources and nuclear power. Infrastructure will not be set up in the early phase, but later in time. The main application of hydrogen will be in transport, stationary fuel cells are not expected to use hydrogen as a fuel.

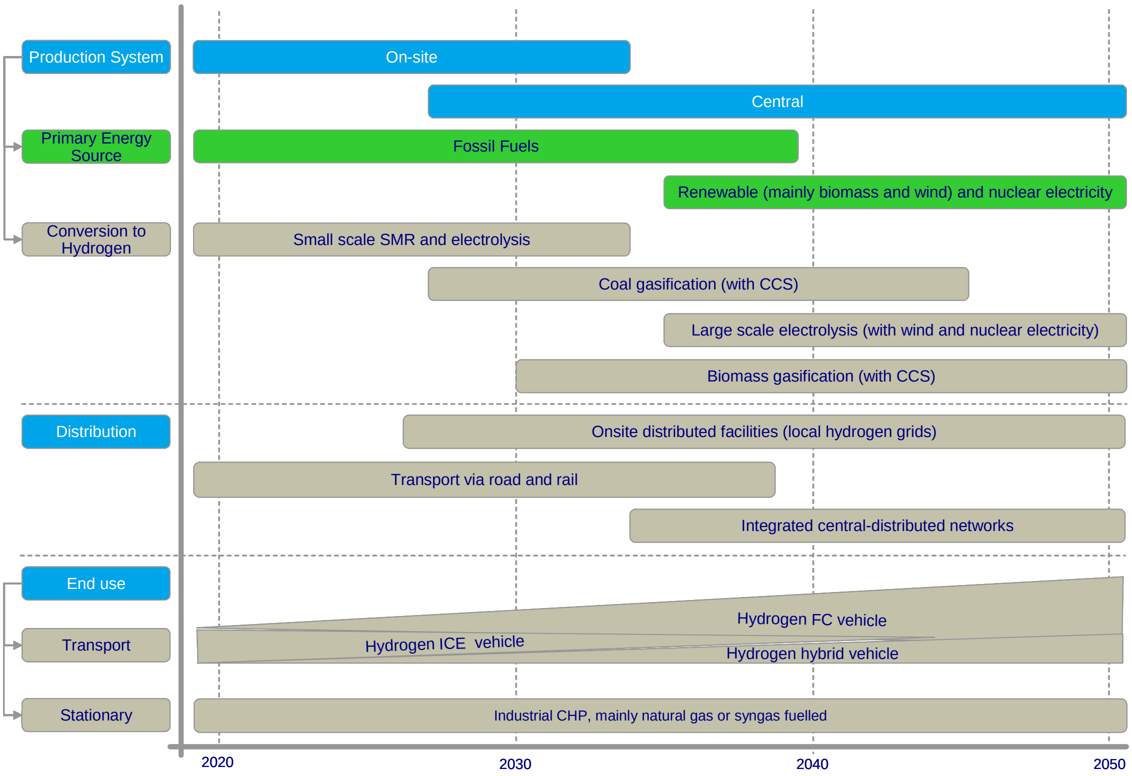

Figure S.1: General evolution of the hydrogen chain in time based on similarities between the IEA and WETO-H2 studies

Note: The bars in the figure give an indication of when the technology will become a viable option, but do not give insight into their share in the market. An exception is the bar for the transport sector. This shows the share of hydrogen FC and hybrid vehicles will increase in time, while the share of hydrogen ICE vehicles will be high in the early years of market introduction, but becomes relatively low as more hydrogen FC and hybrid vehicles are deployed.

1. Introduction

Many scenario studies, vision documents and roadmaps have been written in the last years taking into account or focussing especially on hydrogen as one of the energy carriers for the future. Each of these studies, depending on assumptions made, describe the role of hydrogen and fuel cells and other energy carriers.

The outcome of these studies largely depends on the assumptions of oil price and policy support (CO_2 price). Also assumptions on technological progress or technology learning (learning curves) have a large influence on the entry date of hydrogen and the foreseen technologies used to produce and use hydrogen.

Despite the differences in assumptions, this study aims to review and compare the outcomes of different scenario, roadmap and R&D plans, especially focussing on hydrogen. By doing so it is evaluated what the robust technological options for hydrogen production and end-use are and snapshots in time of the hydrogen energy chain can be formulated based on similarities in outcomes. Apart from that, critical assumptions which have to be made for hydrogen to enter as an energy carrier can be outlined.

The main questions to be answered is: *What are the robust technology chains distinguishable from the scenario studies, roadmaps and R&D reports, of which technologies do they comprise and do these change in time?*

In order to answer these questions this report comprises the following. Chapter 2 describes the methodology used to categorise the different studies analysed in this research. Although this is not the main focus of this report, it helps structure the different studies. Hereafter, Chapter 3, 4, 5 and 6 describe the hydrogen cases for the different scenario studies, roadmaps, pathways, and R&D plans. These chapters will address technologies and technology characteristics considered, assumptions on energy prices, policy measures and the assumed or resulting hydrogen and fuel cell penetration rates. In Chapter 7 some similarities and differences between the different reports are described in order to answer the main research questions. Common snapshots will be described which can be used for further analysis.

2. Methodology

Many articles and reports have been written on the ‘hydrogen economy’ outlining the advantages of a ‘hydrogen economy’, steps to get there and so on. Different types of studies (e.g. visions, roadmaps, scenarios, forecasts, backcasts and pathways are used to describe the transition steps towards the hydrogen economy and how to cope with the uncertainties and long planning horizons related to the introduction of hydrogen. McDowall (2006) distinguishes six types of futures studies. An outline of these six types is given in Table 2.1.

Table 2.1: Overview of different categories, their characteristics and some examples of futures studies

Category	Characteristics
Forecasts (qualitative)	Use of quantitative methods to predict futures based on current trends, or expert opinions mostly including learning curves, demand projections, fuel cost (oil price) and the characteristics of competing technologies to model market penetration.
Exploratory scenarios (qualitative)	Exploration of possible futures emphasising drivers of change, and leave a predetermined desirable end state towards which storylines must progress unspecified.
Technical scenario (qualitative)	Assess the implications of different hydrogen-based technological systems, and assess the implications of these against a range of criteria (such as Carbon Emissions, cost, and technical feasibility), rather than explore how different futures might unfold.
Visions (quantitative)	Elaboration of a desirable (and more or less) plausible future, emphasising the benefits of hydrogen rather than the pathways through which a hydrogen future might be achieved
Backcasts and pathways (quantitative)	Start with a predetermined ‘end’ point (a desirable and plausible future). Then investigate possible pathways to reach that point
Roadmaps (quantitative)	Describe (mostly based on elements from the previous four groups) a sequence of measures designed to bring about a desirable future.

Source: McDowall, 2006, pp 1238.

In this research both the qualitative studies, especially the exploratory scenario, and the quantitative studies, the roadmaps and pathways, will be used to come to shared snapshots of the future uptake of hydrogen. These three types of studies are selected for further analysis, because scenario studies give insight into the future energy system based on, amongst others, technical assumptions and have long planning horizons (2030 or even 2050), while the roadmaps and pathways give insight into stakeholder preferences and usually have a shorter horizon (until 2020).

By making use of the technological status and potential, and stakeholder preference an overview of possible technological developments and uptake in time can be given. The similarities between the studies will lead to ‘snapshots’ of the hydrogen energy chain. However, in order to get more insight into possible drivers for hydrogen uptake, an outline of assumptions made by the different studies is also being reviewed.

2.1 Reviewing assumptions

Setting up technical scenarios requires assumptions to be made. These assumptions influence the outcome of the scenario studies and thus need to be stated explicitly. Main assumptions to be taken into account are:

- Energy prices (i.e. oil and gas prices).
- Technology characteristics and technological learning of both hydrogen as well as reference and alternative technologies.
- Policy targets (mostly reflected in carbon emission price).

These assumptions may cause technology uptake to change in time, because the use of a technology may become economical feasible due to learning (which lowers price), higher oil price, or stringent CO_2 regimes. Therefore, the review of assumptions can give insight into possible drivers and showstoppers for hydrogen uptake.

2.2 Selection of studies

Several studies are selected for use in this study. Scenario studies to be analysed are:

- The IEA energy technology analysis called ‘Prospects for hydrogen and fuel cells’.
- World Energy Technology Outlook 2050: WETO-H_2.

Roadmaps to be reviewed are:

- United States Department of Energy’s ‘National Hydrogen Energy Roadmap’.

Backcasts and pathways to be examined are:

- Hydrogen and fuel cell technology platforms (HFP) ‘Deployment Strategy’.

- Japan's 'Strategic Technology Roadmap (Energy Sector)'. This report is called a roadmap, but was based on a backcasting methodology and thus is put in this category.

- The European Commission (EC) funded project HyWays describing a European roadmap called 'Assumptions, visions and robust conclusions from project Phase I'. Although the project is called a roadmap project, HyWays and does include roadmapping and backcasting activities, it also combines integrated energy system modelling like in the IEA and WETO-H_2 studies, with individual energy chain analyses and more qualitative roadmap activities. The available report (Phase I report) at the moment this report is written fit best in this category.

R&D plans to be studied:

- HFPs 'Strategic Research Agenda'.

- HFPs 'Implementation Plan'.

- 'Hydrogen posture plan; An integrated research, development, and demonstration plan' of the United States Department of Energy.

2.3 Getting to the snapshot

Scenarios mostly result in a description of the demand for a certain energy source and/or carrier in time. Also, the envisaged use of the energy sources and/or carriers in a certain sector in time is described. In this study the main focus will be on hydrogen and its envisaged end-use applications foreseen in scenario studies. By looking at hydrogen demand and use in specific sectors a better overview for the potential of hydrogen in a sector is provided. Outcomes of the roadmap and pathway studies will also be described this way. Although in these studies a description of a desired future situation is mainly based on stakeholder input and not entirely based on energy prices, technological learning and policy support. Although the HyWays project is a combination of several activities (backcasting, roadmapping and scenario calculations), the Phase I report fits best in the backcast and pathway category.

Based on the comparison between scenario, roadmap and pathway studies the similarities between them will be outlined. The time evolution of these similarities, which we call snapshots, will be compared to the R&D plans. R&D plans outline R&D goals for the near future (up to 2015) and may provide useful insight into short term options. By comparing short term goals with the long term uptake of technologies as described in the scenario, roadmap and pathway studies reviewed can be if there are differences in short term R&D and long term technology options. There could be long discussions whether scenarios are used by policy makers to set R&D goals. In this study there will be no review on whether scenario studies are used by policy makers to set R&D goals, this is assumed to be the case. There will be a review whether R&D goals are in line (on the short term) with scenario outcomes.

3. Scenario studies

Technical scenario studies describe possible futures based on assumptions (for instance on carbon emissions, cost, and technical feasibility). Two scenario studies are reviewed. The IEA study called 'Prospects for hydrogen and fuel cells' (Section 3.1), followed by the World Energy Technology Outlook 2050: WETO-H_2 (Section 3.2). For each of these scenario studies the reference case is compared to the other cases. The focus of this study is mainly on hydrogen and fuel cells. Therefore, the general outcomes of the study will be outlined but the main attention goes out to if, where, how and when hydrogen and fuel cells will be used. However, to get a feel for the drivers of hydrogen and fuel cells it is necessary to describe the assumptions made in each of the cases in these studies.

3.1 IEA: Prospects for hydrogen and fuel cells

The International Energy Agency (IEA) published an energy technology analysis called 'Prospects for hydrogen and fuel cells' in 2005. The study provides an assessment of technology prospects, it makes an evaluation of barriers for hydrogen and fuel cells, and describes scenarios for a transition to hydrogen. It utilises the IEA's Energy Technology Perspective model.

3.1.1 The Reference cases

IEA conducted an analysis of two basic scenarios to help define the energy context as a reference case. The BASE scenario is a business-as-usual scenario which includes only currently enacted energy policies. The MAP scenario maps key drivers and policies for hydrogen and fuel cells. Both these cases will be described in more detail in the following paragraphs.

BASE scenario

The BASE scenario builds on the IEA World Energy Outlook Reference scenario (2004) up to 2030 and then further develops this outlook up to 2050. It does not include any significant new climate policies. The only driver for change is changing resource prices, increasing demand for energy services and technology advances due to RD&D.

The outcome of the BASE scenario shows that energy demand more than doubles by 2050 and CO_2 emissions reach almost 60 Gt per year. The transport sector also shows an increase in fuel use, but has a 20% lower fuel demand due to improvements in vehicle efficiency. One of the reasons is the representation of hybrid cars with a share of 29% of all passenger cars and light/medium sized trucks by 2050.

The fuel mix for the transportation sector starts to change beyond 2030. In 2050 40% of the demand in the transportation sector is supplied by alternative fuels. The main fuels used are Fischer-Tropsch (FT) synfuels from coal and natural gas (some 30%) and biofuels/ethanol (less than 10%). Efficiency increasing technologies limit the growth in demand for conventional oil refinery products. However, due to the success of other non-conventional fuels hydrogen plays only a minor role. This can be attributed to the favourable economics of biofuels due to continued cost reductions and its contribution to a significant CO_2 emission reduction.

Stationary FCs are used in 2050. Up to 400 GW is installed, but mostly the stationary fuel cells use other fuels then hydrogen (see also next paragraph).

MAP scenario

In the MAP scenario a global incentive of 50 \$/tCO_2 is set to represent new policy measures aiming to reduce emissions and improve energy-security. This value was chosen because it results in a halving of the emissions in 2050 compared to the BASE scenario. The result of this assumption is a stabilisation of global CO_2 emissions between 23-27 GtCO_2 per year. The energy use declines by 8% in 2050 (850 EJ) compared to the BASE scenario and the use of renewable energy increases at the expense of coal.

Despite of oil still being the main fuel used in the transport sector, hydrogen becomes a player in the transport sector starting in 2020. However, in 2050 oil still accounts for more than 50% of the fuel demand, but biofuels gain 25% of the market, hydrogen gains 10% and FT (from coal and natural gas) synfuels 10%. The reduction of FT fuel use in the transport sector compared to the BASE scenario can be explained by the fact that FT fuels do not result in a reduction of tailpipe emissions, even if CO_2 is captured and stored during their production.

In 2050, 82% of the 15.7 GJ of hydrogen is used in the transport sector, primarily by passenger cars. Initially hydrogen-hybrid vehicles play a role, but from 2020 onwards FCV dominate (see Figure 3.1). Due to the high efficiency of the FCVs the relatively small amount of hydrogen still results in 27% of all passenger cars in 2050 being FCVs. However, there is no significant penetration of hydrogen busses. This is explained by the fact that some 20% of total diesel is derived from biomass (in this scenario) and diesel hybrid buses are the technology of choice.

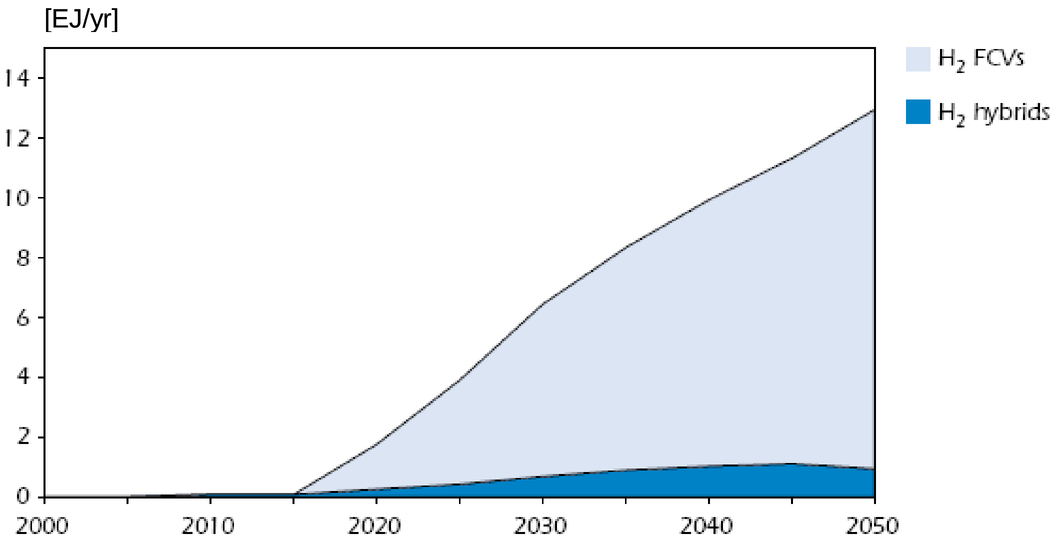

Figure 3.1: Hydrogen use in the transport sector (MAP scenario)

In both the BASE and MAP scenarios stationary FCs are installed and represent 5% of global electricity production capacity in 2050 (2030 30-60 GW, 2050 450 GW). They are used in decentralised heat and power production in the residential, commercial and industry sectors (see Figure 3.2). Natural gas fuel cells play a role with only a limited role for coal-gas and hydrogen fuelled systems (less then 10% each) (see Figure 3.3).

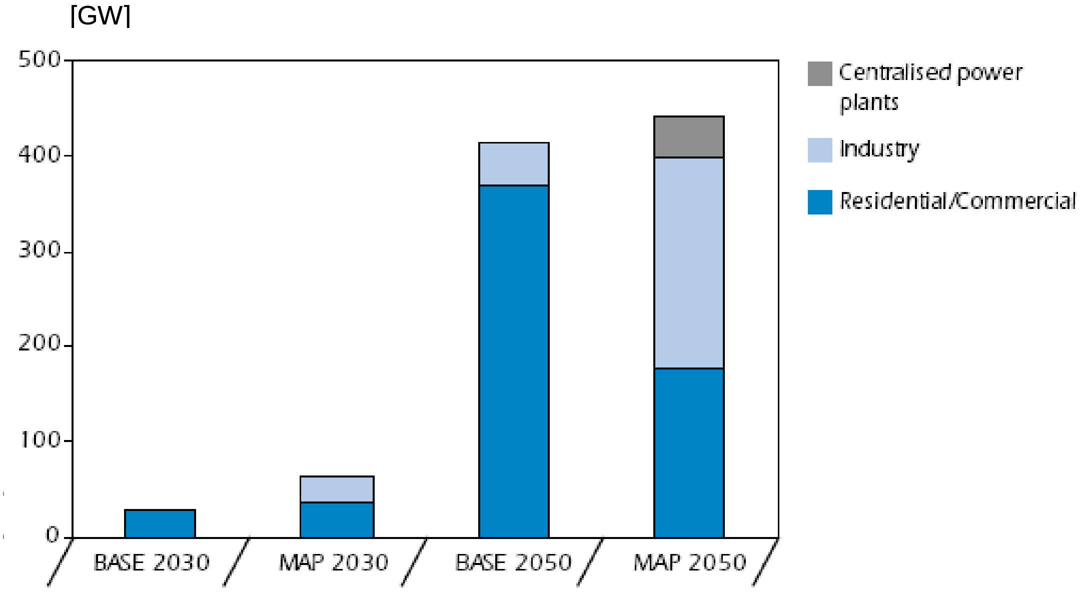

Figure 3.2: Stationary fuel cell capacity by sector (BASE and MAP scenario)

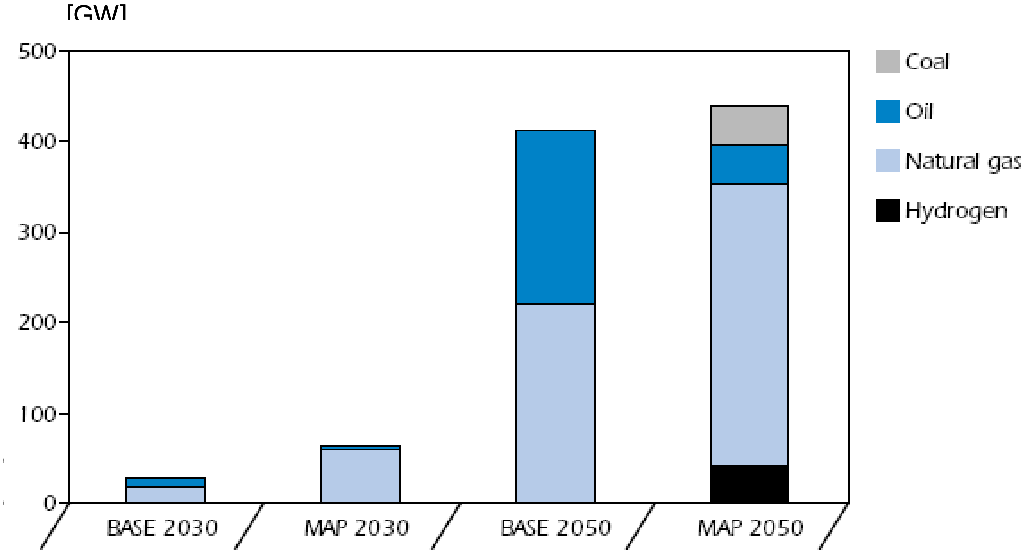

Figure 3.3: Stationary fuel cell capacity by fuel type (BASE and MAP scenario)

Sensitivity analysis

The results of the BASE and MAP scenarios are based on technical, economic and policy assumptions. Key variables for these assumptions are split into government policies and economic parameters, hydrogen and fuel cell technology characteristics, and the characteristics of competing technologies and fuels. In order to test the sensitivity of the outcomes of the model to changes in these variables a sensitivity analysis is performed. The aim of the sensitivity analysis is to determine how sensitive the potential demand for hydrogen and fuel cells is to these individual variables. The outcome of the sensitivity analysis shows:

- Hydrogen demand is sensitive to fossil fuel prices. An increase in fossil fuel price would increase the hydrogen demand. However a very rapid increase of the oil price would not benefit hydrogen (unless rapid technology advances take place at the same time), but benefits synfuels, because they are more market mature.
- Energy-security policies alone do not result in a switch to hydrogen, because other cheaper options exist to achieve diversification of energy supply.
- CO_2 reduction incentives have a large impact on hydrogen demand, because the potential for hydrogen to contribute to reducing emissions is high. This is also shown by the outcome of the BASE case in which business-as-usual trends are used which do not result in a switch to hydrogen and fuel cells (even under the additional presence of energy-security concerns).
- Delaying the introduction of CO_2 reduction incentives in time results in higher emissions in 2030-2050, due to a delayed introduction of hydrogen. This implies early uptake of hydrogen (the next 20 years) is needed to reduce the emission and a rapid introduction of CO_2 incentives helps to achieve this.
- Higher discount rates for investment in the transport sector reduce the hydrogen demand greatly, while for stationary applications the cost of fuel cell systems can become a barrier for consumers to buy the technology.
- Fuel tax on alternative fuels affects hydrogen demand as a fuel as well. Higher fuel tax on alternative fuels (including hydrogen as a fuel for transport) results is an extra advantage for hydrogen, due to the higher fuel efficiency of FCs compared to other alternative fuels.
- If hydrogen is exempt from all taxes the demand would increase especially in high-tax regions such as Japan and Europe (the demand would raise a three fold).
- If renewable energy becomes cheaper in time the demand for hydrogen will decrease, because there will be limited co-generation of electricity and hydrogen from coal; one of the main technologies used to produced hydrogen in the BASE scenario.
- A reduction of biomass potential leads to a higher hydrogen demand, but also increases other synfuels and refinery products.
- Hydrogen production from nuclear will double in the absence of public acceptance constraints for nuclear power and in the event of the successful development of a low-cost nuclear reactor.

