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CASCADE MINTS

CAse **S**tudy **C**omparisons **A**nd **D**evelopment of **E**nergy **M**odels for **IN**tegrated **T**echnology **S**ystems

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CAse Study Comparisons And Development of Energy Models for INtegrated Technology Systems

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A. Introduction

CASCADE MINTS is a project that deals explicitly with the role of technical change and policies designed to promote it in enabling the evolution of the energy system towards sustainable paths. It is a modelling project that delivers enhanced quantitative tools and quantitative analysis with a potential for policy support.

A wide range of problems characterise the present energy system, including global and local pollution, resource depletion, security of supply concerns and doubts concerning the sustainability of present options in electricity production. CO2 capture and storage, renewable and nuclear energy forms have been widely recognised as important options in promoting sustainability (especially tackling climate change and improving security of supply). Part 2 of the CASCADE MINTS project brings together a number of the leading energy, economic and environmental modelling teams in Europe (together with some institutes in the US and Japan that are associated more loosely) with the aim to inform the debate on the prospects of transformation of the European and World energy system towards sustainability, while providing important analytical background for the formulation of energy and environmental strategy.

Fuel cells and the prospects for the transformation of the energy system by hydrogen as a carrier have in recent years attracted enormous interest from industry, policy makers and society at large. In many quarters this technological nexus is viewed as a panacea for solving the widest range of problems characterising the energy system. The analysis of an eventual transition towards a hydrogen economy requires an integrated analytical framework. Part 1 of the project undertakes the creation of such a framework that enables the analysis of the prospects of the hydrogen economy within the overall energy system in an unbiased fashion.

Following the structure of the project, this report is also divided into two parts. Table A-1: below provides a list of institutes and models participating in the CASCADE MINTS project.

Table A-1: List of participants

Participant name	Participant short name	Country	Model
Institute of Communication and Computer Systems of National Technical University of Athens	ICCS/NTUA	Greece	PRIMES
Energy Research Centre of the Netherlands	ECN	Netherlands	MARKAL
Centre National de la Recherche Scientifique	CNRS	France	POLES
International Institute for Applied Systems Analysis	IIASA-ECS	Austria	MESSAGE
Joint Research Centre	JRC-EU	Belgium	POLES
Paul Scherrer Institut	PSI	Switzerland	MERGE-ETL (Part 1) GMM (Part 2)
Zentrum fur Europaische Wirtschaftsforschung GmbH - Centre for European Economic Research	ZEW	Germany	PACE
Deutsches Zentrum fur Luft – und Raumfaht e.V. (German Aerospace Center)	DLR	Germany	
Universitaet Stuttgart*	USTUTT	Germany	TIMES-EE NEWAGE-W
Centrale Recherche S.A. *	CRSA/ERASME	France	NEMESIS

*Part 2 Only

Several non-European organisations participate in Part 2:

Institution	Institution short name	Country	Model
Energy Information Administration of the U.S. Department of Energy (USA)	U.S. DOE/EIA	United States	NEMS
Research Institute of Innovative Technology for the Earth	RITE	Japan	DNE21
National Institute for Environmental Studies	NIES	Japan	AIM
International Energy Agency	IEA	International	ETP
Natural Resources Canada	NRCan	Canada	MAPLE

Part 1:

Modelling possible configurations of a hydrogen economy and using models to study its prospects

B. Common Information Base

B.1 Hydrogen Technologies: Characterisation and Prospects

Energy security, economic growth and environmental protection are prominent challenges facing the world today. The use of hydrogen as an energy carrier and fuel cells as motive devices in transportation and in distributed energy systems has been viewed as the most promising option in view of transforming the whole energy system of Europe and the World in the direction of sustainability. A fuel cell running on pure hydrogen produces zero emissions, whereas fuel cell vehicles are the least polluting vehicles as they extract energy electrochemically and not through fuel combustion. Thus they offer cleaner and more efficient alternatives to conventional energy sources.

The prospects for the hydrogen economy will depend to a very large extent on technological developments concerning applications of fuel cells, production, conversion, delivery and storage of hydrogen. Considerable effort in the context of CASCADE MINTS has been devoted in developing, establishing and monitoring the technological background information to be used by partners in extending their models to describe all possible configurations of a hydrogen economy. To this end, a broad survey of fuel cell and hydrogen-related technologies and their applications has been undertaken, identifying the critical performance characteristics and indicating prospects for future improvement. While discarding the options that are most suitable for very small scale applications (with large potential markets but relatively small potential impact on the energy system) a wide range of options has been identified according to their suitability for conquering different segments of energy markets. The assessment of the technologies in terms of their prospects has been based on both the basic component performance (from the reformer or hydrogen storage point down to the energy service provided) and the overall system characteristics. These have been clearly laid out in order to serve as a guide for the modelling work in Part 1 of the project. All information has been delivered in concrete quantified terms to render it directly usable as model input. This information can be broadly grouped as indicated in the following table:

Table B-1: Summary of technical and economic data gathered for the different Fuel Cell and Hydrogen related technologies

Technical Data					Economic Data
Fuel Cells	**Hydrogen Production**	**Hydrogen Transport**		**Hydrogen Storage**	
Electrical capacity	Hydrogen output	Net delivery	Gaseous/Liquid Road/Sea Transport	Capacity	Investment costs (system)
Electrical net efficiency	Electricity input	Transport distance		Thermal capacity	Long term target costs
Overall efficiency	Feedstock input	Fuel use		Average storage time	Target costs for market introduction
Plant Lifetime	Steam input	Utilisation factor		Boil-off (Liquid)	
System Lifetime	Pressure	System lifetime		Pressure (Gaseous)	Fixed O&M costs
Stack lifetime	Efficiency [a)]	Transport cycles		Utilisation factor	Variable O&M costs
Availability	Technical system lifetime	Yearly mileage (Sea)		System lifetime	System costs
Capacity	Utilisation rate	Transport efficiency	Pipeline		Share of stack costs
	Optimal Capacity	Pipeline length			Share of reformer costs
		Capacity			Floor Costs
		Delivery distance			

a) Based on Lower Heating Value of hydrogen

The construction of the information database has been a very challenging and innovative task. Most of the technologies considered in the database have only been tested in field trial programs or in first proof-of-concept demonstration plants. Others are at very early stages of market introduction whereas very few are commercially available. As a consequence, the availability of reliable data has been poor. Technical and economic data are quite sensitive and confidential, hence not readily disseminated for public use. It has also been difficult to generalise from specific data published by fuel cell manufacturers. Data on current investment costs is uncertain, whereas the information on the cost structure given by different manufacturers often proved contradictory. In cases where the underlying literature indicated a broad range of different values, the final selection has been based on a thorough analysis of the relevant literature, plausibility considerations and expert judgement.

In order to identify possible technological breakthroughs, perspective analysis of the technical-economic possibilities of the technologies considered has also been undertaken; in view of the absence of such data from the literature, expert judgement has been extensively utilised to derive plausible estimates, also establishing comparisons with existing technologies (where appropriate).

For the purposes of CASCADE MINTS an extensive inventory of technologies with good prospects for improvement has been compiled and retained in the database. The final selection of technologies was made on the grounds of their potential impact on future energy balances, their promise in terms of improvement, their interaction with other technologies including power generating technologies and the interest they have attracted in recent years as candidates for R&D support both in the public and private sectors. Short descriptions of the operating principles of the different technologies retained together with current and perceived potential advances of their techno-economic characteristics are given in the following sections. Appropriate applications for fuel cell and hydrogen technologies are also discussed.

B.1.1 Fuel cell technologies

A fuel cell is a device that separates hydrogen electrons with a catalyst to produce electricity via an electrochemical process. Fuel cells are expected to be suitable for a wide range of applications: transport (including vehicle propulsion and on-board auxiliary power generation), portable (including consumer electronics, business machinery) and stationary (including stand-alone power plants, distributed generation, cogeneration, back-up power units, and power for remote locations. CASCADE MINTS focuses on applications that might achieve a significant impact on future energy systems, i.e. stationary applications in power plants (mainly decentralised cogeneration), and vehicle propulsion.

Several different fuel cell technology paths are currently being pursued. These divide into low temperature and high temperature technologies. Low temperature technologies – including phosphoric acid (PAFC) and polymer electrolyte membrane (PEMFC) fuel cells – target transportation, portable power, and lower-capacity distributed power applications. High temperature technologies –molten carbonate (MCFC) and solid oxide (SOFC) fuel cells – target stationary power applications and niche stationary and distributed power as they are characterised by fuel flexibility, high efficiency and have the potential for combined heat and power generation.

Fuel cells are primarily classified by the kind of electrolyte used. The electrolyte determines the kind of chemical reactions that take place in the fuel cell and the temperature range of operation. The requirements of different applications determine the choice of fuel cell technology applied. Some features of the four primary types of fuel cells – discussed in the followings sections – are summarised in the following table:

Table B-2: Summary of features of types of fuel cells

Fuel Cell Type	Applications	Operating Temperature	Power	Electric Efficiency	Overall Efficiency	Plant Lifetime (System/Stack)	Investment Costs €2000/kWel
Polymer Electrolyte Membrane (PEMFC)	Small Scale Stationary Power Vehicle Propulsion	<80°C	1kW-250kW	28% - 35%	76% - 80%	15/2	11500-14000
Solid Oxide (SOFC)	Stationary Applications Auxiliary Power Units in Vehicles and Aircraft	700 - 1000°C	1kW-3MW	28% - 58%	80%	15/1 - 15/5	10000
Phosphoric Acid (PAFC)	Stationary Power Generation Commercial Applications	<200°C	50kW - 200kW	37%	85%	15/2	4500
Molten Carbonate (MCFC)	Decentralised Combined Heat and Power Production	>600°C	250kW-1MW	47% - 55%	83%	15/3 - 15/5	12000

Stationary Fuel Cells

There are currently two main fields of application for stationary fuel cells: small scale house supply fuel cell heating appliances with a capacity of 1 to 5 kWel, and fuel cells of the 200 to 300 kWel class which can be used as a district heating CHP plant or for power and heat supply for commercial or industrial applications.

The phosphoric acid fuel cell (PAFC) has been the first fuel cell technology applied commercially. It is thus considered to be the "first generation" of fuel cells. The cost of the PAFC power plant is approximately three times higher than required for significant market penetration. In 2002 the principal PAFC manufacturer announced the phase out of the production of PAFCs as the cost targets could not be achieved. Accordingly, PAFCs are not considered to be a priority technology for future developments, and thus no technical data and target costs for future configurations are reported in the database.

Molten Carbonate Fuel Cells (MCFC) demonstrate the highest efficiency of all types of fuel cells presented in the database. The high operating temperature does not require the use of expensive catalysts, which is one advantage of MCFCs over low-temperature fuel cells. However, the higher operating temperature, places severe requirements on the corrosion stability of the FC components in order to preserve the cell lifetime. While the initial development of MCFC power plants aimed large scale generation, currently decentralised combined heat and power production is close to commercialisation. Measurement data on demonstration plants confirm that the relatively high electrical efficiency of 47% and overall efficiency of 83% can be reached. As current activities mainly focus on increasing the electrical efficiency, it is expected that future developments will lead to an increase of the electrical efficiency to 52% and of the overall efficiency to 86%. It is expected that a future hybrid system which combines a MCFC with a steam turbine will achieve an electrical efficiency of 55% to 56%, with an overall efficiency of 90%.

Solid oxide fuel cells (SOFC) have grown in recognition as a viable high temperature fuel cell. They represent the most efficient way to generate electricity from fossil fuels, such as natural gas. The high operating temperature allows internal reforming, promotes rapid kinetics with non-precious materials, and produces as a high quality by-product high temperature heat. However, the high temperature operation intensifies the degradation of stack and systems materials, reducing significantly the average lifetime of the stack. Lowering the temperature and developing suitable low cost materials are presently the key technical challenges facing SOFCs. Data from the pre-series phase of the 1 kWel SOFC single-family house application offer 25% to 30% electrical net efficiency, with long-term prospects to reach 32% (with 90% overall efficiency). At the 2 - 3MW capacity level, SOFC/gas turbine hybrid systems have achieved an electrical efficiency of 48%.

Polymer electrolyte membrane fuel cells (PEMFC) are compact and lightweight cells, deliver high power density, operate at low temperatures and have a fast start capability. The PEMFC system has applications for small scale stationary electricity systems, but is considered to be the system of choice for mobile applications (see following section).

Mobile Fuel Cells

Fuel cells can be used to provide propulsion for automotive applications including cars, trucks, buses, trains and ships. Fuel-cell powered vehicles are developed as a more fuel-efficient and less polluting alternative to compete with alternative automotive propulsion systems. A fleet of fuel cell vehicles has been demonstrated, with plans for commercialisation beyond 2012. The development of hydrogen supply infrastructure is expected to play a key role in the market penetration of FC vehicles.

Polymer Electrolyte Membrane (PEM) fuel cells are the most promising options for fuel cell vehicle applications, due to their high efficiency at low temperatures, their light weight and the high degree of integration of their system components. An important barrier to using these fuel cells in vehicles is hydrogen storage. The use of small reformers to produce hydrogen onboard FCVs overcomes direct hydrogen storage problems and omits major infrastructure changes, thus supporting the transition towards fuel cell propulsion at low costs. However, R&D funding on onboard fuel processing has faced severe reductions recently, since technical goals were judged uncertain.

Fuel cell engines typically consist of the system module, the stack module, a control unit, a power distribution unit and a cooling pump. For a direct hydrogen system today the stack is estimated to account for 50%-60% of total system costs. System peripherals costs including turbo-compressors and power conditioners contribute considerably to the overall costs of a fuel cell engine.

Current research efforts are directed at improvements in PEFC stack power densities, reductions of the system complexity and higher operation temperatures with a view to achieve higher efficiency, greater fuel flexibility and lower costs. Projections on system costs for direct hydrogen and reformer systems and on FC stack costs indicate that in order to make the technology commercially viable, mobile fuel cell system costs will have to fall by a factor of 100 and the durability of the technology would have to rise fourfold (U.S. Department of Energy).

Hydrogen engines for automotive application

Hydrogen can be used as a fuel for internal combustion engines (H2ICE). The combination of hydrogen as an energy carrier with proven and well understood engine technologies is seen ultimately as a near-term solution which could bridge the gap up to the full development of fuel cell vehicles.

There are numerous positive features of hydrogen as an ICE fuel, mostly related to its high burning rates, its low combustion temperatures and exhaust emissions. However, engines fuelled with hydrogen suffer from reduced power output, due mainly to the very low heating value of hydrogen on a volume basis. A hydrogen engine is 40 to 60% larger in size than a gasoline engine for the same power and torque output. Due to the volatile nature of the gas, there are serious potential operational problems with uncontrolled pre-ignition and back-firing on the intake manifold, which need to be addressed. High temperatures may also lead to high emissions of nitrogen oxides.

Prototype vehicles using hydrogen internal combustion engines have been demonstrated in the past. Today's hydrogen IC engines do not achieve the specific power of conventional gasoline engines. However with exterior mixture formation or high pressure injection with turbo charging fuel consumption of EURO IV calibrated turbo charged diesel engines are feasible.

B.1.2 Hydrogen production options

Hydrogen is a high quality secondary energy carrier and can be produced from a variety of resources, including fossil fuels, nuclear, biomass and other renewable energy sources (wind, solar, hydro). Today almost 50% of hydrogen is produced from steam methane reforming, which is the most economic route for large scale hydrogen production. To comply with key sustainability targets (climate protection, conservation of non-renewable resources), a future hydrogen economy will have to be based on diverse hydrogen production options. The following sections review the current technical and economic status of hydrogen production technologies, taking into account their respective future prospects for improvement.

The following Hydrogen production processes have been addressed in the database:

Table B-3: Hydrogen production options

Feedstock	Hydrogen Production Process	Feedstock	Hydrogen Production Process
Electricity	Electrolysis Alkaline electrolyser Membrane electrolyser Solid Oxide Electrolyser Cell	**Coal**	Gasification with Pressure Swing Adsorption (PSA) with Pressure Swing Adsorption and CO2 capture with Hydrogen Separation Membrane Reactor and CO2 capture
Natural Gas	Steam Methane Reforming Pyrolysis Solar Methane Reforming	**Biomass**	Gasification Pyrolysis (Bio Oil Reforming)
Oil	Partial Oxidation of Heavy Fuel Oil	**Others**	Photoelectrochemical water splitting Photobiological hydrogen production Thermochemical cycles

Electrolysis

Water is electrolysed in an electrochemical cell to produce hydrogen and oxygen. Water electrolysis was one of the main means of hydrogen production before the steam reforming process was introduced. Electrolysis can be used for decentralised on-site hydrogen production as well as for large scale centralised hydrogen plants. The CASCADE MINTS database incorporates all three different processes that exist for electrolytic water dissociation: alkaline water electrolysers (commercially used), proton exchange membrane (PEM) electrolysers (still in the development stage) and high-temperature steam electrolysis.

Renewable sources like wind, solar or hydro can be used to generate the electricity required to perform the electrolysis, leading to non-carbon emitting production of hydrogen. Nuclear power can also be used to provide electrical supply to generate hydrogen. However, for the electrolysers to be cost competitive the cost of electricity needs to be very low. The efficiency of commercially available pressurised electrolysers ranges between 50% and 70 % related to the LHV of the delivered hydrogen. Future long term developments are expected to result in an efficiency of close to 80%.

Hydrogen from Fossil Fuels

⇨ Steam Methane Reforming

Steam Methane Reforming (SMR) is the process in which high-temperature steam (>800°C) is used to produce hydrogen from a methane source, such as natural gas. It is the most commonly used process for producing hydrogen in large quantities. Natural gas reacts with steam to produce a mixture of hydrogen and carbon monoxide (CO). Subsequently, CO is converted into carbon dioxide producing more hydrogen. To achieve pure hydrogen, the gas is finally cleaned in a pressure swing absorption unit (PSA). As SMR is a well established and mature technology, the potential for technical improvement is limited. Following the relevant literature, it has been assumed that today's process efficiency of 67% (small scale) and 74% (large scale) can only be slightly increased in the future. Thus SMR is only expected to play a role in the transition period. A solar reforming process which provides process heat by solar energy can achieve fuel saving of up to 40%. The off-gas, which is burnt to provide process heat in the conventional process, can be recycled, which increases the overall process efficiency and reduces CO2 emissions. Carbon capture can also be applied to remove the CO2 emitted.

⇨ Partial oxidation of heavy oil

Partial oxidation is used in refineries for the conversion of residues (liquid, highly viscous hydrocarbons) into hydrogen, CO, CO2 and water. Heavy oil partial oxidation is only relevant for large scale hydrogen production. This process is well established; yet a further optimisation of the system integration may result in a reduction of fuel input by 5%, and a reduction of the electricity requirements by 10%, leading to marginal improvements of the total efficiency from the present 73% to 77% in the future. However, it is not expected that technological improvements can significantly reduce capital costs in the future.

⇨ Coal gasification

Coal gasification is a process that converts solid coal into a synthetic gas composed mainly of carbon monoxide and hydrogen. The CO reacts then with water to form carbon dioxide and more hydrogen. Coal gasification for hydrogen production is likely to be applied only for large scale centralised facilities. Current developments mainly focus on the optimisation and integration of the gasification process for electricity production in IGCC power plants. Research also aims at developing and applying carbon capture and sequestration technologies to separate and store the carbon dioxide produced in the process. Investment costs for the state-of-the-art gasification system are significantly higher than the costs for a steam methane reformer or a heavy oil partial oxidation plant. This is explained by the high capital costs, despite the lower feedstock costs. CO2 capture leads to an increase of investment costs by about 30% (1140 $€_{2000}/kW_{H2,}$ not including costs for CO2 disposal) and a reduction in overall efficiency by 4% (to 55%).

Hydrogen from Biomass

For the mid to longer term horizon generating hydrogen from biomass may be the most practicable and viable renewable and potentially carbon neutral option for hydrogen production. Hydrogen can be produced from biomass either through gasification or pyrolysis of biomass feedstocks. Gasification is a two-step process in which biomass is thermochemically converted to a medium-energy-content gas. This process is still in its infancy, as currently only a small number of demonstration facilities are in place and many issues must still be addressed before the technology can become economically competitive. Pyrolysis (gasification of biomass in the absence of oxygen) is attractive because solid biomass and wastes which are very difficult and costly to manage can be readily converted into liquid products (bio-oil) implying transport, storage and combustion advantages.

Technologies for hydrogen production from biomass are still in the R&D or demonstration phase. Data referring to a projected small size biomass gasification plant indicate an overall plant efficiency of 69%, while there is a potential for increasing efficiency by the further use of low-temperature process heat. Various studies suggest a significant potential for reducing the investment costs by increasing the size of the gasification system: cost projections for a 'small scale' plant (25 MWth) in 2025 equal 1,500 €/kWH2 and decline by 40% for large scale gasification plants. The savings from employing economy of scale have however to be balanced with the transportation costs for the low density biomass feedstock.

B.1.3 Hydrogen Delivery System and Infrastructure

The wider use of hydrogen will require a new and extensive infrastructure. Such an infrastructure can be defined broadly to include the facilities and equipment needed to produce, distribute, store, and dispense hydrogen as a vehicular fuel or for electricity generation.

A hydrogen economy requires the development of infrastructure to deliver hydrogen from the point of production to the point of end-use. Hydrogen delivery systems include the transport and delivery from central production operations, and the storage, compression, and dispensing operations. Hydrogen delivery pathways include gaseous hydrogen, liquid hydrogen, and a spectrum of possible (solid or liquid) hydrogen carriers. The specific technology components listed in the following table have been explicitly addressed in the CASCADE MINTS database:

Table B-4: Hydrogen Storage, Delivery and Dispensing options

Hydrogen storage options	Hydrogen Delivery Infrastructure	Dispensing of hydrogen
Liquid hydrogen storage vessels for bulk storage	Hydrogen Road Transport	Gaseous hydrogen based filling stations
Gaseous pressure vessels for bulk storage	Liquid hydrogen transport by road	Liquid hydrogen based filling stations
Gaseous underground storage	Gaseous transport by road	
	Hydrogen Ship Transport	
	Pipeline Transport	

B.1.3.1 Hydrogen Storage

Hydrogen is difficult to store due to its very low volumetric energy density. The most suitable method for storing hydrogen will depend on many factors including the volume to be stored, weight of the storage unit, storage time, space restrictions and the end use. The hydrogen storage options considered in the database include H2 in liquid and gaseous form. The issues of bulk storage have also been specifically addressed.

Liquid H2

The energy density of hydrogen can be improved by storing hydrogen in a liquid state. Hydrogen liquefies at minus 253°C thus special equipment is required for its storage. The temperature requirements for liquid hydrogen storage necessitate expending energy to compress and chill the hydrogen into its liquid state. The energy requirement for hydrogen liquefaction is high: 30% of the lower heating value of hydrogen is required for liquefaction. The challenges for liquid hydrogen storage are energy efficient liquefaction processes and high-efficiency thermal insulation of the storage vessel to limit boil off. Costs for liquefaction are driven in the first place by capital costs (today 63%), then energy costs (29%), and in the third place O&M costs (8%). Energy costs depend strongly on the liquefier efficiency and less on the production rate. In small plants, energy and non-energy costs are comparable. At large scale plants the energy costs become more important.

Automotive On-board hydrogen storage

Different storage systems are competing for hydrogen storage on-board of vehicles, characterised by the physical/chemical properties of the hydrogen: liquid, gaseous or chemically bound. Storing hydrogen on-board of automobiles in gaseous form is currently the simplest, technically mature and cheapest storage method. However, gaseous hydrogen tanks are much larger and heavier than what is desired to render hydrogen-powered vehicles competitive to conventional ones. Liquid H2 tanks can store more H2 than compressed gas tanks but require substantial amounts of energy for liquefaction. High pressure (70 MPa) compressed gas is proposed in the literature as the most satisfactory near term storage technology when factors like volume constraints and energy efficiency are taken into account. The challenge is to create light-weight, efficient and safe composite materials that can reduce the weight and volume of H2 storage systems and to achieve lower refuelling times.

Research towards ways to "store" hydrogen has focused on the reversible chemical reaction and absorption of H2 by various metals and their alloys to form metal hydrides. These can effectively "capture" hydrogen at or near ambient conditions and release the gas as desired, at the point of use. The system for hydrogen storage in metal hydrides consists of the material itself, a pressure vessel and an integrated heat exchanger for cooling and heating during absorption and desorption. The system offers great potential for hydrogen storage but as the developments are in a laboratory phase, little is known about equipment costs.