- CCS also impacts prospects for stationary fuel cells. If CCS succeeds, centralised power plants with CCS have an advantage over decentralised stationary fuel cell power plants. Decentralised stationary fuel cells for power generation thus become less attractive.
- Hydrogen demand increases when the following assumptions for the technological performance of the PEM FC in the transport sector are made:
  - Two FC stacks are needed during the lifetime of a vehicle instead of one.
  - There is a delay in technological learning of 15 years to reach 35 $/kW (which is higher than the MAP scenario).
  - A delay in technological learning of 20 years (but reaching the same level as the MAP scenario).
- Hydrogen demand decreases when the following assumptions for the technological performance of the PEM FC in the transport sector are made:
  - Less power is needed in the FCV to match the power of a comparable internal combustion engine (ICE) due to the superiority of the electric engine.
  - The technological developments are more optimistic and reach 30 $/kW in 2010 for the FC stack and 65 $/kW for the full drive train by 2015.
  - Efficiency gain of a FCV over a ICEV is not 1.82, but 2.27 in 2010 and 2.95 in 2050.
- If the transition issues are taken into account, meaning only decentralised production from electrolysis and natural gas reforming instead of the model choosing the least-cost option, which is central large-scale hydrogen production with a pipeline distribution system from the beginning, the hydrogen demand would decrease. When central production is excluded for the whole period, hydrogen demand would half by 2050. However, in this case hydrogen production from electrolysis emerges in this scenario. This could imply that electrolysis may have an important role in regions without centralised hydrogen production.
- Hydrogen distribution cost affects the use in the commercial and residential sector. When these costs are lowered hydrogen demand increases.

3.1.2 The hydrogen scenarios

The sensitivity analysis shows that a number of variables have significant impact on a scenario outcome. This paragraph outlines the outcome of the most favorable (and only) scenario and its assumption of the main drivers.

Assumptions

Hydrogen plays a significant role only under favorable assumptions. Under less optimistic assumptions for technology development and policy measures, hydrogen and fuel cells are unlikely to reach the critical mass needed for market uptake.

This study reviews hydrogen as an option in the technology portfolio and reviews different scenarios with different assumptions for environment, security of energy supply, technological progress, economic conditions and competing options. The conditions for the only case when hydrogen does enter the market place are the following assumptions:

- CO_2 reduction incentives are set at 50 \$/tCO_2. In industrialised countries this level is reached in 2015, while in developing countries (after introduction in 2020) this maximum is reached in 2030.
- The security of energy supply target meant to reduce oil import is set at one third of the total transportation fuel demand. Taxation policies that favour the use of alternative fuels over conventional oil are set.
- As indicators for technological progress the cost of the FCV drive system and the efficiency of the FCVs are set at 65 \$/kW for a FCV drive system together with a high relative efficiency of FCVs (2.95 by 2050) compared to advanced ICE vehicles.
- Oil and gas price assumptions in the transport, service and residential sectors are set at 35 \$/bbl by 2030 increasing to USD 40/bbl[4] in 2050, gas prices follow this increase in price.

Table 3.1 gives an overview of the foreseen introduction period and cost of hydrogen technologies.

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[4] Real $\$_{2000}$ price.

Table 3.1: Overview of IEA cost assumptions and in time

		2010	2020	2030	2050
Production					
SMR of NG	[$/GJ]	10-15 (small scale)		10 (large scale)	
Electrolysis (with renewable electricity)	[$/GJ]	34.4		17	
Gasification of coal/biomass	[$/GJ]	7-10		<10	
Nuclear thermo-chemical water splitting				10-20	
Distribution					
Road, rail, truck and pipeline	[$/GJ]	5-10			
Refuelling	[$/GJ]	35-50			
Storage					
Large scale	[$/GJ]		2.7		
On-board (gaseous, liquid, hydrate and carbon)	[$/kg]	600-800		225 (gaseous)	
End-use					
Transport	[$/kW]	500 (2200 hrs. durability)		35-75 (3000-5000 hrs. durability 58% efficiency)	
Stationary	[$/kW]	145-170		(>60,000 hrs. durability 60-90% efficiency)	

Outcome

In the most favourable case, with high CO_2 incentive and rapid declining of hydrogen and fuel cell costs, hydrogen emerges in the future transport sector beyond 2030. Some 12.4 EJ (0.3 Gtoe) of hydrogen would be used in 2050. If hydrogen use in refineries is added 22 EJ would be used in 2050 (see Figure 3.4). The total primary energy supply will be 785 EJ (18.8 Gtoe). Compared to a case without hydrogen and fuel cells the net benefit is a 5% reduction in CO_2 emissions (1.4 Gt of CO_2) and 2% reduction in oil use in 2050. Still the total CO_2 emission is 28 $GtCO_2$/yr.

Hydrogen production in 2030 is dominated by decentralized technologies using natural gas, but by 2050 centralised production technologies dominate the production of hydrogen (from coal and natural gas (NG) with CCS) (see Figure 3.5). The production from nuclear and renewable energy does not play an important role, even in 2050. This is due to the cost assumptions. Electrolysis appears in Europe and US based on the overnight production strategy that uses off-peak electricity, however in absolute terms the quantities are rather small. In 2050 renewables represent a significant share of the electricity mix, ranging from 40 to 50% of total electricity production in 2050. Therefore, the combination of renewable electricity production and electrolysis could become a viable option after 2050.

Hydrogen use will start around 2015-2020 in Europe and North America, and around 2025 in the other regions. If ambitious climate and energy-security policies are adopted world wide, hydrogen fuel cell vehicles will dominate the hydrogen market. The main use of hydrogen will be in transport. By 2050 97% of the hydrogen is used in the transportation sector, 75% by passenger cars, 25% by delivery vans and 1% by buses The limited use of hydrogen in buses is due to competition in this market segment and the limited expected energy efficiency gains for hydrogen fuel cell buses (20% better than diesel buses, compared to a factor of almost three for cars).

Of the global fleet of passenger cars 30% (some 700 million cars) would be fuelled by hydrogen. In 2050, the largest share of hydrogen FCV will be found among the Chinese car fleet (60%) followed by India (42%). In OECD countries, the shares are 10% in Australia, 22% in Japan, 35% in Canada, 36-48% in Europe (Western Europe 36% and Eastern Europe 48%) and 42% in the United States. The differences in FCV share can be explained by a range of factors, such as the availability of other transportation fuel options, annual driving range, region-specific cost factors, and technology lock-in due to existing infrastructure.

For stationary application there will be a rapid introduction of fuel cells from 2020 onward, with the total global stock of fuel cells reaching around 300 GW by 2050. The most common FC types will be SOFC and MCFC. Up to 22% of these FCs will use oil products (natural gas) for fuel. The main use will be by the industry and the residential and commercial sector.

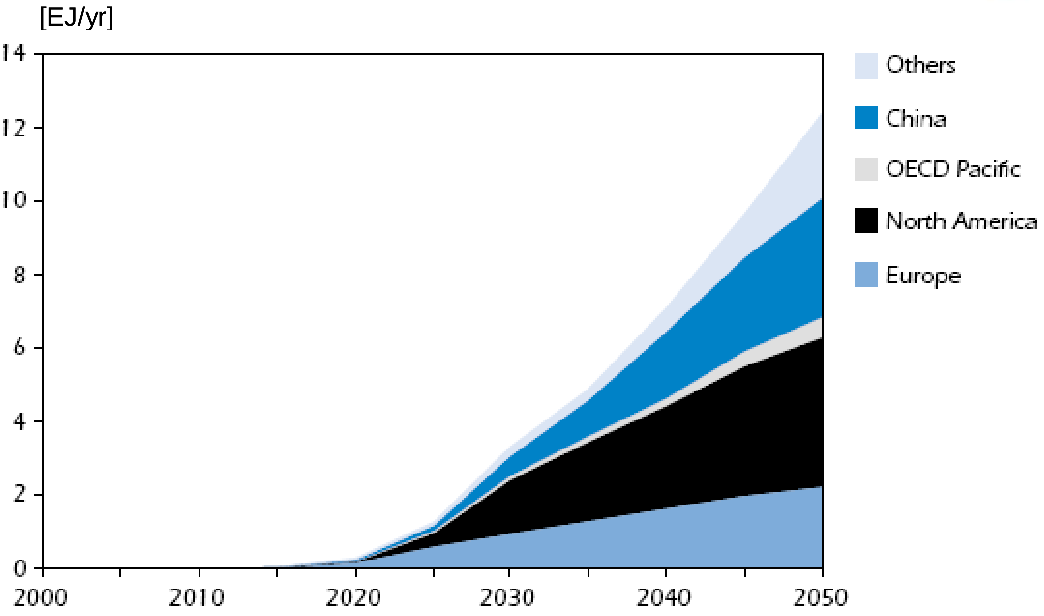

Figure 3.4: Hydrogen demand by region

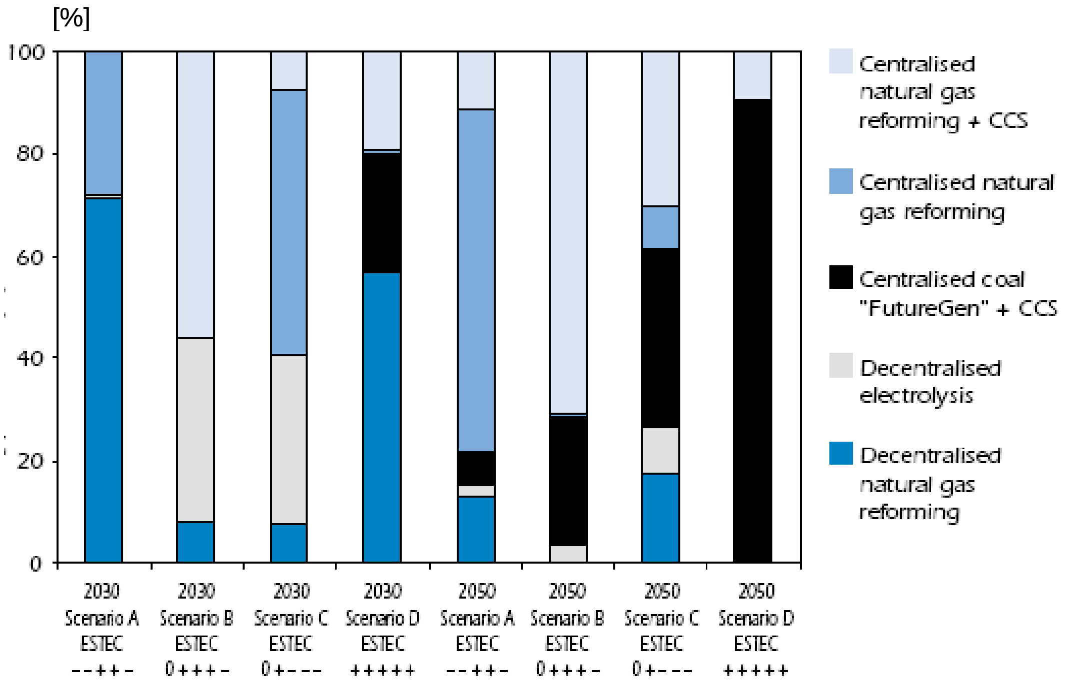

Figure 3.5: Hydrogen production by technology (case described is 'Scenario D')

3.2 WETO-H_2

The WETO-H_2 project is an EC funded project with the goal to evaluate two EU sustainable energy strategies in the light of a very long-term projection of global energy parameters and technological breakthroughs. It considers the implications of two EU energy-environment strategies: (i) implementation of a hydrogen-based energy system and (ii) reduction of energy-related CO_2 emissions by a ‘factor 2’. For each of these cases projections and evaluations for the energy system are made in a quantitative way using the POLES model[5] - a global sectoral model of the world energy system, but implications for the European energy system[6] are reviewed as well.

The POLES modelling system is used as a tool and provides an economic analysis of world energy scenarios under environmental constraints. The main (exogenous) inputs are: world population and economic growth as the main drivers of energy demand; oil and gas resources as critical constraints on supply and the future costs and performances of energy technology that define the feasible solutions.

An important aspect of the projections is that they rely on a framework of permanent competition between technologies with dynamically changing attributes. Inter-technology competition depends on three sets of variables:

- The investment and O&M cost and the performance of a technology,
- Primary fuel cost,
- The carbon value and penalty.

This chapter will continue with a description of the reference case, followed by the Carbon Constrained case and ending with the hydrogen case. For each of the cases the results on World and European level are described.

3.2.1 The reference case

Assumptions

The reference case visualizes a world adjusting to constraints on access to oil and gas and a constraint on emissions of CO_2. Assumed is that the oil price (of 80 $/bl in 2006) falls to 40 $/bl in 2010 and then increases to 60 $/bl in 2030 and near to 110 $/bl in 2050. Oil production (of conventional oil) reaches a peak before 2030 and that of gas between 2040 and 2050.

The high oil price also impacts the gas price, which follows the same trend. This provides a structural advantage for coal. The coal price therefore roughly doubles

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[5] The POLES modelling system is a partial equilibrium model with a dynamic recursive simulation process.

[6] Europe: Albania, Austria, Belgium, Bosnia-Herzegovina, Bulgaria, Croatia, Czech Republic, Cyprus, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Macedonia, Malta, Netherlands, Norway, Poland, Portugal, Romania, Serbia & Montenegro, Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey, United Kingdom

with respect to the current level, and in terms of oil equivalent reaches the price of 22 $/bl in 2050.

The assumptions for the reduction of CO_2 emissions are reflected in the carbon price (€/tCO_2). These are differentiated throughout the World. In Europe carbon is valued at 10 €/tCO_2 in 2010 and increases linearly to 20 €/tCO_2 in 2030 and 30 €/tCO_2 in 2050. For the rest of the Annex B countries an increase from 5 €/tCO_2 in 2010 is assumed and thereafter the value stays at half the European level. The non-Annex B countries are also included. Carbon starts being valued after 2010 and reaches 15 €/tCO_2 in 2050.

Outcomes

Based on these assumptions the outcome of the reference case for the world energy system shows a primary energy supply in 2050 of 933 EJ (22 Gtoe). The foreseen contribution of oil for this supply is 250 EJ (6 Gtoe), gas contributes for 171 EJ (4 Gtoe) and coal for 338 EJ (5.5 Gtoe). Nuclear energy provides 133 EJ (3 Gtoe), which is an increases by a factor four compared to present time. The total share of renewables (wind, solar, biomass and hydro, geothermal) is 141 EJ (3 Gtoe).

By using these sources the CO_2 emissions develop from 29 GtCO_2 in 2010, 39 GtCO_2 in 2030 to 44 GtCO_2 in 2050. This means that in 2050 the emissions of CO_2 are 2.25 times greater than in 1990. However, CCS plays a role in the total emission of CO_2. CCS starts after 2040, when the carbon value outside Europe is around 15 €/tCO_2. This results in 13% of the electricity generation coming from plants equipped with CCS in 2050. The annual amount stored in 2050 is 2.5 GtCO_2.

The reference case shows only limited use of hydrogen. The amount of hydrogen produced in 2050 is 15.8 EJ (378 Mtoe)[7]. Production is mostly from non-fossil fuels, primarily from renewable sources and nuclear (see Figure 3.6). The production from steam reforming of natural gas is limited by high prices and is generally more costly than hydrogen from coal gasification. This results in a larger share of hydrogen production from coal than from natural gas.

There is unfortunately no information on which sector uses hydrogen in the world energy system.

Under these same assumptions, the outcome of the *European energy system* shows a primary energy supply of 67 EJ (1.6 Gtoe) in 2050. This is mainly provided by fossil fuels 3.6 EJ (0.09 Gtoe) oil, 8.8 EJ (0.2 Gtoe) gas and 9.4 EJ (0.2 Gtoe) coal and nuclear energy 26 EJ (0.6 Gtoe). This is an increase by a factor three for nuclear energy production. Renewables (wind, solar, biomass and hydro, geothermal) also increase to 19 EJ (0.447 Gtoe).

The high use of nuclear and renewable energy cause CO_2 emissions to almost stabilize between 2010 and 2030 at 4.5 GtCO_2 and thereafter fall to 3.9 GtCO_2 in 2050. This is equal to a 10% lower level in 2050 than in 2001.

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[7] Hydrogen production in 2010 is 0.08 EJ (2 Mtoe), in 2020 0.33 EJ (8 Mtoe), in 2030 1.3 EJ (32 Mtoe).

Another reason is that by 2050 one fourth of the total thermal power generation in Europe uses CCS. The penetration of this technology is stimulated by a carbon value that is higher in Europe than in the rest of the world. The annual amount stored in 2050 is 0.5 $GtCO_2$.

Hydrogen use in Europe is also limited. The production starts after 2030[8] and is mainly done by renewable and nuclear (see Figure 3.7). By 2050 2.5 EJ (60 Mtoe) of hydrogen is produced in Europe. This hydrogen is used by H_2 thermal power plants or residential houses in this scenario. No hydrogen FC vehicles are used in Europe.

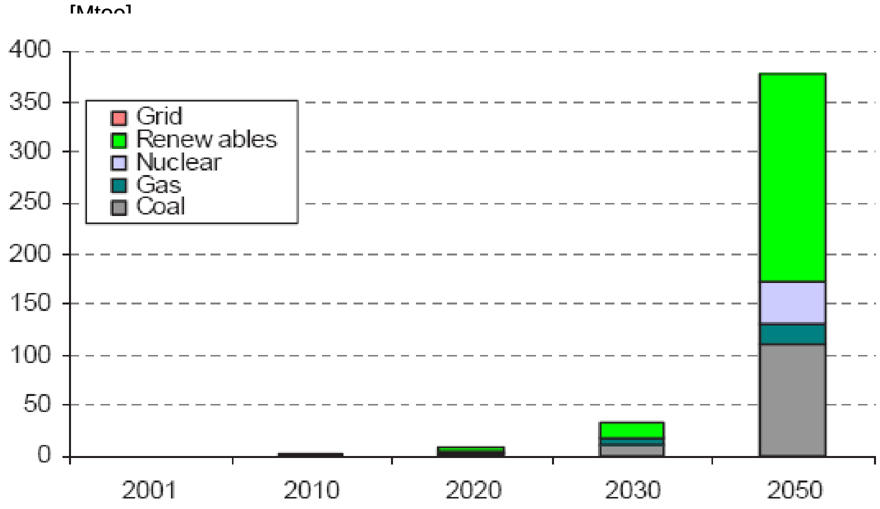

Figure 3.6: Hydrogen energy production by technology for the reference case for the world energy system

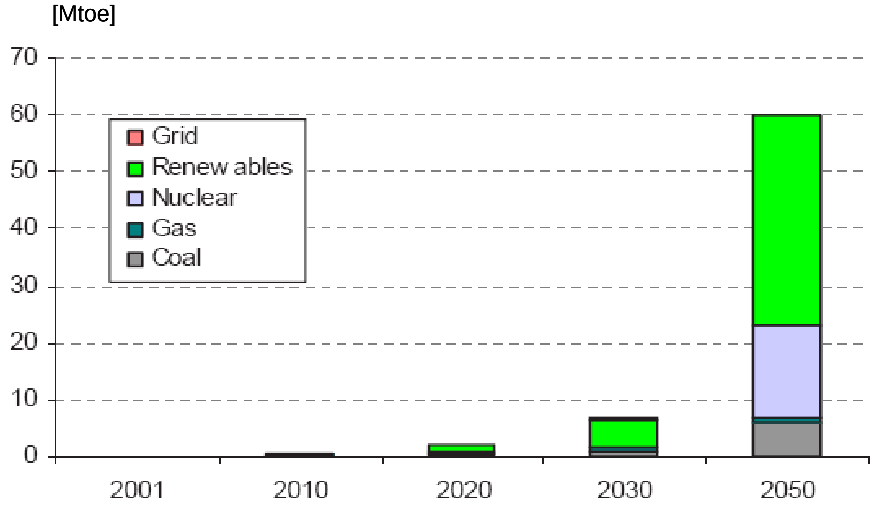

Figure 3.7: Hydrogen production in Europe in the reference case

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[8] In 2020 0.08 EJ (2 Mtoe) of hydrogen is produced in Europe and in 2030 0.29 EJ.