Bulk storage of hydrogen

Storage of larger quantities of hydrogen will be necessary at central production plants or at distribution centres, like e.g. fuelling stations. Storage vessels for liquid hydrogen are state-of-the-art technology today. Costs for liquid storage however are considerable, driven by the installation costs of the tank and the energy penalty of hydrogen liquefaction. As liquid hydrogen storage is a proven technology and considerable capacity has already been installed its potential for cost improvement is restricted unless a breakthrough in H2 liquefaction energy intensity and capital costs is achieved.

Today the most commonly used industrial storage method for hydrogen are pressure vessels for gaseous hydrogen storage with about 5 to 7 MPa. Approximately 6% to 7% of the stored energy is used to compress the hydrogen. High weight and space requirements for the vessel are general disadvantages of gaseous pressurised storage. The costs of compressed gas vessels increase with operating pressure and capacity. With increasing pressure, energy expenses for compression have to be taken into account. These systems are considered mature technology and are applied for all kinds of industrial gases worldwide, implying that there exists limited potential for cost reductions.

Underground gaseous storage can also be used to store large quantities of hydrogen to balance demand with supply, i.e. in the case of fluctuating renewable energy. Underground storage is probably the most inexpensive storage for large quantities of hydrogen. Due to the accumulation of considerable experience on underground natural gas storage and the minor differences in its development and organisation relative to underground hydrogen storage, no potential for lower costs is seen.

B.1.3.2 Hydrogen Delivery

Three primary options for hydrogen delivery are considered in the database: road, ship and pipeline transport of gaseous or liquid hydrogen. Road transport of gaseous and liquid hydrogen is commonly applied in industry today. Gaseous hydrogen can be shipped in compressed gaseous hydrogen tankers, this method however is expensive and it is cost-prohibitive for long-distance transport. Over long distances, liquid trailer transport of hydrogen is less expensive due to its considerably larger capacity (more than ten times larger). The main potential for lower costs for liquid and gaseous hydrogen transport is located in improving the storage vessel, and the liquefaction technology. Achieving economies of scale will also lead to cost reductions.

Liquid hydrogen can also be transported overseas in hydrogen tank ships, however the very low-temperature cryogenic technology required implies substantial costs. To handle cryogenic temperatures investment costs for hydrogen ships are assumed to be 25% higher than costs for LNG tankers. Assuming that the ship is propelled by hydrogen, boil-off losses (typically between 0.2-0.4 per day) can be recovered to fuel the engine of the ship.

Pipelines are effective for handling large flows. Hydrogen pipelines are today in use in several areas of the US, Canada and Europe, serving primarily industrial purposes. For a hydrogen economy, two different types of pipelines may be needed: a large capacity long distance system and a local small capacity system to provide the link to hundreds of refuelling stations and customers. Hydrogen pipelines are in principle similar to natural gas pipelines; converting natural gas pipelines to carry a mixture of hydrogen and natural gas may require only modest modifications to the gas pipeline; converting existing natural gas pipelines to transport pure hydrogen however leads to a capacity de-rating of approximately 20-25% on a delivered energy basis, thus requiring substantial modifications.

Hydrogen pipeline costs have been estimated on the basis of natural gas pipeline costs. Natural gas pipelines however are considered a mature technology, whereas hydrogen pipelines will need adjustments at compressing stations and piping material (to address embrittlement and safety concerns), implying higher costs. The investment costs for NG pipelines have therefore been used as minimum costs. Three types of pipeline layouts have been considered in the database serving different purposes: 3 inch pipes (local network), 12inch pipes (representative for connecting pipes to fuelling stations) and large diameter pipes (2m), used for longer distances.

Key challenges to hydrogen delivery include reducing the delivery cost, increasing energy efficiency minimising hydrogen leakages and addressing safety concerns. At very large volumes, an extensive pipeline infrastructure is the most cost-effective and energy efficient known means to transport hydrogen over long distances. At any rate, current research investigates methods to reduce costs and produce energy-efficient hydrogen delivery technologies for hydrogen to become a major energy carrier.

B.1.3.3 Hydrogen Dispensing

The road transport sector may be supplied with hydrogen via hydrogen filling stations similar to today's petrol stations. Hydrogen is either received from centralised plants via road or pipeline transport or it is produced on-site. Gaseous hydrogen based filling stations provide compressed H2 to be used in vehicles, whereas liquid hydrogen based filling stations can either provide liquid or compressed gaseous H2 to vehicles, or a combination of both. In a gaseous hydrogen delivery case, the hydrogen must be compressed, stored, and dispensed at the refuelling site. With cryogenic liquid approaches, the liquid hydrogen is provided by road tankers from the central liquefaction plant and is stored in cryogenic tanks at the station. For liquid dispensing, LH2 is pumped into the vehicles tank, however specialised cryogenic filling equipment is needed. For gaseous dispensing, LH2 is compressed to about 45 MPa (today) or 88 MPa (future) and subsequently vaporised.

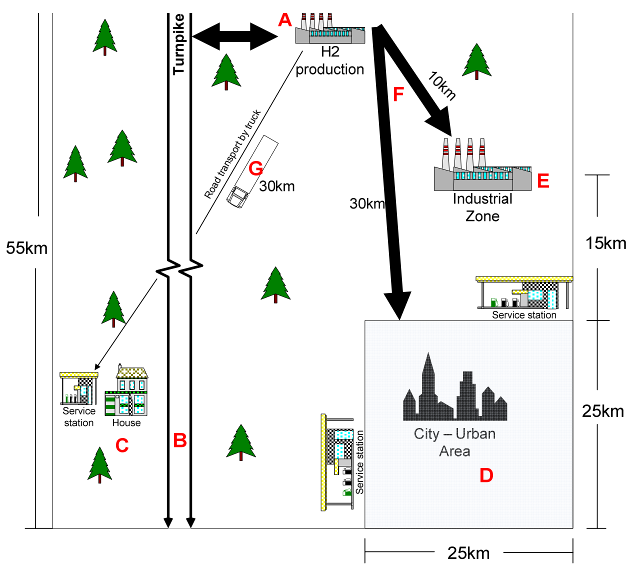
Dispensing both gaseous and liquid hydrogen to vehicles is in the early stages of development, and demonstration projects are under way. Due to the uncertainty in cost estimation for filling stations comparisons to natural gas filling stations cost data have been made.

B.1.3.4 Reference Case for Hydrogen Distribution

A key element for the development of the overall hydrogen system is the hydrogen storage and delivery infrastructure. It is widely recognised that a future integrated hydrogen-based energy system would be particularly infrastructure intensive (more so than natural gas and electricity) and a great number of configurations are possible.

The CASCADE MINTS technology database contains several options for liquid or gaseous hydrogen storage and distribution, providing flexibility in the choice of the components for the future hydrogen infrastructure system. However, complete modelling of the hydrogen storage and distribution infrastructure system is a very complex task, since it is a "chicken-egg" problem: it is not possible to have infrastructure developments without demand and vice-versa. Therefore, a vision is needed about the development of the hydrogen infrastructure system, in which its main components will be identified and fully characterised in terms of their technical and economic performance.

Figure B-1: Reference case for hydrogen storage and distribution in an average European Union area



Within CASCADE MINTS, a reference system for hydrogen storage and distribution suitable for energy system models has been developed. The system has been configured as an analogue to the present gas supply and refined oil distribution networks. In this sense, pipelines can distribute hydrogen to high-demand areas, and trucks or rail can distribute hydrogen to rural and other lower demand areas. On site hydrogen production and distribution facilities can be built where demand is high enough. Hydrogen can be stored either in gaseous or liquid form. However, given the high costs of liquid hydrogen delivery (mainly due to the liquefaction process), liquid hydrogen is more likely to be used in hydrogen fuelled vehicles than in stationary applications.

The reference case for hydrogen distribution assumes an average EU region supplied with hydrogen in around 50 years. It represents a situation at the initial stages of a take-off of a hydrogen economy falling well short of maturity of such an economy. This is done on purpose because at this stage the economic performance of the network could play a crucial role in determining the extent of penetration of hydrogen as an energy vector.

The stylised configuration of the reference system is presented in Figure B-1. The system assumes a single hydrogen production plant which theoretically satisfies all the hydrogen demand in the area. The plant is connected to similar plants via a turnpike pipeline (55km long within the region under consideration). This turnpike serves as an intermediate storage and load balancing tool. A high pressure transmission pipeline (38 km long–6 MPa pressure) links the hydrogen plant to the urban area. A medium pressure urban ring pipeline (5 km long – 2 MPa pressure) for the distribution backbone is also included to ensure a high delivery and support peak demand. The medium pressure pipeline is directly connected to service stations. Service stations absorb more than half of the central plant output and are situated at rural areas along the roads crossing the region and on the outside ring of the urban area. The latter assumption stems from the difficulty to build large new pipeline networks in areas of high population density. It can be reasonably assumed that all rural stations will be supplied by truck. A low pressure distribution network is finally assumed, connecting final consumers to the hydrogen grid.

B.2 The TECHPOL Database

TECHPOL is a database built on past experience with technology data collection developed in the course of former European research projects (namely the SAPIENT and SAPIENTIA projects partly financed by the 5th Framework Programme of European Commission). Its aim has been to provide reliable data on the costs and performance of representative supply and demand energy technologies in order to assess the drivers and inducement factors in the dynamics of new energy technologies. The previous version of the database gathered a first set of data on new energy carriers (hydrogen) and new technologies (capture and storage, 4th generation nuclear, fuel cells, highly energy-efficient technologies) based on reference papers and reports and on expert assumptions. In the context of the CASCADE-MINTS project the TECHPOL database has been utilised in order to collect and organise the quantitative information on new energy technologies provided by partners. Building on the specific and detailed work carried out in the course of the project on the characterisation of hydrogen technologies (see section …) and on the relevant datasets existing in the database, reference values on the costs and performance of key power and hydrogen generation technologies including capture and storage and transportation technologies have been established.

Considerable effort has been devoted to the update of the TECHPOL database, a task which has involved continuous interacting process with all partners almost throughout the project. Accordingly, the fixed and variable O&M costs for electricity and hydrogen production technologies have been recalculated, CO_2 capture costs have been revised, marginal supply cost curves for CO_2 storage have been introduced and capacities and costs of vehicles have been re-estimated. Finally, ιn order to preserve a coherent evolution in the performance of stationary and mobile fuel cells, three types of fuel cell technologies have been considered two for stationary applications (large and small scale) and one mobile application. Performance, costs and progress rates for the new types of technologies also had to be adjusted to avoid inconsistencies.

The final version of the TECHPOL database covers almost 50 different generic technologies which can be classified into the following five categories:

- Centralised/large scale power generation, which includes fossil and nuclear electricity production. Nine fossil fuel power generation technologies are considered three of which with carbon capture and storage devices. Nuclear power technologies cover conventional and advanced (4th generation) nuclear power reactors.
- Distributed or Renewable power generation. Key decentralised technologies include both small and large renewable power generation units and fossil distributed production systems including conventional cogeneration units and fuel cells.
- Hydrogen production, which includes nine different hydrogen production processes (gas steam reforming with the option of solar steam reforming, coal gasification, heavy oil partial oxidation, biomass gasification and pyrolysis, solar/nuclear thermochemical cycle and water electrolysis).
- Hydrogen storage and delivery including hydrogen liquefaction, storage tanks, technologies for road, sea and pipeline transport of gaseous and liquid hydrogen and filling stations.
- Transport technologies: Five different mobile applications are considered in the TECHPOL database: conventional internal combustion engine vehicles, pure electric vehicles, hybrid vehicles, hydrogen powered internal combustion engine vehicles and fuel cell hybrid vehicles fuelled with hydrogen (gaseous or liquid) or gasoline.

For each technology, different sets of data on costs and performance are provided including, overnight investment costs, lifetime, operation and maintenance costs, efficiency and availability. The database is presented in excel format and provides a framework for a standardised calculation procedure for electricity/hydrogen levelised production costs for three time periods: 2000, 2025 and 2050. This allows to calculate and compare the production costs for each technology on the basis of a given methodology and common assumptions (discount rate, load factor) improving thus the cross-consistency of the large number of hypotheses which are further integrated in the modelling process.

Furthermore, floor costs are calculated for each technology, representing the ultimate cost that can be reached by the technology when the learning process is achieved and the technology has exploited all economies of scale opportunities.

B.3 R&D expenditure database

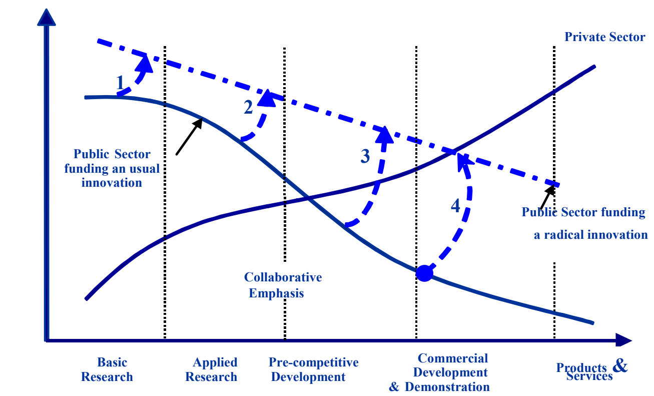
In recent years, fuel cells and to a lesser extent other hydrogen economy related technologies have benefited from public R&D support and have attracted growing private R&D interest in developed economies. Time series on R&D efforts – although not so long and not easily traced to existing generic statistical sets – are essential for the estimation of the CASCADE MINTS technology dynamics mechanisms. To further increase the reliability of the Two Factor Learning estimates (see section C.1.2) it has been decided in the CASCADE-MINTS project to develop a full set of consistent data for the key explanatory variables considered in the Two Factor Learning Curves, i.e. cumulative government energy R&D (GERD) and cumulative Business energy R&D (BERD), in order to complement the datasets on cumulative capacities and costs.

Data on public R&D of OECD countries has been obtained through a systematic survey of multiple sources of information: different publications (particularly IEA «Hydrogen & Fuel cells: review of national R&D Programs»), the CORDIS and FERD databases (which accommodate over 12.000 energy projects). Sources for private R&D however have proved more difficult to identify. To obtain reasonable estimates recourse to indirect methods has been necessary. These included gross R&D expenditure of companies that are key players in technological development in the relevant technological domains, patent application data for apportioning such expenditure to specific technologies and other indirect methods depending on relevant indices. Again, the starting point has been the utilisation of the CORDIS and FERD databases. Cumulative research has also been examined for a set of key technologies, and considered as a "proxy" for accumulated knowledge for each technology.

Most of hydrogen, fuel cell and CCS programs correspond to disruptive technologies, so longer and larger basic research is required, since the creation of new scientific knowledge should be supported by the development of new scientific disciplines or sub-disciplines. The applied research stage is also deemed to be longer and more costly because of the requirement to develop new practical devices and new artefacts that are initially characterised by low performances and which require continual adaptations in order to improve their key functionality. Radical innovations require also a high public support for demonstration, market-entry and infrastructure investments (hydrogen networks and storage), while in the case of incremental innovations the costs incurred by these activities are comparatively less important and entirely supported by private investment. So public/private partnerships are necessary to speed up the cost reduction process by accelerating early market development and reduce lead time to commercial operations in order to avoid the 'valley of death' risk.

The following figure shows that the ratio of GERD to BERD may be changing over time, according to the maturity of each technology. This partly explains the difficulties to estimate this ratio for the future for hydrogen and related technologies.

Figure B-2: The initial GERD / BERD ratio is probably higher for H2 and FC programs than for other emerging technologies (all BERD in Public Private Partnership programs)



Source: Bernard Bourgeois, LEPII-EPE

Furthermore, hydrogen, fuel cells and CCS programs are based on complex networking RD architectures with overlapping of GERD and BERD money (eg. DOE's Hydrogen, Fuel Cells & Infrastructure Programme, or NHP) and an increasing share of international partnerships (eg. IEA Collaboration).

In this context it has been difficult to elaborate a general methodology for a consistent treatment of the available information. Therefore specific published R&D data concerning hydrogen, fuel cells and CCS from large R&D projects undertaken in the USA, Europe and Japan has also been collected to complement data from the CORDIS and FERD databases. The cumulative government research profiles show that total cumulative R&D spending rose to 150bn $00 in 2002, while cumulative GERD for Hydrogen and related technologies represented only 7 bn $00 in 2002, although it increases very rapidly thereafter.

C. Model Extensions to represent Hydrogen Economy Configurations

In the context of CASCADE MINTS, considerable effort has been devoted to the development, re-specification and extension of all large scale deterministic models and the stochastic model to enable them to describe possible configurations of a hydrogen economy according to their philosophy, geographical coverage and time horizon. A wide range of models has been involved: perfect foresight models (MERGE-ETL, MESSAGE, MARKAL-EUROPE), detailed behavioural models for the World (POLES) and Europe (PRIMES), computable general equilibrium models (PACE-T(H2)) and stochastic models (PROMETHEUS). At any rate, a great amount of effort has also been devoted to model modifications aiming at harmonising their characterisation according to the specifications arrived at in the course of the construction of the common information base. Modelling work has also aimed to equip all models participating in the CASCADE MINTS Part 1 project with the set of technology dynamics mechanisms for the key fuel cell and hydrogen supply technologies. Such work has aimed to enable models to represent endogenously the technical change that can lead to the transformation of the energy system in the direction of a hydrogen economy.

C.1 Modelling Technology Dynamics: Basic Tools

C.1.1 Clustering and Technological Spillovers

CASCADE MINTS examines the system related aspects of hydrogen technologies with emphasis on identifying and describing learning networks created around hydrogen technologies or technology clusters. A technology cluster is formed by a group of technologies that share a common component. Taking into account – to the extent possible – learning effects that could operate synergetically (by improving several hydrogen related technologies together) or competitively (by favouring at the same time hydrogen technologies and other integrated technology options) different hydrogen technology cluster matrices have been set up. These matrices have been used by the energy system models participating in the project to model technology spill-over and learning effects involving the different types of hydrogen technologies.

Key components have been introduced in hydrogen production technologies, also shared by technologies in other sectors. Learning takes place at the level of these components, rather than at the level of individual technologies. The set of all technologies sharing a learning component forms a cluster. The costs of a technology with learning components is proportional to the costs of the key components that make up the technology, plus optionally some additional non-learning part. The non-learning part may stand for 'Balance of System' costs, or for some other parts of the technology. As for the learning part of the costs, due to the investment in the particular clustered technology, the costs of the key technology defining the cluster decrease according to a learning-by-doing principle. Through the clustering, the investment costs in the other technologies in the cluster also decrease. Thus, with learning in clusters it is possible to describe technological spill-over effects, in the form of cost decreases as a reflection of sharing experience among related technologies, even between technologies in different sectors.

This approach has been applied to all technologies identified in the CASCADE MINTS database that are suitable for clustering. More specifically, technologies for H_2 production, storage and transport as well as H_2 fuel cell technologies (mobile and stationary) have been split up component by component resulting in the construction of six cluster matrices. For H_2 production, due attention has been paid to synergies with learning components from other sectors, in particular the power sector. Examples of the latter are gasifiers and CO_2 capture technologies.

C.1.2 Two Factor Learning Curves specification and estimation

CASCADE MINTS places particular emphasis on the importance of R&D in influencing the penetration of hydrogen in the energy system. In addressing this issue, two factor learning mechanisms have been employed, forming the main vehicle through which R&D effort is translated to an improvement in technological performance. This mechanism recognises learning attributed to research effort (learning-by-research) and learning arising from the experience gained through technology uptake (learning-by-doing).

The datasets constructed within CASCADE MINTS containing information on the recent improvements in the technical and economic characteristics of the hydrogen related technologies in the light of R&D effort directed to them, have provided the critical information for the statistical estimation of the TFLC equations with regard to different technological clusters of hydrogen related technologies.

The specification of the two factor learning curves was driven by the aim to capture with the fewest parameters possible a set of desired properties, including:

- Endogenisation of as much of the technological progress reported in the CASCADE MINTS common information base as possible, by incorporating both learning by experience and learning by research.
- Constrain the learning mechanism to technical possibilities as they emerge from perspective analysis. This means that the progress of a particular technical economic characteristic (such as the capital cost) cannot go beyond a notional absolute limit, which is here loosely identified as a "floor".
- Incorporate "clustering" as much as possible, on the understanding that it provides synergies that could accelerate the transformation of the energy system. As a rule, "clustering" was introduced by analysing the technology characteristics reported in the information base. However, when no clear indication could be derived on how to form clusters of technologies, "weak clustering" was introduced.

'Weak clustering' does not identify individual components which learn separately (e.g. steam turbines, boilers, gasifiers, etc.) but uses a whole technology as the 'basis' for other similar (and probably more complex) technologies. The TFLC equations for technologies, which are "structured" from the 'basic' technology, capture the additional – specific to the technology only – progress of a particular technical-economic characteristic. This connection is identified as "weak" because the largest part of the improvement of the technologies belonging to such a cluster is specific to each technology and independent of the progress of the basic technology.

Two factor learning curves have been estimated for 34 technological options covering hydrogen supply, storage, distribution and end-use technologies, the CO2 carbon capture filter (post-combustion and pre-combustion) and private passenger cars. Learning parameters have been estimated for a number of technical-economic characteristics – where applicable – such as capital costs, fixed operating and maintenance costs, efficiencies, fuel cells stack lifetime and capacity of car engines. Table C-1 summarises the technologies for which two factor learning curves have been estimated

Table C-1: Technologies for which TFLC equations have been estimated in the context of CASCADE MINTS

Hydrogen production technologies	**Hydrogen infrastructure**
Gas Steam Reforming	Liquid hydrogen on board storage
Solar Methane Reforming	Gaseous hydrogen on board storage
Coal Gasification	Liquid hydrogen storage vessel in trucks
Gasifier component	Gaseous hydrogen storage vessel in trucks
Biomass Gasification (Small scale)	Liquid hydrogen storage in service stations
Biomass Gasification (Large scale)	Gaseous hydrogen storage in service stations
Biomass Pyrolysis	Large scale liquid hydrogen storage
Biomass Handling component	Low pressure pipelines
High Temperature Thermochemical cycle component	Other service stations costs not related to storage
Large Scale Electrolyzer	**CO2 capture technologies**
Oil Partial Oxidation	Post combustion CO2 capture in Gas Turbine Combined Cycle
Fuel cells	Post combustion CO2 capture in Supercritical coal
Mobile fuel cells with/without reformer	Pre combustion CO2 capture in Coal Gasification for electricity production
Large scale stationary fuel cells with/without reformer	Pre combustion CO2 capture for hydrogen combustion
Small scale stationary fuel cells with/without reformer	**Other technologies**
Passenger cars	On board reformer
Gasoline ICE cars	Small scale reformer in stationary fuel cells
Hybrid cars	Batteries for electric motors
Hydrogen ICE cars	
Pure electric vehicles	

A particular problem that emerged during the estimation of the TFLC equations was the unavailability of historical data on capacity installation for the majority of technologies. Accordingly, the estimation was performed using only information on historical R&D expenditures and base year technology performance as reported in the common information base. Installed equipment has been derived from the PROMETHEUS (in deterministic mode) baseline, as produced using the characterisation and the prospects of the technologies from the common information base and projections of R&D expenditures by technology elaborated by ICCS-NTUA. The stochastic properties of the estimators have been derived in the light of past experience gained from similar TFLC estimations. As a consequence the process adopted is better characterised as calibration rather than estimation and its results are highly dependent on a host of assumptions related to the technology performance projections and PROMETHEUS model results on technology uptake.

C.2 Model extensions to represent Hydrogen Technology Configurations

C.2.1 World Partial Equilibrium Model: POLES

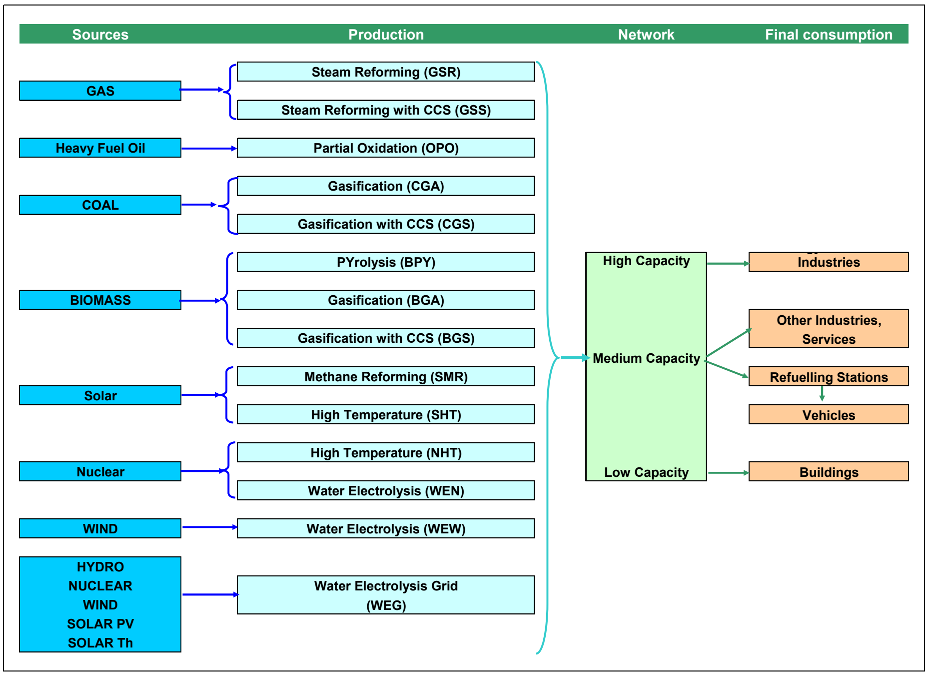
The POLES world simulation model for the energy sector has been updated and considerably enhanced with a view to an improved representation of hydrogen economy configurations. This has entailed significant changes to its modelling system, as the hydrogen technologies identified in the common information base (those not already represented) had to be introduced in the model, altering significantly its structure.