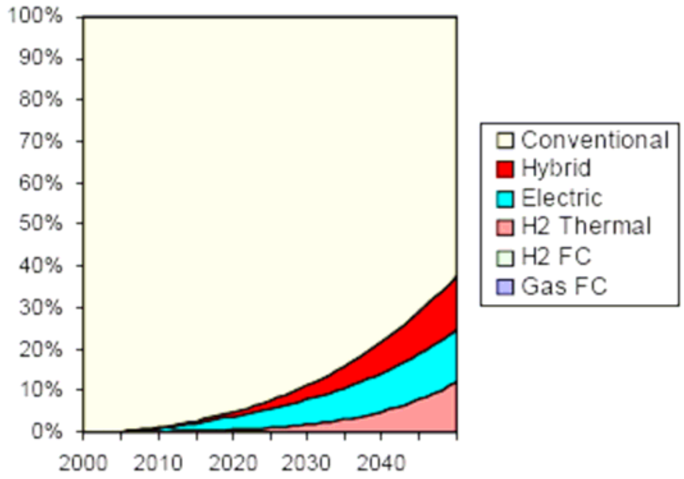

Figure 3.8: Low emission vehicles in Europe in the reference case

3.2.2 The carbon constraint case

The carbon constraint case looks at a 'factor 2' or 50% reduction of CO_2 in Europe and the other Annex 1 countries. The carbon constraint is input in the model in a pure economic way by a carbon price. The carbon value is set at 10 €/tCO_2 in 2010 increasing to 200 €/tCO_2 in 2050 in Europe, while for the other countries the rate goes up by 10%/yr after 2010 eventually catching up in 2050 at 200 €/tCO_2. Other main assumption is the lower demand for oil and gas compared to the reference case, so prices in 2050 are 90 $/boe.

Outcomes for the *world energy system* are the total primary energy supply is 821 EJ (19 Gtoe) in 2050, of which 160 EJ (3.8 Gtoe) is supplied by gas, oil supplies 204 EJ (4.9 Gtoe) and coal supplies 110 EJ (2.6 Gtoe) (less then today). Renewable and nuclear energy represent shares of 168 EJ (4.0 Gtoe) and 178 EJ (4.3 Gtoe), a combined share of 40%.

Electricity comes for 30% from renewable and almost 40% from nuclear energy. In 2050, 42% of renewable electricity and 13% of total electricity comes from wind. The share of CCS in thermal generation plants in 2050 is 62% and the annual storage of CO_2 is 6.5 Gt/yr or 20% of total gross emissions. CO_2 emissions are 24 GtCO_2/yr.

Hydrogen production starts to take of in 2030 and reaches 24.5 EJ (585 Mtoe) in 2050. 75% of the hydrogen is produced by using renewables, the rest is mainly produced using nuclear energy. This is mainly due to the high carbon penalty when using oil, gas or coal to produce hydrogen.

In the *European energy system*, primary energy supply increases to 71 EJ (1.7 Gtoe) in 2050. By then the share of fossil fuel and natural gas in the total energy supply fall to less then 50% and 20% respectively. By 2050, energy production in Europe shows an increase in use of nuclear energy by 40% and renewable energy by 30% (see Figure 3.9).

The production of hydrogen in Europe reaches 3.9 EJ (93 Mtoe) in 2050 (see Figure 3.9). There is no hydrogen produced from fossil fuels by the year 2050. Two thirds are produced from renewable sources and one third from nuclear energy. Total CO_2 emissions are 2.6 $GtCO_2$/yr.

In the carbon constraint case the use of hydrogen in the transport sector is mainly in low emission vehicles (see Figure 3.10). The joint market share for hybrid and electric cars is 45%, there is almost no market share for hydrogen FC cars.

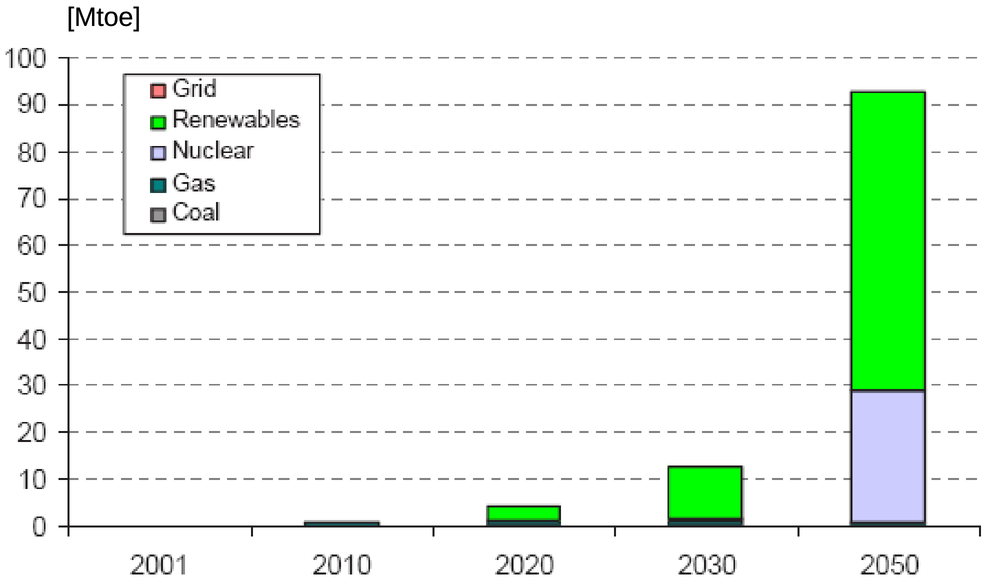

Figure 3.9: Hydrogen production in Europe (Carbon constraint case)

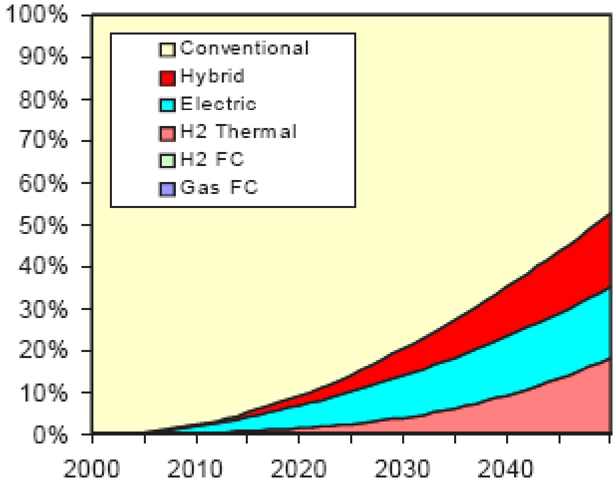

Figure 3.10: Overview of vehicles in Europe (Carbon constraint case)

3.2.3 The hydrogen case

The hydrogen case assumes technological breakthroughs. These breakthroughs show that improvements in technological performance and costs are predominantly required in the distribution and consumption segments of the hydrogen chain.

Assumptions

In this study hydrogen plays a significant role in the hydrogen case. It uses favourable assumptions and is compatible with ambitious climate policies and a long-term stabilization of GHG-emissions of 550 ppm(v) (38.5 $GtCO_2$). Also in the reference case and the carbon constraint case hydrogen plays a role, but to a lesser extent due to the assumptions made.

The hydrogen scenario case considers alternative technological and socio-economic pathways that illustrate possible ways of incorporating hydrogen into the world energy system. It implies a certain number of technological breakthroughs mainly on the end-use site to make hydrogen technologies attractive and more cost effective. The assumptions for this scenario case are:

- For Europe the carbon value is set (equal to the CC-case) at 10 €/tCO_2 in 2010 increasing to 100 €/tCO_2 in 2030 and 200 €/tCO_2 in 2050 in Europe for other countries the value reaches the same value in 2050, but until 2040 does not increase more than 10%/yr.
- The trajectory of the oil price shows that it raises to 2006 and then drops to 40 $/bl in 2010, hereafter increasing to 70 $/bl in 2030 and nearly 100 $/bl in 2050.
- The trend in the prices of oil and gas create an advantage for coal. Assumed is the absolute coal price doubles from the current level, in terms of oil equivalent the price is 22 $/bl in 2050.

Further assumptions for hydrogen technologies are:

- The cost of hydrogen production with steam reforming of natural gas from a large scale plant is 5 to 8 €/GJ, with a natural gas price set between 2 to 4 €/GJ. This is without CCS. CCS would add 20% to the cost. Small scale plants can produce hydrogen at a price of 19 to 22 €/GJ. Production of liquid hydrogen will cost 25 €/GJ.
- Based on a coal price of 1.5 €/GJ, hydrogen production on a large scale using coal gasification is between 8 and 10 €/GJ. Here also applies when CCS is added, the cost will increase by 20%.
- Biomass gasification can produce hydrogen between 9 and 12 €/GJ.
- Electrolysis using base load electricity from coal or nuclear plants produce hydrogen for 22 to 25 €/GJ, however using wind electricity the costs rise to 30 - 50 €/GJ and cost get even higher if other renewable sources are used (90 - 450 €/GJ).
- Solar thermolysis produces hydrogen for over 50 €/GJ.

- Distribution of gaseous hydrogen by truck (depending on the distance) is assumed to be between 10 and 30 €/GJ, while the pipeline transportation cost varies between 6 and 20 €/GJ. Liquid hydrogen supply by truck (excluding the liquefaction) costs 1 to 3 €/GJ.
- Gaseous (pressurised) hydrogen storage in a car now costs € 25,000, but the goal is set at €200 - € 500.
- For the end-use in stationary applications the costs assumed for CHP in residential houses is 6,000 - 10,000 €/GJ. For transport (only PEM, not whole drivetrain) costs are assumed to be 8,000 - 12,000 €/kW and 3000 €/kW for on-board reforming of compressed natural gas. By 2020 the cost of the fuel cell will have dropped to 100 €/kW.

Outcome

In this case, for the world energy system, the total energy supply is 856 EJ (20.5 Gtoe/yr). CO_2 emissions in 2050 fall by 40% (equal to 18 Gt of CO_2) to 27 $GtCO_2$ and the share of fossil fuels is slightly less than 60%. By that time hydrogen production reaches 43.8 EJ (1 Gtoe/yr) after taking off in 2030.

Until 2030, two third of hydrogen production is from fossil fuels, of which about 40% is from steam reforming of natural gas and 60% from coal gasification. Because of high carbon prices, the production from non-fossil energy sources increases sharply. By 2050, the share of production from coal and natural gas has fallen to 10%, although the absolute volume is increasing. Around 65% of plants for hydrogen production using fossil fuels are equipped with CCS facilities in 2050, against 35% in 2030. The share of renewable energy use for hydrogen production is 50% and of nuclear 40%. Biomass is the dominant source of renewable hydrogen production with a share of 70% in 2050 (see Figure 3.11).

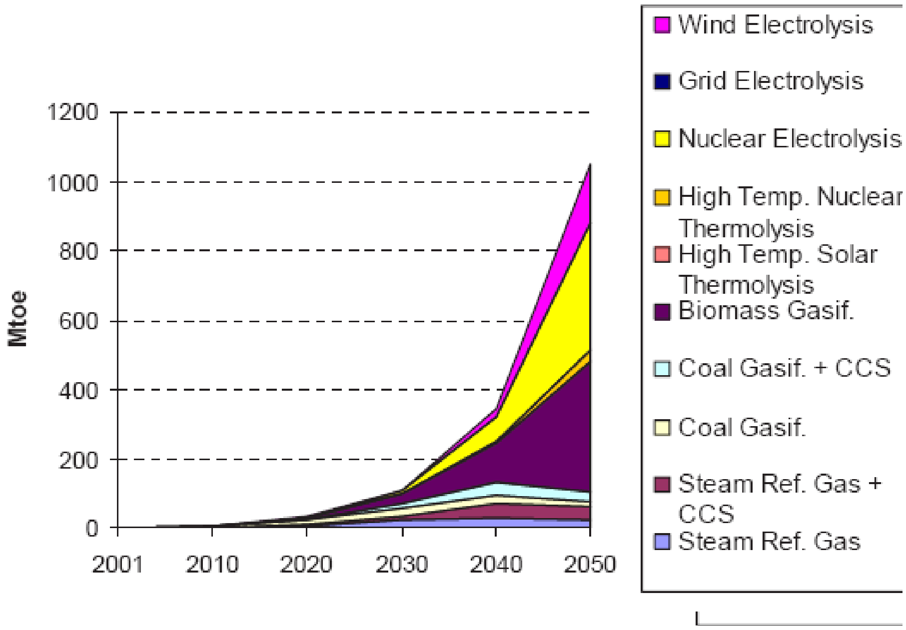

Figure 3.11: Technology mix in world hydrogen production

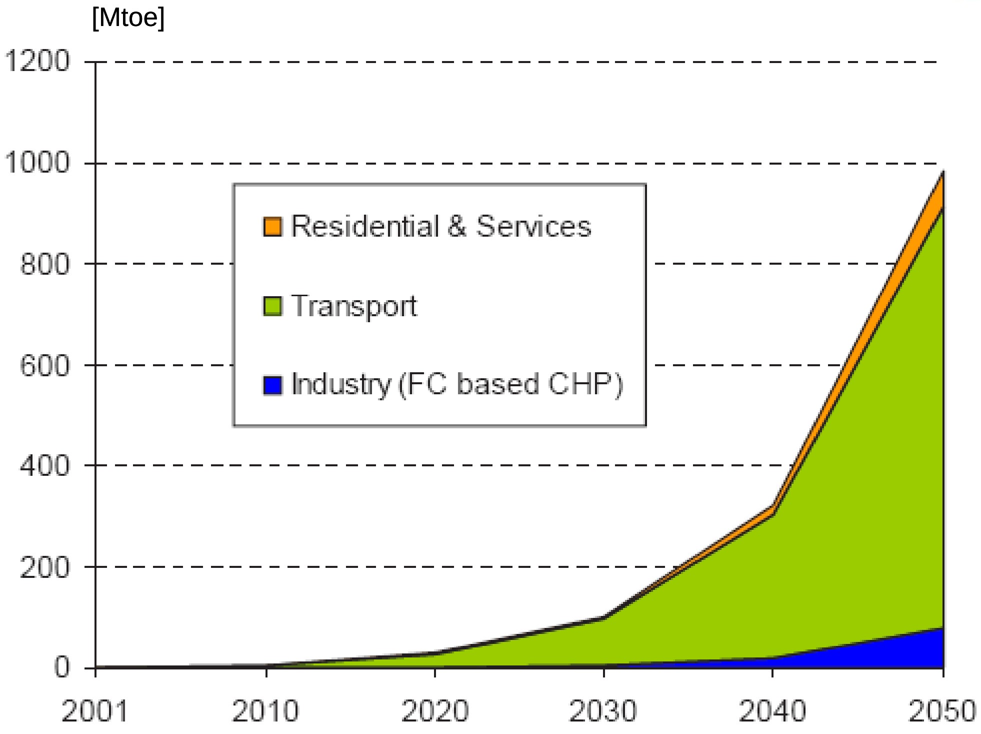

Figure 3.12: World final hydrogen consumption by sector

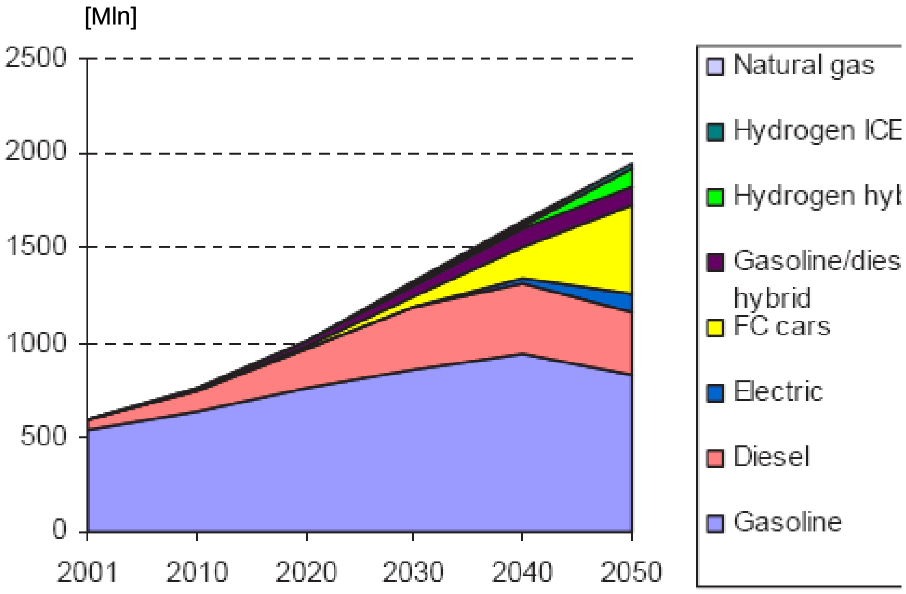

Figure 3.13: Developments in passenger car technology in the world

Hydrogen consumption is for 90% in the transport sector, the remaining 10% goes for one third to residential and tertiary sectors and for two thirds to fuel cell based CHP in industry (see Figure 3.12). The hydrogen uptake in the transport sector starts in 2010 reaching a 5% share of the transport market in 2030. By 2050 this share is almost 30%, mainly used for passenger cars. The build-up of this 30% of the vehicle fleet consists of 80% FCV (approximately 447 million vehicles), 15% H_2 hybrids (approximately 70 million vehicles) and 5% H_2ICE (approximately 30 million vehicles) (see Figure 3.13).

For the *European energy system* energy supply is 71 EJ (1.7 Gtoe/yr) and CO_2 emissions are 2.8 Mtoe CO_2. Hydrogen provides 7% of the final energy consumption in Europe. This implies the production of hydrogen reaches 5 EJ (120 Mtoe/yr) by 2050 (12% of the hydrogen produced in the world). The production increases rapidly after 2030 and is mainly produced from electrolysis using nuclear electricity. Elsewhere mainly renewable sources are used, but in Europe the share of the production from renewable electricity still represents 40% of the total hydrogen production (see Figure 3.14).

In 2050 about three quarters of the hydrogen produced in Europe goes to transport (compared to 90% worldwide). The remaining quarter is allocated to the residential and tertiary sectors (20%) and to the fuel cell based CHP industry (5%). In the transport sector gasoline, diesel and other petroleum products still represent 70% of the energy consumption by 2050, but the remaining 30% is mainly hydrogen. 80% of the passenger cars are FCV, 15% hybrid cars and 5% are H_2ICEs (see Figure 3.15).

Main applications for the production of hydrogen for this scenario are shown in Table 3.1. This table also shows the cost for the different production technologies.

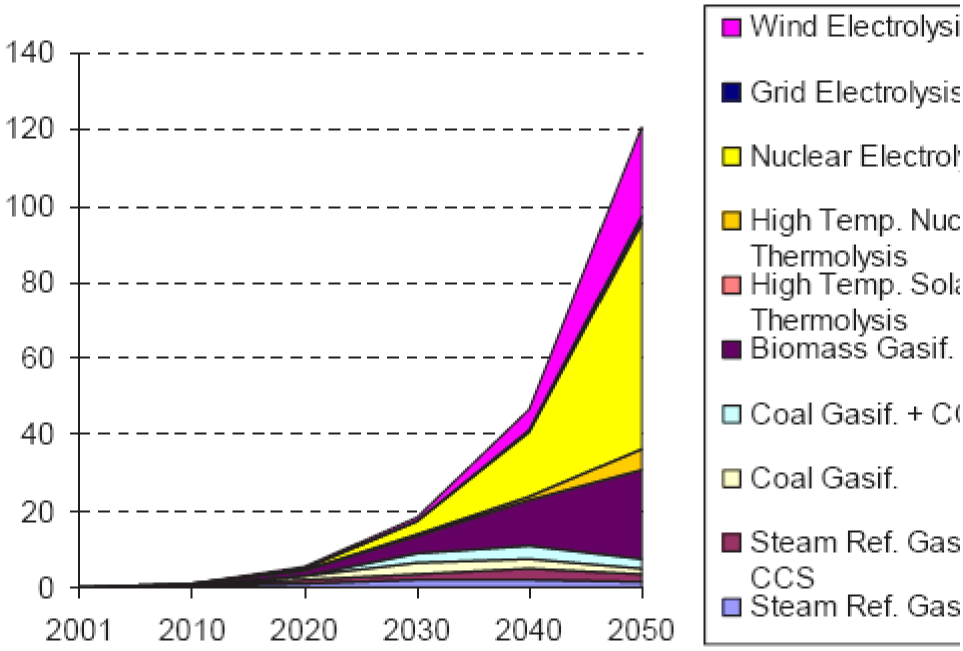

Figure 3.14: Technology mix of hydrogen production in Europe

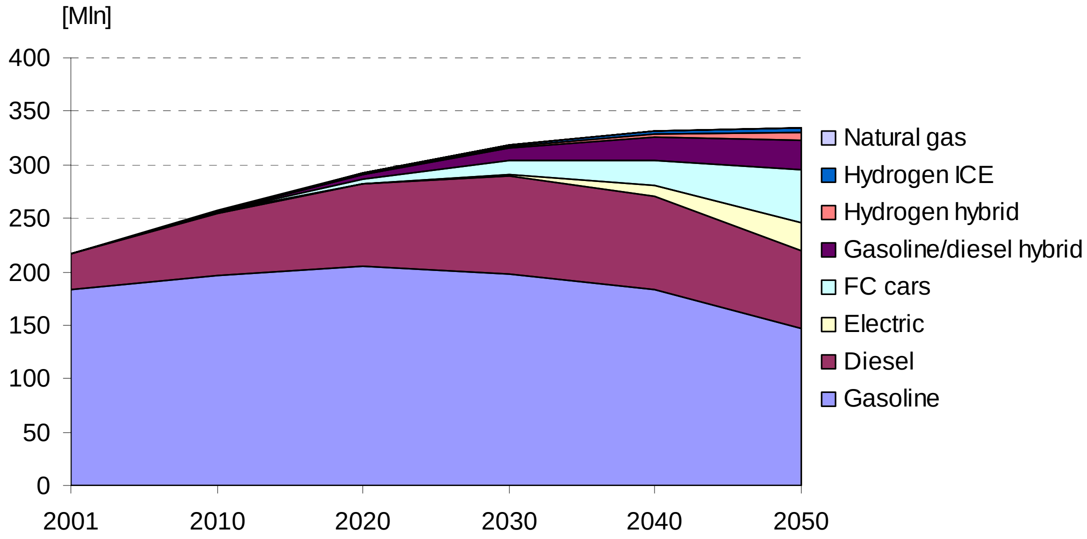

Figure 3.15: Developments in passenger car technology in Europe

Table 3.2: Overview of WETO-H2 cost assumptions and technology pathways in time based on the outcome of the scenario analysis

		Today	2025	2050
Production				
Large scale SMR of NG (with CCS)	[€/GJ]	5-8 (CCS adds 20%)	5-6	4-5
Small scale SMR of NG	[€/GJ]	19-22		
Electrolysis		Base load 22-25 €/GJ Wind electricity 30-50 €/GJ Other renewables 90-450 €/GJ	80 €/Nm^3/d	60 €/Nm^3/d
Gasification of coal (with CCS)	[€/GJ]	8-10 (CCS adds 20%)	7-9	3-5
Gasification of biomass (with CCS)	[€/GJ]	9-12 (CCS adds 20%)		
CCS	[€/tCO_2]	20-30	8-16	6-12
Solar thermolysis	[€/GJ]	50 €/GJ		
Distribution				
By truck (liquid)	[€/GJ]	10-30 (liquid 1-3)	8	4
Pipeline	[€/GJ]	6-20	4	3
Refuelling				
Storage				
Large scale				
On-board (gaseous, liquid, hydrate and carbon)	[€]	200-500		
End-use				
Transport	[€/kW]	6,000-8,000	400	40
Stationary	[€/kW]	8,000-10,000	800	200

4. Roadmaps

Roadmaps describe commercialisation plans, or a desirable future based on stakeholder visions. It takes into account measures and intermediate steps to get to commercialisation in the future. In this chapter the US 'National Hydrogen Energy Roadmap' of the US Department of Energy is reviewed, giving insight into the US roadmap for hydrogen in the future (Section 4.1).

4.1 US DoE 'National Hydrogen Energy Roadmap'

The purpose of this roadmap is to define a common set of objectives and activities agreed upon by government, industry, universities, National laboratories, environmental organisations and other interested parties. In the following sections the current status, future challenges and paths forward are outlined for the different parts of the hydrogen chain.

4.1.1 Production

Currently 95% of the hydrogen produced in the US is produced by steam reforming of methane. Partial oxidation and electrolysis of water are other ways to produce hydrogen, but not used on a large scale. Thermochemical water-splitting using nuclear and solar heat, photolytic (solar) processes using solid state technologies (photoelectrochemical electrolysis), fossil fuel hydrogen produced with carbon sequestration and biological techniques (algae and bacteria) are technologies still in the early development phases.

A pathway for scaling up hydrogen use would build from the existing hydrogen industry. Small reformers and electrolysers will provide hydrogen for small fleets. The next stage will include mid-sized community systems and large centralised hydrogen production facilities with fully developed truck delivery systems for short distances and pipeline delivery for long distances. As markets grow, CCS and advanced direct conversion methods using photolytic renewable, and nuclear technologies will be commercialised. These various combinations of the production technologies are likely to be used for different applications. Challenges that need to be addressed are production cost, low demand, CO_2 emissions of current technologies, and advanced production technologies.

Efforts should focus on improving existing commercial processes such as steam reforming of methane, multi-fuel gasification and electrolysis (by looking at high-temperature and high-pressure electrolysis). Development should continue on advanced production technologies, like biological methods and nuclear (or solar) thermochemical water-splitting.

4.1.2 Distribution

The (limited amount of) hydrogen produced today is currently transported by pipeline or by road via cylinders, tube trailers, and cryogenic tankers, with a small amount shipped by rail car or barge. Hydrogen distributed via high-pressure cylinders and tube trailers have a range of 100 to 320 kilometres. For distances up to 1,600 kilometres hydrogen is usually transported as a liquid over the road.

Current delivery systems will need to expand significantly to deliver hydrogen at all regions of the country. Distributed hydrogen production is likely to play a significant role. Research needs to test the feasibility of delivery methods from centralised and distributed hydrogen production plants as well as compressors, storage systems, and other components integrated into complete delivery systems. Keeping in mind the current investments in delivery systems need to be justifiable beyond 2020 to support adequate returns on investment.

Initial efforts should focus on hydrogen sensors, pipeline materials, compressors and high-pressure breakaway hoses. Demonstrations should test various hydrogen infrastructure components for both centralised and on-site distribution systems. To address the ‘chicken and egg’ fuel/use dilemma, demonstration projects should emphasise testing the hydrogen infrastructure components in applications such as fuelling stations and power parks.

4.1.3 Storage

Currently available technologies permit the physical storage, transport and delivery of gaseous or liquid hydrogen in tanks. Compressed tanks (350 or 700 bar) and cryogenic tanks are used mostly, but no current technology appears to satisfy all of the desired storage criteria sought by manufacturers and end users.

Mature compressed and liquid hydrogen storage technologies may achieve short term goals, but advances need to be made in terms of cost, weight and volume storage efficiency. Metal hydrides offer the advantage of lower pressure storage, conformable shapes and reasonable volumetric storage efficiency, but have penalties in terms of weight. Nanotubes are still in the lab R&D phase and alanates and cryotanks are also still being developed.

Hydrogen storage is a critical element in the hydrogen chain, therefore government-industry coordination on research and development is needed to lower costs, improve performance and develop advanced materials. Efforts should focus on improving existing technologies, including compressed hydrogen and liquid hydrogen amongst advanced materials such as lightweight metal hydrides and carbon nanotubes, to reach the goal of giving vehicles a range of 480 to 644 kilometres (roughly 5 kilograms of hydrogen to be stored). Fleet application with central refuelling facilities may be satisfied with a range of 160 to 241 kilometres, so storage of 3 kilograms of hydrogen may be sufficient.

4.1.4 End-use

Today the use of hydrogen in engines is a fairly well developed technology, while other combustion applications are under development. Fuel cells are in various stages of development, with efficiencies ranging from 40 to 50 percent at full power, 60 percent at quarter power and 80 percent with combined heat and power applications.

Combustion of hydrogen in gas turbines are foreseen for distributed power, CHP and central station power applications, while ICEs can and are being used in vehicles.

For the different fuel cell technologies the table below outlines the application possibilities indicated by the roadmap.

Table 4.1: Fuel cell technologies and applications as shown in the US roadmap

Fuel cell technology	Application
PEM	• Vehicles • Distributed power • CHP • Portable power
AFC	• Vehicles • Distributed power
PAFC	• Distributed power • CHP
MCFC	• Distributed power • CHP
SOFC	• Truck APVs • Distributed power • CHP

The vision of the end-use applications indicates that established technologies, such as turbines and ICEs as well as developing technologies (the fuel cells) show great potential. However, the FCs cannot yet provide the level and quality that consumers are seeking (in terms of durability, reliability and cost). Research is required on advanced materials, electrochemistry and fuel cell stack interfaces together with the exploration of the fundamental properties of hydrogen combustion.

Ultimately hydrogen should be used for transportation, electric power generation and portable devices. Key customer demand includes safety, convenience, affordability and environmental friendliness.

5. Backcasts and pathways

Backcasts and pathways start with a predetermined ‘end’ point (a desirable and plausible future). They then investigate possible pathways to that point. Three studies are described in this chapter. Firstly, the HyWays Phase I report outlining roadmaps for Germany, France, the Netherlands, Greece, Italy, and Norway (Section 5.1). Secondly, the Hydrogen and Fuel Cell Technology Platform (HFP) document ‘Deployment Strategy’ is described outlining the industry view on hydrogen and fuel cells in Europe (Section 5.2). This document is selected as a pathway, because it is written based on the ‘end’ point as written in the HFP’s Strategic Research Agenda (see Section 6.1). The third Paragraph (Section 5.3) will describe Japans vision on energy by reviewing their ‘Strategic Technology Roadmap (Energy Sector)’. Although the name indicates the document is a roadmap, the methodology used does fit the definition of a pathway.

5.1 HyWays

The HyWays project (www.hyways.de) is funded by the EC aiming for the aggregated member state specific results for greenhouse gas emissions, preferred hydrogen production and infrastructure technologies, the build-up of supply infrastructure and end-use technologies. These visions will be integrated into a proposal for an EU Hydrogen Energy Roadmap for the participating areas. The timeframe is 2020, 2030 and 2050.

HyWays will combine technology databases and socio-/techno-/economic analysis to evaluate selected stakeholder scenarios for future sustainable hydrogen energy systems. This will lead to recommendations for a European Hydrogen Energy Roadmap reflecting country specific realities in the participating member states. Main characteristic of this roadmap is that it reflects real life conditions by not only accounting for technological but also for institutional, geographic and socio-economic barriers and opportunities which are representative for the different member states. Therefore this roadmap will be based on inputs from European industry, research institutes and government agencies, and backed up with the best-available data.

It will systematically describe the future steps to be taken for large-scale introduction of hydrogen as an energy carrier in the transport and power market and as storage medium for renewable energy.

Although the project is called a roadmap project, HyWays combines integrated energy system modelling like in the IEA and WETO-H_2 study, with individual energy chain analyses and more qualitative roadmap activities. But because the phase I report mainly gives an overview of the envisaged pathways by the project and member state stakeholders the study is put in this category.

Assumptions

HyWays selected the ‘European Energy and Transport: Trends to 2030’ to serve as a basis for the development of the baseline scenario. Because the projections do not extend into the period after 2030 some additional assumptions are made until 2050:

- Oil price leads up to 50 $/boe
- Gas price of 34.9 €/boe
- Coal price stays at 2020 - 2030 level, at 7 €/boe.

Policy related assumptions are also made. The assumed targets for renewables are 22% of all electricity produced in the EU15 in 2010 and 27.6% for 2020 remaining constant until 2050. Also policy on the emission of GHG beyond 2012 is made. A 35% reduction target of CO_2-emissions in the whole EU-region is assumed with an emission-trading scheme by 2050.

Limits on fuel consumption and on the SO_2 content of fuels are adopted for transport. Two scenarios are analysed differing in the penetration rate of hydrogen and in the technology development (and cost by using the learning curves). These assumptions are shown in the tables below for transport and stationary applications using hydrogen.

Table 5.1: Scenarios for the potential development of hydrogen vehicles, share in vehicle stock

Total share of fleet [%]	2010	2020	2030	2040	2050
High penetration	Demonstration only	3.3	23.7	54.4	74.5
Low penetration	Demonstration only	0.7	7.6	22.6	40.0

Table 5.2: Scenarios for the potential development of stationary hydrogen applications in the residential sector

Total share of households [%]	2010	2020	2030	2040	2050
High penetration	-	1	4	8	10
Low penetration	-	0.1	0.5	2	3

Table 5.3: Scenarios for the possible development of stationary hydrogen applications in the commercial and services sector

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

With this vehicle share (the high penetration) the total H_2 demand is shown in Table 5.4.

Table 5.4 Hydrogen demand for the high penetration scenarios

[EJ/yr]	2010	2020	2030	2040	2050
Transport	0	0.22	1.49	3.19	4.37
Stationary	0	0.02	0.16	0.45	0.96
Total	0	0.24	1.65	3.64	5.33

Learning curves are used for modelling the future cost developments of technologies. A learning curve describes technological progress - expressed in the progress ratio - as a function of accumulated experience with a specific technology. For example, a technology with a progress ratio of 0.8 indicates that with each doubling of the cumulative output the unit price is reduced by 20%. The assumptions in the HyWays project concerning the progress ratios for key components are shown in the table below.

Table 5.5: Progress ratios of H2 technology components for a fuel cell car

Component	Low PR (fast cost reduction)		High PR (low cost reduction)	
	Initial phase	After 10 years	Initial phase	After 10 years
Alternative fuel tank	0.85		0.85	0.85
Electric motor	0.90		0.90	0.98
Li-Ion battery	0.90		0.30	0.98
FC system	0.80	0.90	0.82	0.92
H2-ICE	1.00		1.00	

Fully validated roadmaps for the introduction of hydrogen are made for six countries taking these assumptions into account. Stakeholders were involved to express their views. The outcomes are described in the following sections.

5.1.1 Vision of Germany

Starting after 2010, hydrogen will be used mainly for transport. Initially industrial by-product hydrogen will be used. Additional hydrogen will be produced by on-site steam reforming (SMR) and electrolysis. Demand centers in densely populated areas will arise and for hydrogen transport liquid or compressed hydrogen trucks will play a relevant role.

After 2020 hydrogen production options will broaden to local and central hydrogen production. Hydrogen production with electrolysis will use electricity from renewable sources. CCS will be used for hydrogen production from NG and coal. At this stage, Pipelines will play a relevant role in hydrogen transportation. On-site production by

SMR and electrolysis will still play an important role, especially in rural areas with warranted demand profiles.

After 2030 hydrogen plays a major role in transport and a remarkable role for stationary applications. CCS is already established at industrial scale. Central hydrogen production from fossil fuels could dominate in Germany either from SMR or coal gasification. The share of renewable hydrogen will increase, with as main supply chains wind (on- and off-shore) as well as de-central biomass gasification. Import of hydrogen (from e.g. Norway via a European pipeline network) may become another option. Transport will still be by pipeline or liquid hydrogen truck.

5.1.2 Vision of France

By 2010, there is a small requirement of hydrogen which can be produced by steam methane reforming (SMR) or water electrolysis, using the existing infrastructures (pipelines, tube trailers).

Between 2010 and 2030 demand will increase and CCS (at industrial size) at SMR installations is not envisaged before 2020. This option would be privileged assuming a dissuasive CO_2 tax. The existing natural gas pipelines will be used to transport the hydrogen.

From 2030 and beyond SMR would be privileged in areas with large population density and with a high demand. CO_2 storage technology should be used at these locations. In other areas local or central electrolysis using the French electricity mix (90% from non-fossil sources) will be used, meaning renewable electricity in favourable locations or nuclear electricity in others will be needed. The emergence of high temperature nuclear reactors could allow a massive production of CO_2 free hydrogen.

Hydrogen distribution by pipeline would be the most attractive option for significant amounts of hydrogen, whereas the transport by truck would be preferred for more limited quantities.

5.1.3 Vision of Greece

By 2010 wind energy and electrolysis should be considered as the first applications for the production of hydrogen in local based supply schemes.

Up to 2030 NG will have the primary role, representing a share of more than half of the expected hydrogen production by then. Centralised SMR is seen as the most economically attractive options where CCS schemes should be considered in terms of their applicability and viability at large-scale installations.

Lignite gasification for hydrogen production is foreseen to have a limited but continuous contribution. Moreover, electricity from renewable energy sources (RES-e), mainly wind-electrolysis concepts are expected to achieve a significant position.

Renewable energy sources are foreseen to have the dominant role in the hydrogen production from 2030 on. In densely populated areas supply will mainly go through pipelines. Supportive actions to link RES-e to the production of hydrogen are foreseen. Hydrogen will mainly be used for transport applications followed by stationary applications for households.

5.1.4 Vision of Italy

In the short term (after 2010) with hydrogen consumption will be less then 100kton. The main production method will be SMR in decentralised plants. Hydrogen will be transported by truck both (compressed) gaseous as well as in liquid form and wherever possible mixed in the NG pipelines.

Up to 2030 hydrogen production will be dominated by fossil fuel fed (NG and coal), centralised plants where CCS can be viable. Fossil fuels will cover three quarters of the total production, as the other quarter will consist of renewable sources (biomass, urban wastes, wind and maybe solar from a large demo). Hydrogen will be delivered through pipelines (10-50 km) from a centralised production plant.

By 2050 hydrogen will still be produced from different sources but the share of solar will increase considerable. Wind is still the most important RES-e source. The total share of RES-e will be one third. The pipeline infrastructure will be increasing to hundreds of km.

5.1.5 Vision of the Netherlands

NG will play a dominant role up to 2030 and will also be important up to 2050. On-site NG SMR will be the hydrogen production option of choice. Pipeline infrastructure will be build-up (starting at Rijnmond).

After 2030, biomass gasification and coal gasification with CCS will provide hydrogen. Of-shore wind will provide electricity for renewable hydrogen, which will be transported via pipelines in the Randstad (densely populated area on the west coast of the Netherlands) while in other regions onsite reforming will dominate or liquid hydrogen will be transported by truck.

5.1.6 Vision of Norway

By 2010 the small demand for hydrogen will be met by the use of industrial by-products or on-site electrolysis, SMR and biomass utilisation. With increasing demand (up to 2030) local industrial by-product hydrogen remains an important source. Central production from fossil fuel will not be likely. CCS from NG is not envisaged before 2020 at industrial scale. In the long run (up to 2050) hydrogen production from RES-e with electrolysis (at coastal areas using wind and wave energy, and biomass utilisation mainly connected to wood waste in southern Norway), and natural gas reforming with CCS is expected to dominate the production of hydrogen. Export of hydrogen to other European countries (e.g. Germany, Netherlands) is part of the Norwegian vision.

Stationary hydrogen use is only foreseen in remote locations or at small scale. Hydrogen transport by pipeline will become more and more attractive, but transport by truck is also expected in locations with a low population density.

5.2 HFP 'Deployment Strategy'

In January 2004 the European Commission initiated the HFP. The aim of the HFP is to prepare a strategy for hydrogen economy for the period up to 2050. One of the key documents describing intermediate milestones (called 'Snapshot 2020') to reach long term goals and amongst others make a market assessment of hydrogen and fuel cell technologies is the 'Deployment Strategy' published in August 2005.

The document is extensive and takes into account all possibilities for hydrogen and fuel cells, but for this research the main focus will be on transport and stationary related applications. This is because the scenario studies and other roadmap do not pay attention to portable FCs and therefore comparison is not possible.

After starting with outlining the market assessment a more detailed overview of the different technologies of the hydrogen chain is given. The table below indicates the deployment status for applications by 2020, expressed in numbers of sold units per year and cumulative sales projections respectively.

Table 5.6: Key assumptions on hydrogen and fuel cell applications for a 2020 scenario

	Portable FCs (for handheld electronic devices)	Portable Generators & Early markets	Stationary FCs (CHP)	Road transport
EU H2/FC units sold per year projection 2020	~250 million	~100.000 (~1 GWe)	100,000 to 200,000 (2-4 GWe)	0.4 - 1.8 million
EU cumulative sales projections until 2020	n.a.	~600.000 (~6 GWe)	400,000 - 800.000 (8-16 GWe)	1-5 million
EU expected 2020 market status	Established	Established	Growth	Mass market roll-out
Average power FC system	~15 W	10 kW	<100 kW (Micro CHP) >100 kW (industrial CHP)	80 kW
FC system cost target	1-2 €/W	500 €/kW	2,000 €/kW (Micro CHP) 1,000 €/kW (industrial CHP)	<100 €/kW (for 150,000 units per year)

5.2.1 Hydrogen production

In order to allow for a medium term impact only pathways that have been identified to mature before 2015 have been taken into account. Three pathways are identified for production, of which cost assumptions are shown in Table 5.7, these comprise of:

- Hydrogen derived from refineries and chemical plants. Maximum advantage is taken of existing low cost hydrogen sources.
- In parallel, on-site hydrogen production based on different technologies (electrolysis, reforming) and sources (natural gas, biomass, electricity and, in particular renewable) in order to stimulate these industries to develop the necessary technologies.
- Large-scale, centralised hydrogen-production based on natural gas or other available fossil resources with future options for CCS.

By 2020 two main technologies will be in place: high efficient and low cost electrolysers and gasification processes. Hydrogen will thus be produced from a variety of sources like (carbon-free) electricity or directly from fossil fuels with coal gasification processes or natural gas steam reforming both including CCS. Hydrogen produced from electricity will be mainly produced on-site at the filling station. Coal gasification or natural gas steam reforming requires large scale production units in centralised plants; because they are process efficient and economically viable only in larger installations. The produced hydrogen will be mainly distributed in liquid form with trucks, and at first a few pipeline distribution systems will be installed in areas with a high consumption. On-site steam reforming may decline due to the lack of applicable technologies for CCS in small quantities

Due to a typical plant lifetime of at least 20 years for key equipment such as electrolysers, filling stations or large scale steam reformers the pathways that will be chosen now for large-scale demonstration projects and the following market introduction phases, will have an impact beyond 2030.

Table 5.7: Assessment of relevant hydrogen pathways until 2020

	Natural Gas (SMR)	Grid Electricity (electrolysis)	Wind (electrolysis)	Biomass (gasification)
Hydrogen cost (excl. distribution)	1.0 €/kg (8.3 €/GJ)	3.75 €/kg (31.3 €/GJ)	6-8 €/kg (50-67 €/GJ)	3-4 €/kg (25-33 €/GJ)
Positive impact on security of energy supply	Modest	High	High	High
Positive impact on GHG emission reductions	Neutral - modest	Negative - neutral	High	High

5.2.2 Hydrogen storage and distribution

Distribution options differ for the three production pathways. Besides, the distribution options also depend on the end-use application and storage technology.

Envisaged options for hydrogen distribution for usage of by-product hydrogen pipeline transport over short distances is the most efficient way. For stationary application the use of natural gas and connection to the grid is foreseen. Even natural gas mixed with hydrogen or dedicated hydrogen micro-grids (a mid term option) that could be connected to chemical plants and refineries are optional. For transport use of hydrogen, the produced hydrogen can be supplied by truck in liquid or gaseous form. Pipelines could be considered in an advanced phase of market uptake. Distribution is of course not necessary when the hydrogen is produced on-site.