The modelling of the Hydrogen economy in POLES begins with the demand side. Hydrogen is principally used through fuel cells, which have better efficiency than conventional engines in both stationary and mobile uses. Stationary H2 Fuel Cells for distributed electricity in cogeneration (HFC) are introduced in the model in competition with electricity supply from the grid and alternative distributed electricity production technologies (CHP, decentralised photovoltaics, gas-powered fuel cells). Mobile hydrogen-related applications in POLES include the H2 Fuel Cell and H2 ICE vehicles which compete with conventional, electric, hybrid and gasoline FC vehicles. To avoid the exclusion of some possible niche market uses, thermal hydrogen vehicles are also considered as part of hydrogen demand. The inter-technology competition (translated into market shares) depends on the total cost of each vehicle (investment, operation, energy costs) under a scraping rate constraint for existing equipment.

The POLES hydrogen production module has been updated in the light of the information derived in the CASCADE MINTS database: this has not only implied the detailed representation of the technological options identified in the database, but also the omission of others. Technologies featuring promising prospects (Heavy Fuel Oil Partial Oxidation, Coal Gasification, Biomass Gasification, Solar Methane Reforming) have been introduced in the model whereas the existing technologies have been covered in more detail. The updated POLES H2 production technology portfolio comprises a set of 14 options for hydrogen production using natural gas, coal, biomass, nuclear and renewable energy as feedstock.

The updated hydrogen module in the POLES model is described in the following figure:

Figure C-1: POLES Structure of the Hydrogen Economy



The hydrogen delivery system in POLES is defined as the whole set of equipment between the H2 production plant and the nozzle of a dispenser including compression or liquefaction, H2 storage and H2 distribution in trucks or pipelines. Delivery and storage costs strongly influence the development of H2 and had to be treated carefully in the modelling system. Delivery costs depend on demand patterns (size, density), the infrastructure configuration, the choice of technologies and a suite of other parameters (among others the flowrate, the distance and the size of the refuelling station).

Carbon sequestration is applied to three electricity generation technologies (Pressurized Supercritical Coal, Integrated Coal Gasification, Gas turbine in combined cycle) and five hydrogen production technologies (Coal Partial oxidation, Heavy Oil Partial oxidation, Gas Steam reforming, Coal Gasification, Biomass Gasification). The modelling of carbon capture and sequestration has encompassed the calculation of the capture and storage costs, the calculation of the carbon stored for each country and at the world level and the calculation of the unit cost of the carbon stored.

C.2.2 European Partial Equilibrium Models: PRIMES-H2

PRIMES is a partial equilibrium energy modelling system that simulates a time-forward market equilibrium for energy supply and demand in the European Union (EU-27) Member-states. In the context of Part 1 of the CASCADE MINTS project a special version of the PRIMES model has been developed in order to specifically serve the modelling of the hydrogen economy for Europe. This involved the further development of its detailed Reference Energy System (RES), with inclusion of hydrogen demand and supply processes and links.

The new Reference Energy System

The new RES of PRIMES represents eleven hydrogen production technologies according to the definitions given in the 'Common Information Base'. In addition a number of other technologies were added related to decentralised ('forecourt') hydrogen production (e.g. small scale electrolysis or other energy sources like methanol, ethanol, gasoline, LPG, diesel). The production of methanol and ethanol from biomass has also been modelled in detail in the separate PRIMES biomass sector.

Regarding the end use technologies, the transport sector of the PRIMES demand model has been enriched with a more detailed techno-economic representation of hydrogen technologies for road and rail transport. For the residential and industrial sectors, stationary H2 and natural gas fuel cells, along with direct combustion of hydrogen/natural gas mixture were introduced and/or updated. These technologies were applied to specific electricity and heat demand applications (water, space, cooking etc) in the residential and tertiary sector and specific electricity and steam\heat demand for industrial processes in the industrial sector. Table C-2 provides an overview of the new technologies that were added in the different sectors.

Table C-2: The new technologies introduced in the existing sectors of PRIMES

Transport	Industrial	Residential
• H_2 Fuel Cells (cars, trucks, busses, trains) • Methanol FC (cars, trucks, busses, trains) • H_2 ICE (cars, trucks, busses) • Ethanol ICE (cars, trucks, busses)	• H_2 FC stationary • H_2 ICE • Natural Gas FC stationary • Methanol FC stationary	• H_2 FC stationary • Natural Gas FC stationary • H_2 ICE

The representation of the delivery infrastructure includes the transportation of hydrogen, ethanol or methanol, either through a pipeline network (gaseous hydrogen and hydrogen/gas mixture) or via trucks (gaseous or liquid form, metal hydrides etc) and the hydrogen storage stations for gaseous hydrogen, liquid hydrogen and gas/liquid hydrogen. In the latter cases the compression or liquefaction processes have also been modelled.

The Hydrogen Supply model

The hydrogen supply model of PRIMES constitutes a process based representation of the hydrogen supply sector. It formulates the economics of the production processes of hydrogen and the expansion of process plants and infrastructure. Capacity use and expansion is represented as a full vintage model with endogenous investment. Dynamics of technology improvement is fully tracked through the vintages of process units.

Twenty one hydrogen production technologies have been included in total, with primary resources ranging from traditional fossil fuel to nuclear and renewable energy. The option of carbon capture and storage (CCS) is possible for the technologies listed in Table C-3.

Table C-3: List of technologies with CCS option in PRIMES

Technologies with CCS	
Coal gasification with syngas	Heavy Oil partial oxidation
Coal gasification with membrane	Heavy Oil reforming
Coal supercritical gasification	Heavy Oil gasification with syngas
Gas reforming	Heavy Oil gasification with membrane

C.2.3 Perfect Foresight World Energy Model (Very Long Term): MESSAGE

MESSAGE is a multi-regional "bottom up" energy-system optimisation model with perfect foresight, covering the very long term (up to 2100). In the context of CASCADE-MINTS, MESSAGE has been substantially restructured and extended to allow for an improved representation of the transport sector and the incorporation of the mechanisms of endogenous technological learning for the technologies related to the hydrogen economy. A complete update of the MESSAGE data specifications for the production of hydrogen and electricity has been performed using the TECHPOL database.

Updated Transport sector

The description of the transport sector, previously only stylised, was split into passenger car transport, air transport, and other (mainly freight) transport, including a detailed description of 14 different passenger car technologies, which now comprise:

- Internal combustion cars using gasoline, natural gas, methanol, and ethanol;
- Internal combustion cars, with an electric battery hybrid system using gasoline, natural gas, methanol, ethanol, and hydrogen;
- Fuel cell cars using hydrogen, gasoline, natural gas, and methanol; and
- The electric passenger car.

Implementation of endogenous learning in MESSAGE

In MESSAGE, technologies are defined by inputs, outputs, investment costs, efficiencies, fixed and variable O&M costs, plant factors, plant lifetime, emission coefficients, and other parameters. All these parameters can be given as time series to reflect improvements with time (exogenously defined learning). In the context of CASCADE MINTS effort has been placed in introducing endogenous learning for the technologies relevant to the hydrogen economy. This implies that the technological characteristics and costs do not automatically improve with time (as exogenous input time series) but only as a result of model decisions on R&D spending (learning by research) and on technology installations (learning by doing). The new endogenous learning methodology implemented in MESSAGE is described in the following sections.

⇨ Implementation of learning spillovers in MESSAGE using clustering and subcomponents

The new endogenous learning methodology implemented in MESSAGE begins with the representation of learning spillovers among technologies with similarities: the learning of one technology leads to technological progress in technologies that are, to some extent, related. This spillover effect is modelled using technological subcomponents, standalone technologies and clustered learning. Table C-4 illustrates how learning through clustering and spillovers has been implemented in the passenger car sector. Different car types have common parts (for example the hybrid component shared by many advanced car systems) implying that technological learning of one car type influences cars with related parts.

Table C-4: The endogenous learning parts of passenger cars, as implemented in MESSAGE

	Mobile Fuel Cell System	Hybrid System	Mobile Nat.Gas/ Methanol Reformer	Mobile Gasoline Reformer	H2 Storage
Conv. Gasoline Car					
Conv. Natural Gas Car					
Conv. Methanol Car					
Conv. Ethanol Car					
Gasoline Battery Hybrid Car		x			
Natural Gas Battery Hybrid Car		x			
Methanol Battery Hybrid Car		x			
Ethanol Battery Hybrid Car		x			
Hydrogen Battery Hybrid Car		x			x
Gasoline Fuel Cell Car	x	x		x	
Natural Gas Fuel Cell Car	x	x	x		
Methanol Fuel Cell Car	x	x	x		
Hydrogen Fuel Cell Car	x	x			x
Electric Car		x			

The implementation of spillovers and 2FL in MESSAGE is straightforward in cases where a technology is modelled with only one learning component. In that case, all the technologies with the same component make up a cluster. All technologies in the cluster have one common R&D spending variable and contribute to the common cumulative installations of the cluster. The common cumulative installations and the cumulative spending of the common R&D variable are used to calculate the cost of the learning component using the two-factor learning curve, as defined in section C.1.2. The TECHPOL database has been used to calculate the cost of the non-learning parts. The sum of these costs provides the total technology cost for all members of the cluster. In cases where a technology is modelled with more than one independently learning part, then the costs of the most important learning part dominate and define the cost matrix.

Endogenous two-factor learning in MESSAGE is introduced through the technologies, clusters, and subcomponents listed in Table C-5. Learning is implemented through six clusters and three independent standalone learning (sub) technologies. Seventeen technologies and six subcomponents are fully 2FL. One subcomponent is one factor learning (learning-by-doing). Three exogenous learning technologies have 2FL subcomponents. The specification follows closely the definition of the TFLC provided in section C1.2.

Table C-5: Implementation of the endogenous two-factor learning in MESSAGE

Technology	Learning Properties	Cluster	Subcomponent 1	Subcomponent 2
Hydrogen fuel cell car	full 2FL	Mobile FC	Hybrid subcomp.	Mobile H2 storage subcomp.
Gasoline fuel cell car	full 2FL	Mobile FC	Hybrid subcomp.	Gasoline reformer subcomp.
Methanol fuel cell car	full 2FL	Mobile FC	Hybrid subcomp.	Nat. gas/alcohol reformer subcomp.
Natural gas fuel cell car	full 2FL	Mobile FC	Hybrid subcomp.	Nat. gas/alcohol reformer subcomp.
Mobile fuel cell stack subcomp.	full 2FL	Mobile FC		
Stationary H2 fuel cell CHP		Stationary FC		Mobile fuel cell stack subcomp.
Stationary nat. gas fuel cell CHP		Stationary FC		Mobile fuel cell stack subcomp.
Gasoline reformer subcomp.		Mobile reformer		
Nat. gas/alcohol reformer subcomp.		Mobile reformer		
Steam methane reformer H2 plant		SMR		
Solar methane reformer H2 plant		SMR		
Mobile H2 storage subcomp.		Stand alone		
Hybrid subcomp.		Hybrid		
Gasoline battery hybrid car		Hybrid		
Natural gas battery hybrid car		Hybrid		
Ethanol battery hybrid car		Hybrid		
Methanol battery hybrid car		Hybrid		
Hydrogen battery hybrid car		Hybrid		Mobile H2 storage subcomp.
Electric car		Hybrid		
Electrolyser H2 plant		Stand alone		
Gasifier subcomp.		Gasifier		
Coal gasification H2 plant		Gasifier		
Biom. gasification H2 plant		Gasifier		Biomass handling subcomp.
Biomass handling subcomp.		Stand alone		
IGCC	Exogenous learning		Gasifier subcomp.	
Biomass gasification power plant	Exogenous learning		Gasifier subcomp.	Biomass handling subcomp.
Biomass power plant	Exogenous learning			Biomass handling subcomp.

⇨ Two Factor Learning Implementation in MESSAGE

The direct implementation of 2FLCs to MESSAGE poses considerable difficulties. These difficulties arise from its perfect foresight optimisation nature. The TFLC through its learning by doing component implies non-convex feasible sets which combined with the non-linearities in the specification of the TFLCs (included to ensure the representation of saturation effects) creates a formidable computing challenge. It is however possible to model changing technology characteristics (driven by the endogenously determined cumulative installed capacities/R&D spending) using discrete learning steps and applying mixed integer programming algorithms.

The idea behind the two factor learning curve implementation in MESSAGE is that if a technology T is made a 2FL technology, then the single technology T is replaced by a whole set of technologies. Each technology in the set represents the same technology, but with characteristics that change because of different Learning by Doing (LBD) and Learning by Research levels. Four levels of cumulative R&D spending and five levels of cumulative installed capacity were defined giving a set of 20 (4x5) technologies. For a technology to be installed in the model and become active a specific level of cumulative installation needs to be reached and of cumulative R&D to be spent. Three different states of learning by research and four different levels of learning by doing are defined for each cluster. The technology T is replaced by a set of technologies with improved characteristics, after learning due to a cumulative spent R&D and cumulative installed capacity of a combination of levels occurs.

This approach applies for investment costs. For simplicity reasons, a different procedure was used for the other technology parameters such as efficiency, plant factor, fixed/variable operation and maintenance costs, or the amount of subcomponents need to be installed per unit of main technology. If one of these parameters is assumed to be learning, then the initial value and the final value after full learning for these parameters were taken from TECHPOL or C.1.2 (see Table C-6).

Table C-6: The initial cost in 2000, the cost after full mixed integer learning (investment costs after third level cumulative R&D and four level cumulative capacity) and the floor cost of different representative learning technologies

	Units	Initial Cost	Cost after full MIP learning	Floor Cost
Veh. FC Comp. of the H2 FC car	$90/car	2743556	2867	1631
Stationary fuel cell CHP	$90/kW	7438	553	169
H2 steam methane reformer	$90/kW	264	210	189
Gasoline Car Reformer	$90/kW	5747	6.2	6.2
Mobile H2 Storage	$90/kgH2	577	60	44
Generic Hybrid Component	$90/car	3522	997	995
H2 Electrolyser	$90/kW	487	281	261
Gasifier Component	$90/kW	461	276	216
Biomass Handling	$90/kW	288	136	108

The model operates in five different 2FL operation modes:

1) For 2FL clusters a common R&D budget time series can be specified and the model set to optimize endogenously on which cluster to spend the available R&D budget for each time period.
2) Assuming that the R&D budget is unlimited but that each euro spent on R&D in a given time period has a cost entry of one euro in the objective function, the model is set to invest in R&D only if the lower costs achieved worth more than the R&D spent. The model will also try to optimize the timing of the R&D so that the R&D is only spent just before the respective technology is needed.
3) A combination of the above. The R&D spending can be limited and have a cost entry in the objective function.
4) Supplying exogenous R&D time series for each cluster and solving the problem as a one-factor learning where the costs over time improve only due to learning by doing.
5) Combinations of the above (technology clusters having a common budget whereas other clusters having predefined budget time series, and others having free spending with costs).

C.2.4 Perfect Foresight Integrated Assessment Model: MERGE-ETL

MERGE-ETL is the updated version of the MERGE model developed within the Fifth Framework Programme of DG Research which allows considering different endogenous technological learning (ETL) options to describe fossil fuels, renewables and nuclear energy including carbon capture and sequestration options. In the context of CASCADE MINTS the model has been modified and extended to address – in more detail – the processes and technologies related to the hydrogen economy at a global level. The model has also been substantially restructured to incorporate endogenous technical change mechanisms for hydrogen related technologies.

The model extensions have taken place in the bottom-up part of MERGE, called ETA, which represents the energy supply system. MERGE-ETL has been extended to include an electric and non-electric sector, hydrogen and synthetic fuel production and their infrastructures. The technological options to generate hydrogen have been enriched with the inclusion of various feedstocks (fossil fuels, bio-fuels, nuclear energy and renewables). The hydrogen produced is either used to produce electricity or to cover end-use demand. CO2 sequestration options have also been included for hydrogen production based on fossil fuels or biomass.

The new version of MERGE-ETL allows the explicit treatment of transportation technologies. Private transport is introduced as an independent sector that consumes part of the non-electric energy to satisfy the demand for mobility. The formulation of the transportation sector is general enough to be extended to other end-use sectors.

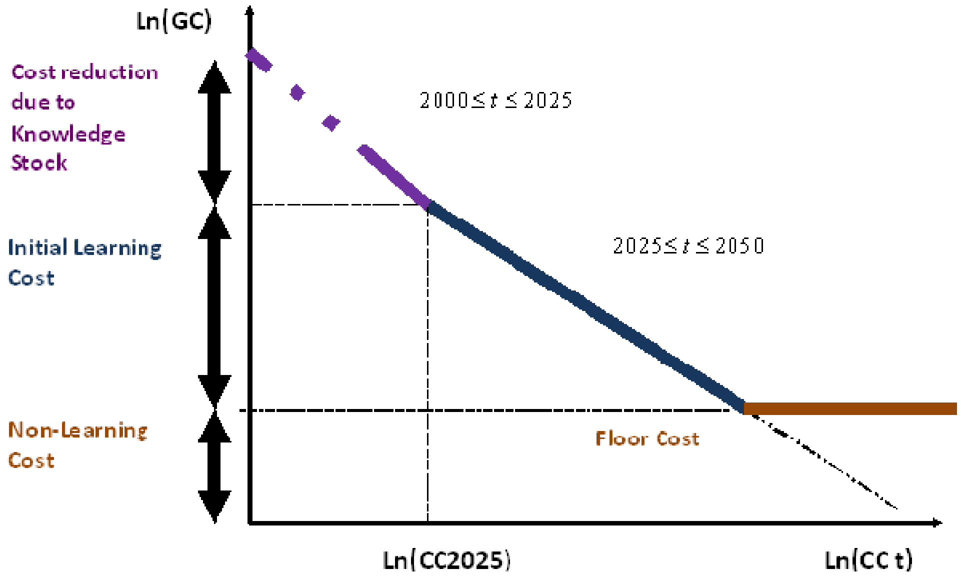
Modelling hydrogen technology dynamics has been a quite challenging task, given that the overall methodology adopted in CASCADE MINTS is more relevant to recursive dynamics models incorporating consumer behaviour algorithms rather than to optimisation models with perfect foresight like MERGE-ETL. After testing alternative specifications, the formulation that produced the most useful results assumed a pre-defined R&D budget, a-priori allocated to the technologies considered. According to this methodology, and with regard to hydrogen technologies, production costs are split in three parts (see Figure C-2):

- The first part corresponds to the early technology development phase where dedicated R&D investment enables the learning by research mechanism, until costs reach the levels reported in the TECHPOL database for 2025.
- The second part results from the combined effect of learning by doing and learning by research and becomes active when the technology enters its commercial phase.
- Two factor learning applies until the technology reaches its floor cost. The third part of the cost remains constant at the level of the floor cost.

Each of these costs is treated differently in the model: the first two parts are non-linear while the third cost component can be expressed with a linear relation.

Figure C-2: Illustration of the endogenised leraning curve costs reduction.

(There is a cost component that assumes learning by searching starting from GC2000 and going to the cost valid in TECHPOL in 2025, i.e., GC2025. Then, the TFLC applies until the floor cost is reached. Afterwards, the cost remains constant to the level of the floor cost.)



The NLP formulation of the learning-by-doing and learning-by-research parameters has been successful, allowing the performance of policy simulations on learning subsidies and/or on R&D spending. To model technology dynamics a clustering approach has been developed following closely the clustering and technological spill-over specifications arrived at in the course of the project (see section C.1.1).

C.2.5 Dynamic Energy System Optimisation Model for Europe: MARKAL

MARKAL is a “bottom-up” energy-systems optimisation model with endogenous learning which describes the Western European energy system. In the context of CASCADE MINTS, MARKAL-WEU has been substantially restructured and extended to allow for improvements in the representation of the hydrogen economy. The new MARKAL model incorporates a larger number of production and consumption technologies and includes a more detailed representation of hydrogen handling between production and consumption. Production occurs on a large and small scale level for gaseous H2, although production can be followed by liquefaction. H2 produced by renewables is directly linked to liquefaction and further distribution of liquid H2. Transportation and distribution of H2 occurs through pipelines (gaseous) or trucks (either in gaseous form or as liquefied hydrogen) with or without temporary storage. H2 storage recipients are modelled in MARKAL for both stationary applications as well as mobile (fuel tanks) and for both liquid and gaseous H2. Stationary storage includes the necessary working storage capacity in filling stations as well as large scale temporary storage in built vessels or in underground caverns. Stationary end use draws power directly from a H2 grid whereas mobile applications are serviced by filling stations. The stationary end use technologies follow the demand pattern of the sector to which they belong, e.g. residential fuel cell systems will deliver electricity and heat fitted on these residential demand patterns as configured in the MARKAL model.

The transport sector has been reconfigured to allow for a detailed representation of fuel cell and hydrogen mobile applications. The remodelling of the transport sector involved the incorporation of additional demand classes such as passenger transport and freight transport. For the private passenger transport, an even more detailed definition at the level of drive cycle (city, regional, interregional) has been introduced. The potential for hydrogen system spillovers between mobile and stationary fuel cell applications has also been considered, reflecting the possibility that advances in one sector may stimulate knowledge that will also benefit the other.

C.2.6 Computable General Equilibrium Models: PACE-T(H_2)

To serve the macroeconomic analysis of policies promoting the penetration of hydrogen, CASCADE MINTS also draws on the use of a General Equilibrium paradigm. The analytical framework is based on an existing multi-sector, multi-region dynamic Computable General Equilibrium (CGE) model (PACE-T) that integrates the bottom-up description of the energy system into a top-down representation of the remaining economy. In the context of CASCADE MINTS this model has been further developed and considerably enhanced to represent a potential hydrogen economy. The model extensions include the incorporation of mobile applications in the passenger sector (conventional and hydrogen cars assumed to be perfect substitutes), the integration of discrete alternative options for hydrogen production and the inclusion of stationary applications.

The separate hydrogen production sector incorporated in the model is characterised by fixed input shares. An aggregate hydrogen production technology is introduced which covers all costs of the different hydrogen production, distribution and storage technologies: investment, fuel input, operation and maintenance. Hence, the inputs into the aggregate production technology and thus the costs for hydrogen are driven overtime by the different mix of hydrogen technologies.

A separate automobile capital stock for hydrogen cars is also considered. Consumers choose between transportation services that are a composite of services from fossil fuel and hydrogen powered cars. Three different size classes for cars (small, medium and large cars) are distinguished, powered by either a conventional technology or by hydrogen. Conventional and hydrogen cars are assumed to be close to perfect substitutes. The formulation also takes into account further factors affecting car demand, like e.g. noise or driving properties, which may restrain hydrogen cars from being perfect substitutes to conventional cars. A major advantage of this approach is that hydrogen penetration is endogenous in consumer demand. Thus it is not only possible to analyse the macroeconomic effects of the introduction of hydrogen in passenger transport but also the effects of different technology and/or policy assumptions on the penetration of hydrogen in the consumer demand sector.

Finally, micro heating systems are introduced as a second durable consumption good at the household level. Consumers choose between heating services that are a composite of services from fossil fuel-based and hydrogen-based installations. Again it is assumed that these two alternatives are perfect substitutes.

C.2.7 Stochastic World Energy Model: PROMETHEUS

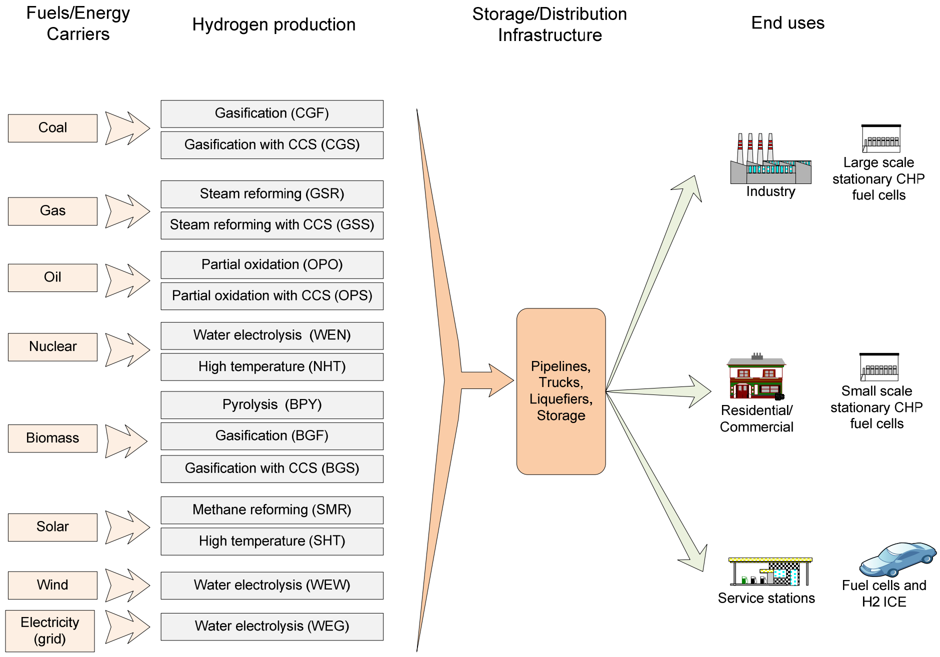
All models presented so far are essentially deterministic in character. The projections and variants produced using these models provide many interesting insights as to the future course of energy system variables. Such analysis offers a valuable means of exploring possibilities in a transparent and readily justifiable way particularly useful in supporting policy analysis. It does not however give any quantitative indication as to how likely some occurrences may be. Such information is often strategically important and could add a different dimension to the analysis performed. Stochastic models are appropriate tools for providing this type of information however very few of them exist covering energy systems.

ICCS-NTUA has developed PROMETHEUS, a tool capable of performing precisely this type of analysis. PROMETHEUS is a self-contained world energy model consisting of a set of stochastic equations developed with assistance from the 5th Framework Programme of DG Research (SAPIENT project). Initially built to study the risks associated with energy technology R&D investments the model has grown to cover a wide range of energy variables and is particularly detailed with respect to energy technologies on a global scale. Within CASCADE MINTS, the model has been extended to contain stochastic relations for all the main quantities concerning the hydrogen economy. These are represented in reduced form, but specific effort has been made to retain the key structural elements, as these are the main vehicles through which stochastic dependence of the impacts of possible scenarios can be established. Thus risks that are specific to hydrogen technology evolution can be confronted with a very wide range of risks associated with other key elements of the energy system including uncertainties due to lack of precise knowledge of the system itself.

Hydrogen Economy Characterisation

The hydrogen module of the PROMETHEUS model has been extended to incorporate a large number of technologies for hydrogen production, distribution and end use. In order to describe more accurately some key technologies, such as fuel cells, these technologies are included in the model on a component-by-component basis. The characterisation of the technologies and their components has been based on the common information base of the CASCADE MINTS project. The following figure presents in summary, the resulting new hydrogen module in PROMETHEUS:

Figure C-3: Overview of the hydrogen economy as represented in PROMETHEUS



The Hydrogen module considers 16 technologies to compete on the supply side for the centralised production of H2. On the demand side, hydrogen is introduced in the residential/commercial and industrial sectors through four stationary fuel cell applications covering small and large scale CHP fuel cells with and without reformer). Hydrogen is also introduced as an energy carrier in the road transport sector, where eight different technologies are considered, covering mobile fuel cells stacks and systems, on board hydrogen storage (liquid and gaseous), on board reformers and H2 internal combustion engines. Following the "Reference case for hydrogen distribution" (see section B1.3 of the final technical report) a large number of technologies for hydrogen distribution and storage have been introduced in the model including pipelines, service stations, trucks for transporting H2, liquefaction facilities and liquid storage options.

Other Improvements in PROMETHEUS

Significant extensions/improvements have also been made in the model, which do not directly relate to the hydrogen economy but were necessary since they enhance crucial parts of the model and enable a more accurate evaluation of the implications of hydrogen penetration in the energy system. A fourth region which includes the 12 new member states of the European Union after its last two expansions has been introduced in the model (NMS-12). In view of the importance of road transport for hydrogen prospects a major re-design and re-estimation of the transport module of PROMETHEUS has also taken place during the CASCADE MINTS project. Additional to the hydrogen powered cars, the new car types introduced in the model include biodiesel internal combustion engine cars and plug-in hybrids. In total, the model now includes 11 different car types: 5 hydrogen powered, 2 conventional internal combustion engines (gasoline and diesel), 1 using biodiesel, 2 types of hybrid and 1 type of pure electric car. Cost-supply curves for biomass and uranium have also been introduced, endogenising the biomass and nuclear fuel price in the model. Using information provided by the IPTS, exponential cost-supply curves were also estimated for CO2 sequestration per region.

In view of the importance of renewable energy sources in the future, the model has been equipped with cost-supply curves for the electricity and hydrogen production from hydro, wind and solar sources. This has been rendered necessary since the absence of any kind of constraint in the penetration of renewable energy sources – as a result of exhaustion of the available sites – often led to unrealistic results, in cases of strong climate policy. To allow for the possibility of a future hydrogen taxation in the road transport, PROMETHEUS has been further equipped with a function which gradually increases the tax in hydrogen as the share of hydrogen cars in total stock increases.

The previous version of the model considered annual public and private R&D expenditures on energy technologies to be stochastic, depending on the cost of energy and the GDP growth. In the context of CASCADE MINTS, the share of each technology in total annual public and private R&D also became a stochastic variable, increasing in this way the uncertainty in the R&D expenditures.

The nature of hydrogen end use technologies is such that they can successfully penetrate only if the associated infrastructure is developed in parallel. In addition, consumer decisions are also guided by mimetism and social networking effects. PROMETHEUS has been equipped with a decision mechanism in order to simulate the above social and infrastructure network effects in consumer decisions. The mechanism enhances the share of a specific technology in new investments, as the penetration of this technology increases. Stochastic real interest rates have been introduced in the decision mechanisms of the model, to represent more fully the uncertainty in the decisions for new investments.

Technology Dynamics

The PROMETHEUS stochastic model is equipped with technology dynamics mechanisms in the form of two factor learning curves making improvement a function of experience and research.

PROMETHEUS incorporates endogenous learning (both by research and by experience) for all hydrogen related technologies in the form of two factor learning curves as they have been described in section C1.2 of this report. PROMETHEUS, being a stochastic model, treats the learning parameters as random variables, which implies that the stochastic characteristics of the parameters play a crucial role in determining the uncertainties surrounding the learning characteristics. In particular they may influence the uncertainty surrounding the efficacy of R&D effort. For this purpose, during the estimation of the two factor learning curve equations, particular attention was given to ensure both statistical fit and sufficient robustness.

The joint distributions of the learning parameters within a single technology indicate that learning by experience and learning by research estimates are strongly and negatively correlated. This tends to reduce variability of learning, since in the cases where one parameter is large the other has significant probabilities to be small. Also, learning parameter estimates of the same type for different technologies within the same cluster tend to be positively correlated, which implies some uniformity in the stochastic behaviour of the whole cluster. Learning parameters also tend to be positively correlated when the same type of learning coefficient is considered (either learning by doing or learning by research)

Covariance in learning parameters is one of the reasons producing covariance in technology prospects. This mechanism operates in a variety of ways: for example a positive covariance between two learning by research parameters will tend to produce a positive covariance for improvements only if the R&D directed towards them displays a similar time profile and is effectively statistically correlated. In fact a host of other considerations all of them subject to risk (and positive or negative covariance) will also tend to play a role in shaping stochastic patterns for technology improvement. These will include the degree of clustering as well as the type of condition that may favour a particular option as opposed to another. Such effects are transmitted primarily through learning by doing parameters but can be modified to the extent that technical limits to improvement are reached at varying speeds.

D. Model based analysis of Hydrogen Economy Prospects

The advanced versions of participating models have next been applied to perform scenario analysis in order to explore under what conditions and to what extent the hydrogen economy may materialize. A Baseline representing a median, or “Business-as-usual” projection has been developed to serve as a benchmark against which alternative and more optimistic scenarios are examined. Such scenarios have been constructed primarily by assuming favourable technological developments combined with supportive policies to produce a more rapid transformation of the energy system towards a hydrogen economy. R&D policy scenarios have also been developed, designed to assess the possible role of R&D in enabling or accelerating the introduction of H2 as a major vector in energy balances.

D.1 Common Assumptions

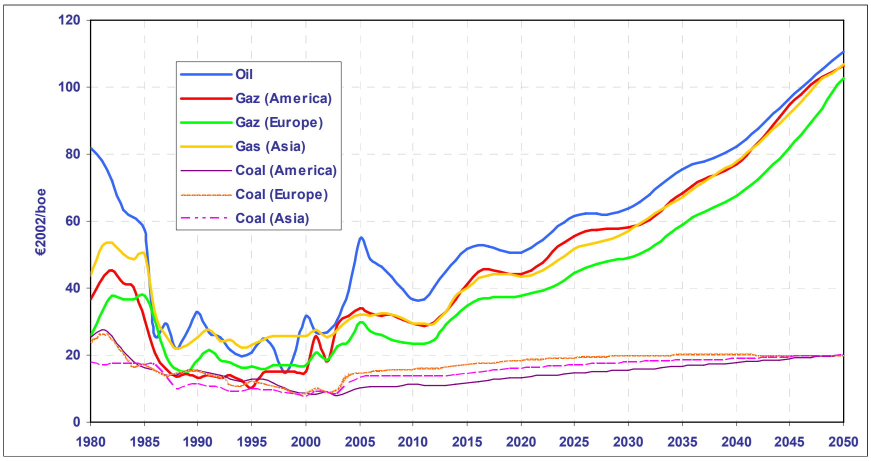
Given that models are characterised by different philosophies (having been designed for different purposes) and have different sectoral, geographical and temporal coverage, the assumptions harmonisation effort had to be restricted to some broad aggregates, namely demography, overall economic activity, climate policy intensity and R&D effort. The following paragraphs report on these common CASCADE MINTS baseline assumptions.

D.1.1 Macro-economic and world price assumptions

World GDP is expected to grow steadily until 2050, although at a pace that progressively slows down, from 3.9%pa in the current decade, to 2.9%pa in the 2010-2030 period and 2.2%pa in the 2030-2050 period. Despite this slowdown, world output increases fourfold to 2050. A significant decrease in the average annual growth rate of GDP per capita for the developed world - compared to the observed growth in 2000-2007 is expected. A slow decrease in the average annual growth rate for the developed world – compared to the observed growth in the present decade – is expected: 2%pa to the 2030 period and 1.4% thereafter. China and India – the fastest growing regions in the current decade - experience a significant slowdown in growth after 2010; this slowdown is particularly noticeable in China and is connected to the evolution of demography and to the ageing of the population.

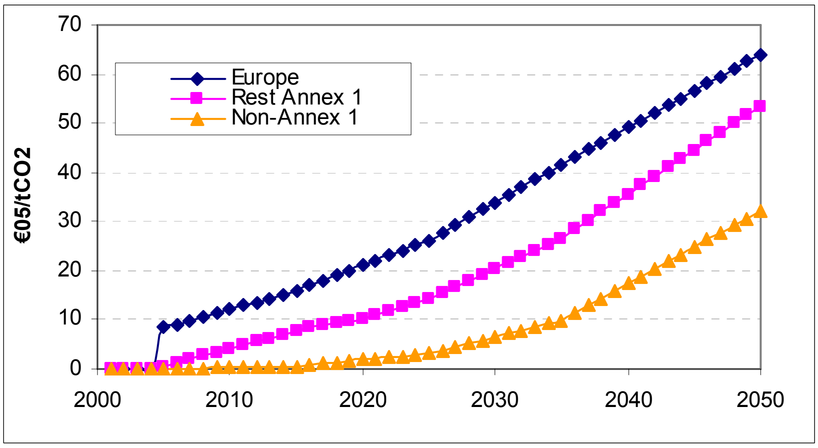
The primary energy prices assumed in the CASCADE MINTS Reference case are presented in Figure D-1. The price outlook reflects a situation where no strong supply constraints occur at least in the period to 2020. The decline in the oil price to 37€02/bl in 2010 is explained by relatively abundant supply due to competition among key producers and a slow down of some geopolitical tensions. After that, when the production of the Gulf and OPEC regions has to expand more rapidly to keep pace with world demand, the oil price increases regularly reaching 110 €02/bl in 2050, nearly double the 2005 level, a year characterised by particularly tight supply conditions. While the oil market is fairly integrated at a global level ("one great pool"), this is not the case for gas and coal, the markets of which display strong regional patterns arising from high transportation cost of gas and coal, relative to their production cost. The projection suggests tightly linked oil and gas prices: in 2050 the gas price equals to 105 €02/boe in the American and Asian markets and 102€02/boe in Europe. Coal prices on the other hand converge at the end of the projection at a level of 20€02/boe, equivalent to one sixth of the oil price.

Figure D-1: Primary energy prices in the Reference scenario



CASCADE MINTS uses climate policy intensity assumptions as implemented in the SAPIENTIA project. They were derived from a Delphi-type process and incorporate the expert judgement of participants. This policy is incorporated as a time-dependent CO2 carbon penalty in all regions. The EU is assumed to lead the climate abatement effort worldwide which implies that it experiences the highest effective carbon values. Developing regions undertake abatement efforts only after industrialised regions do and their efforts are smaller or equal to those in industrialised regions. It is assumed that beyond 2025 climate policy intensity accelerates in response to tougher climate targets. The resulting mean estimates for the carbon values in Europe, the rest of OECD countries and the Rest of the World are illustrated in the following figure:

Figure D-2: Carbon values in €2005/tn of CO2 in the baseline scenario for the world regions

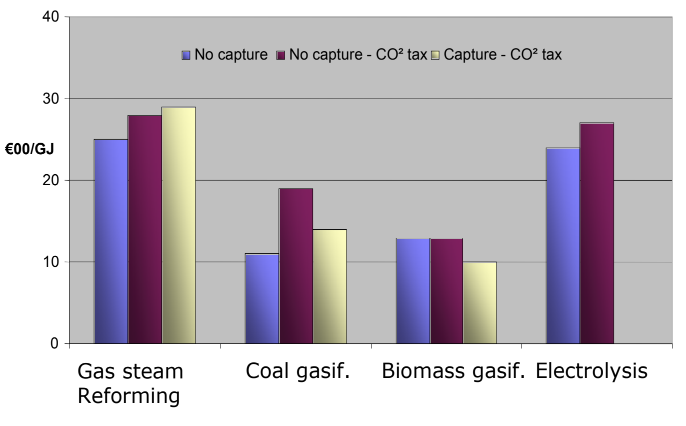


D.1.2 Technological prospects to 2050

Model assumptions on the prospects of technologies have been revised and harmonised according to the specifications arrived at in the course of the construction of the Common Information Base. This chapter provides an overview of the technological prospects to 2050 for the hydrogen-related technologies considered in the database.

As stated in chapter B2.2 of the present report different processes for the production of hydrogen are considered in the database using fossil or nuclear fuels, renewable energy or electricity. Some of these processes correspond to almost mature technologies which demonstrate limited potential for further cost improvements (for example natural gas reforming), whereas others (electrolysis) display better prospects. Hydrogen production from coal gasification is an established technology,which however displays significant prospects of cost decrease and comparably low CCS costs. Processes at an early development stage, such as biomass gasification are surrounded by significant uncertainty in terms of cost development and penetration prospects. More futuristic options are also considered (thermochemical cycles) but long term costs for these technologies have been difficult to establish since no technical and economic data is currently available.

Figure D-3: Hydrogen Production costs in 2050



Natural gas and coal are currently the cheapest sources of H_2: production costs of hydrogen from gas steam reforming and coal gasification range between 7 and 8€00/GJ, whereas costs for electrolysis are typically above 20€00/GJ. The projected increase in the price of natural gas however renders gas steam reforming costly, altering significantly the hydrogen production mix in the outlook. Coal and biomass are mostly favoured, registering significant cost improvements in 2050. Biomass gasification is the least expensive H_2 production option in both the cases when the carbon tax reaches 50€/tCO_2. Under such conditions, CCS could give this technology an overwhelming advantage (see Figure D-3).

Applying CCS on gas steam reforming implies 30% higher investment costs in 2000 (50% higher in 2000). CCS also reduces the efficiency of the process by 8 percentage points in 2050 (12% lower in 2000). With regard to coal gasification, the introduction of CCS results in 15% higher investment costs and 6% lower efficiency in 2050.

Table D-1: FC vehicles–Engine costs (€/кW)

H2 FC/Liquid H2 FC			
Stack Cost	1500	38	24
FC system/engine cost	35500	38	24
Total engine cost	37000	76	48
Gasoline Fuel Cell			
Stack Cost	2100	150	42
FC system/engine cost	35500	38	24
Total engine cost	37600	188	66

As regards the technology options considered in the road transport sector, the technical possibility of fuel cell vehicles is perhaps the most far reaching. As shown in Table D-1 very high costs have been reported in the year 2000, reflecting the experimental status of the technology and the lack of industrial development. Already by 2025, fuel cells are expected to achieve significant stack and system cost reductions boosting their competitiveness. Values in 2025 and beyond represent target costs, reflect optimistic assumptions on technological innovation and learning (standardised products) and are based on the hypothesis that the rapid pace of cost reductions observed in recent years will be sustained in the medium term.

Hydrogen Fuel Cells and Electric vehicles are and will remain significantly more efficient than ICEs and Hybrid vehicles over the outlook: the former two vehicles demonstrated 3 times lower average fuel consumption than ICE cars and 2 times lower than Hybrid cars in 2000. In 2050 they are expected to have two times lower consumption than both ICE and Hybrid vehicles. The most significant progress in fuel efficiency is expected for internal combustion engines, which are assumed to end up with 33% lower fuel consumption in 2050, the largest reduction of which (25%) taking place before 2025. Improvements in efficiency are also expected for fuel cell and electric vehicles with sustained progress beyond 2025 (25% lower fuel efficiency in 2050 relative to 2000).

D.1.3 R&D Outlook

The use of two factor learning curves requires the availability of information on capacities (for learning by experience) and R&D (for learning by research) for each hydrogen related technology. Although most models generate values for capacity/technology take-up endogenously, very few include endogenous mechanisms for determining R&D expenditures on hydrogen technologies. For this purpose, it was necessary to elaborate an outlook for R&D effort directed to different technological options, to be used as a common assumption for the construction of the baseline scenarios of the different models. This Outlook is based on past trends, recent changes in emphasis and perspective analysis based on judgement, but does not intend to be the result of rigorous modelling logic. On the other hand, effort was devoted to maintain some consistency in order to allow a clear picture on a probable direction of future R&D to emerge.

Figure D-4: Shares in total GERD (left) and BERD (right) of hydrogen related technologies and CCS

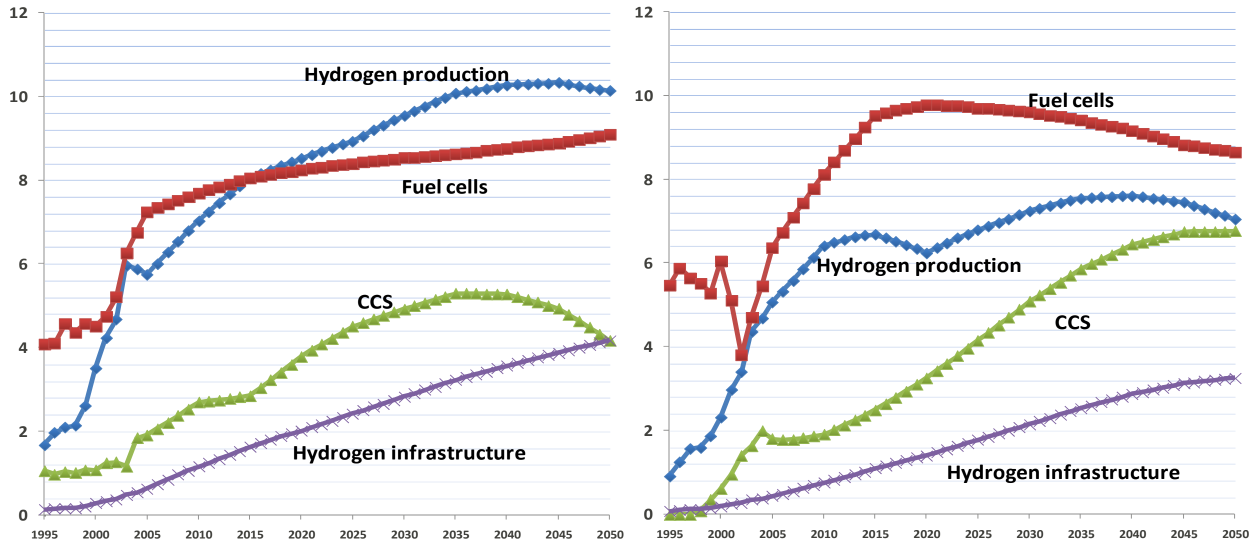
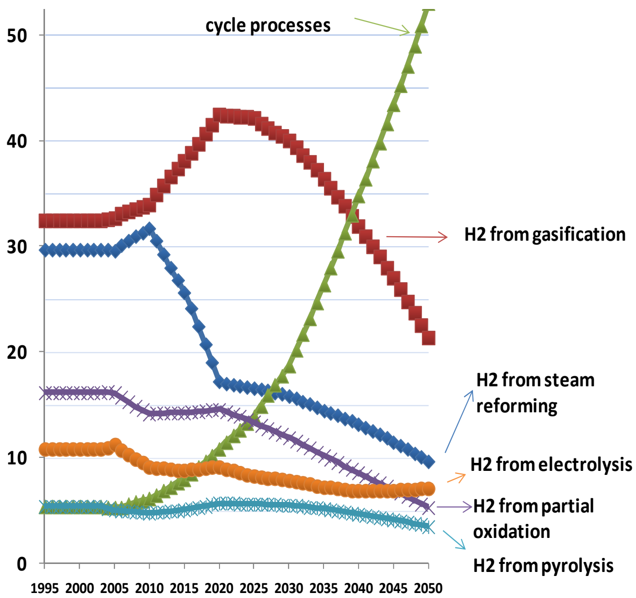


Figure D-4, which presents the shares in total GERD (Government Energy-related R&D) and BERD (Business Energy-related R&D) of hydrogen related and CCS technologies shows a shift in the public R&D expenditures from fuel cells and CCS to hydrogen production and infrastructure technologies. This shift occurs when fuel cells and CCS research reaches its maturity: in 2015 for the former and in 2035 for the latter. Beyond these periods, the public sector turns its interest to new hydrogen production technologies (such as hydrogen production from high temperature thermochemical cycle) and to new hydrogen infrastructure options (such as compact on-board hydrogen storage). These shifts are mainly attributed to the fact that the character of the research supported by the public sector is mainly pioneering, i.e. exploring new possibilities rather than improving products to increase profits. On the other hand, the research of the private sector (and in particular the automobile industry) is mainly focused on fuel cells during the whole horizon to 2050, although signs of "saturation" occur after 2015. CCS technologies attract increasing R&D budgets until around 2040, when both the private and public funding of their further development is reduced.

Figure D-5: Shares of H2 Production Options in Total Energy Related R&D for H2 Production



The reduction in business R&D directed to hydrogen production that occurs at around 2020 is attributed to the fact that until that time research is focused mostly on steam reforming and coal gasification technologies, but as climate policy concerns accentuate, research is shifted to biomass gasification and to nuclear high temperature thermochemical cycles. This is further illustrated in Figure D-5 which presents in detail the allocation of the R&D directed to the different hydrogen production options. Three main periods can be distinguished. The first is the period to 2010, where around 2/3 of the R&D directed to hydrogen production supports the research on coal gasification and steam reforming. The second period is the period 2010-2030, where the interest in steam reforming options recedes and the interest in gasification turns to biomass gasification instead of coal. Finally the third period is from 2030 to 2050, where gasification technologies almost reach their potential improvement and research focuses on the more futuristic options such as the nuclear high temperatures thermochemical cycle process.

The rest of the available options for hydrogen production (electrolysis, partial oxidation and pyrolysis) do not attract a significant share due to their limited prospects for future improvements, and their high production costs, which constrain them to a low penetration into the hydrogen production sector. Some interest is maintained in the longer term in the form of hedging and in the case of electrolysis because of prospects in decentralised hydrogen production and dedicated power plants.