The storage of hydrogen is described as a possible hinder of the introduction of hydrogen vehicles. No preference is given for a storage option, but targets are set for 2015 (see Table 5.8)

Table 5.8 Hydrogen storage performance expected by 2015

	Usable H2 mass fraction (2015 perspective) [%]	Remarks
LH2	12	Ongoing fleet tests
CGH2 700 bar	9	First fleet test (ongoing with 350 bar)*
Complex metal hydrides (alanates)	7	Laboratory phase
Chemical hydrides (NaBH4)	9	Demonstrator in USA, requires not only refilling but also draining of hazardous chemical liquid; recycling process not reasonable

* Recently the first 700 bar tanks are being tested

5.2.3 Stationary applications

Two main applications for penetration until 2020 are described. The first is fuel cell based CHP systems (below 50 kW_e) for residential and small commercial use with a main focus on small systems in the range of 1 to 5 kW_e. The capacity that can be installed if supported by policy are:

- 2006 - 2008 1 MW_e installed capacity (target cost 12,000 €/kW)
- 2007 - 2010 5 MW_e installed capacity (target cost 6,000 €/kW)
- 2009 - 2012 200 MW_e installed capacity (target cost 4,000 €/kW).

The second application is (high temperature MCFC and SOFC) CHP in the range of 200 to 500 kW_e for industrial use. The capacity that can be installed if supported by policy are:

- 2006 - 2008 3 MW_e installed capacity (target cost 12,000 €/kW)
- 2007 - 2010 20 MW_e installed capacity (target cost 10,000 €/kW)
- 2009 - 2012 400 MW_e installed capacity (target cost 3,000 €/kW).

The projections for these two applications for 2020 in terms of numbers sold, average power, cost, etc. are shown in Table 5.9.

Table 5.9: Snapshot 2020: market targets for stationary fuel cell applications

		Micro CHP (<50 kWe)	Industrial CHP (200-500 kWe)
Mass market introduction	-	≥2010	≤2010
EU FC units sold per year projection 2020	[GWe/yr]	(~0.4 GWe)	(~3 GWe)
Average power FC system	[kWe]	~3	~350
FC cost target	[€/kWe]	2,000	1,000 - 1,500
Estimated EU added value due to FC system manufacturing (2020 estimate)	[€/yr]	~1 billion + installation and energy services	~1 billion + installation

The total projected annual production of approximately 3.4 GW for the residential, commercial an industrial CHP market would represent <1% of the expected gross installed generating capacity in the EU25 in 2020.

However, most of the fuel cells running in 2020 will be fuelled by natural gas or syngas. Only when large volumes of hydrogen are available, industrial FC application can be foreseen, although hydrogen fuelled gas turbines and combined cycle power plants should be considered.

5.2.4 Transportation applications

Hydrogen application in transport will be mainly by PEMFC and H_2ICE. Vehicles with hydrogen fuelled ICEs are viewed as a possibility to provide a faster pathway to a broad market introduction of hydrogen vehicles, while further development of PEMFCs are required (see Table 5.10).

Table 5.10: Comparison of the actual status with 2015 targets for FC systems for passenger cars

		Actual status	2015 target
Power density	[l/kW]	3.0	1.5
Cycle efficiency (NEDC)	[%]	37	>40
Life time	[Full load hours]	<2,000	>5,000
Specific cost	[€/kW]	>4,000	<100*

* >150,000 units/yr.

The introduction of hydrogen in transport starts in 2015 leading to a few percent in 2020, but no real significant contribution of hydrogen vehicles is expected. Some early applications untill 2020 are identified. These are:

Inner city traffic such as public transport (buses), city vehicles for private or fleet users and light duty fleets for passenger transport and delivery services.

Industrial material handling such as forklifts, cargo handling.

Airport apron vehicles such as passenger transport, VIP shuttle, cargo handling, delivery services.

Auxiliary Power Units (APU) running on conventional fuels for trucks, boats and recreational vehicles or premium cars (but also in other transportation categories like flight, railway and maritime).

For the 2020 snapshot is an upper range of 5% of all new vehicles being hydrogen fuelled is assumed, resulting in a range of 360,000 up to 1,825,000 vehicles sold per year being hydrogen fuelled (this assumption is also used in HyWays). If the hydrogen is derived from NG in combination with fuel cell powered vehicles, this offers savings of about 30% in GHG emissions.

Table 5.11 shows further transition steps. Some essential notes are made related to these transition steps. First, the timing of industry development cycles needs to be considered. It requires more test-fleet generations to develop completely new technologies like FC systems up to the point where they are competitive with conventional drive trains in terms of reliability, lifetime or cost. Secondly, on-board storage is essential especially in the step from >2010 to >2020.

Table 5.11: Transition steps for fuel cell vehicles towards mass market penetration

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

5.3 Japan 'Strategic Technology Roadmap (Energy Sector)'

The 'Strategic Technology Roadmap' of the energy sector was developed by backward examination (backcasting) of the technology portfolio on a long-term basis until 2100. Since Japan depends on imports to supply most of their energy needs, the roadmap takes into account constraints on oil and natural gas production and assumes existing energy production can be replaced with other energy (renewable) sources and reduced by increasing efficiency of energy usage.

Several constraints are taken into account for future the resources and the environment. These are:

- Peak oil production in 2050
- Natural gas peak in 2100
- An annual CO_2 emission intensity per GDP (based on 2000[9]) of 1/3 in 2050 and 1/10 in 2100.

Three cases are reviewed with these constraints and are described below (see Figure 5.1).

Case A: Maximum use of fossil resources (e.g. coal) with CO_2 capture and sequestration

This case depends on fossil resources such as coal and non-conventional fossil fuels. The CO_2 will be captured and stored. However, CCS reduces the impact on CO_2 emissions significantly and immediately, but is merely seen as a transition solution. Because the CO_2 storage capacity is limited in Japan, realization of ocean sequestration is an essential condition. For this, impact on the maritime ecosystem has to be verified first. Moreover, CCS is efficient for central sources producing large scale emission, however, it is difficult to capture CO_2 emissions from diversified sources commonly utilized in transport or households. An example of the progression in time of the final energy demand and power generation for this case can be found in Appendix A:.

Case B: Maximum use of nuclear energy

The energy for all sectors is supplied by nuclear power (with no CO_2 emissions). Electricity and hydrogen (produced by electrolysis or with heat) will be the energy carriers for the transport and industry sector. Based on resource limitations of uranium ore, deployment of non-conventional nuclear fuel such as recovery of uranium from seawater, or the establishment of a nuclear fuel cycle is essential. Since long lead-time is required to install a facility, long-term planning is necessary. An example of the evolution of final energy demand and power generation in time for this case can be found in Appendix A:.

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[9] Japan's GDP will be 1.5 times 2000 GDP in 2050 and about double in 2100.

Case C: Maximum use of renewable energy combined with ultimate energy-saving

Besides maximum use of renewable energy (of any source), energy demand will reduce as much as possible due to energy-saving and self-sustainability. Essential is that energy-saving technologies are fully established and deployed, because of local constraints and operational conditions of renewable energy. Significant improvements are required for both renewable and energy saving technologies. In the industrial sector, drastic changes in the production process, and the development and deployment of comparable large renewable energy sources are required. In the residential/commercial and the transport sectors application in a wide range of areas is required. Especially, self-sustainable systems combined with energy-saving and renewable energy are important. An example of the progression in time of the final energy demand and power generation for this case can be found in Appendix A:.

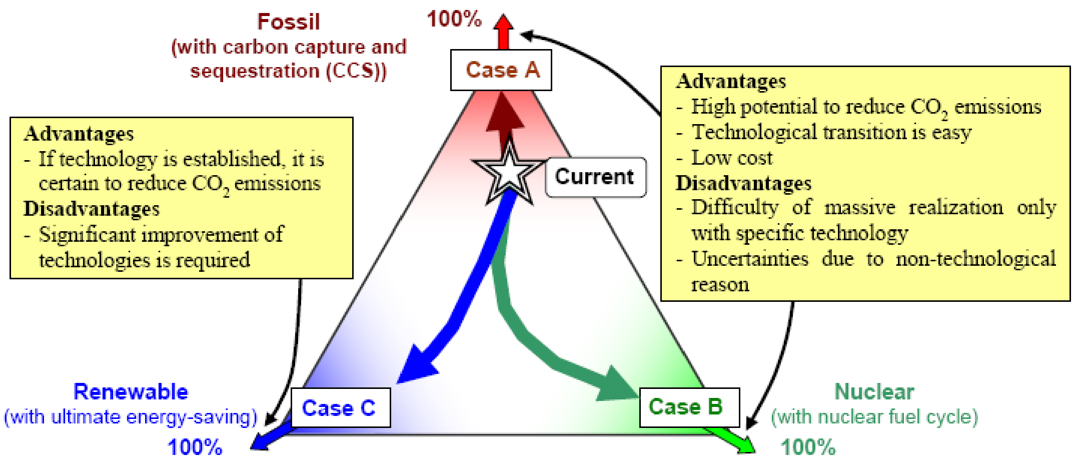
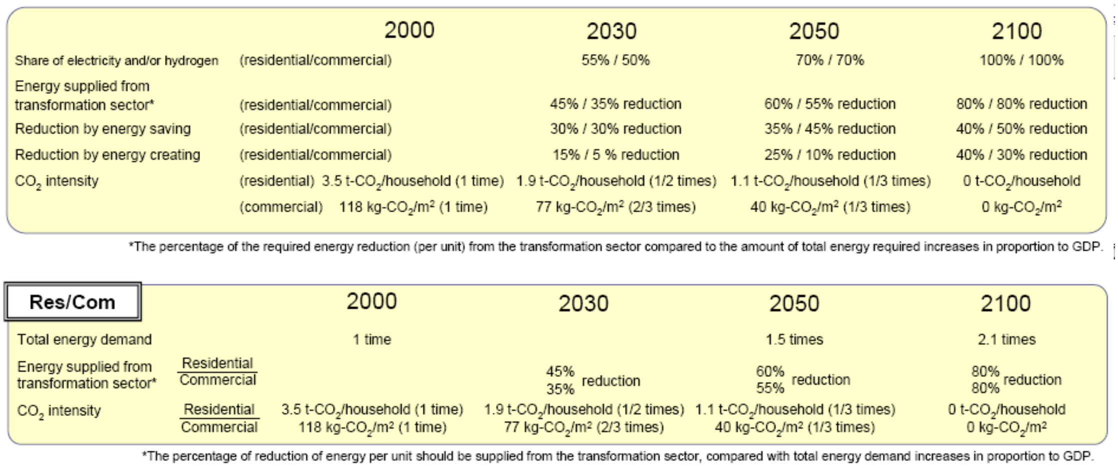


Figure 5.1: Overview of three cases of primary energy supply structures

Based on the three cases (described above) a roadmap is developed, starting with a desired situation in 2100 and backcasting this to 2050 and 2030. However, Case A is not seen as a long-term solution due to limitations in fossil fuel, so a combination of Case B and C is desirable for the Japanese society. Based on these cases the roadmap describes the technological specifications and market introduction timeline for several technologies for the different sector taking into account the constraints for future resources and environment. An outline is given, mainly focussing on the role of hydrogen.

5.3.1 Residential and commercial sector

For this sector it is assumed the energy saving is carried out in the residential sector first and in the commercial sector later Electrification and/or switch to hydrogen will progress evenly from the current level. The deployment will occur by the introduction and market expansion of energy saving equipment followed by an increase of supplied energy in the form of electricity and hydrogen as well as the decrease of fossil energy supplied from grids. Fuel cells will amongst others be used for distributed power generation and cogeneration. The full shift from fossil fuels to electricity and/or hydrogen will be between 2040 and 2050, because by then hydrogen cookers and ultra-high efficiency fuel cells using hydrogen will be available. An outline for the residential and commercial sector is given in the figure below.



		2000	2030	2050	2100
Share of electricity and/or hydrogen	(residential/commercial)		55% / 50%	70% / 70%	100% / 100%
Energy supplied from transformation sector*	(residential/commercial)		45% / 35% reduction	60% / 55% reduction	80% / 80% reduction
Reduction by energy saving	(residential/commercial)		30% / 30% reduction	35% / 45% reduction	40% / 50% reduction
Reduction by energy creating	(residential/commercial)		15% / 5 % reduction	25% / 10% reduction	40% / 30% reduction
CO_2 intensity	(residential)	3.5 t-CO_2/household (1 time)	1.9 t-CO_2/household (1/2 times)	1.1 t-CO_2/household (1/3 times)	0 t-CO_2/household
	(commercial)	118 kg-CO_2/m^2 (1 time)	77 kg-CO_2/m^2 (2/3 times)	40 kg-CO_2/m^2 (1/3 times)	0 kg-CO_2/m^2

*The percentage of the required energy reduction (per unit) from the transformation sector compared to the amount of total energy required increases in proportion to GDP.

Res/Com		2000	2030	2050	2100
Total energy demand		1 time		1.5 times	2.1 times
Energy supplied from transformation sector*	Residential Commercial		45% 35% reduction	60% 55% reduction	80% 80% reduction
CO_2 intensity	Residential Commercial	3.5 t-CO_2/household (1 time) 118 kg-CO_2/m^2 (1 time)	1.9 t-CO_2/household (1/2 times) 77 kg-CO_2/m^2 (2/3 times)	1.1 t-CO_2/household (1/3 times) 40 kg-CO_2/m^2 (1/3 times)	0 t-CO_2/household 0 kg-CO_2/m^2

*The percentage of reduction of energy per unit should be supplied from the transformation sector, compared with total energy demand increases in proportion to GDP.

Figure 5.2: Overview of the Japanese residential and commercial sector according to the technology roadmap

5.3.2 Transport sector

Mainstream automotive changes are from an internal combustion engine car to an internal combustion hybrid car and, in time, to a fuel cell hybrid car (see Figure 5.3). This requires hydrogen/electric vehicles to be commercialised to compete in the market by 2030[10] in order to achieve 40% electricity/hydrogen use in 2050 (see Figure 5.4). Electric cars are mainly used as compact cars for short-range transport. In order to reach 80% reduction of energy demand in 2100 all automobiles will be replaced with highly efficient fuel cell hybrid cars (using hydrogen as fuel), meaning there will be no more ICE vehicles. For the intermediate step of 60% reduction of energy demand the total share of fuel cell hybrid cars and electric cars has to be around 40% and most of the remaining cars should be hybrid ICE cars. To stimulate market uptake public procurement of pubic vehicles, taxation discount and subsidies can/will be applied as well as by giving FCV higher priority on parking lots and allowing them to drive into restricted places.

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[10] The Ministry of Economy, Trade & Industry (METI) in Japan expects 5 million hydrogen vehicles on the road in 2020 (source: HFP, DS).

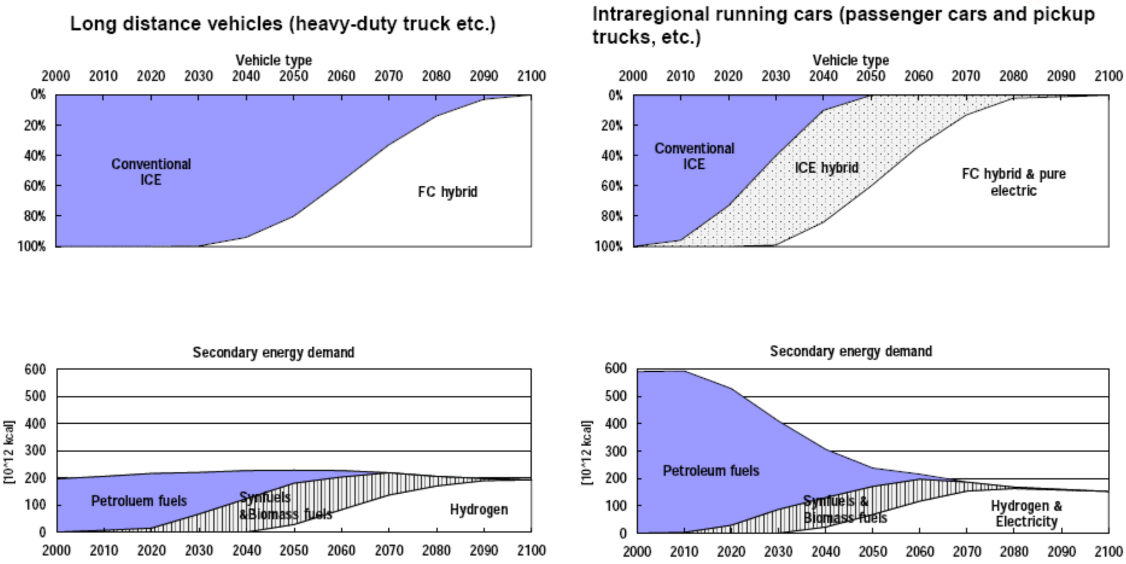
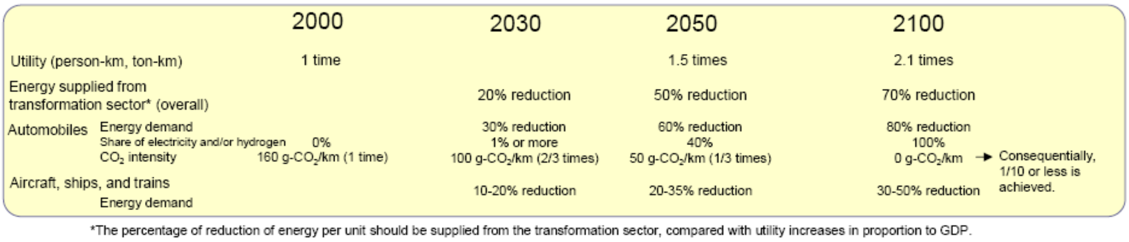


Figure 5.3: Overview of the foreseen energy source and carriers used in the transport sector in time in Japan

The introduction of hydrogen will start by using by-product hydrogen and transporting this in batches. Between 2030 and 2050 on-site fuel reforming of fossil fuel, followed by on-site water electrolysis (when fossil fuel prices increase) will become mainstream. After 2050 a pipeline network will emerge in regions where enough demand density is realised. Hydrogen supply networks will be developed by government investments.

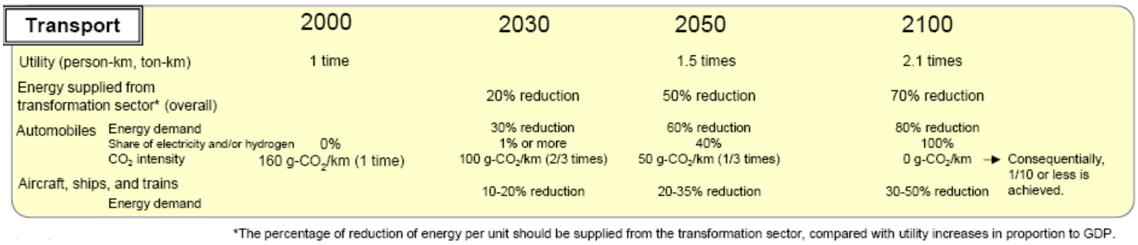
For the storage of hydrogen all options are open. Storage capacity and wt% will increase to 20 kg and 15wt% (see Appendix B: for more detail).

Maritime transport (the recreational vessels) will also start using hydrogen by 2040. Also hydrogen FC/battery hybrid trains will start emerging round that time.



		2000	2030	2050	2100	
Utility (person-km, ton-km)		1 time		1.5 times	2.1 times	
Energy supplied from transformation sector* (overall)			20% reduction	50% reduction	70% reduction	
Automobiles	Energy demand		30% reduction	60% reduction	80% reduction	
	Share of electricity and/or hydrogen	0%	1% or more	40%	100%	
	CO_2 intensity	160 g-CO_2/km (1 time)	100 g-CO_2/km (2/3 times)	50 g-CO_2/km (1/3 times)	0 g-CO_2/km	→ Consequentially, 1/10 or less is achieved.
Aircraft, ships, and trains	Energy demand		10-20% reduction	20-35% reduction	30-50% reduction	

*The percentage of reduction of energy per unit should be supplied from the transformation sector, compared with utility increases in proportion to GDP.



Transport

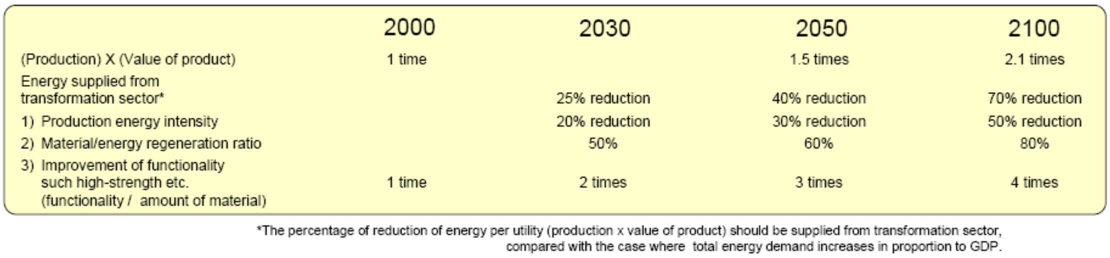
		2000	2030	2050	2100	
Utility (person-km, ton-km)		1 time		1.5 times	2.1 times	
Energy supplied from transformation sector* (overall)			20% reduction	50% reduction	70% reduction	
Automobiles	Energy demand		30% reduction	60% reduction	80% reduction	
	Share of electricity and/or hydrogen	0%	1% or more	40%	100%	
	CO_2 intensity	160 g-CO_2/km (1 time)	100 g-CO_2/km (2/3 times)	50 g-CO_2/km (1/3 times)	0 g-CO_2/km	→ Consequentially, 1/10 or less is achieved.
Aircraft, ships, and trains	Energy demand		10-20% reduction	20-35% reduction	30-50% reduction	

*The percentage of reduction of energy per unit should be supplied from the transformation sector, compared with utility increases in proportion to GDP.