D.2 Baseline Scenarios

D.2.1 Baseline Scenarios using different deterministic models

The CASCADE MINTS baseline does not incorporate any specific measures to promote hydrogen as an alternative for the energy system: market forces and technological development alone are assumed to drive the penetration of hydrogen in the transport sector and in the decentralised electricity and heat production. In this sense, the main aim of the baseline scenario is to examine the limitations in the evolution of the hydrogen economy, when this evolution is supposed to be based on the continuation of the policies and measures of the past.

Model generated baseline scenarios aim to establish a benchmark against which the impact of hydrogen promoting policies can be evaluated. The latter is discussed in the sections dealing with the technology stories and R&D scenarios below (see sections D.3 and D.4). This is an essential task as the extensive modelling activity undertaken within Part 1 of CASCADE MINTS, altering in some cases drastically the coverage of the models in terms of sectors and technologies has implied a substantial expansion of their output, which has to be monitored and validated by all modelling teams participating in the project. Essentially, use of the models producing the baseline is complementary. PRIMES and MARKAL concentrate on Europe. The former uses a behavioural logic while the latter a normative one assuming perfect foresight. All the other models are regionalised world models but differ considerably in terms of model logic and emphasis. All models cover the period to 2050, which according to CASCADE MINTS is the earliest date at which hydrogen could make an impact. The horizon of MESSAGE extends to 2100 and the model is used to provide indications for longer term prospects albeit in a perfect foresight environment.

The analysis in this section concentrates on the prospects of hydrogen penetration in the energy system. Developments in the rest of the energy system are only discussed when their impact influences the evolution of hydrogen supply and demand.

D.2.1.1 Hydrogen penetration in the energy system

Hydrogen in the road transport sector

The transport sector displays the highest possibilities for hydrogen penetration across most baseline projections beyond 2030. Prior to that year, virtually no hydrogen for any use is registered in any of the models. This reflects the large cost disadvantage of hydrogen vehicles relative to conventional cars. Table D-2 presents an overview of the cost[1] per kilometre of the passenger car technologies in Europe. Diesel engine cars are currently the most cost effective option especially when long annual distance travelled is considered (in the table the benchmark is 15000 km per year). This cost advantage explains to a large extent the gradual "dieselisation" of the European vehicle stock that has occurred in the last twenty years. This technological option retains the overall advantage until 2035 even though oil prices rise and the taxation on diesel is harmonised with gasoline. However in the course of the projection this advantage is steadily eroded vis-à-vis just about all other automotive options. Hybrid cars with onboard generation have been introduced in the market during the last seven years and sales have picked up recently. According to the calculations in the table, the cost of this technology at the moment stands at 8.3% above the cost of gasoline Otto powered vehicles. This differential is projected to be reduced steadily and be eliminated towards the late 2030's. On the other hand, plug-in hybrids (currently a less mature option) are around 27% more costly than gasoline cars. Improvements in battery costs after 2020 mean that this differential would be constantly eroded despite increasing electricity prices due to higher carbon values. This option, however, together with the pure electric car option is not expected to become fully competitive even at the 2050 horizon.

[1] The cost includes annualised acquisition costs, fixed operating and maintenance costs and fuel cost (including taxes)

Table D-2: Vehicle kilometre cost in cents €05/km in the baseline scenario

	2005	2010	2020	2030	2040	2050
Gasoline ICE	38.5	41.2	41.2	41.2	42.1	43.0
Diesel ICE	37.0	38.6	39.7	40.1	41.1	42.2
Hybrid	41.7	43.3	42.4	41.9	42.1	42.4
Plug-in hybrid	49.4	51.7	49.5	47.0	46.1	45.3
Electric car	56.5	60.2	56.3	50.9	48.6	46.4
H2 ICE	45.7	45.2	42.8	41.1	41.0	42.5
Fuel cells	2392.9	717.8	76.4	48.5	44.6	42.1
Fuel cells on board reformer	2884.6	948.4	117.1	68.1	54.9	47.4

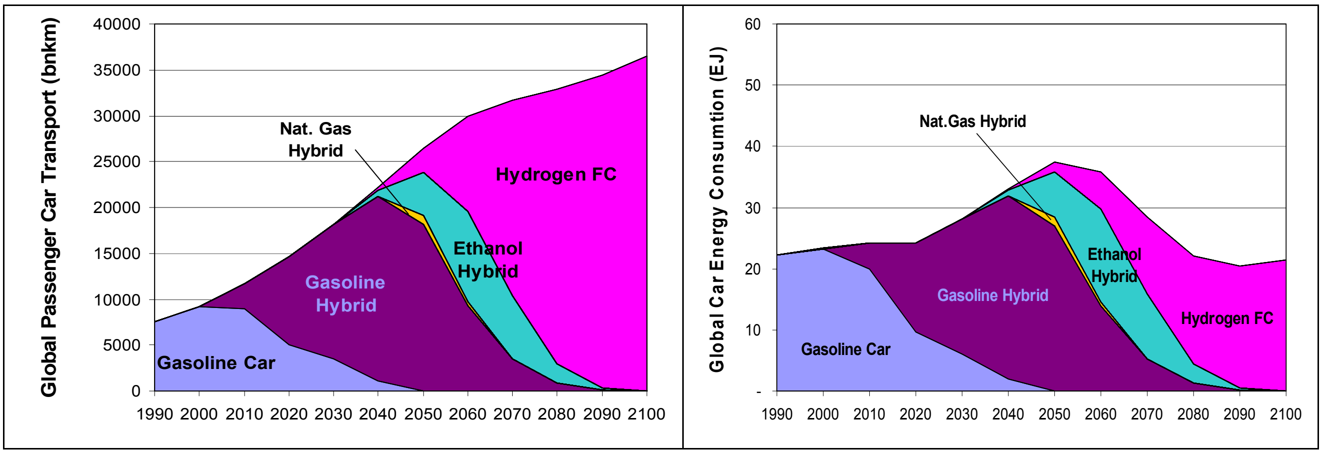
Source: PRIMES

Hydrogen powered internal combustion engines can in theory be used even today at a cost no more than 19% higher than conventional gasoline vehicles, despite the additional onboard storage cost (but assuming that hydrogen is not taxed). Naturally the lack of hydrogen production and distribution infrastructure impedes their introduction in the market. This technology is projected to increase its attractiveness and attain gasoline ICE costs by 2030. According to PRIMES-H2 baseline assumptions the large scale introduction of hydrogen in the automotive sector would trigger a gradual increase in taxation for this vector leading to an increase in overall costs for this option after 2035. Fuel cells, which provide the biggest opportunities for transforming the passenger car stock, are currently prohibitely expensive and unlikely to become other than a niche option before 2025.

Towards the end of the projection period and assuming the development of a hydrogen production and distribution infrastructure, fuel cells become genuine competitors of conventional vehicles. This holds despite the assumed increase in hydrogen taxation, because of the very high efficiency of fuel cell powered engines. Assuming the existence of a hydrogen distribution infrastructure, fuel cell vehicles with onboard reformers are not attractive even as a transitional option.

The longer term prospects of hydrogen in transport - as quantified with the MESSAGE model – indicate that hydrogen fuel cell cars, which make their market entry shortly before 2050, dominate the market with a larger to 90% share in global passenger cat transport from 2080. Ethanol hybrid cars and natural gas hybrid cars also gain a small market share between 2040 and 2080. Figure D-6 on the left shows that passenger transport demand increases by a factor of 4.9 from 7,500 to 36,500 billion kilometres over the century. On the other hand, energy consumption trends do not reproduce this growth: despite growing demand for passenger car transport, the efficiencies of hybrid and fuel cell cars lead to a reduction in energy consumption in the passenger car sector from 22.2 EJ in 1990 to 21.4 EJ 2100.

Figure D-6: Global Passenger Car transport in the MESSAGE reference case



Source: MESSAGE

Four principle stages can be identified in the evolution of the shares of the different vehicle options in total vehicle stock at both the World and European levels, as simulated by MERGE-ETL, MESSAGE and PRIMES. The first corresponds to the period to 2020, where all erosion to the dominance of conventional vehicles is only challenged by the penetration of hybrids. The second refers to the 2020 to 2040 period, which is characterised by transition with many options essentially competing resulting in a relative erosion of conventional vehicle dominance. Hydrogen is first introduced in ICE vehicles, fuel cells make their appearance, while hybrids start saturating. The period 2040 to 2050 sees a faster introduction of fuel cells accompanied by tapering-off in the stock of H2 ICE vehicles, particularly evident in Europe. The fourth phase covers the second half of the century where hydrogen fuel cell cars start dominating the market reaching more than 90% share in 2080 and 100% by the end of the century.

Hydrogen for heat and power production

According to the PRIMES-H2 reference, hydrogen penetrates the European decentralised heat and power production in the form of fuel cell CHP systems. These are characterised by very high efficiencies but their relative attractiveness depends on both stack/system costs (which according to the perspective analysis are expected to be considerably higher than for mobile applications) and the cost of obtaining heat and especially power from alternative sources.

Stationary fuel cells become cost effective after 2040. This is particularly evident in the residential/commercial sector, where small scale stationary fuel cell technologies exhibit significant potential for cost improvements. Residential/commercial applications are favoured both by the significant potential for cost improvements for smaller fuel cell systems but also by the very high retail prices of fossil fuels rendering the value of the heat (a negative cost in CHP comparisons) greater. Turnover of heat and steam raising equipment stock is slow among other things because of stagnant industrial demand for process heat. This improvement in the performance in the final years of the projection together with the expansion of urban distribution networks result in a situation of higher penetration potential. Even so, the lags involved mean that by 2050 stationary applications make only a minor contribution in the respective sectors.

This low contribution notwithstanding, such applications play a significant role in terms of total hydrogen demanded. According to PRIMES, stationary fuel cells account for 40% of the European hydrogen market in 2050. The main part of this demand occurs in small scale stationary applications in the residential/commercial sector with important implications for infrastructure needs to distribute hydrogen in towns and cities.

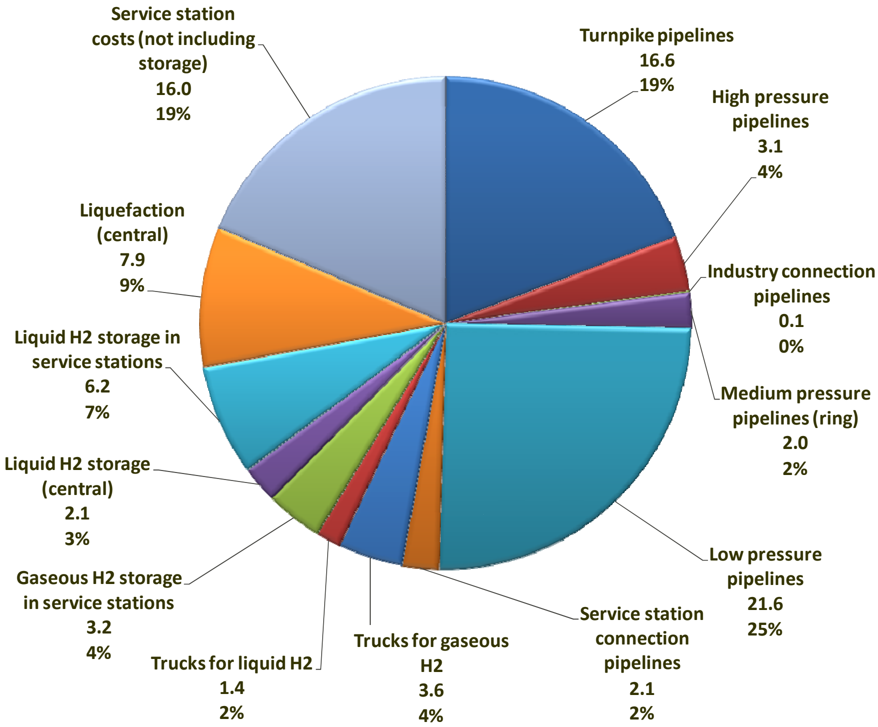
D.2.1.2 Hydrogen supply: infrastructure and production

Infrastructure development

In most model baselines the hydrogen transportation infrastructure is dominated by pipelines. This is due to the cost-effectiveness of pipeline options compared to other distribution forms as long as demand is sufficient to justify their construction. According to PRIMES-H2 Hydrogen demand and distribution networks in Europe emerge initially in areas of high population and energy demand density (big conurbations) and gradually spread into areas of lesser intensity. This pattern is consistent with cost effective expansion of infrastructure and can also be justified by the greater environmental pressure characterising dense population areas that could favour the early introduction of hydrogen as an energy vector even before it has become competitive with more conventional alternatives.

Connections of turnpike pipelines to industrial uses do not show rapid expansion beyond 2040 because of the sluggish demand growth of large scale stationary fuel cells. On the other hand, this period experiences very rapid expansion of medium pressure pipelines (reflecting the increasing number of cities supplied with hydrogen) and especially low pressure pipelines supplying households in line with the increased take-up of small scale stationary fuel cells for residential/commercial applications. The service station connection pipelines see a rapid increase in the earlier periods with the introduction of H2 ICE vehicles. Beyond 2035 they expand more slowly than the overall pipeline system because of increases in utilisation rates following the spread of hydrogen for road transport as well as because of the introduction of fuel cell vehicles that require almost 40% of the hydrogen consumed by the H2 ICE vehicle variety. The expansion of the pipeline system is supplemented by an increase in the use of trucks to reach remoter rural areas or other areas that are not connected to the grid.

Figure D-7: Required infrastructure for hydrogen storage and distribution in EU-27 in 2050 (billion €05, and shares in total infrastructure expenditures)



Source: PRIMES

The pipeline network expansion as described above is projected to cover around 12.5% of the geographical area of EU-27 and reach approximately 22% of consumers in 2050. This broadly implies that given baseline assumptions on key drivers in 2050 the European energy system will still be at relatively early stages of transition to a hydrogen economy.

Pipelines are not the only type of infrastructure required to meet the demand as it emerges in the PRIMES baseline. Apart from pipelines in order to meet the demand as it emerges in the PRIMES baseline the construction of liquid storage facilities, liquefaction units, as well as hydrogen carrying trucks and specialised service stations is required. Figure D-7 presents the baseline cumulative infrastructure investments to 2050 by infrastructure type.

According to the projection total cumulative infrastructure investments will amount to 86 billion €05. This figure may seem somewhat low, especially compared to the cumulative sales of other hydrogen related equipment (e.g. fuel cell system and hydrogen production plants). This is directly linked to the pattern of gradual geographical expansion of the system that characterises the baseline. As mentioned earlier this pattern is economical in terms of infrastructure. Pipelines represent the bulk of this infrastructure investment (around 52%). Storage accounts for 14% of the investments primarily for liquid facilities of different scales (on-board is not included). Six percent of the investment goes on hydrogen carrying trucks, the main part of which takes the form of gaseous H2 transportation. Liquefaction accounts for 9% while specialised equipment (compressors, dispensers, pumps) for service stations take-up around 11%.

Hydrogen production

Total hydrogen production can be viewed as a crude measure for the transformation of the energy system towards a hydrogen economy (it is crude because it gives no indication of the part of different types of energy requirement that is met by this new energy vector). Global models participating in the CASCADE MINTS project suggest hydrogen production requirements for the world ranging between 290Mtoe (MESSAGE) – to 330Mtoe (POLES and MERGE-ETL) in 2050. The PRIMES and MARKAL baseline scenarios imply a final demand for hydrogen equivalent to 49 and 43 Mtoe respectively, whereas European hydrogen production as simulated by POLES reaches 65Mtoe in 2050.

The high carbon values in the last two decades of the projection (90€05 per tonne of CO2 in 2050) mean that hydrogen demand appears at a time when fossil options without CCS are uncompetitive. They make very minor contributions in hydrogen production (mostly gas steam reforming due to the earlier adoption of this technology as a transition production mode). Solar high temperature suffers from the high capital costs projected. Electrolysis from the grid is disadvantaged by the high electricity prices whereas dedicated wind based electrolysis is prohibitively expensive due to its capital intensiveness and low utilisation rates. Gas steam reforming and oil partial oxidation with CCS are disadvantaged by high feedstock costs. All the other options in Table D-3 below effectively constitute viable alternatives for producing hydrogen in the context of the baseline.

Table D-3: Share in hydrogen production and production costs in EU-27 in 2050

	Share in production %	Production cost in €05/toe
No CCS	**25.0**	
Fossil fuels	***4.0***	
Solar methane reforming	*0.2*	*1732*
Gas steam reforming	*2.5*	*1541*
Coal gasification	*0.2*	*1135*
Oil partial oxidation	*1.1*	*1519*
Non-fossil energy sources	***21.0***	
Solar high temperature thermochemical cycle	*0.1*	*1703*
Electrolysis from grid	*0.8*	*1575*
Dedicated wind turbine for electolysis	*0.4*	*1663*
Dedicated nuclear power plant for electrolysis	*6.8*	*955*
Nuclear high temperature thermochemical cycle	*9.1*	*692*
Biomass pyrolysis	*2.1*	*936*
Biomass gasification with steam reforming	*1.7*	*774*
CCS	**75.0**	
Gas steam reforming	*0.4*	*1708*
Coal gasification	*59.6*	*739*
Oil partial oxidation	*0.3*	*1639*
Biomass gasification with steam reforming	*14.6*	*650*

Source: PRIMES

The cheapest option for producing hydrogen is through biomass gasification with steam reforming. However, this technology is characterised by a relatively low introduction and therefore a degree of immaturity even by the end of the projection period. Nuclear high temperature thermochemical cycle constitutes a highly speculative option with a particularly uncertain timing. It is highly unlikely to be sufficiently available to make a major contribution before 2050.

All models arrive at a broad consensus with regard to the main options for satisfying this demand in the outlook. Biomass gasification appears to be the leading production option in the World at large, as indicated by all world model projections. In the presence of intensive climate policies around the world assumed to apply in the last two decades of the projection, coal based options with CO2 capture and sequestration also gain a significant share in hydrogen supply. This is particularly marked in Europe where according to PRIMES-H2 coal gasification options with CCS account for around 60% of hydrogen production, as they offer at the same time relatively low cost and intermediate maturity. At the world level 12% of electricity generation and 23% of hydrogen production comes from coal plants equipped with CCS according to the POLES outlook. Nuclear power is projected to gain a 16,5 percent share in European and 4% share in global hydrogen production according to the PRIMES and POLES baselines respectively. Renewables other than biomass make insignificant contributions in Europe but receive a considerable share in world hydrogen production, with solar and wind power accounting both for 13.2% of global hydrogen production in 2050 (4.2% for the former and 8.9% for the latter). Gas steam reforming with and without CCS - despite being disadvantaged by high feedstock costs - makes a 3% to 5% contribution in European and World hydrogen production respectively, mostly driven by the earlier adoption of this technology as a transition production mode. Other options constituting viable alternatives for producing hydrogen in a world context are oil partial oxidation (5.6%) and electrolysis from the grid (1.8%) according to the POLES baseline.

D.2.2 Stochastic Evaluation of Hydrogen Economy Prospects using PROMETHEUS

The discussion in D.2.1 concerns the analysis of hydrogen prospects in a deterministic context. Using deterministic models uncertainties can be explored in the form of contrasting scenarios. Such exploration, however, is not systematic in that it makes no attempt at evaluating the likelihood of different occurrences: it explores possibilities but not probabilities.

PROMETHEUS has been applied in the context of CASCADE MINTS to provide a systematic evaluation of the risks (and opportunities) facing the evolution of the hydrogen economy in an attempt to make an assessment as to how likely different paths towards it are. In this way risks that are specific to hydrogen technology evolution are confronted with an exhaustive range of risks associated with other key elements of the energy system including uncertainties due to lack of precise knowledge of the system itself.

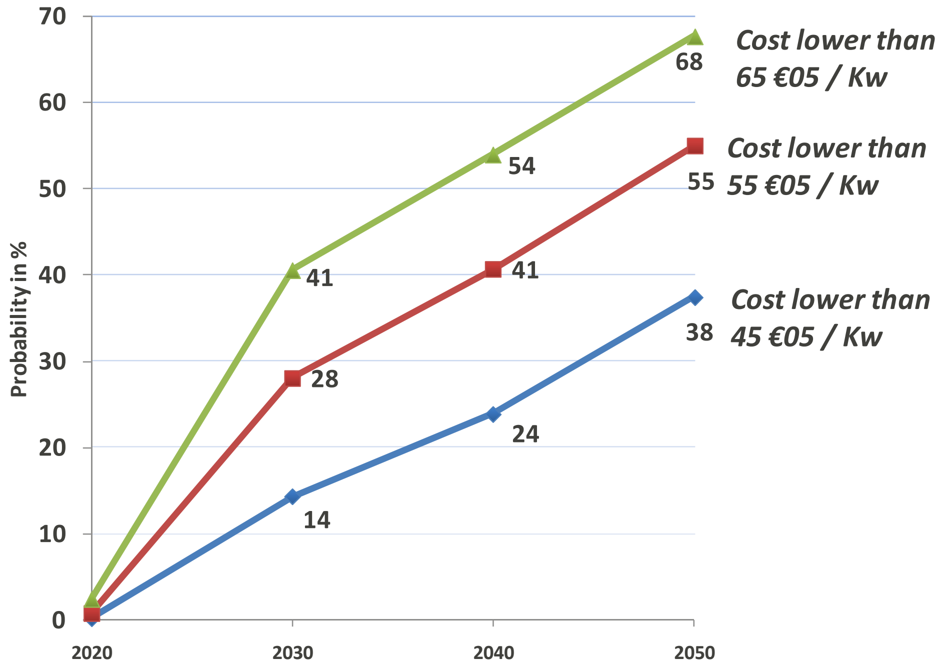
The basic output of PROMETHEUS is a data set of Monte Carlo simulations containing values for all the variables in the model. This constitutes an extensive set of information containing the equivalent of the distillation of a very large number of alternative scenarios involving alternative assumptions about activity levels and structures, resource availabilities, prices, policy stances on various issues (notably the climate change issue) and crucially technological developments while considering at the same time the fact of the imperfection of the modelling itself (omitted variables that can generate considerable "noise", measurement problems etc.). It therefore provides a large set of probable visions of the hydrogen economy both in terms of the extent to which it may transform the energy system but also alternative paths for an eventual transition. In addition it enables the probabilistic evaluation of these alternatives thus adding an extra dimension to scenario analysis.

Technology improvements

The PROMETHEUS stochastic model is equipped with technology dynamics mechanisms in the form of two factor learning curves making improvement a function of experience and research. The parameters of these equations in PROMETHEUS are jointly distributed random variables (they co-vary). Technical progress is also subject to independent random variation. Apart from these random elements of the technology dynamics mechanisms the PROMETHEUS outlook also incorporates uncertainties regarding the size and direction of R&D, which are endogenous to the model. By analysing historical observations on R&D on energy technologies relations have been established, linking R&D to economic factors and particularly measures of energy cost. These relations are also reflected in the outlook. Considerable R&D effort has been devoted to the development of fuel cells in the period between 1985 and 1995. In recent years there seems to be a revival in interest from the private sector. According to the PROMETHEUS outlook there is a 76% probability that outlays directed to fuel cells in the period 2005-2020 will exceed those of the period 1980-2000.

According to the PROMETHEUS projections the crucial technologies for the introduction of hydrogen are those related to mobile applications for the road transport sector. PROMETHEUS identifies two distinct technology clusters for mobile applications (i) the fuel cell stack and (ii) other supplementary systems. Both are subject to considerable improvement, which will indeed be necessary if fuel cell vehicles are to become competitive at all. According to the outlook success in each one of them is not completely statistically dependent on success of the other.

Figure D-8: Probability that the mobile fuel cell stack and system costs will be lower than certain levels



PROMETHEUS has provided an indication concerning the time profile of probabilities of reaching different success benchmarks for mobile fuel cell costs. Three benchmarks have been chosen. The first, set at 65 €05/Kw, broadly corresponds to the stage at which fuel cells start being considered as an option beyond strict niche markets. The second benchmark set at 55 €05/Kw corresponds to a stage where take-off becomes a possibility, especially for large annual mileages, Finally, the third benchmark of 45€05/Kw broadly corresponds to a cost below which fuel cells could easily make major inroads into the road transport market.

The PROMETHEUS outlook indicates that by 2020 technical progress in fuel cells is unlikely to occur to a sufficient degree to allow introduction of fuel cells in anything but niche markets. Even benchmark 1 can be reached with only a 2.5% probability. By 2030 the likelihood of different success levels improves markedly. This is particularly so for the modest breakthrough implied by benchmark 1, which registers more than 40% probability of being achieved. In 2040 there is a more than even probability of technological success of some sort with more than 40% chance that it will be substantial (benchmark 2). By 2050 there is a two-in-three probability that mobile fuel cells will be a valid choice in road transport and a more than even chance that they will be genuinely competitive. On the other hand the probability of a big breakthrough will still be less than 40%. Even at this late stage there is nearly 20% probability of what can be construed to represent a complete technical failure (costs above 80€05/Kw).

Concerning the technical-economic evolution of the hydrogen related technologies that have figured prominently in the scenario results, PROMETHEUS results suggest that in general the technological attributes that experience the most pronounced improvements are also those that display the biggest variability. These technologies are often the most prospective in character with non negligible probabilities for relative technical failure. Mobile fuel cells are subject to the biggest uncertainty. Stationary fuel cell costs (both stack and system) also have large variances. On board hydrogen storage cost variability is likely to affect the variability of cost performance of hydrogen internal combustion engine cars as storage represents the main additional cost for such vehicles. The variability in efficiencies for mobile hydrogen applications is relatively small and for stationary applications almost insignificant.

Looking at hydrogen production technologies, the nuclear high temperature thermochemical cycle displays the highest variability. This technology is based on the yet unproven new nuclear designs that are not expected to appear before 2020 and their use for hydrogen production is subject to additional variability. Most of this variability is founded on lack of knowledge today rather than uncertainties surrounding R&D or other economic factors. Biomass gasification with CCS also displays uncertainty especially with regard to capital costs (in 2050 the standard deviation represents almost 10% of capital cost). Coal gasification and particularly gas steam reforming are subject to much smaller uncertainties but at the same time tend to improve less.

Penetration of hydrogen technologies

Road Transport

Table D-4: Cost performance of vehicle types in 2050

	% Probability that a given option has lowest cost per vehicle km for 15000km/yr						% Probability that a given option has lowest cost per vehicle km for 25000km/yr					
Car type	Europe		Rest of OECD		Rest of the World		Europe		Rest of OECD		Rest of the World	
	2030	2050	2030	2050	2030	2050	2030	2050	2030	2050	2030	2050
Conventional	97,4	80,6	100,0	79,4	100,0	78,4	92,7	72,9	100,0	78,2	100,0	71,2
Hybrids/Electric	0,0	4,2	0,0	0,9	0,0	0,7	0,0	5,3	0,0	0,0	0,0	0,0
H2 ICE	2,2	2,8	0,0	10,4	0,0	5,8	3,4	1,9	0,0	6,1	0,0	2,9
Fuel cells	0,4	12,4	0,0	9,4	0,0	15,1	3,9	19,9	0,0	15,7	0,0	25,9

Table D-4 above gives a stochastic assessment of the cost performance of the different vehicle types in 2050. Fuel cell vehicles are characterised by high acquisition costs and low running costs. Therefore it is reasonable to expect that their performance improves as annual vehicle use increases. In 2030 conventional cars almost certainly remain the most cost-effective option outside Europe, whereas there is a small probability that in Europe hydrogen powered cars (ICE in the 15000km per year case and both ICE and fuel cells in the 25000km case) dominate in terms of cost effectiveness. The reason for this is the high taxation of transport fuels in Europe, which, given the low penetration of hydrogen that is most probably attained at this date, provide an opportunity for a cost advantage. By 2050 there are distinct probabilities for cost effectiveness of fuel cell vehicles throughout the world and particularly in the developing countries where hydrogen costs are likely to be lower. Hydrogen ICE chances for competiveness are better if a low mileage is considered. With the exception of Europe (where there is around 5% probability), there is little chance that hybrid or fuel electric cars will dominate. However, even by that date according to PROMETHEUS there is more than 70% probability that conventional vehicles, especially diesel powered ones, will remain the most cost-effective option despite the big probabilities for high petroleum prices.

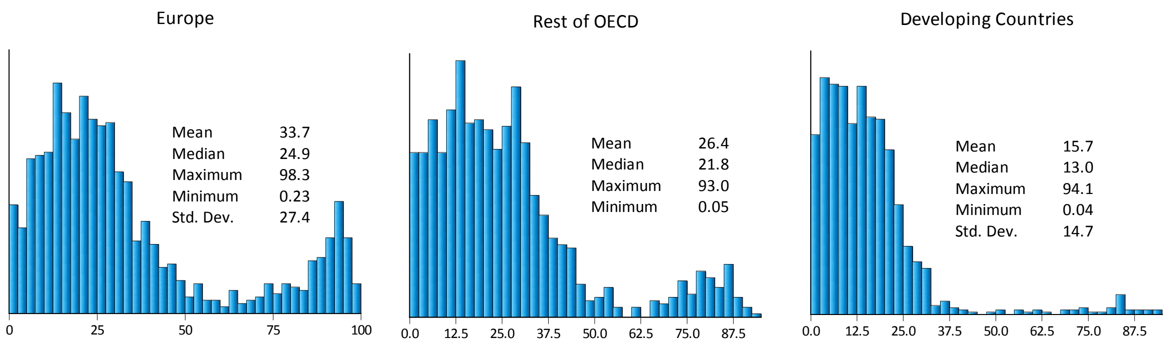
Table D-5: Summary statistics of the share of fuel cell vehicles in vehicle stock in 2050 (%)

Probabilities to exceed certain shares % share of fuel cells in vehicle stock				
Probability	Europe	Rest of OECD	Developing Countries	World
95%	2	1	1	1
80%	6	4	3	4
50%	14	11	8	10
20%	24	20	15	17
5%	40	30	21	24

Table D-5 gives an indication of the likelihood of penetration of mobile fuel cells in the vehicle stock of different regions in 2050. The median value for the world is around 10%. In Europe this figure is higher (14%) because of the higher likelihood of heavy taxation for conventional vehicles and the geographical compactness of demand that is likely to lead to an earlier development of infrastructure. There is a 20% probability that less than one in twenty five vehicles in circulation will be fuel cell powered in 2050. In Europe there is a 5% probability that their share could exceed 40% (a value implying a radical transformation of the vehicle stock).

In 2020, the probability that fuel cells will have moved beyond the demonstration stage is virtually nil. In 2030, there is only about 15% probability that one in twenty new vehicles will be fuel cell powered. The probability for low shares (between 5 and 10%) increases sharply between 2030 and 2040 but it is only in the last decade of the outlook that any noticeable probabilities for fuel cell domination occur (4% probability that the share of fuel cell vehicles will exceed 50%). The probability distributions of shares of fuel cells in new registrations present a trough around or just above 50% with a resurgence of probability densities for higher shares (see Figure D-9). This phenomenon is primarily due to the social network effects: in some cases technological success is combined with accelerated social acceptance thus snowballing into very high penetration rates. This upper hump is particularly noticeable in Europe where it accounts for around 20% i.e. there is one in five chance for radical and seemingly irreversible transformation of road transport towards hydrogen. By contrast the probability density for penetration rates of between 0 and 20% is almost uniform suggesting normal simultaneous competition between different road transport options.

Figure D-9: Share of fuel cell vehicles in new registrations in 2050 (%)



Stationary applications

PROMETHEUS results indicate that the introduction of stationary applications will lag behind mobile uses: the probability that fuel cells will contribute more than 5% of energy requirements in the industrial and residential/commercial sectors is 7% and 8% respectively. This result is partly due to the fact that even in cases where the technical-economic performance of the technology improves enough to make it cost effective *vis-à-vis* its competitors, this improvement in general takes place in the final years of the horizon and the slower turnover of equipment in these markets means that there is not sufficient time for radical transformation. In Europe the probability of the cost of energy from hydrogen based CHP being lower than alternatives for producing heat or purchasing power is much greater than it is in developing countries. This is primarily due to the high likelihood of a strong climate policy in Europe.

The use of fuel cell installations with reformers offers the opportunity for an early introduction of fuel cell technologies because they do not depend on the existence of the hydrogen production and distribution infrastructure. The likelihood of fuel cells with reformer exceeding installations without is high in the early stages (2020-2030) in Europe but declines rapidly thereafter especially in view of the development of the distribution infrastructure. On the other hand, in developing regions natural gas prices are sufficiently low to ensure that reformers remain a valid option by 2040 and beyond.

Hydrogen balance (supply and costs)

PROMETHEUS results suggest mean supply of hydrogen of just under 600Mtoe for the world and just under 90Mtoe for Europe in 2050. On average the road transport sector accounts for two thirds of demand worldwide and 40% in Europe. Despite the relatively low likelihood of fuel cells making large contributions to energy requirements of the residential/commercial sector, in terms of hydrogen requirements such uses can be important because of the size of overall requirements in this sector. It is noticeable that there is a 5% probability that the residential/commercial sector in Europe will account for more than 64% of hydrogen needs in 2050. Centralised hydrogen production will on average cover more than 85% of worldwide and more than 90% of European hydrogen requirements. The bulk of decentralised production according to PROMETHEUS results takes the form of natural gas steam reforming. This technology appears to be particularly reserved for decentralised applications and is unlikely to contribute more than 10% of centrally distributed hydrogen.

Table D-6: Summary statistics of the hydrogen balance in 2050

Hydrogen balance in 2050

	World					Europe				
	Mean	Median	Std. Dev.	Lower 5%	Upper 5%	Mean	Median	Std. Dev.	Lower 5%	Upper 5%
Hydrogen consumption (Mtoe)	**584**	**480**	**380**	**276**	**1127**	**87**	**70**	**53**	**28**	**197**
Industry	82	57	85	15	221	18	13	17	2	56
Residential/Commercial	150	94	198	13	432	39	29	30	4	92
Transport	352	329	130	214	567	30	27	13	15	55
Mobile fuel cells	136	121	97	15	298	14	13	10	2	33
Hydrogen ICE cars	216	202	75	141	330	16	14	10	4	33
Hydrogen production (Mtoe)	**584**	**480**	**380**	**276**	**1127**	**87**	**70**	**53**	**28**	**197**
On site steam reforming	**83**	**63**	**69**	**15**	**213**	**7**	**6**	**5**	**2**	**17**
Centralised production	**501**	**405**	**354**	**246**	**995**	**80**	**61**	**51**	**25**	**188**
Gas steam reforming	23	22	11	7	43	2	2	1	0	4
with CCS	*6*	*3*	*6*	*1*	*17*	*0*	*0*	*0*	*0*	*1*
Solar methane reforming	1	1	1	0	3	0	0	0	0	0
Coal gasification	292	256	170	146	524	46	36	29	15	106
with CCS	*162*	*119*	*182*	*23*	*437*	*43*	*33*	*30*	*10*	*105*
Oil partial oxidation	14	13	8	5	28	2	2	1	0	4
with CCS	*6*	*4*	*6*	*1*	*16*	*1*	*1*	*1*	*0*	*3*
Biomass pyrolysis	15	13	9	6	29	1	1	1	0	3
Biomass gasification with steam reforming	84	33	140	9	335	16	8	18	1	57
with CCS	*73*	*19*	*142*	*1*	*326*	*14*	*6*	*19*	*0*	*56*
Nuclear high temperature therm. Cycle	42	20	84	2	148	7	3	10	0	28
Dedicated nuclear plant for electrolysis	17	11	23	3	48	4	3	5	1	14
Solar high temperature therm. Cycle	1	0	1	0	2	0	0	0	0	1
Electrolysis from grid	9	7	10	2	25	1	0	1	0	3
Dedicated wind turbine for electrolysis	2	1	3	0	6	0	0	1	0	2
Shares in hydrogen consumption (%)										
Industry	**12.8**	**12.1**	**5.8**	**4.6**	**23.1**	**19.2**	**18.5**	**8.9**	**5.7**	**34.3**
Residential/Commercial	**20.6**	**19.7**	**11.9**	**4.2**	**41.4**	**39.7**	**40.4**	**15.5**	**14.3**	**63.8**
Transport	**66.6**	**67.3**	**14.6**	**41.6**	**89.0**	**41.0**	**38.7**	**16.6**	**19.5**	**71.7**
Mobile fuel cells	23.4	23.4	11.9	3.9	42.7	18.4	16.6	10.8	3.2	39.6
Hydrogen ICE cars	43.3	41.5	16.3	19.9	73.8	22.7	18.1	16.2	4.6	56.3
Shares in hydrogen production (%)										
Fossil fuels without CCS	**47.2**	**47.7**	**23.1**	**8.6**	**80.6**	**19.7**	**15.7**	**15.2**	**2.8**	**51.0**
Gas steam reforming	18.1	17.0	9.2	5.1	35.1	12.1	10.8	7.6	2.5	26.0
Onsite	*14.3*	*12.5*	*8.4*	*3.7*	*29.9*	*9.6*	*8.4*	*6.3*	*2.0*	*22.0*
Centralised	*3.8*	*3.3*	*2.7*	*0.4*	*8.8*	*2.4*	*2.1*	*1.7*	*0.1*	*5.8*
Solar methane reforming	0.2	0.2	0.1	0.1	0.5	0.2	0.2	0.1	0.1	0.4
Coal gasification	27.0	24.8	19.6	0.5	61.0	6.4	1.2	10.0	0.0	28.4
Oil partial oxidation	1.9	1.6	1.5	0.1	4.9	1.0	0.7	1.0	0.0	3.1
Non Fossil fuels	**15.0**	**13.8**	**6.8**	**6.4**	**28.4**	**16.7**	**15.0**	**8.4**	**6.4**	**33.1**
Biomass pyrolysis	2.9	2.6	1.5	0.9	5.9	2.0	1.5	1.6	0.3	5.3
Biomass gasification with steam reforming	2.2	1.9	1.4	0.4	4.8	2.5	1.4	2.8	0.3	8.1
Nuclear high temperature therm. Cycle	5.4	4.1	4.8	0.7	14.0	6.3	4.4	5.8	0.8	17.4
Dedicated nuclear plant for electrolysis	2.6	2.3	1.5	0.8	5.5	4.5	3.9	2.6	1.5	9.6
Solar high temperature therm. Cycle	0.1	0.1	0.1	0.0	0.3	0.2	0.1	0.2	0.0	0.5
Electrolysis from grid	1.5	1.4	0.8	0.5	3.0	0.8	0.7	0.5	0.2	1.7
Dedicated wind turbine for electrolysis	0.3	0.2	0.2	0.1	0.7	0.4	0.4	0.3	0.1	1.1
Facilities with CCS	**37.8**	**36.4**	**23.1**	**7.1**	**76.2**	**63.6**	**66.6**	**16.2**	**33.4**	**85.6**
Gas steam reforming	1.0	0.6	1.0	0.2	3.1	0.4	0.4	0.2	0.1	0.8
Coal gasification	26.1	25.7	15.3	6.0	52.9	48.0	48.2	13.2	24.7	69.8
Oil partial oxidation	1.0	0.8	0.8	0.2	2.6	1.4	1.2	0.9	0.4	3.4
Biomass gasification with steam reforming	9.7	3.9	13.1	0.1	38.7	13.7	9.2	14.5	0.3	43.2
Shares in hydrogen production by energy form (%)										
Coal	53.0	52.9	12.4	32.4	73.1	54.4	55.1	12.5	33.4	73.8
Gas	19.3	18.3	9.2	6.3	36.2	12.7	11.3	7.8	2.8	26.9
Oil	2.9	2.7	1.7	0.7	6.0	2.5	2.2	1.4	0.6	5.1
Biomass	14.8	10.3	12.1	4.3	41.9	18.2	14.5	13.5	3.4	45.6
Nuclear fuel *	8.0	6.6	5.9	1.6	18.8	10.8	8.5	7.8	2.5	26.3
Electricity (grid)	1.5	1.4	0.8	0.5	3.0	0.8	0.7	0.5	0.2	1.7
Solar	0.1	0.1	0.1	0.0	0.3	0.2	0.1	0.2	0.0	0.5
Wind	0.3	0.2	0.2	0.1	0.7	0.4	0.4	0.3	0.1	1.1

* includes dedicated nuclear power plant for electrolysis and nuclear high temperature thermochemical cycle

Coal gasification is the leading technological option to producing hydrogen in both Europe and the world. There is a 50% probability that hydrogen from coal gasification will be produced in facilities equipped with CCS worldwide. This probability is 95% for Europe reflecting the high chances for a strong climate policy. Biomass gasification with steam reforming also registers a high mean (84Mtoe); combined with CCS it accounts on average for 10% of world hydrogen production in 2050. Another technology of a highly speculative nature that emerges in some PROMETHEUS experiments with moderately large shares is the nuclear high temperature thermochemical cycle. According to PROMETHEUS there is a 10% probability that it makes virtually no contribution (less than 1%) to worldwide supplies. On the other hand, there is a 13% probability that it may contribute more than one tenth. This wide spread is consistent with the technological uncertainties surrounding this option. Renewables other than biomass have a very low likelihood of making more than niche contributions. Wind power and solar high temperature thermochemical cycle are costly, but there are distinct probabilities of sufficient improvement in the longer term for the latter making it potentially attractive beyond the 2050 horizon.

Following is an attempt at a probabilistic assessment of the baseline results of the main models participating in the CASCADE MINTS project with respect to the baseline predictions of total hydrogen production. According to the graphs in Figure D-10, the baselines of the two world models (MESSAGE and POLES) are very close to the mode of the distribution. Likewise the MARKAL baseline is situated near the mode of distribution for Europe, while POLES predicts very close to the median and PRIMES is situated between the two. The mean values as evaluated by PROMETHEUS are considerably higher than the model predictions. This is because they are influenced by the relatively small possibilities of major technico-economic breakthroughs, which the deterministic models naturally do not consider. On the other hand, none of the baseline predictions can be considered as an outlier: this is reassuring in terms of robustness of the results obtained across the project. At the same time it is not really surprising, given the attempt made to homogenise the technological database and assumptions on key drivers.

Figure D-10: Distribution of the centralised hydrogen production in 2050 (Mtoe)

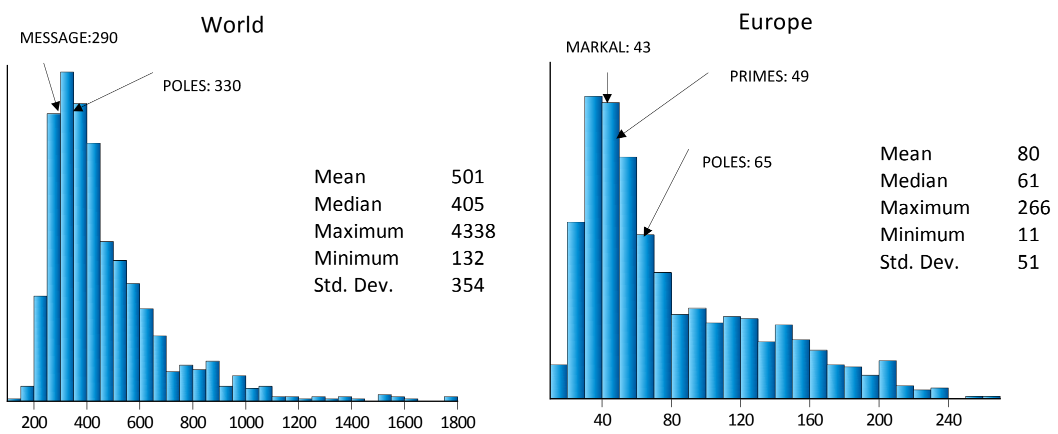


Figure D-11 presents the distribution of average hydrogen production cost in the different regions. A striking feature of these distributions is the similarity in terms of mean and standard deviation, as well as in terms of the general shape even over the less probable values. This is despite the fact that different pathways and intensities of climate policy have been assumed for the different regions.

Figure D-11: Distribution of the hydrogen production cost in the three regions in 2050 (€05/toe)

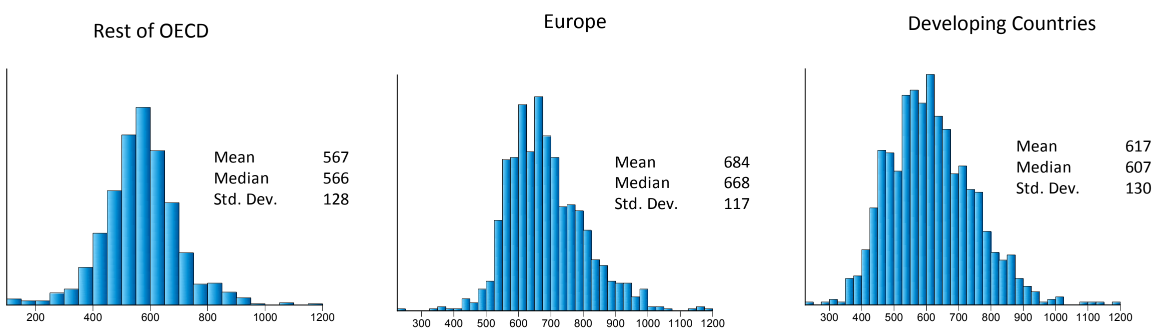
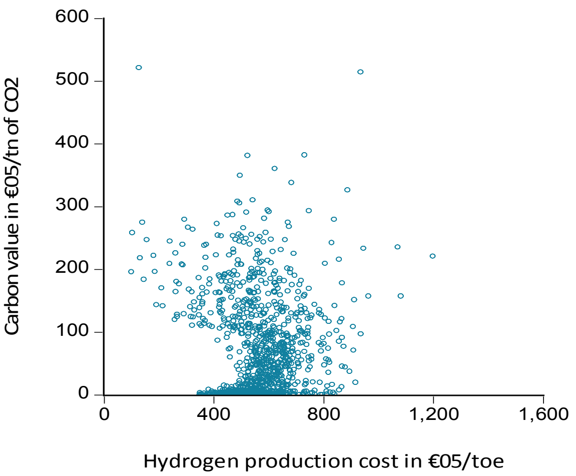


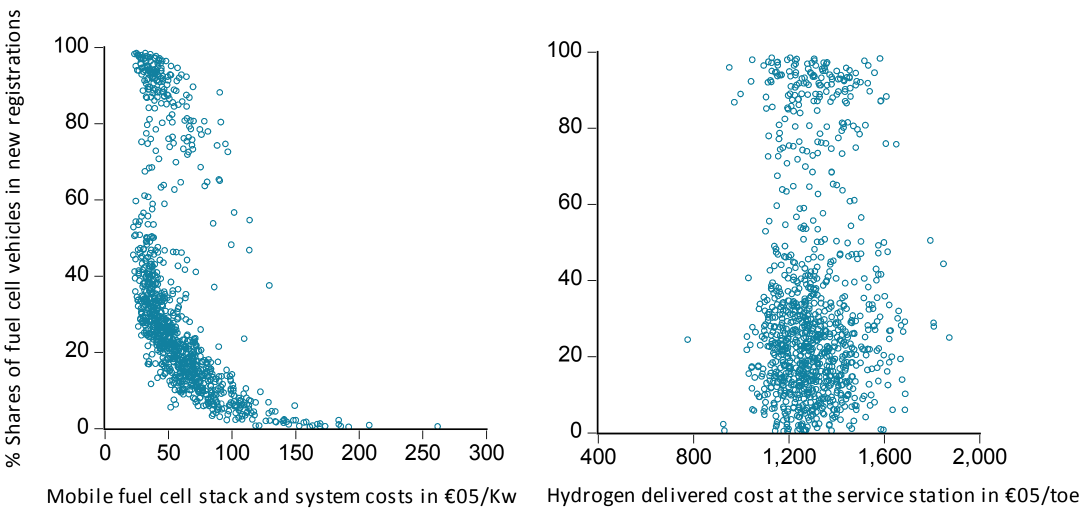
Figure D-12: Relative importance of effective carbon value variability for H2 production cost variability (Rest of OECD, 2050)



A general observation encountered with PROMETHEUS work in particular but also with other models is that the relation between the cost of producing hydrogen and effective carbon values is far from being straightforward. It can be noted that for effective carbon values that are zero or close to zero hydrogen production costs tend to vary independently. For carbon values between 20 and 80 €05/tn of CO_2 the relation seems to be broadly positive but less and less pronounced as the higher end of the range is approached. For values above 80 €05/tn of CO_2 there even appears to be some indication of reversal to a negative relation. This is due initially to decoupling as a result of large scale introduction of hydrogen free production technologies and CCS. In any case the tendencies discussed above are far from being systematic and production costs display a lot of independent variation all along the possibilities space but particularly in the zone around 120 to 150 €05/tn of CO_2.