Figure 5.4: Overview of the Japanese transport sector according to the technology roadmap

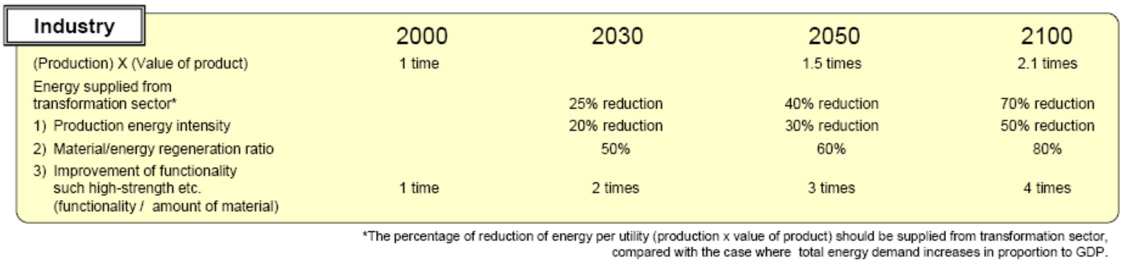
5.3.3 Industry sector

The main aim for the industry sector (see Figure 5.5) is on reducing the energy intensity for production (by energy saving and co-production of material and energy), the regeneration of energy from materials and improvement of the produced materials (high strength, low amount of material). Hydrogen and electricity co-production is foreseen from approximately 2015[11], while hydrogen deployment will start after 2025. Also in this sector, the initial applications of hydrogen will be fed by by-product hydrogen.



	2000	2030	2050	2100
(Production) X (Value of product)	1 time		1.5 times	2.1 times
Energy supplied from transformation sector*		25% reduction	40% reduction	70% reduction
1) Production energy intensity		20% reduction	30% reduction	50% reduction
2) Material/energy regeneration ratio		50%	60%	80%
3) Improvement of functionality such high-strength etc. (functionality / amount of material)	1 time	2 times	3 times	4 times

*The percentage of reduction of energy per utility (production x value of product) should be supplied from transformation sector, compared with the case where total energy demand increases in proportion to GDP.



Industry

	2000	2030	2050	2100
(Production) X (Value of product)	1 time		1.5 times	2.1 times
Energy supplied from transformation sector*		25% reduction	40% reduction	70% reduction
1) Production energy intensity		20% reduction	30% reduction	50% reduction
2) Material/energy regeneration ratio		50%	60%	80%
3) Improvement of functionality such high-strength etc. (functionality / amount of material)	1 time	2 times	3 times	4 times

*The percentage of reduction of energy per utility (production x value of product) should be supplied from transformation sector, compared with the case where total energy demand increases in proportion to GDP.

Figure 5.5: Overview of the Japanese industry sector according to the technology roadmap

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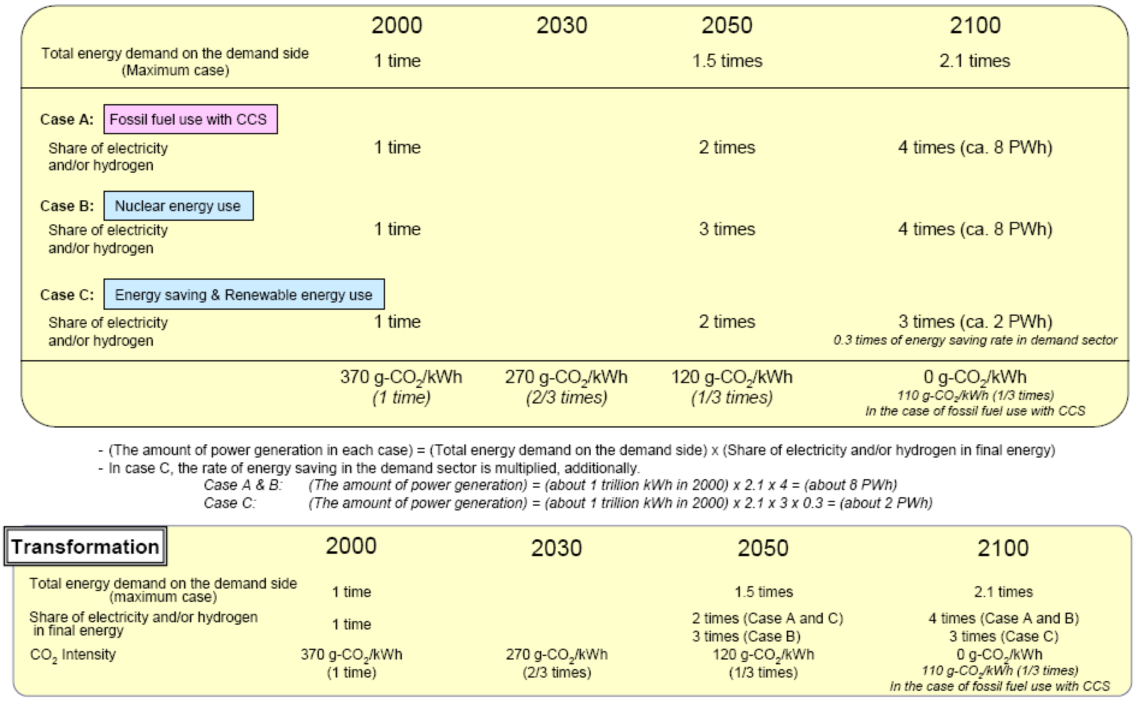
[11] The Ministry of Economy, Trade & Industry (METI) in Japan expects a cumulative installed capacity for stationary fuel cell systems of 10 GW_e in 2020 (source: HFP DS).

5.3.4 Transformation sector

For the transformation sector the impact on the future pathway is different for each of the three cases. In each of the cases hydrogen will be used and produced differently. For ‘Case A’ (fossil fuel with CCS) hydrogen will be produced by coal gasification. Hydrogen will be used indirectly by the integrated coal gasification fuel cell combined cycle power generation (IGFC). For ‘Case B’ (nuclear power) fourth generation reactors are foreseen combined with high temperature steam electrolysis (from 2050). For ‘Case C’ (renewable energy) hydrogen is produced on a large scale using electrolysis by photovoltaic generation, water splitting by photo-catalyst or thermo-chemical processes using solar heat. The share of electricity and/or hydrogen in the final demand will grow to 60% by 2100 by using the most cost competitive and efficient technologies as previously mentioned. Hydrogen production using biomass gasification will also be used from 2030 and approximately from 2075 biomass fermentation for hydrogen production also contributes to the amount of hydrogen produced.



	2000	2030	2050	2100
Total energy demand on the demand side (Maximum case)	1 time		1.5 times	2.1 times
Case A: Fossil fuel use with CCS				
Share of electricity and/or hydrogen	1 time		2 times	4 times (ca. 8 PWh)
Case B: Nuclear energy use				
Share of electricity and/or hydrogen	1 time		3 times	4 times (ca. 8 PWh)
Case C: Energy saving & Renewable energy use				
Share of electricity and/or hydrogen	1 time		2 times	3 times (ca. 2 PWh) *0.3 times of energy saving rate in demand sector*
	370 g-CO_2/kWh *(1 time)*	270 g-CO_2/kWh *(2/3 times)*	120 g-CO_2/kWh *(1/3 times)*	0 g-CO_2/kWh *110 g-CO_2/kWh (1/3 times)* *In the case of fossil fuel use with CCS*

- (The amount of power generation in each case) = (Total energy demand on the demand side) x (Share of electricity and/or hydrogen in final energy)
- In case C, the rate of energy saving in the demand sector is multiplied, additionally.

Case A & B: (The amount of power generation) = (about 1 trillion kWh in 2000) x 2.1 x 4 = (about 8 PWh)
Case C: (The amount of power generation) = (about 1 trillion kWh in 2000) x 2.1 x 3 x 0.3 = (about 2 PWh)

Transformation	2000	2030	2050	2100
Total energy demand on the demand side (maximum case)	1 time		1.5 times	2.1 times
Share of electricity and/or hydrogen in final energy	1 time		2 times (Case A and C) 3 times (Case B)	4 times (Case A and B) 3 times (Case C)
CO_2 Intensity	370 g-CO_2/kWh (1 time)	270 g-CO_2/kWh (2/3 times)	120 g-CO_2/kWh (1/3 times)	0 g-CO_2/kWh *110 g-CO_2/kWh (1/3 times)* *In the case of fossil fuel use with CCS*

Figure 5.6: Overview of the Japanese transformation sector according to the technology roadmap

6. R&D plans

Three R&D plans are reviewed. This chapter starts with outlining the R&D targets set by the HFP in the 'Strategic Research Agenda' (SRA) in Section 6.1, herewith giving insight into European industry's R&D goals. The goals set in the SRA and DS are refined in the HFPs 'Implementation Plan' giving insight into short term R&D goals (2015 and/or 2020). This will be described in Section 6.2. This chapter finishes with an outline of the R&D targets set in the US in the 'Hydrogen Posture Plan' written by the US Department of Energy (Section 6.3).

6.1 HFP's Strategic Research Agenda

The report includes an energy strategy on hydrogen and fuel cells. The Strategic Research Agenda was compiled by a European panel of stakeholders in July 2005 and is designed to:

- Act as a realistic and inspirational guide to defining a comprehensive research programme that will mobilise stakeholders and ensure the European competences are at the forefront of science and technology worldwide.
- Help stimulate investment in research.
- Provide guidance for policy options.

The SRA also defines priorities for investment in R&D and later industrial exploration, which is the focus of the Deployment Strategy (see Section 5.2). It provides a prioritised 10-year research programme, a well-founded medium-term strategy up to 2030 and a long-term strategic outlook up to 2050. The research agenda indicates those areas that are vital for the introduction and rollout of hydrogen as an energy carrier from now until 2050.

6.1.1 SRA outlook

In the medium term (2030) a significant fraction of hydrogen will be produced from fossil fuel with the use of CCS. Hydrogen will be produced via electrolysis and used for transportation purposes or local power balancing. On-site hydrogen production will play a significant role. Highly efficient fuel cell technology will utilise the different fuels.

With a share of up to 50% by 2050, hydrogen is expected to serve as a major transport fuel for vehicles. In centralised power generation hydrogen will serve as a storage medium to match energy generation (from renewables) with demand. Water electrolysis, hydrogen storage and re-conversion into power via fuel cells, gas turbines or combined cycles are the intermediate steps.

Distributed power generation using hydrogen will also grow in importance, seeking synergy with the existing natural gas pipeline network. A hydrogen pipeline infrastructure will have been set up, while road transport and on-site production of hydrogen are expected to become marginal distribution methods.

6.1.2 Areas of research

Hydrogen production from fossil fuels is considered a mature technology, but research is needed to reduce the cost (mainly associated with the energy needs for the production process). In the long term investigation of new production methods from renewables and nuclear power is regarded as important. Key research issues are:

- Reforming and gasification, including process control, system and safety monitoring.
- Liquefaction efficiency improvement and system integration.
- High temperature electrolyser cost, compactness and efficiency.
- Basic research of thermochemical processes and biological hydrogen production routes.
- Safety aspects for the whole production process.

Storage of hydrogen is of importance because for existing storage technologies the energy density is fairly low. At the moment gaseous and liquid hydrogen are the main candidates for transport applications. Basic research is recommended for new storage principles like alanates and large-surface-area materials. It is advised to set-up a hydrogen pipeline infrastructure to create a number of local hydrogen supply clusters, which can be connected later. Key research areas are:

- Storage systems with energy densities exceeding 1.1 kWh/l, a useable hydrogen mass fraction[12] of 6% and cost below 10 €/kWh, including metal hydrides, chemical storage media and nanostructured materials.
- Core components for hydrogen management at transfer, filling and fuelling stations.
- Storage components for liquid hydrogen use in transport, boil-off and cost reductions are key, to reach the target of a boil-off of 1% per day starting after 5 days. Boil off management should also be researched.
- Basic research of new materials for hydrogen storage.
- All safety aspects related to hydrogen storage.

The main use in stationary applications will be residential cogeneration and district cogeneration in the 100 kW range for the near and medium term. The PEM FC offers solutions for residential use, while solid oxide fuel cells (SOFC) are preferred for units in the MW power range. Key research areas are:

- Design of all types of fuel cell stacks, balance of plant, component development and industrial production methods.

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[12] A usable hydrogen mass fraction means the % kg H_2 per kg of the storage tank.

- Efficient hydrogen turbine systems and ICEs.
- Basic research of catalyst concepts for easy and efficient recycling of stack components.

Application of hydrogen in transport and fuel cells has been the major driver for the past 15 years and remains the most important application. Research needs to focus on:

- Optimisation of the power density, durability, humidification, water management and contamination tolerance of PEM fuel cells.
- High/elevated temperature (120 to 160 oC) PEMFC.
- New hydrogen storage systems based on 700 bar gaseous hydrogen and alternative storage options.
- Reformer systems combined with auxiliary power units using a SOFC.
- Improvement of the ICE to bring hydrogen to the market.
- Basic research on injection technology for ICEs and on all components related to improved PEMFC.

6.2 HFPs ‘Implementation Plan’

The HFPs ‘Implementation Plan’ focuses on R&D budget shares for the next 7 years to reach the targets as described in the ‘Deployment Strategy’ (see Section 5.2, Table 5.6). The report also includes technical targets for several technologies for the short term, which are outlined in Appendix C: to Appendix E:.

6.3 US DoE ‘Hydrogen Posture Plan’

The US Department of Energy published the ‘Hydrogen Posture Plan’ in 2004. It outlines cost and performance targets for hydrogen and fuel cell technology. The report is based on the ‘National Hydrogen Energy Roadmap’ of the DoE (see Section 4.1). The milestone in this plan is the ‘go/no go’ decision for commercialisation of hydrogen related technologies in 2015.

Targets are outlined in Table 6.1. These targets are set assuming feedstock cost for natural gas is 4 $/million Btu and the coal cost is 29 $/short ton.

Table 6.1: R&D targets for the US set in the 'Hydrogen Posture Plan' by the Department of Energy

		2010	2015	2020
Production				
SMR of NG	[$/GJ]	(2009: 18) 2010: 11		
Electrolysis (with wind electricity)	[$/GJ]	21	16	
Gasification of coal with CCS	[$/GJ]	6		
Nuclear thermo-chemical water splitting	[$/GJ]	2011: 18 (pilot scale demonstration)		2017: 15 (engineering scale demonstration)
Distribution				
Road, rail, truck and pipeline	[$/GJ]	<10	<7	
Refuelling				
Storage				
Large scale				
On-board (gaseous, liquid, hydrate and carbon)	[$/kg]	133	67	
End-use				
Transport	[$/kW]	PEMFC 45*	PEMFC 30	
Stationary	[$/kW]	400 - 750**	400***	

* PEMFC operation at 60% peak efficiency, 220 W/L density.

** Distributed stationary generation NG/propane 50 - 250 kW FC developed with 40% electrical efficiency, 40,000 hours durability.

*** Fuel cell/turbine hybrid operating on coal developed at a cost with a system efficiency of 70% with CCS.

The impact on oil use and GHG emissions are briefly reviewed, considering the set targets are met and with further assumptions being:

- Energy efficiency assumed for FCVs relative to conventional vehicles is 2.25 in 2018 and 2020, 2.5 in 2030 and 2040 and 3.0 beginning in 2050 with linear interpolation for intervening years (average passenger car has a fuel economy of 24.3 mpg).
- Penetration rate of FCV in the passenger can segment is assumed to be 4% in 2018, 27% in 2020, 78% in 2030 and 100% by 2033.
- Hydrogen produced from natural gas or zero carbon fuels is 93% in 2018, 90% in 2020, 55% in 2030, 15% in 2040 and 0% by 2050.

This results in a reduction of the oil consumption of passenger cars in 2040 by 11 million barrels per day. On top of that, by 2040 carbon emissions of passenger cars are reduced by more than 500 million metric tons of carbon equivalent per year.

7. Comparison and similarities

The previous chapters give an outline of the outcomes of scenario studies, roadmaps and pathways together with the R&D targets set by industry and government. This chapter will make a comparison of the different studies and gives insight into common described technology pathways by outlining 'snapshots'. Before this can be done the similarities between the outcomes (e.g. energy demand and CO_2 emission) of different studies are compared in the first paragraph of this chapter. Then the focus will turn to hydrogen. Section 7.2 describes the expectations on the hydrogen penetration and end-use, giving insight into the main use of hydrogen. Hereafter, an overview of different hydrogen production technologies and their related costs and cost targets are outlined in Section 7.3. This chapter concludes with an overview of the progress of the hydrogen chain in time in Section 7.4. Based on similarities in outcomes, snapshots in time are made of hydrogen production, distribution and end-use technologies.

7.1 Comparison of similarities and assumptions between studies

Although the different studies have different assumptions on oil price, technological learning and CO_2 price (see Table 7.1), some general similarities can be found in their outcomes. Looking at the general outcomes of energy demand, net CO_2 emission[13] and CCS of the different scenario studies (see Figure 7.1 and Appendix F:), there is not a great difference in total energy demand and CO_2 emissions between the different studies on a global level (see Figure 7.1). The same can be noticed for the European level (see Figure 7.2). Since the energy demand and CO_2 emissions are almost similar between all the cases while the oil and CO_2 price varies greatly. An explanation can be found in the shares of different energy sources and technologies (e.g. oil, gas, coal, nuclear and renewables) to foresee in the total energy demand. This is however not the scope of this research, although some information can be found in the previous chapter. The different sources and technologies used to produce hydrogen is within the scope of this research and will be discussed further on in this chapter.

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[13] Net CO_2 emission is the total CO_2 emission reduced by the CO_2 captured and stored (CCS).

Table 7.1: Overview of assumptions of oil and CO2 price in time for the different scenario studies

		IEA	WETO-H2		
			Reference case	Carbon constraint case	Hydrogen case
Oil price [$/bbl]	2010	20	40	40	40
	2020	30	50	50	55
	2030	35	60	60	70
	2050	40	110	90	100
CO2 price [€/tCO2]	2010	25	10	10	10
	2020	50	15	50	50
	2030	50	20	100	100
	2050	50	30	200	200

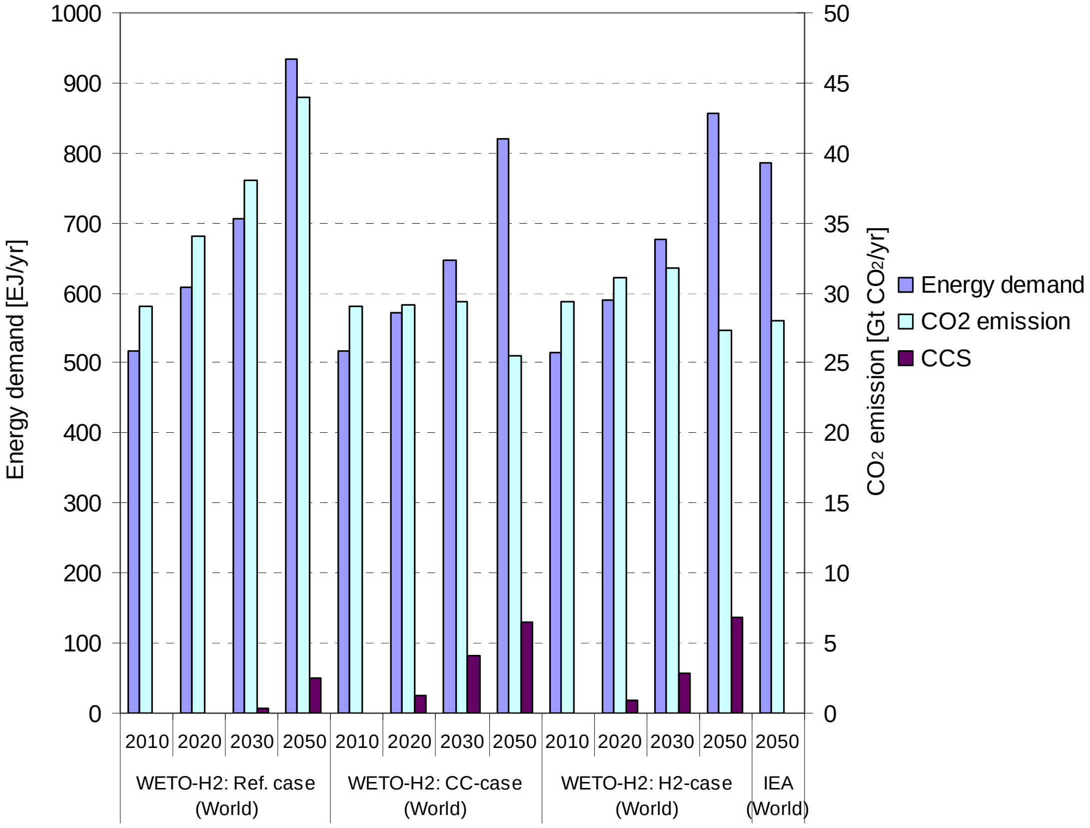

Figure 7.1: Comparison of total energy demand, net CO2 emission and CCS on world level

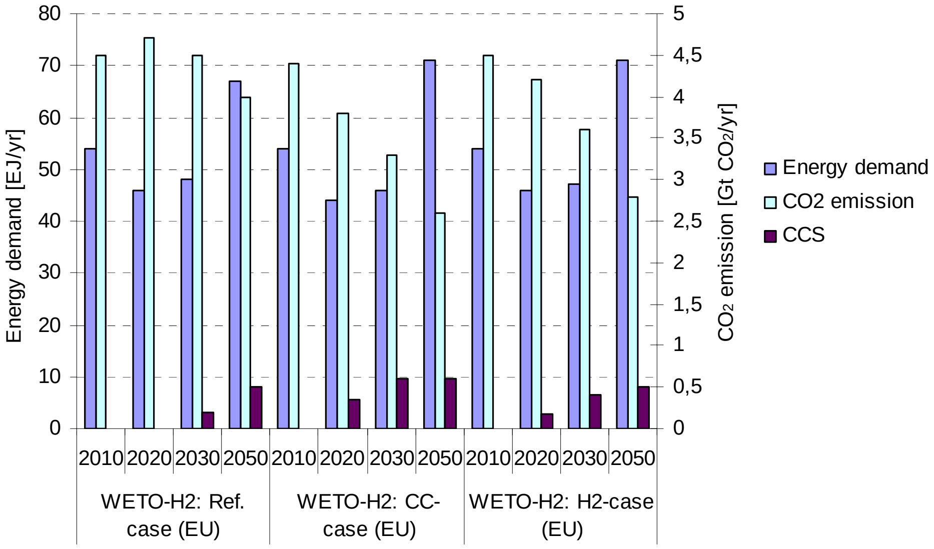

Figure 7.2: Comparison of total energy demand, CO2 emission and CCS on European level

7.2 Hydrogen end-use and penetration

This section will focus on the similarities between the different studies in penetration and end-use of hydrogen. In Figure 7.3 and Figure 7.4 the hydrogen demand is shown for the world and Europe. Comparing these results with the total energy demand (as shown in Figure 7.1 and Figure 7.2) it becomes clear in the overall energy demand hydrogen plays a minor role (around 10% of the total energy demand).