The first market where hydrogen is likely to be – on a thermal basis – less costly than fossil fuel alternatives is small scale heat and power in industry, where already by the second half of 2020's there is more than one in four probability that hydrogen can be delivered at a lower cost than natural gas. By the early 2030's this probability exceeds 50% and by 2040 it stands at 70%. The cost of hydrogen at the pump has only a 10% probability of being lower than the cost of gasoline (excluding tax) in 2030. Thereafter it increases relatively rapidly reaching 50% by 2040 and 70% by 2050. Due to high transportation and distribution costs the delivered hydrogen cost to the residential/commercial sector is almost completely unlikely to be lower than natural gas in 2030 and there is less than a 15% probability that the situation is reversed by 2040. On the other hand towards the end of the final decade of the outlook the chances become even. The evolution of these probabilities has more to do with the likelihood of high fossil fuel prices in the longer term than the possibilities for cheap hydrogen production and distribution. It should be noted that the cost of delivered hydrogen is far from being an appropriate indication of the cost effectiveness of hydrogen use, which will depend primarily on the improvements on hydrogen end use technologies. This is particularly true for fuel cell vehicles, the penetration of which in the new vehicle market is statistically independent from the cost of delivered hydrogen but depends strongly on stack and system cost improvements (see Figure D-13 below).

Figure D-13: Relative importance of hydrogen production cost variability for hydrogen penetration variability (Europe, 2050)



D.3 Technological Scenario analysis using the different models

D.3.1 Introduction to Technology Stories

The "technology stories" have been constructed primarily by assuming favourable technological developments for hydrogen related technologies, combined with supportive policies to produce a more rapid transformation of the energy system towards a hydrogen economy. The scenario definitions take the form of rapid improvements of the technical and economic characteristics of mobile and stationary Fuel Cells (stacks and systems) and hydrogen production technologies, suggesting early and dramatic developments. The choice of combinations has been guided to a considerable extent by technology perspective analysis and by the insights gained in the process of modelling the hydrogen economy. These very optimistic scenarios have been further examined in the presence of a set of policy measures, such as emission constraints, selective and discriminating taxation or subsidies on infrastructure, in an attempt to examine how such supportive policies may accelerate developments.

In total seven distinct scenarios were examined, as indicated in the following box:

Demand Pull

- 1a) **Breakthrough in Fuel Cells (FC Case):**
  All technical and economic parameters of mobile and stationary fuel cells reach their limits as defined in the technology perspective analysis from 2025 onwards.
- 1b) **Breakthrough in Fuel Cells and Urban Environmental Considerations (FC+TAX case):**
  FC case plus increasing the tax on fossil fuels for road transport by 0.5€00/lt from 2025 onwards.
- 1c) **Breakthrough in FC, Urban Environmental considerations and Strong Climate Policy (FC+TAX+CV case):**
  FC+TAX plus doubling the baseline carbon value from 2010 onwards.

Supply Push

- 2a) **Breakthrough in Hydrogen production (H_2P case):**
  All technical and economic parameters of all hydrogen production technologies reach their limits as defined in the technology perspective analysis from 2025 onwards.
- 2b) **Breakthrough in H_2 production and Subsidy of hydrogen infrastructure (H_2P+INFR case):**
  H_2P case plus free infrastructure for hydrogen distribution and storage
- 2c) **Breakthrough in H_2 production, Subsidy of hydrogen infrastructure and Strong Climate Policy (H_2P+INFR+CV case):**
  H_2P+INFR case plus doubling the baseline climate policy

Combined Case

- 3a) **Breakthrough in Fuel Cells and Hydrogen Production technologies combined with strict climate policy, increased taxation of all non-zero emission vehicles and subsidies in Hydrogen infrastructure. The policy is applied from 2025 onwards.**

D.3.2 Results from deterministic models

It is widely accepted that the road transport sector is the key to the success of a transition to a hydrogen economy and the technology stories scenarios address very specifically this sector. Table D-7 below presents an overview of the penetration of hydrogen in road transport. The table focuses on 2050, as this is the year with the highest hydrogen penetration in all models involved.

According to the FC scenario, stack and system costs will represent one third of the baseline values in 2020 and only one quarter from 2030 to 2050. The electric engine cost is downsized to the tune of around 25%, while electric storage is increased (bigger batteries) to enable smoother operation and longer ranges. Fuel efficiency improves by more than 40%. To the extent that a bigger deployment of hydrogen powered cars may lead to earlier and fuller harmonisation of hydrogen taxation with the taxation of hydro-carbon competitors, few advantages can be expected in terms of fuel cost, despite the gains in efficiency. If taxation follows the path implied above, the effect on the competitiveness of hydrogen ICE would be particularly adverse, since according to the scenario they do not benefit from gains in efficiency. The worldwide application of the technology story results in reduction in oil demand which leads to lower pressure on oil prices that end-up around 35€05/bl lower in 2050 (an average of 92 instead of 126 €05/bl according to PROMETHEUS). These lower prices are reflected in the cost performance of conventional vehicles to the tune of around 0.4 eurocents per vehicle kilometre.

Table D-7: Technology story comparison of different models: Share of Hydrogen Powered vehicles in road transport (2050)

Share of FC and H_2-ICE vehicles in passenger cars stock

	REF	FC	FC+TAX	FC+TAX+CV	H2P	H2P+INFR	H2P+INFR+CV	COMBINED
POLES	18.3	20.2	29.3	30.1	18.3	28.0	28.7	30.1
MESSAGE	9.6	47.6	98.5	99.0	16.0	26.2	41.3	100
MERGE-ETL	17.2	30.5	39.5	42.0	22.4	22.4	22.4	42.0
PRIMES*	18.4	56.8	63.9	65.6	19.3	21.8	23.7	65.9

Share of Fuel Cell vehicles in new car registrations

	REF	FC	FC+TAX	FC+TAX+CV	H2P	H2P+INFR	H2P+INFR+CV	COMBINED
PRIMES*	24.8	70.0	76.9	79.0	25.6	27.1	29.8	79.1
PACE-T-H2	25.6	45.1	77.1	79.1	39.2	41.0	41.0	95

* Europe Only

The net effect of such developments is that fuel cells become highly competitive *vis-à-vis* all other options from around 2025 onwards. They end-up gaining around 70% of EU new registrations in 2050, and 45.1 of world registrations (according to the PACE-T-H2 model) in 2050 (see Table D-7). This technological push effect appears to be the principal determinant in the penetration of hydrogen in road transport. Additionally taxing conventional fuels in most cases adds less than 10% in H2 powered vehicles share, while the effect of doubling the carbon value produces very small increases in the percentages. The supply push scenarios, by comparison, have resulted in small changes with regard to H2 powered vehicles. This is mainly due to the low importance of hydrogen prices on the total cost of running fuel cell driven cars in particular. The effect is somewhat more marked for hydrogen ICE vehicles, which in the demand pull scenarios are adversely affected but gain over baseline values in the case of infrastructure subsidies. The combined case produces a picture very close to the FC+TAX+CV scenario further underlying the small importance of supply measures in accelerating hydrogen developments.

As is the case for road transport, the reduction of fuel cell stacks and systems costs is the key for the successful penetration of hydrogen in electricity and steam production. Stationary fuel cells face wider competition than the mobile fuel cells and lag behind developments in the road transport sector. Scenario results have in general produced increases in the share in electricity production in the technology push cases. On the other hand, the technological developments in hydrogen production do not succeed in producing a high penetration of stationary fuel cells for electricity production. This is attributed to the fact that the majority of the hydrogen production technologies present few technical possibilities for major improvements. However, a subsidy on hydrogen distribution and supply infrastructure has a significant impact on the penetration of stationary applications (unlike the results obtained for road transport). This comes as a result of the fact that the hydrogen distribution and storage costs represent a large fraction in the consumer price for hydrogen. Finally, the introduction of a stronger climate policy favours the penetration of stationary fuel cells to the extent that key competitors such as natural gas fired CHP become more expensive.

In general, the combined case has not produced significant additional penetration of stationary fuel cells compared to the FC+TAX+CV technology story. This suggests that in the absence of policies specifically accelerating capital stock turnover the technological developments, subsidies and taxes are not likely to produce an early transformation.

The implications of the scenarios on key aggregates of the energy balance have also been examined. The dramatic improvement in the cost and performance of fuel cells (scenario FC) produces reductions in final energy consumption, mostly attributable to the introduction of fuel cell vehicles which are four times more energy efficient than conventional equivalents. Additional taxation of petroleum products leads to further reductions in energy consumption. On the other hand, doubling the carbon value has a very small effect: this comes as a result of the general feature of the projections where future demand is dominated by electricity and to a lesser extent transportation; mitigation within the electricity sector takes the form of substitution towards non-emitting generation options with relatively small impact on electricity prices; on the other hand, carbon values play a small role in mitigation in the transport sector where taxation is already heavy in most developed regions. The effect of the supply push scenarios on final consumption is insignificant with a minor increase registered especially in the scenario involving the free provision of infrastructure services.

The impact of the fuel cell improvement on gross inland consumption is much less marked. This is primarily due to the effects of substitution towards hydrogen in the heat and power sector: substitution in favour of hydrogen does not involve an overall reduction in energy intensity. This is particularly the case because the additional hydrogen in these scenarios is produced from biomass with and without CCS, coal-fired CCS facilities, and in the case of PRIMES nuclear thermochemical cycles, which are not characterised by very high conversion efficiencies (in part due to CO2 capture). The arguments above are particularly applicable to the supply push scenarios where the energy intensive hydrogen production does not occur in conjunction with increased fuel cell efficiency. The combined case in fact results in static gross inland consumption.

The following tables summarise the results of the Demand Pull (Table D-8), Supply Push and Combined cases (Table D-9) on the shares of different options in hydrogen production, as simulated by different models.

Table D-8: Demand Pull Cases: Shares in hydrogen production

	REF			FC CASE			FC+TAX CASE			FC+TAX+CV CASE		
	POLES	MESSAGE	PRIMES	POLES	MESSAGE	PRIMES	POLES	MESSAGE	PRIMES	POLES	MESSAGE	PRIMES
Coal	23.2		55.5	25.4		58.4	26.2		57.5	7.3		55.2
Gas	5.2		9.1	5.1	11.0	7.9	5.3	17.0	9.1	5.9	1.6	3.6
Heavy Oil	5.6		1.5	5.9		2.5	7.0		3.1	3.5		1.3
Biomass	47.3	90.0	17.6	43.8	78.0	17.7	41.8	76.6	18.0	61.8	85.0	24.7
Nuclear	3.7	6	15.5	3.9	6.6	12.7	3.8	3.8	11.5	4.9	8.0	14.3
Grid	1.8	4	0.8	2.0	4.4	0.7	2.0	2.5	0.7	1.7	5.4	0.8
Solar	4.2		0.1	4.5		0.1	4.8		0.1	4.4		0.1
Wind	8.9			9.4			9.1			10.5		

PRIMES: Europe Only

Table D-9: Supply Push and Combined Cases: Shares in hydrogen production

	H2P CASE			H2P+INFR CASE			H2P+INFR+CV CASE			COMBINED CASE		
	POLES	MESSAGE	PRIMES	POLES	MESSAGE	PRIMES	POLES	MESSAGE	PRIMES	POLES	MESSAGE	PRIMES
Coal	20.2		45.7	21.4	3.0	50.5	5.4		46.1	6.0	4.0	49.6
Gas	4.7		6.0	4.7	25.0	3.6	4.7	36.0	1.8	5.1	32.0	2.4
Heavy Oil	5.4		1.0	6.2		1.1	2.7		0.5	3.1		1.0
Biomass	40.3	87.5	14.2	38.3	60.0	12.8	60.1	49.0	18.3	52.9	50.0	21.3
Nuclear	7.3	7.5	32.0	7.3	7.2	30.8	6.6	7.2	31.9	8.6	6.6	24.4
Grid	1.4	5.0	0.8	1.5	4.8	0.8	1.1	4.8	0.9	1.3	4.4	0.8
Solar	4.5		0.4	4.7		0.4	3.9	4.0	0.4	4.5	4.0	0.4
Wind	16.2		0.0	16.0		0.0	15.6		0.0	18.5		0.0

PRIMES: Europe Only

According to the scenario analysis carried out with most of the models, high carbon values do in general favour the penetration of fuel cells. This is especially pronounced in the CHP applications. This outcome is based on the fact that production of hydrogen in the baseline is dominated by low carbon and carbon free processes making hydrogen impermeable to cost spillovers, while affecting competing options like gas-fired CHP with gas turbines.

Table D-10: Summary results on the impact of the different scenarios on CO2 Emissions

	FC	FC+TAX	FC+TAX+CV	H2P	H2P+INFR	H2P+INFR+CV	COMBINED
POLES	-1.1	-2.3	-16.3	-0.1	-1.1	-16.3	-17.5
MESSAGE	-2.0	-2.0	-22.0	-0.4	-20.0	-32.0	-32.0
MERGE-ETL	-1.8	-1.8	-50.0	-1.0	-1.0	-1.0	-50.0
PRIMES*	-14.6	-17.0	-40.8	-1.7	-4.6	-26.9	-42.2

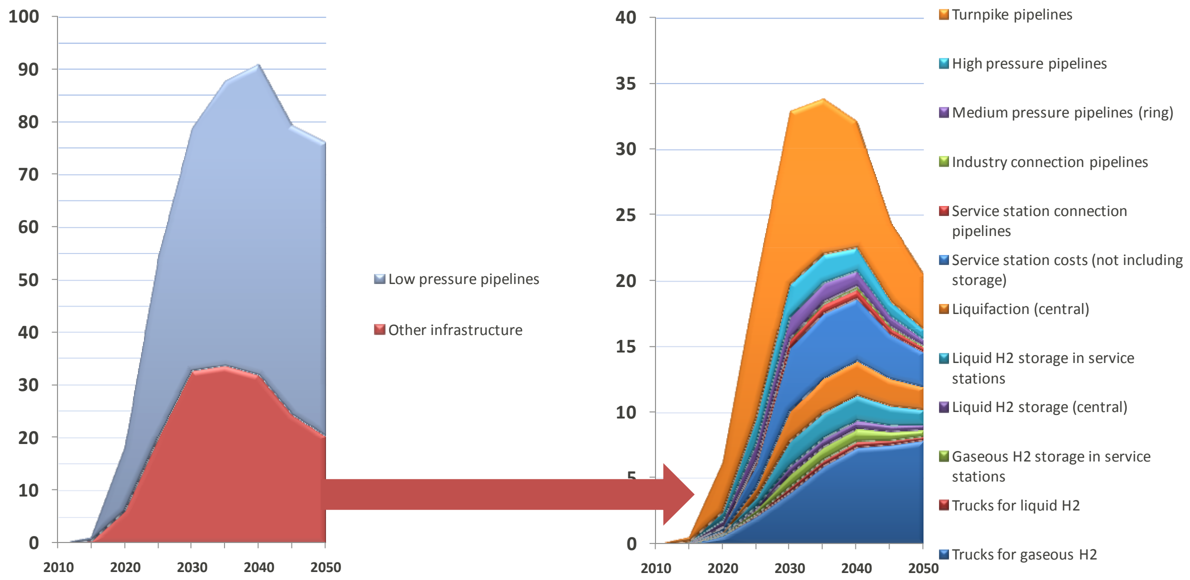
*Europe Only

Table D-10 above summarises the results of the different models concerning the impact of the scenarios on CO2 emissions. Global models (POLES, MESSAGE, MERGE-ETL) have produced relatively small reductions in CO2 emissions in the cases of technological breakthrough in fuel cells, even when penetration is assisted by means of discriminating taxation. This impact is more pronounced in the results of the PRIMES-H2 European model. The impact of technological improvement of hydrogen producing technologies is generally minor. This is also the case when subsidies to infrastructure are additionally implemented. Naturally, all models display the strongest results in cases involving doubling of the effective carbon value.

The analysis of the scenarios with the PRIMES model has given special emphasis on issues of infrastructure requirements especially in cases where a pronounced transition towards a hydrogen based economy is implied. In order to provide some insights on the impact of a more rapid penetration of hydrogen on infrastructure requirements the combined case was chosen for illustration purposes as it is characterised by the most rapid penetration.

Figure D-14 below presents the evolution of investments by major infrastructure category. It should be noted that the figures on the vertical axis refer to investments over a whole 5-year period (5-years is the time interval in the PRIMES model).

Figure D-14: Infrastructure investments in bn€05 in the combined case (values refer to cumulative investments over 5-years terminating at a given date)



Source: PRIMES

Looking at the graph on the left of the figure it is clear that investments peak up very sharply in the period from 2020 to 2030 then reach a plateau between 2030 and 2040 before starting to decline moderately. This decline at the end of the period is an indication that the scenario does indeed represent a more accomplished transition. In fact the total investment figure is maintained high in this latter period only because of the continuing expansion of the low pressure pipeline network supplying users in the residential/commercial sector, which, as discussed in the analysis of the scenarios, is lagging behind road transport in hydrogen penetration. Investments in low pressure pipelines represent around two thirds of total infrastructural investment in the period to 2050. Other types of investment (enlargement on the graph on the right of the figure) peak in the 2025 to 2030 period and then decline sharply after 2040.

The most important category among the latter types is investment in turnpike pipelines connecting hydrogen producing plants and acting as a storage medium in order to balance the hydrogen supply and demand system. These peak in 2025 to 2030 period at over 2.5 billion per year. By the end of the outlook they fall to under one billion per year. This is due to the pattern of hydrogen propagation across the continent: at the beginning low intensity networks are developed in densely populated areas, serving essentially niche markets. During this phase, expansion takes place mostly by the multiplication of such areas. However, as familiarity of consumers with the technology increases expansion of hydrogen consumption takes place increasingly by a more intensive utilisation of existing basic infrastructure (this also explains why the expansion of the low pressure network continues unabated). On the other hand as the network starts growing into less densely populated areas, this growth is not accompanied by equivalent increases in hydrogen volume and this development eventually puts a break on the geographical expansion of the basic network. Another important category of infrastructure investment consists of trucks for compressed gaseous hydrogen transportation. The constant expansion of hydrogen driven cars not only in densely inhabited areas but also rural areas implies that investment needs for this type of equipment is maintained continuing increasing until the mid '40s. Such investment requirements are also influenced by replacement of scrapped trucks that were introduced in the period of rapid expansion. Investments in service stations reach a plateau of around 1 billion euro per year in 2030. They decline sharply between 2040 and 2045, but are maintained at over 500 million euro per year thereafter.

D.4 R&D Policy Scenarios

D.4.1 Introduction –Definition

The CASCADE MINTS project Part I has established a common specification for a technology dynamics module which was used by most of the models. As mentioned earlier, (see section C.1.2) the module is based on the concept of the two factor learning curve explaining technological improvement in terms of R&D expenditure and cumulative experience gained by technology implementation. In fact, according to this concept, R&D is a primary mover for technological change providing initial improvements which lead to additional technology take-up that in turn leads to further improvement via learning by experience. In this sense, learning by experience is a factor magnifying the initial impetus given by research.

Once the models have been equipped with this mechanism and calibrated to approximately reproduce the Baseline scenario they are capable of carrying out R&D policy scenarios. The scenario definitions take the form of large additional (above Baseline) R&D funding addressed at specific clusters of hydrogen economy related technologies or to several clusters at the same time. The choice of combinations is guided by information arising from perspective analysis. A limited number of scenarios combining enhanced R&D effort with other policies such as emission constraints or internalisation of external costs through taxation, subsidies on infrastructure are also considered in an attempt to examine how such non- R&D policies may improve R&D productivity in terms of policy objectives or conversely how R&D policies may reduce the cost of attaining given objectives.

To analyse the possible role of R&D on hydrogen related technologies for accelerating their introduction in the energy system a number of R&D policy scenarios have been defined in the context of the CASCADE MINTS project. The scenarios were also designed to examine R&D in the context of other policies specifically aimed at promoting the use of hydrogen.

In summary the scenarios were defined as follows:

Zero R&D

- No R&D in hydrogen related technologies from 2007 onwards

Demand side scenarios

- D1.1: Tenfold increase in R&D expenditures on fuel cells from 2007 to 2015
- D1.2: Scenario D1.1 together with additional tax in fuels for road transport of the order of 0.5€/lt from 2025 onwards
- D1.3: Scenario D1.2 plus using 5% of the tax revenues as additional R&D in fuel cells and hydrogen infrastructure
- D1.4: Scenario D1.3 combined with doubling baseline effective carbon values

Supply side scenarios

- S1.1: Tenfold increase in R&D expenditures on hydrogen production options between 2007 and 2015
- S1.2: Scenario S1.1 together with additional tax in fuels for road transport as in Scenario D1.2
- S1.3: Scenario S1.2 together with 100% subsidy to all hydrogen distribution and storage infrastructure

Combined Case

- Scenarios D1.4 and S1.3

D.4.2 R&D policy scenarios results

The baseline projection incorporates around 22 billion €05 of worldwide R&D expenditure directed at fuel cells in the period 2007 to 2015. This is assumed to represent a median estimate of likely outlays both from public and private sources. The basic R&D scenario (D1.1) assumes a tenfold increase in R&D of this period, which represents in R&D terms a very large sustained effort and presupposes a strong belief in early success for this technology.

The table below presents the impact of scenario D1.1 on the key technical and economic characteristics of fuel cells and the delivered cost of hydrogen to different market segments. The figures are derived from PROMETHEUS simulation, but refer to European averages as they have been introduced in the PRIMES-H2 model.

Table D-11: Impact of R&D in fuel cell costs and delivered hydrogen cost in €05

Mobile applications

		2025			2050		
	unit	**Baseline**	**10x R&D**	***% change***	**Baseline**	**10x R&D**	***% change***
Stack cost	€/kW	57	21	*-63%*	30	19	*-36%*
System cost	€/kW	63	28	*-55%*	30	27	*-9%*
On board storage cost	€/kgH²	88	85	*-3%*	66	65	*-1%*
On board batteries	€/kWh	343	346	*1%*	246	245	*0%*
Maintenance cost	€/yr	418	271	*-35%*	263	204	*-22%*
Fuel input	kgr/100km	0.58	0.46	*-20%*	0.49	0.40	*-17%*
Cost of running the vehicle	€ cents /km	54	42	*-22%*	42	40	*-5%*

Stationary applications (1-5 Kwe)

		2025			2050		
	unit	**Baseline**	**10x R&D**	**% change**	**Baseline**	**10x R&D**	***% change***
Stack cost	€/kW	392	203	*-48%*	224	166	*-26%*
System cost	€/kW	1509	868	*-42%*	896	799	*-11%*
Stack lifetime	Years	9	11	*25%*	10	12	*14%*
Fixed O&M cost	€/kWy	72	30	*-59%*	22	18	*-16%*
Overall fuel efficiency	%	92	95	*3%*	94	95	*2%*
Electrical efficiency	%	34	37	*7%*	36	38	*5%*
Thermal efficiency	%	58	58	*1%*	57	57	*-1%*
Electricity production cost *	€/MWh	328	218	*-34%*	140	126	*-10%*

* the value of heat is substracted from this figure

Hydrogen delivered cost to

		2025			2050		
	unit	**Baseline**	**10x R&D**	***% change***	**Baseline**	**10x R&D**	***% change***
Industry	€/toe	853	833	*-2%*	849	839	*-1%*
Transport	€/toe	1182	1159	*-2%*	1140	1129	*-1%*
Residential/commercial	€/toe	1113	1085	*-3%*	1066	1054	*-1%*

A general remark concerning these results is that the impact in 2025 is considerably bigger than in 2050. The main reason for this is that the baseline assumes considerable R&D effort beyond 2015 (around five billion euro per year on average). In this sense the main effect of the R&D scenario is to bring forward improvements.

Stack costs for both mobile and stationary applications are the economic characteristic that registers the biggest improvements as a result of R&D. Large improvements are also registered for operating and maintenance costs and system acquisition costs. On board hydrogen storage is little affected: this is due to the effects of learning by doing that is influenced both by applications on fuel cell vehicles (which increase substantially) and applications on hydrogen ICE vehicles (which in this scenario take much smaller shares). R&D also has a very pronounced effect on the overall efficiency of fuel cell vehicles, while little gain over baseline values is registered for the efficiency of stationary fuel cells (for this application R&D tends to increase the electrical efficiency but overall efficiencies are 94% already in the baseline with little room for further improvement). In terms of competitiveness of fuel cell options it is worth noting that in the R&D scenario the cost per vehicle kilometre for fuel cells is already broadly competitive with conventional equivalents by 2025. In that year, small scale stationary fuel cells for household applications produce electricity at a cost around 20% higher than residential electricity tariffs. By 2050 the R&D scenario implies a highly competitive cost for producing heat and power from such stationary applications assuming heat utilisation rates of around 1500 hours per year.

The impact of the R&D on supply options (hydrogen production, storage and distribution) in terms of reduction of delivered costs of hydrogen is very small, even in 2025. This is mainly due to the poor prospects for improvement of such technologies following the perspective analysis carried out within CASCADE MINTS. On the other hand, one of the findings of the project is that hydrogen costs play a relatively minor role in shaping the prospects for a hydrogen economy (this is particularly the case for mobile applications).