Taking a closer look at Figure 7.3 and Figure 7.4 interestingly the reference case of the WETO-H_2 study shows almost the same amount of hydrogen usage in comparison with the IEA (scenario D) for 2050, both for the world as for Europe. Taking into account the higher oil prices (see Table 7.1) used by the WETO-H_2 study there is a difference in production technology used. In 2050 the IEA study mentions natural gas and coal as main sources to produce hydrogen, while the WETO-H_2 study describes the use of renewables and coal as most used. Since the gas price often follows the oil price SMR of natural gas becomes quite expensive according to the WETO-H_2 study and will be used less.

It is also remarkable to compare the IEA case, the most optimistic case (scenario D) described by the IEA study, with the other most optimistic hydrogen cases i.e. the WETO-H_2 hydrogen case and the HyWays high penetration case (this latter only for Europe). These latter cases have a more then double demand for hydrogen in 2050 compared to the IEA case. Until 2030 all the cases have almost the same hydrogen demand but in 2050 there is a big difference in demand. Although it is difficult to explain precise why this difference occurs it has to do with the combination of the assumptions on oil and CO_2 price and penetration rates of the technology. The WETO-H2 hydrogen case has higher oil and CO_2 prices compared to the IEA and this has a big impact on hydrogen uptake (see the sensitivity analyses done by the IEA; Chapter 3.1.1)

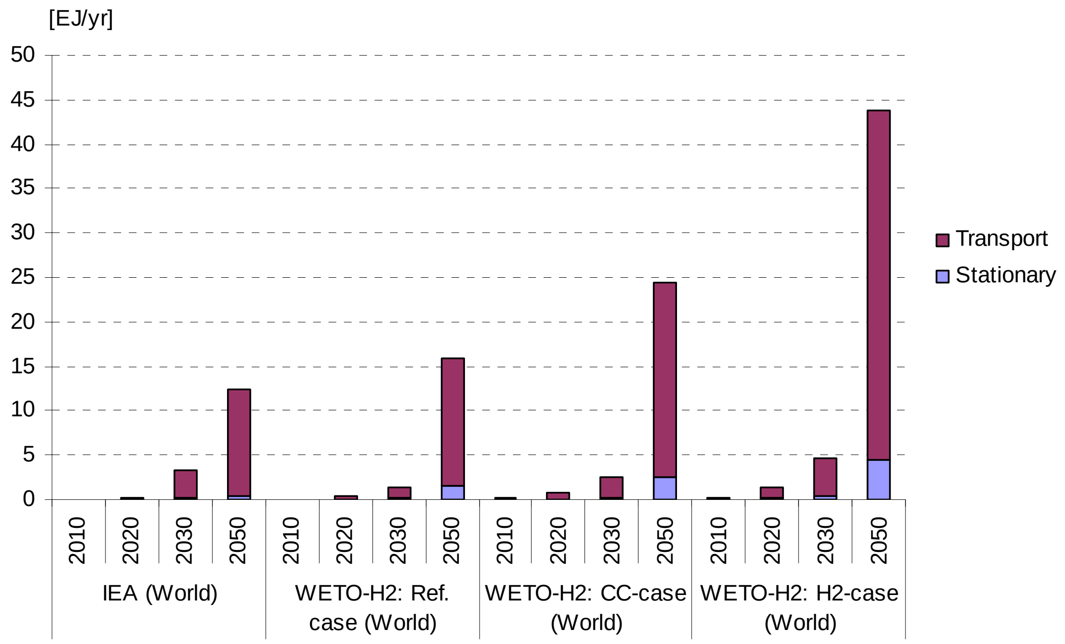

Figure 7.3: World hydrogen demand for the stationary and transport sector in time

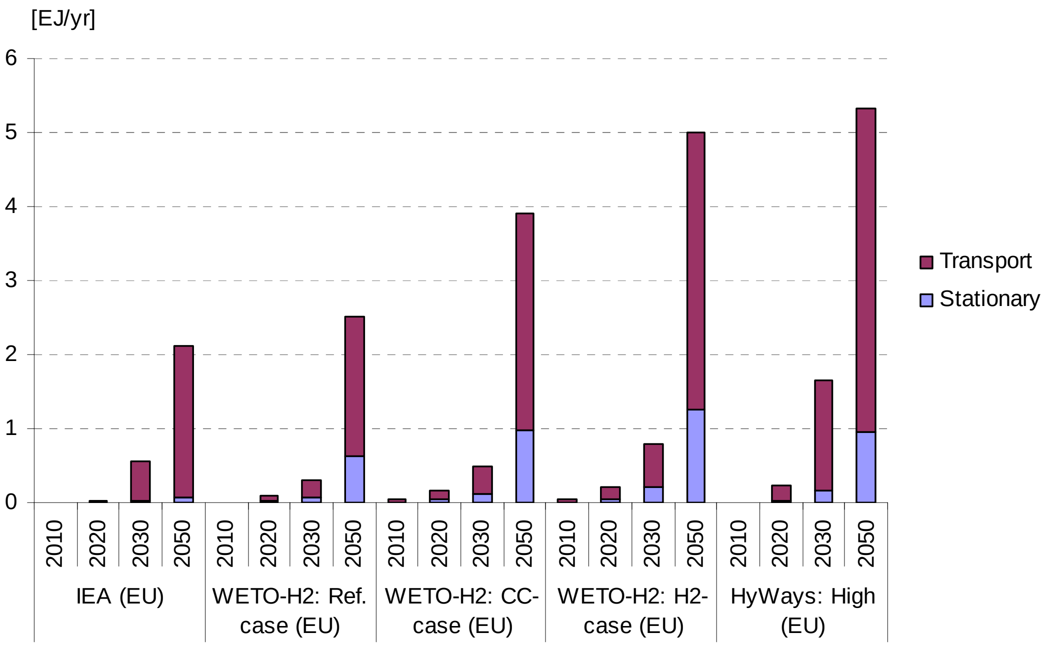

Figure 7.4: European hydrogen demand for the stationary and transport sector through time

Nevertheless, the different studies and cases also show similarities. Both the IEA as well as WETO-H_2 state quite clearly in their outcome that the transport sector will use most of the hydrogen. The IEA indicates in 2050 97% of the hydrogen will be used in the transport sector (on a world wide bases). The WETO-H_2come to almost the similar number; 90% hydrogen use in transport on a world wide bases (75% for Europe) for both the H_2 and the Carbon Constraint case. The HyWays study also shows there is a higher expectation of hydrogen use in transport then in stationary applications, at least for the high scenario (see Table 5.4). The insensitivity to the chosen scenario for the WETO-H_2 study strengthens our view of the transport sector being the dominant consumer of hydrogen although hydrogen use in the non-hydrogen favourable scenarios was not displayed in the other studies. The hydrogen demand per sector for the world is shown in Figure 7.3 and Figure 7.4 does the same only for Europe.

Related to this hydrogen demand and the main application of hydrogen in the transport sector are the penetration rates for these different studies. These are shown in Figure 7.5. Noteworthy is that the fleet penetration on world level is much lower then the fleet penetration on European level. Also, there is a small difference in fleet penetration on world level in 2050 between all the studies. The difference in vehicle penetration on EU level is much larger (almost 35%). The HyWays high EU fleet penetration scenario offers the most optimistic version.

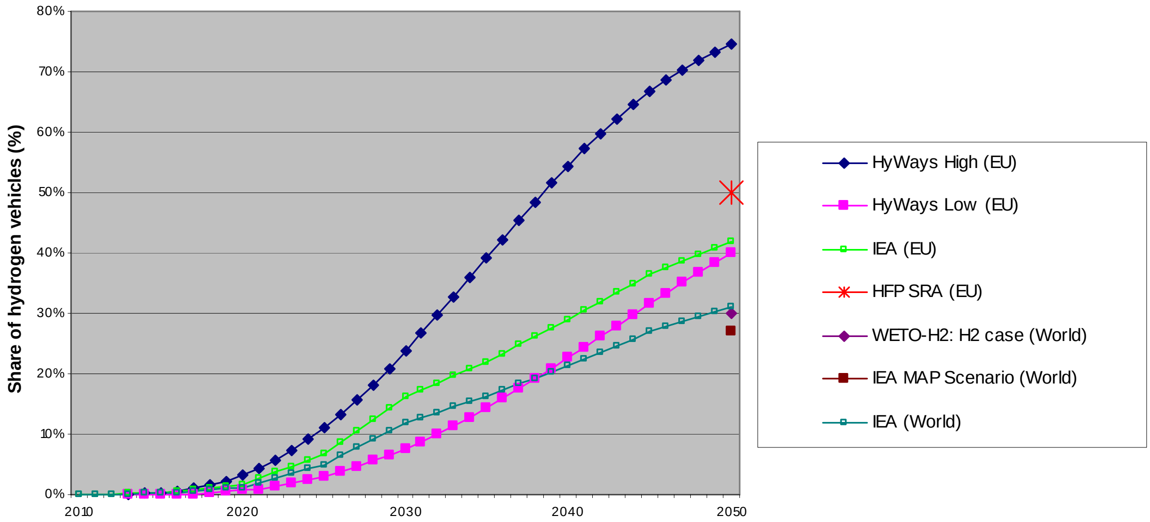

Figure 7.5: Fleet penetration of hydrogen FC and hydrogen ICE vehicles in time

Taking a closer look at the stationary use of fuel cells, most studies show that the CHP in the industry sector is the main use. Both the IEA and WETO-H_2 study mention the highest use of stationary fuel cells for the CHP industry sector. An explanation of the little use of hydrogen for stationary applications may be the use natural gas or syngas for these applications. At least the IEA and HFP Deployment Strategy mention this. Unfortunately, the WETO-H_2 study does not mention the fuel mix for stationary fuel cells other then hydrogen.

7.3 Hydrogen production

Since the studies show differences in oil and CO_2 price it is interesting to see if this has an effect on the envisaged technological options used to produce hydrogen. Taking into account the assumed cost for the technological options to produce hydrogen can even gain more insight. Both the IEA and the WETO-H_2 scenario studies give information of production cost, but unfortunately the HyWays project does not. It is also possible to take a closer look at the R&D goals (in terms of production cost) set by the US DoE and the HFP and compare these to the cost assumptions in the scenario studies.

7.3.1 Comparison of production cost targets

Unfortunately the data for hydrogen production cost are quite scattered in the studies and thus difficult to compare. Nevertheless, Figure 7.6 gives an overview of the hydrogen production cost assumed or set as target by the different studies.

The figure shows that for three options almost complete data sets are gathered from the different studies; these are large scale steam reforming of natural gas, electrolysis and coal gasification. Comparing the scenario studies (IEA and WETO-H_2) with the R&D targets (HFP and Posture Plan) for these three options gives the following insights:

- The cost assumptions of large scale steam reforming by the WETO-H_2 study are estimated quite low compared to the other scenario study and R&D targets.

- The R&D targets set for electrolysis by the US is ambitious compared to the scenario studies, while the EU target (indicated by the HFP) seems rather un-ambitious.

- The cost assumptions of coal gasification by the IEA study are estimated quite low compared to the other scenario study, but the R&D target set by the US is even lower.

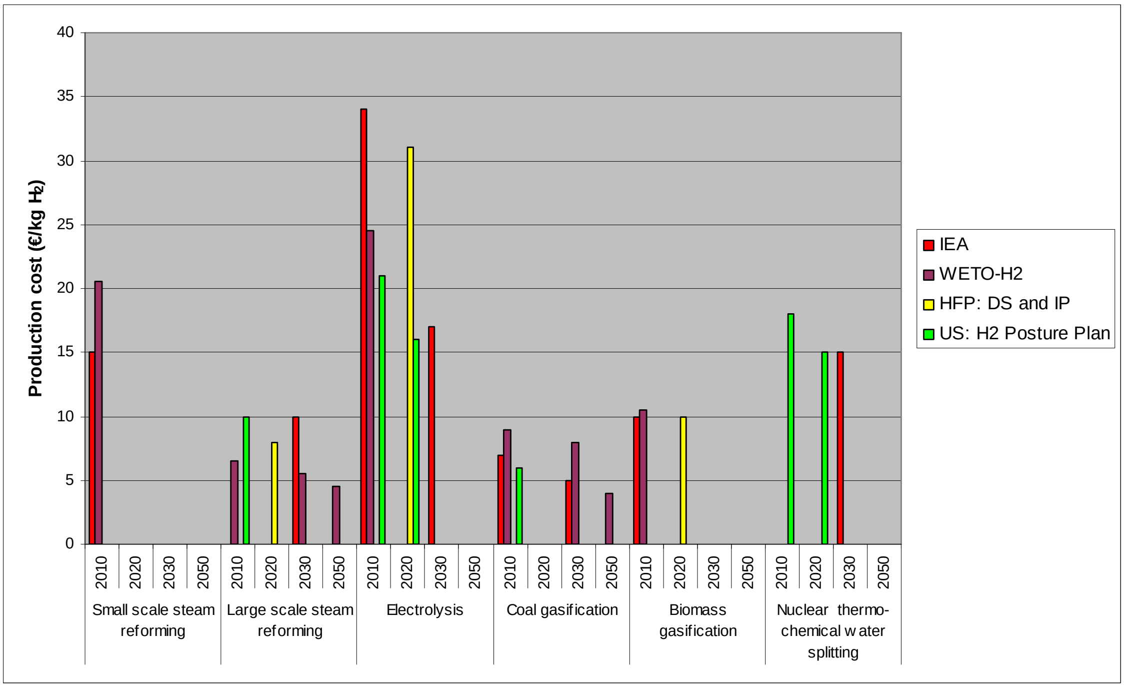

Figure 7.6: Hydrogen production cost targets and assumptions in time

Note: HFP targets for 2015 are shown for 2020.

7.3.2 Foreseen production options

Although the data of hydrogen production cost is incomplete and comparison between the scenario studies and R&D plans is difficult (due to different time lines), a more qualitative approach can give more insight into preferred and foreseen options for hydrogen production in the future.

Before getting into the technological preferences for hydrogen production, a conclusion which can be drawn based on all studies is the production of hydrogen will first be on-site (or decentralised) and around 2020 becomes more centralised. All studies agree on the use of by-product hydrogen in the starting years of hydrogen use.

Taking a closer look into the technological preferences most studies show the decentralised production of hydrogen will either be done by SMR or by electrolysis (or a combination). After 2020 production of hydrogen will become more centralised, but still be strongly dependant on fossil fuels (mostly natural gas). Most studies mention CCS will be used or at least becomes viable by then. From 2030 and beyond the production is still largely dependant on fossil fuels, but renewable energy use for hydrogen production is envisaged and increasing by that time. Wind electricity combined with electrolysis and biomass gasification with CCS are the most listed options for renewable hydrogen production.

A big difference between the IEA and the WETO-H_2 scenario studies is their outline for 2050. The IEA outlines there will be centralised production SMR of natural gas and coal gasification, both with CCS producing 80% of the hydrogen. The share of NG and coal differs for each scenario within the IEA study. On the other hand the

WETO-H_2 study (the hydrogen case) describes a big role (50%) for renewable (especially biomass gasification) and nuclear energy use for electrolysis (40%) in 2050. A possible explanation of this difference is largely caused by the high CO_2 price, pushing towards clean hydrogen sources. The difference in oil price (see Table 7.1) has some effect in moving the WETO-H_2 scenarios away from using natural gas.[0]

7.4 Snapshots

Based on the previous chapters, overall snapshots for the hydrogen energy chain can be made for 2020, 2030 and 2050. These snapshots are based on similarities between the analysed studies. Similarities are:

- Hydrogen production starts by using fossil fuels as an energy source, but will shift to more sustainable (or other then fossil fuel) production methods.
- The infrastructure starts with tube trailer transport, then local pipelines will emerge and in the long term integrated national pipeline networks will emerge.
- Main application of hydrogen is in transport, especially passenger cars. The share of FC vehicles will on the long run dominate. Stationary fuel cells will mainly be used by CHP industry, but these will mainly use natural gas and only represent a small share in the total energy system.

Figure 7.7 gives an overview of these snapshots. However, keep in mind these similarities describe the most general aspects in time of the hydrogen energy chain. The development of early markets (markets in which the circumstances privilege other types of technologies used in the hydrogen energy chain) are not taken into account, but play a valuable role in the technology deployment of the hydrogen energy chain. There are also differences in introduction time between the different scenario studies. The snapshots do not account for these differences. Introduction dates and market shares are different, however, the overall picture is in general consistent.

Comparing this outcome with the first results from the mapping analysis of potential hydrogen communities in Europe (JRC, 2007) some similarity and differences can be found. There seems to be a mismatch between the community focus and the general outline. Based on the information gathered from communities in Europe, the majority of the projects (74%) which involve hydrogen production, focus on using renewable energy sources. Looking at the general picture, renewable energy usage for hydrogen production is envisaged in the long run, but not in the near future. Taking a closer look at the community profiles and the application areas, stationary fuel cells and hydrogen application may also be overrepresented.

From a transition point of view these mismatches prevent RD&D from focussing just on short to mid term solutions and thus may not be alarming. However, if the general outline of the scenario studies proofs to be correct, RD&D and community preferences may have to shift in order to accelerate the short term transition to hydrogen. Regions with more preferable production methods (e.g. with industries producing H_2 as a by-product, fossil fuels with coal gasification processes or natural gas steam reforming) should become more involved in setting up hydrogen communities.

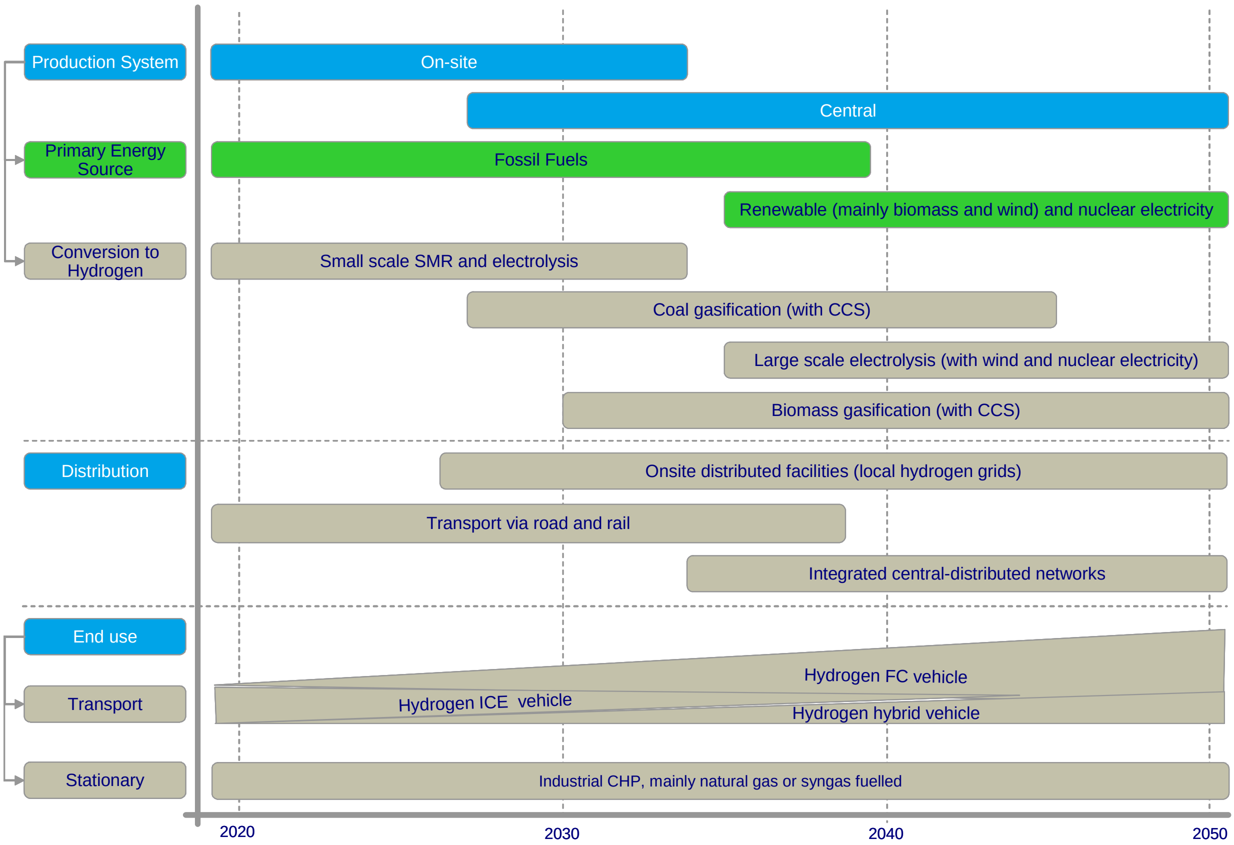

Figure 7.7: General evolution of the hydrogen chain in time based on similarities between the IEA and WETO-H2 studies

Note: The bars in the figure give an indication of when the technology will become a viable option, but do not give insight into their share in the market. An exception is the bar for the transport sector. This shows the share of hydrogen FC and hybrid vehicles will increase in time, while the share of hydrogen ICE vehicles will be high in the early years of market introduction, but becomes relatively low as more hydrogen FC and hybrid vehicles are deployed.

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Appendix A: Japan’s Roadmap cases

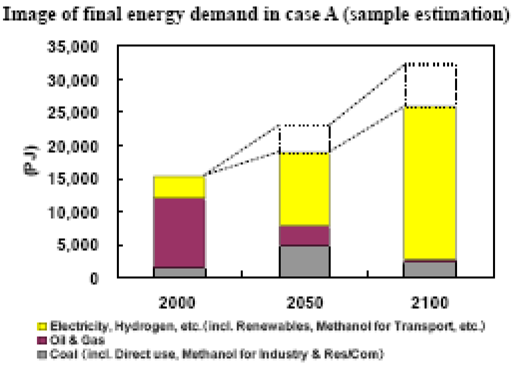
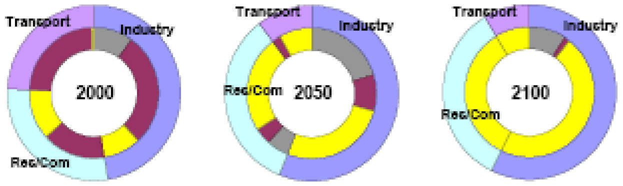
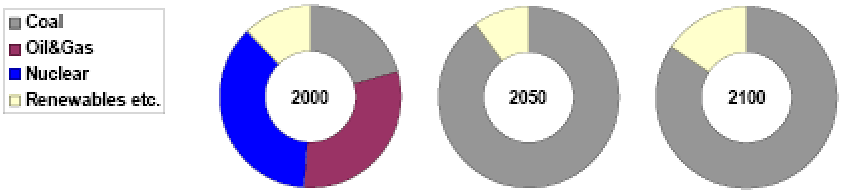


Image of final energy demand in case A (sample estimation)

Note: The future estimation is one of the examples based on various assumptions and conditions.



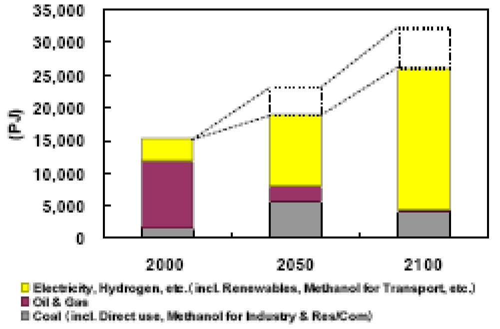
Demand composition in the sample estimation above (per sector)



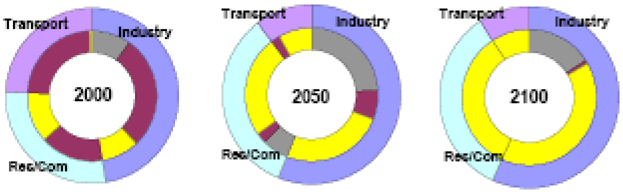
Composition of power generation and hydrogen production in the sample estimation above (breakdown of power hydrogen, and others (yellow area))

Figure A.1: Final energy demand and power generation estimates for Case A of Japan’s Roadmap

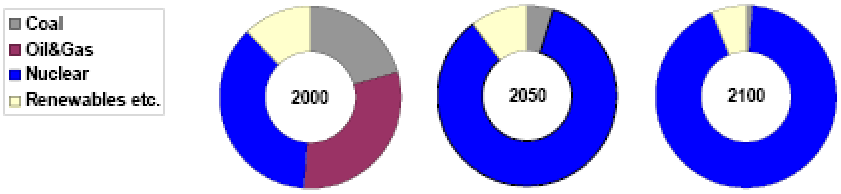
Image of final energy demand in case B (sample estimation)



Note: The future estimation is one of the examples based on various assumptions and conditions.

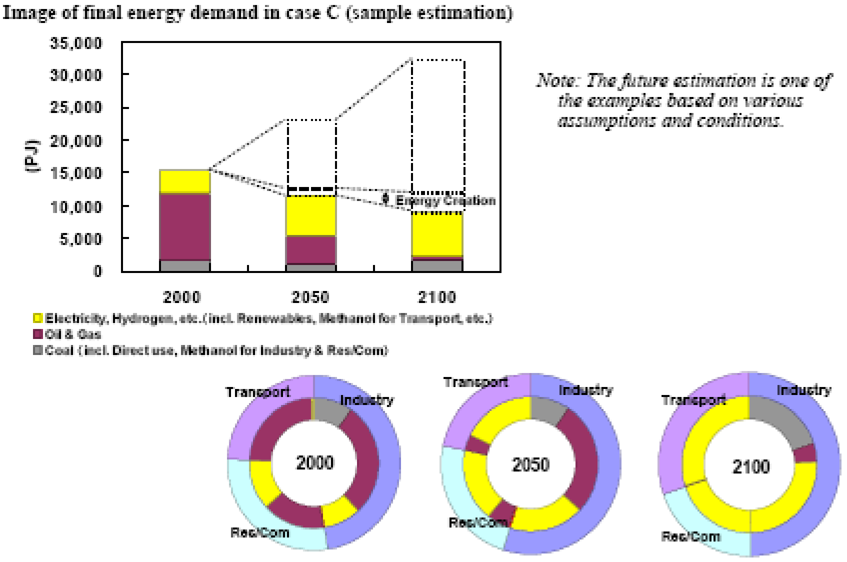


Demand composition in the sample estimation above (per sector)

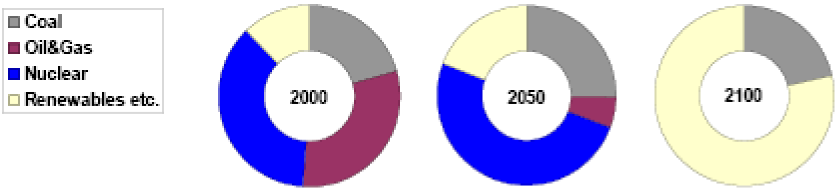


Composition of power generation and hydrogen production in the sample estimation above (breakdown of power hydrogen, and others (yellow area))

Figure A.2: Final energy demand and power generation estimates for Case B of Japan's Roadmap



Demand composition in the sample estimation above (per sector)



Composition of power generation and hydrogen production in the sample estimation above (breakdown of power hydrogen, and others (yellow area))

Figure A.3: Final energy demand and power generation estimates for Case C of Japan’s Roadmap

Appendix B: Japanese Roadmap: transport sector

Fuel cell hybrid vehicles

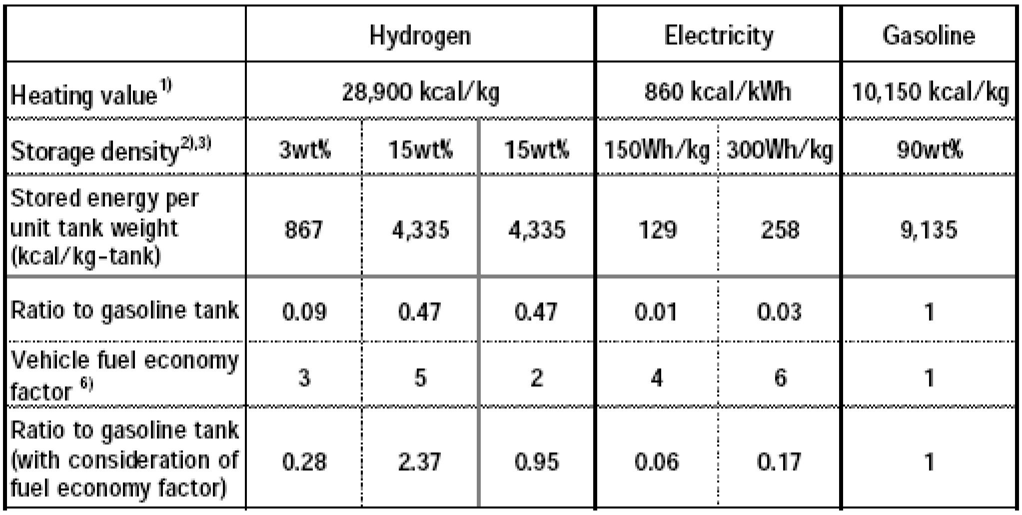
- Fuel efficiency is a ratio of the mileage for each consumption of the unit hydrogen which is converted to that of gasoline (or diesel oil). The weight and volume of the hydrogen tanks are critical to secure a driving range of 500 km.
- The most important challenge is performance improvement of on-board hydrogen storage technology. The efficient improvement of fuel cells and vehicle weight reduction also contribute to the decrease of the weight and volume of the hydrogen tanks. High performance is requested for hydrogen storage technology to be applied to heavy-duty trucks.
- The hydrogen supply will start with the use of by-product hydrogen and on-site reforming of hydrocarbons, and then on-site water electrolysis becomes mainstream with an increase in fossil fuels prices. It is assumed that concentrated production with pipeline transportation may be done in regions where enough demand density is realized through the increasing consumption of hydrogen.

The value of fuel efficiency is a ratio to that of current ICE vehicles (including effect of weight reduction)

Non-technical factors

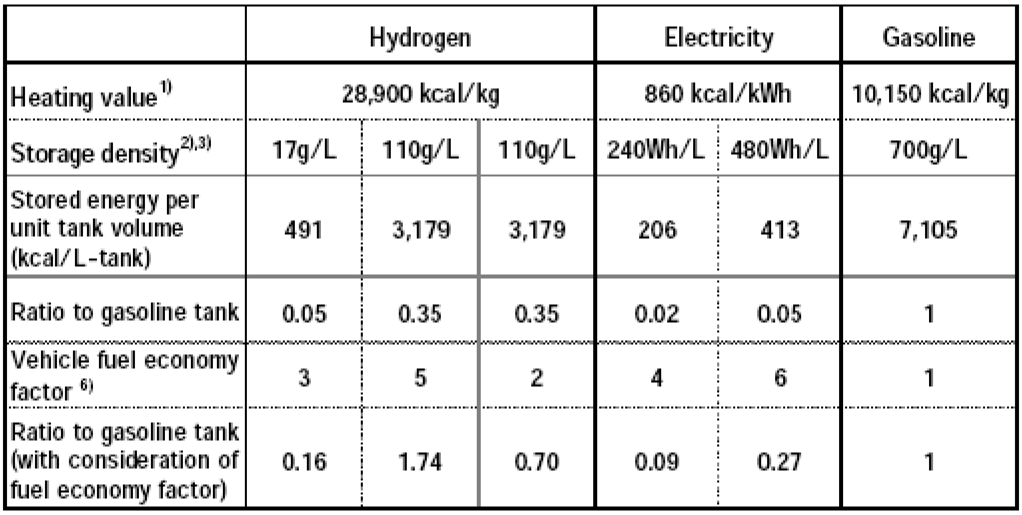
- Hydrogen supply networks developed by governmental investments, a strong initiative to introduce FCV into public vehicles, and FCV special zones
- Incentives to convert to FCV and a hydrogen society (favorable tax changes, higher priority on parking lots, and deregulation for driving into restricted places, etc.)
- Establishment of standards for FCV, fuel and hydrogen fueling equipments, and technological standards (both national and international)
- Promotion of maintenance industries and recycling systems for parts and materials of FCV.

(1) Weight base comparison



	Hydrogen			Electricity		Gasoline
Heating value 1)	28,900 kcal/kg			860 kcal/kWh		10,150 kcal/kg
Storage density 2),3)	3wt%	15wt%	15wt%	150Wh/kg	300Wh/kg	90wt%
Stored energy per unit tank weight (kcal/kg-tank)	867	4,335	4,335	129	258	9,135
Ratio to gasoline tank	0.09	0.47	0.47	0.01	0.03	1
Vehicle fuel economy factor 6)	3	5	2	4	6	1
Ratio to gasoline tank (with consideration of fuel economy factor)	0.28	2.37	0.95	0.06	0.17	1

(2) Volume base comparison



	Hydrogen			Electricity		Gasoline
Heating value 1)	28,900 kcal/kg			860 kcal/kWh		10,150 kcal/kg
Storage density 2),3)	17g/L	110g/L	110g/L	240Wh/L	480Wh/L	700g/L
Stored energy per unit tank volume (kcal/L-tank)	491	3,179	3,179	206	413	7,105
Ratio to gasoline tank	0.05	0.35	0.35	0.02	0.05	1
Vehicle fuel economy factor 6)	3	5	2	4	6	1
Ratio to gasoline tank (with consideration of fuel economy factor)	0.16	1.74	0.70	0.09	0.27	1

Appendix C: Technical targets for hydrogen vehicle and infrastructure

Road propulsion FC system		
Characteristics	Units	2015 Target
Efficiency (NEDC)	[%]	>40
Specific cost	[€/kW]	100
Volumetric power density	[l/kW]	1.5
Gravimetric power density	[kg/kW]	1.5
Lifetime	[hr]	
Car		5,000
Bus		10,000
Operating temperature limits of the environment	[oC]	- 25 / + 45

Road APU system		
Characteristics	Units	2015 Target
Efficiency (Pmax)	[%]	35
Specific cost	[€/kW]	-
Volumetric power density	[l/kW]	5
Gravimetric power density	[kg/kW]	5
Lifetime	[hr]	
Car		5,000
Heavy Good Vehicles		10,000
Environment temperature limits	[oC]	- 25 / + 45

ICE propulsion for passenger car			
Characteristics	Units	Target	
Target year		2010	2015
Torque		Equivalent to diesel	
Speed		Equivalent to gasoline	
Efficiency (NEDC)	[%]	>26	>>26
Power density	[kW/l displacement]	>60	>80

ICE propulsion for public transport bus		
Characteristics	Units	2015 Target
Efficiency (best value)	[%]	40
Power density	[kW/l]	18

On-board hydrogen storage		
Characteristics	Units	2015 Target
Gravimetric storage density	[wt %]	7 - 12
Volumetric storage density	[kWh/l]	1.1
Operating temperature	[oC]	- 40 / + 85
Refueling cycles	[cycles]	>1,500

Maritime fuel cell power unit (SOFC/MCFC)		
Characteristics	Units	2013 Target
Investment cost	[€/kW]	<1,000
Efficiency (full load)	[%]	>55
Gravimetric power density	[kg/kW]	<10
Volumetric power density	[l/kW]	<20
Cycle life	[hr]	10,000
RAMS (Reliability, Availability, Maintainability, Safety)		>= Reciprocating engine

Rail fuel cell propulsion unit (PEM)		
Characteristics	Units	2013 Target
Investment cost	[€/kW]	500
Efficiency (NEDC)	[%]	>45
Gravimetric power	[kg/kW]	6
Volumetric power density	[l/kW]	6
Lifetime	[hr]	50,000
Operating temperature	[oC]	-25 / +45

Hydrogen infrastructure			
Characteristics	Units	Target	
		2015	2020
Hydrogen production and distribution cost	Reduction factor on current cost		3
Cost of hydrogen delivery at the pump (centralised and decentralised)	[€/kg]	<x	

Appendix D: Technical targets for hydrogen production technologies according to the HFP IP

Medium term portfolio

low temperature electrolysers		
Characteristics	Units	2015 Targets
Energy efficiency (LHV gasis)	[%]	>70
Current density	[A/cm2]	1
Cost of modular system	[€/Nm3]	1,000
System availability	[%]	>99
New design efficient/high pressure module		2012 target
Production flow rate	[Nm3/hr]	Several hundreds
Operating pressure	[MPa]	3 to 5
PEM electrolyser		
Production flow rate	[Nm3/hr]	100
Lifetime	[hr]	40,000

Biomass to hydrogen standalone pyrolysis/gasification units		
Characteristics	Units	2015 Targets
Hydrogen production cost	[€/GJ]	<25

Biomass to hydrogen co-gasification (large scale integrated gasification combined cycle)		
Characteristics	Units	2015 Targets
Hydrogen production feedstock	[€/GJ]	10
Biomass feedstock cost	[€/GJ]	3

Long term technology portfolio

High temperature thermo-electrical-chemical processes with solar/nuclear heat sources		
Characteristics	Units	2015 targets
Hydrogen production cost	[€/kg]	<2
Reduction of CO2 emissions for fossil reforming	[%]	>25
Hydrogen production from biomass - mass efficiency	[%]	>40

low temperature temperature processes: photo-electrolysis and photobiological / fermentation		
Characteristics	Units	2015 targets
Photoelectrolysis		
Proved efficiency vs PV + electrolysis system	[%]	>25
Lifetime	[hr]	>5,000
Hydrogen production cost	[€/kg]	<5
Photobiological		
Conversion efficiency	[%]	10

Hydrogen by dark fermetation		
Characteristics	Units	2015 targets
Molar efficiency of sugar to H2 conversion (under stable conversion processes)	[Mol H2/mol sugar]	

Refueling station (CG H2 & liquid H2)		
Characteristics	Units	2015 targets
Multiple consecutive refuellings	[Nbr per hr per dispenser]	10
Pressure (CGH2)	[Bar]	700
Filling time	[min]	3
On-site production and brought-in hydrogen	[kg/H2 per station per day]	150
		2020 target
On-site production and brought-in hydrogen	[kg/H2 per station per day]	300

Refueling station (compressed H2 & liquid H2)			
Type of H2 storage	H2 tank system density by volume (kWh/l) present	H2 tank system density by weight (%) present	H2 tank system density by weight (kWh/l) 2015
Liquid H2	1.2	6	12
Compressed gaseous 700 bar	1.3	4	9
Metal hydrides (AB2, AB5)	1.8	1.5	2
Complex Metal hydrides (alanates)	0.7	1.8	4.5
Chemical hydrides (boro-amino hydrides, and organic liquids)	1.4	6	9
Activate carbons, nanoporous materials	0.2	1	2

Appendix E: Technical targets for FCs for CHP and Power Generation according to the HFP IP

		Early field tests	Demonstration	Lighthouse and deployment
		Stationary applications 1 - 10 kW (residential)		
Timeframe		2006 - 2008	2007 - 2009	2009 - 2012
Electrical efficiency @ BOL[14], including DC/yrC conversion	[%]	30 - 40	32 - 40	34 - 40
Total fuel efficiency BOL, @ best point	[%]	>70	75	80
System cost]	[€/kW	20,000	10,000	6,000
Stack durability (90% BOL performance)	[h]	5000	8000	>12000
Number of low-temperature start-ups from 15oC	[#/yr]	20	35	50
		Stationary applications >= 100 kW (community/industrial)		
Timeframe		2006 - 2008	2007 - 2009	2009 - 2012
Electrical efficiency @ BOL, including DC/yrC conversion	[%]	45	50	50
Total fuel efficiency BOL, @ best point	[%]	80	85	90
System cost	[€/kW]	8 - 12000	3000 - 8000	1500 - 5000
Stack durability (90% BOL performance)	[h]	10 - 20000	15-30000	>30000

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[14] BOL: Beginning Of Life

Appendix F: Energy demand, CO_2 emission and CCS

Table F.1 Overview of energy demand, hydrogen demand, CO2 emission and CCS

Study	Year	Energy demand [EJ/yr]	H2 demand [EJ/yr]	CO2 emission [GtCO2/yr]	CCS [GtCO2/yr]
WETO-H2: Ref. case (World)	2010	517	0.08	29.0	0.000
	2020	608	0.33	34.0	0.010
	2030	706	1.30	38.0	0.300
	2050	933	15.80	44.0	2.500
WETO-H2: CC-case (World)	2010	517	0.16	29.0	0.000
	2020	571	0.70	29.2	1.275
	2030	648	2.60	29.4	4.064
	2050	821	24.50	25.5	6.442
WETO-H2: H2-case (World)	2010	514	0.20	29.4	0.000
	2020	591	1.30	31.1	0.910
	2030	677	4.60	31.8	2.874
	2050	856	43.80	27.3	6.863
IEA (World)	2050	785	12.40	28.0	
WETO-H2: Ref. case (EU)	2010	54	0.00	4.5	0.000
	2020	46	0.08	4.7	0.009
	2030	48	0.29	4.5	0.200
	2050	67	2.50	4.0	0.500
WETO-H2: CC-case (EU)	2010	54	0.04	4.4	0.000
	2020	44	0.17	3.8	0.353
	2030	46	0.50	3.3	0.609
	2050	71	3.90	2.6	0.595
WETO-H2: H2-case (EU)	2010	54	0.04	4.5	0.000
	2020	46	0.20	4.2	0.177
	2030	47	0.80	3.6	0.412
	2050	71	5.00	2.8	0.498

Appendix G: Overview of cost assumptions for production

Table G.1 Cost assumptions for different hydrogen production technologies

Production technology [$/GJ]	Study	2010	2020	2030	2050
Large scale SMR of NG	IEA			10	
	WETO-H2	5 - 8		5 - 6	4 - 5
	HFP (DS & IP)		8		
	US DoE	10			
Small scale SMR of NG	IEA	15			
	WETO-H2	19 - 22			
	HFP (DS & IP)				
	US DoE				
Electrolysis	IEA	34		17	
	WETO-H2	22 - 50			
	HFP (DS & IP)		31 - 67		
	US DoE	21	<16		
Gasification of coal	IEA	7		5	
	WETO-H2	8 - 10		7 - 9	3 - 5
	HFP (DS & IP)				
	US DoE	6			
Gasification of biomass	IEA	10			
	WETO-H2	9 - 12			
	HFP (DS & IP)		10		
	US DoE				
Solar thermolysis	IEA				
	WETO-H2	50			
	HFP (DS & IP)				
	US DoE				
Nuclear thermo-chemical water splitting	IEA			10 - 20	
	WETO-H2				
	HFP (DS & IP)				
	US DoE	18	15		