The heterogeneity of hydrogen related technologies and the very high efficiencies of fuel cells create some problems for an overall aggregation of results. In order to obtain such an overall assessment a special index is used: percent share of potential index. The potential is calculated by hypothetically assuming that all useful energy demand for categories that are susceptible to substitution by hydrogen was met by this energy vector. In this way, the ratio to this potential gives an indication of overall success for the hydrogen economy. It is worth noting that although R&D and the additional measures produce a clear tendency for improvement of the prospects as measured by this index, even in the combined case its median value only stands at 26% with an upper five percentile of around 35%. Measures specifically directed at the road transport sector fare relatively worse than those involving interventions on the infrastructure.

Figure D-15: Probability of hydrogen penetration levels

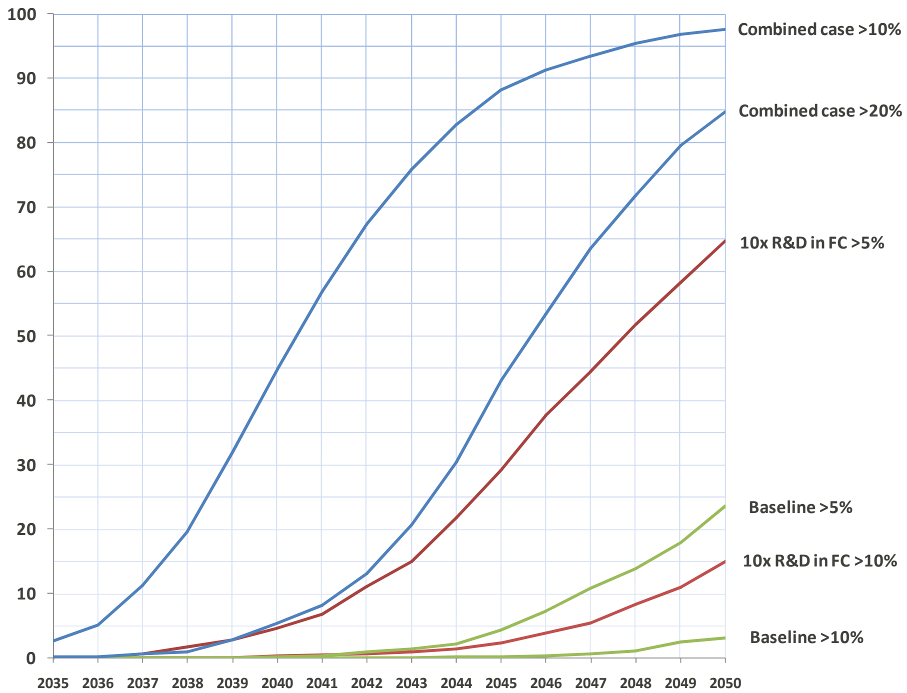


Figure D-15 gives the time profile of probability prospects in terms of the percent share of potential index. The benchmarks examined are the 5 and 10 percent levels for the baseline and tenfold increase in R&D directed to fuel cells scenario, and the 10 and 20 percent levels for the combined case. It is worth noting that probabilities of this index reaching any of these benchmarks for any of the scenarios are very small or virtually zero before 2035. After that date the chances of the index exceeding 10% improve rapidly for the combined scenario (it should be remembered here that these are conditional probabilities, assuming that all the additional policies and measures are in place worldwide; this in itself is a highly unlikely occurrence). In the tenfold increase of R&D in fuel cells case, prospects for exceeding a 5% value improve sharply around 2045 and become more than even by the end of the decade. However, under this scenario the probability of the index exceeding 10% is still only 15%.

An overall examination of Figure D-15 additionally points to another feature that has emerged constantly in the modelling work undertaken in the CASCADE MINTS project and in particular work undertaken using the PROMETHEUS model: the lags involved between R&D action and technological improvement, between the latter and technology take-up and the inertia implied by capital stock turnover mean that the time dimension becomes a key element in the assessment of the prospects for a hydrogen economy. In other words under any scenario, as for example the baseline, prospects tend to improve with time (e.g. the probability that the percent share of potential index will exceed 5% is virtually nil in 2040 but gets close to 20% in 2050). This leads to an alternative way of looking at the impact of scenarios by examining their effect on bringing forward developments.

Figure D-16: Forcing the pace by additional R&D: % share of fuel cell cars in vehicle parc in World

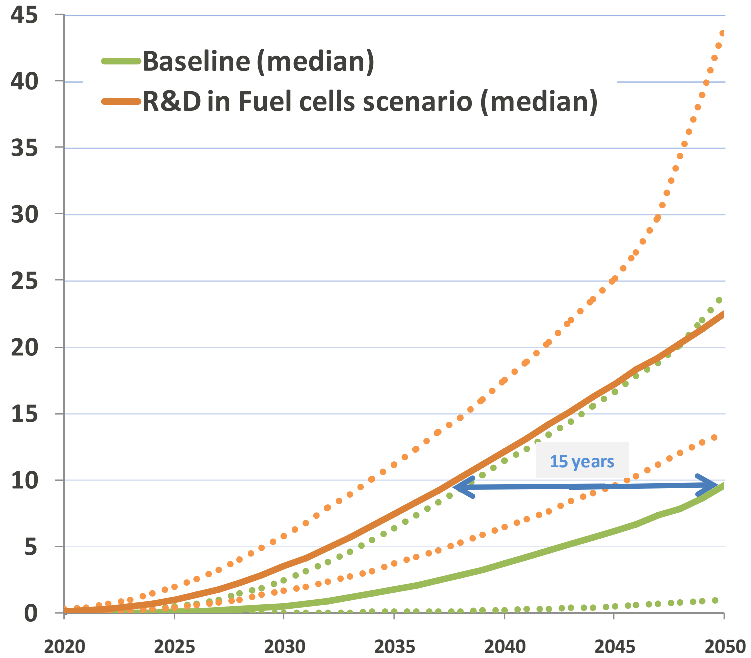


Figure D-16 plots the median value and upper and lower five percentiles of the share of fuel cell cars in the world vehicle parc for the baseline and tenfold increase of R&D in fuel cells scenarios. According to these results the additional R&D of 170 billion €05 directed towards fuel cell technologies brings forward the median penetration rate of 10% (baseline) by about 15 years. On the other hand the probability of exceeding 20% in the R&D scenario is only 5% in the early 40's – which is about the same probability applying for the baseline in the late 40's. These results seem to suggest that R&D can drastically bring forward the more modest developments but given the considerable inertias of the system are less likely to have the same effect on breakthroughs.

The no R&D to hydrogen related technologies scenario has naturally resulted in insignificant contributions of hydrogen over the whole period with perhaps the exception of H2 ICE vehicles the prospects of which depend more on urban pollution policies than on technological improvements. This lack of progress underscores the importance of R&D, and especially R&D on fuel cells at the early stages, in enabling, facilitating and accelerating the introduction of hydrogen technologies.

Table D-12: R&D Scenarios - comparison of different models: Share of Hydrogen Powered vehicles in road transport - Share of FC vehicles in italics (2050)

	REF	No R&D	D1.1. 10x R&D in FC	D1.2 D1.1 + TAX	D1.3 D1.2 + INFR	D1.4 D1.3 + CV	S1.1 10x R&D in H2Prod	S1.2 S1.1 + TAX	S1.3 S1.2 + INFR	Combined R&D case
PROMETHEUS	**13.8**	**3.1**	**25.9**	**40.4**	**51.2**	-	**14.8**	**21.7**	**39.1**	**74.7**
	9.6	*0.0*	*22.6*	*35.1*	*45.1*	-	*10.2*	*14.9*	*25.7*	*53.2*
MESSAGE	**9.6**	**0.0**	**33.6**	**99.0**	-	-	**10.3**	-	**25.6**	-
	9.6	*0.0*	*33.6*	*78.5*	-	-	*10.3*	-	*25.6*	-
MERGE	**17.2**	**15.0**	**25.4**	**34.9**	**37.5**	-	**17.5**	**26.5**	**26.5**	-
	0.0	*0.0*	*22.2*	*23.0*	*31.2*	-	*0.0*	*0.0*	*0.0*	-
PRIMES*	**18.4**	**3.2**	**29.8**	**37.8**	**40.1**	**42.5**	**19.0**	**24.0**	**26.8**	**43.2**
	13.3	*0.0*	*27.0*	*34.5*	*36.7*	*38.5*	*13.7*	*17.6*	*18.7*	*39.6*

* Europe Only
**PROMETHEUS Median Estimates

Table D-12 above summarises the results of the R&D scenarios and variants on the penetration of hydrogen powered vehicles in the European and World road transport in the year 2050. Table D-13 illustrates the amount of hydrogen produced globally per scenario and model.

Table D-13: World Hydrogen Production (Mtoe)

	REF	No R&D	D1.1. 10x R&D in FC	D1.2 D1.1 + TAX	D1.3 D1.2 + INFR	D1.4 D13 + CV	S1.1 10x R&D in H2Prod	S1.2 S1.1 + TAX	S1.3 S1.2 + INFR	Combined R&D case
PROMETHEUS	480	151	784	1146	1635		517	715	2044	3230
POLES	331				505	557	331	399	567	724
MERGE-ETL	330	328	119	239	567		330	446	447	-

**PROMETHEUS Median Estimates

The demand technology R&D scenarios in general result in earlier competitiveness of fuel cells especially in the road transport sector. This results in increased penetration of fuel cell cars. For some models this penetration takes place to a considerable extent at the expense of hydrogen ICE cars. Since the latter are much less efficient than fuel cells their increased technology uptake is not translated into equivalent increases in hydrogen use. The PROMETHEUS median values for world hydrogen production are considerably higher than the scenario results obtained from deterministic models. The main reason for this apparent discrepancy lies in the fact that the PROMETHEUS median is influenced by changes in the tale of the distribution: to the extent that the scenario assumptions improve the prospects of real breakthroughs in hydrogen use, central statistics of distributions would tend to move more than proportionally.

PROMETHEUS results can go some way in investigating the role of R&D budget size and the "efficacy" of R&D effort. Before such analysis can proceed a measure of "efficacy" must be devised in a way that it corresponds broadly to the main objectives of the R&D undertaken. On average, in the last 30 years 70% of R&D on fuel cells has been financed by the business sector. The CASCADE MINTS outlook implies broadly the maintenance of this share in the outlook. Naturally the main motivation of business R&D is the prospects for future sales of technologies. This preoccupation with future sales can be both offensive (i.e. creating new markets for technologies) and defensive (ensuring that in case of success of a particular option a company would not lose market share by failure to diversify). Given the preponderance of such preoccupations it is appropriate to build an R&D "rate-of-return" index combining the discounted future flow of sales and the discounted R&D outlays. The choice of a discount rate poses particular problems especially when R&D decisions are considered. In usual business practice the discount rate utilised depends on returns on risk free alternatives and the amount of risk involved in the particular investment. R&D is usually a very risky investment and would normally be evaluated using a high discount rate. On the other hand, PROMETHEUS is capable of generating risk information. This means that a "reasonable" discount rate can be used for calculating the RoR and subsequently it is possible to examine explicitly risks of failure to reach specific benchmarks associated with the RoR (however defined). This leads to a second problem with this type of analysis: the choice of appropriate benchmarks. In classical investment analysis profits on sales rather than total sales would constitute the benefit component of the RoR calculation. It is very hard to establish what future rates of profit would be appropriate on technologies that do not even have a market at present. In any way a lot will depend on future market structure (the degree of oligopoly). It is clear, however, that the profit rate would normally be a relatively small fraction of sales (say from about 8% to about 25%). In the case of defensive R&D strategies, very low benchmarks become acceptable because the issue is no longer profitability but risk of loss.

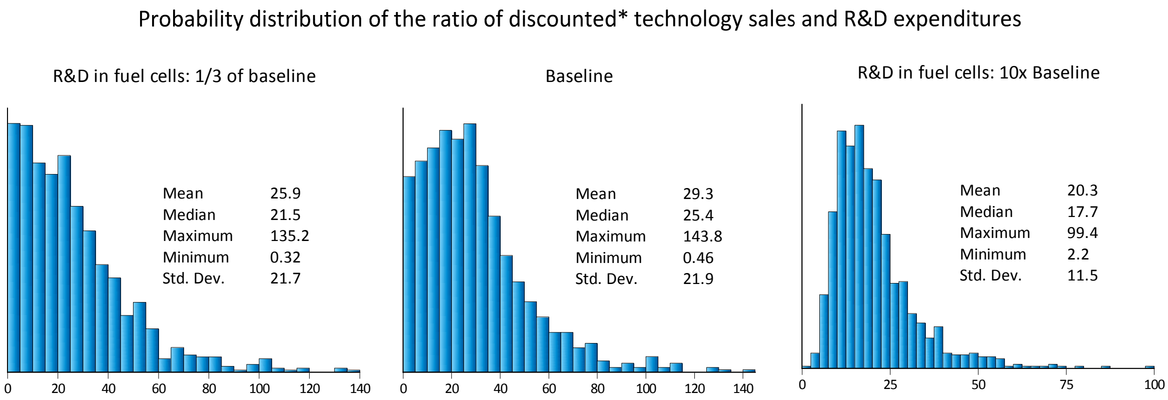
For the purposes of the assessment of the efficacy of R&D investment in PROMETHEUS a "normal" discount rate of 6%+a risk free real rate-of-return has been used. The notion of risk free in a stochastic model like PROMETHEUS is very relative; usually long term real interest rates are used for such calculations since they come closest to low risk return on bank deposits. However, even long term real interest rates vary over time and in PROMETHEUS their variation is explicitly taken into account. In this sense, it can be said that the discount rate chosen is, on average, 8% but is subject to random variation. Concerning the benchmarks, PROMETHEUS is capable of producing results for a number of them, but the analysis carried out below concentrates on the values of 6, 10, 20 and 60. Their appropriateness to particular decisions will depend on the decision context and the choice is best left to decision makers. In summary, the RoR index chosen is defined as follows:

$$RoR = \frac{Cumulative\_discounted\_sales_{from 2005 to 2050}}{Cumulative\_discounted\_RD\_outlays_{from 2005 to 2050}}$$

The baseline scenario naturally incorporated R&D on fuel cells throughout the forecast horizon 2005-2050. In order to carry out the efficacy assessment the D1.1 scenario involving tenfold increase in R&D in fuel cells in the period 2007-2015 used to examine the impact of an increase R&D effort. In order to complete the assessment an additional scenario was evaluated involving a postponement of R&D: it assumes that over the period 2007-2015 R&D on fuel cells will stand at 1/3 of the baseline values.

Figure D-17 summarises the results obtained on the RoR as defined above for all three scenarios. The lower R&D scenario performs worse than the baseline on almost every count: it has lower mean and median RoR and appears to display higher risks of failure with lower probabilities of a breakthrough. This result suggests that postponing efforts is not an effective R&D strategy.

Figure D-17: Effectiveness of R&D in fuel cells



	1/3 baseline R&D	baseline	10x baseline R&D
Probability to fall below 6	16%	11%	2%
Probability to fall below 10	26%	18%	13%
Probability to exceed 20	53%	61%	40%
Probability to exceed 60	7%	9%	1%

* discount rate: Real interest rate + 6%

On the other hand the comparison of the ten times baseline R&D to the baseline scenario produces a more mixed picture. It implies a considerable drop in mean and median RoR (they are even lower than in the low R&D scenario). This would suggest decreasing returns to additional R&D effort. At the same time, the standard deviation of the high R&D scenario is almost half the baseline value. As a result the risk of serious failure is drastically reduced, while even the probability of obtaining no better than a mediocre return (less than 10) is lower (13% instead of 18%). At the other extreme, the probability of very big returns is much lower. The shapes of the probability density functions (p.d.f.) in Figure D-17 underpin these findings. The low R&D p.d.f. has a mode close to zero and is very heavily skewed to the right. For the baseline the mode shifts close to the mean and median, but the p.d.f. remains markedly skewed to the right. In the high R&D case a second tail at the low end emerges implying much lower probabilities of failure. At the same time the distribution becomes more concentrated around the mean, median and mode, which get closer to each other suggesting a movement towards symmetry.

Finally Table D-14 below summarises the results of the different models concerning the impact of the R&D scenarios on CO2 emissions.

Table D-14: Summary results on the impact of the different scenarios on CO2 Emissions (2050)

	No R&D	D1.1. 10x R&D in FC	D1.2 D1.1 + TAX	D1.3 D1.2 + INFR	D1.4 D1.3 + CV	S1.1 10x R&D in H2Prod	S1.2 S1.1 + TAX	S1.3 S1.2 + INFR	Combined R&D case
PROMETHEUS	0.3	-1.2	-1.3	-1.7	-	0.0	0.3	0.2	-3.3
MERGE-ETL	0.9	3.7	0.0	-1.9	-47.2	0.0	-1.9	-1.9	-48.1
PRIMES*	4.9	-3.5	-7.0	-7.7	-32.4	-0.3	-3.2	-5.6	-32.6
MESSAGE**	6	-2	-3	-	-	-	-	-20	-32

* Europe Only
** In 2100

E. Conclusions

Part 1 of CASCADE MINTS is a modelling project 'par excellence'. It has involved the development of a modelling capability for representing an eventual hydrogen economy and simulating alternative paths towards it. The different models involved in the project have to the extent to this was possible used the same technology characterisations, technological data and perspective analysis. They have also been tested through the use of similar sets of scenarios. On the other hand the models differ widely in terms of coverage, modelling philosophy and emphasis. As the main purpose of the project was to build the capability for quantitative analysis rather than produce roadmaps for policy support the insistence in common information base and common scenarios has not been extended to the harmonisation and reconciliation of model results. The diversity of the latter notwithstanding, some common analytical threads have emerged in the course of the project and are summarised in the present section.

The consensus of the CASCADE MINTS project indicates that a hydrogen based energy system offers the best prospects for overcoming petroleum dominance of road transport. This is a crucial segment of the energy market and a major source of security of supply concerns as well as environmental sustainability especially in the form of pernicious urban air pollution problems. Potential applications in other sectors also exist that could create a snowball effect facilitating production capacity and infrastructure development. In such sectors though competition from a wider spectrum of alternatives can be expected. A key feature of an eventual transition towards a hydrogen based economy is that on the one hand it constitutes a distinct and radically different technical economic energy system configuration but on the other does not imply a radical change in patterns of energy use. This latter feature means that there is a small likelihood of social (as opposed to technical and economic) barriers being encountered in the path to such a transition.

Demand Prospects

Automotive applications constitute the key segment for the future of fuel cells. They are likely to experience the highest penetration rates, and lead improvements that can spill over to other applications and carry forward infrastructure development.

The major obstacle that mobile fuel cells face is the continuous improvement in internal combustion engine cars. The latter maintain a high share in cases where only hydrogen supply is promoted but they decline sharply in the cases where fuel cells experience a technological breakthrough and are fiscally advantaged.

Hydrogen powered internal combustion engine cars are characterised by fewer prospects for technological improvements and their penetration is stunted in cases where fuel cells emerge as a dominant option. On the other hand, in terms of hydrogen consumption they can be disproportionately important and their market penetration could provide an early stimulus for the development of hydrogen infrastructure assuming always perceived prospects for fuel cell vehicle introduction.

Technological improvements in mobile fuel cell stacks and systems as well as storage and liquefaction are likely to spillover to stationary applications.

In general, most models have shown fuel cell applications in the heat and power sectors lagging behind developments in the road transport sector, even in cases where they experience equivalent technological improvements. This is because they face wider competition from other options. On the other hand, the projected heat and power market is so large that even small penetrations of fuel cell CHP could result in important segments of the hydrogen market.

Infrastructure & Production

In cases of large scale introduction of hydrogen in the energy system, the bulk of investments in infrastructure will take the form of low pressure pipelines supplying consumers in the residential/commercial sector. Most other investments peak fairly early in the transition and would only account for around one third of cumulative outlays in any case.

Hydrogen production is overwhelmingly dominated by centralised options, especially in those scenarios that involve large-scale hydrogen penetration. Model results largely point to the widespread use of biomass gasification with or without Carbon Capture and Sequestration as an important source of hydrogen production especially in a carbon constrained world. Other options that emerge with important shares in centralised production involve coal gasification with CCS and dedicated nuclear plants (via electrolyser or the high temperature thermochemical cycle). The bulk of decentralised production takes the form of natural gas steam reforming.

Consequences of eventual Success

A future hydrogen-based energy system will not necessarily be a less energy intensive system. Gross inland consumption in general will not be greatly affected and will even increase in cases where stationary applications are promoted.

This is the case because gains in efficiency arising from the use of fuel cells are counterbalanced by transformation losses in the production of hydrogen itself. The use of CCS in production means even lower conversion efficiencies.

On the other hand, an eventual hydrogen based energy system would in general be environmentally friendly:

- It clearly reduces local atmospheric pollution strains. Concerns about the latter could even provide an impetus for hydrogen introduction even in cases where it is uneconomic.
- It would also be compatible with global climate mitigation, because of high efficiencies in final use combined with a wide spectrum of possibilities for very low carbon intensity in hydrogen production (e.g. CCS, Biomass)

All model based scenario results have shown that a stronger climate policy favours the introduction of hydrogen without on the other hand being the decisive factor.

Keys to Success

The key to the success of the hydrogen economy is found in technological change. The improvement of technical and economic characteristics of Fuel Cell stacks and systems in mobile applications are an absolute pre-requisite. Stationary versions can improve as spin-offs.

The cost of producing hydrogen offers fewer prospects for reduction but is not an important consideration, in view of the high efficiencies and the capital intensive nature of hydrogen-using equipment. In any way, fossil fuel costs are projected to be high both because of scarcity (hydrocarbons) and climate policy.

Storage, Transportation and Distribution infrastructure development will follow (with some lag) demand as long as it shows prospects of materialising on a sufficient scale.

The Pace of Transition

Perspective analysis concerning the prospects of the hydrogen economy performed without the use of integrated models has in general taken two distinct forms: a pessimistic view doubting prospects altogether and concentrating on technological and other barriers; very optimistic scenarios (usually forming the backbone of hydrogen roadmaps) suggesting early and dramatic developments.

According to results from the CASCADE MINTS project hydrogen in general and fuel cells in the key road transport sector are unlikely to emerge before 2030, gain significant shares (e.g. 10% of vehicle stock) before 2040 and be a dominant choice before 2050.

Many scenarios produced conditions of take-off during the decade before 2050, suggesting that the prospects of a massive introduction improve beyond. The main reasons for this relatively slow introduction can be found in the low technical maturity of the key options, the inherent inertia in equipment turnover and the lags in infrastructure investment.

Making it Happen

Extensive scenario analysis in CASCADE MINTS broadly indicates that supportive policies such as selective and discriminating taxation, subsidies on infrastructure even when applied in very strong doses are inadequate for producing drastic results in the absence of rapid technical progress. On the other hand, such measures would tend to be superfluous in the presence of such progress. At any rate, such policies would in general tend to be costly both in terms of the economy as a whole (diversion of investments towards hydrogen infrastructure) and on government budgets (loss of taxation revenue, subsidies).

In contrast to the above, additional R&D aimed at inducing technical change in demand technologies has been shown to accelerate developments at a considerably lower cost than other supportive policies. For example a tenfold increase in R&D for Fuel Cells during the 2007-2015 period has been shown to bring forward developments by about 15 years. It can be reasonably assumed that large scale additions to R&D outlays will have to come from the private sector motivated by high expected sales. However, there are diminishing returns to such increases in R&D effort (the rate of return on R&D investment declines with its size). These diminishing returns notwithstanding, additional R&D tends to reduce the risk of failure. This could be an important consideration in view of the highly speculative nature of the effort undertaken.

Part 2:

Joint Case Studies on Policy Issues with Operational Energy Models

F. Introduction

This report presents results of Part 2 of the CASCADE MINTS project. In this project, 15 re-nowned modelling teams in Europe, the US and Japan have provided an outlook to possible developments in Europe and at the global level. The objective of this project is to use a wide range of existing operational energy and energy/economy models in order to build analytical consensus (to the extent possible) concerning the impacts of policies aimed at sustainable energy systems. The emphasis is placed on evaluating the effects of policies influencing technological developments.

F.1 Objectives

The objectives of PART 2 of the project are:

- to address policy questions that are currently relevant to the main stakeholders, i.e. policymakers and their policy advisors, with emphasis on the EU and global level;
- to investigate the role of different policies fostering deployment of more advanced and climate-friendly or climate-neutral energy technologies in improving security of supply and reducing GHG emissions.

To achieve these objectives, a wide range of existing models has been applied to build scientific consensus on the impacts of policies aimed at promoting sustainable energy systems – in particular through technological developments.

F.2 Methodologies and approaches

The main objective of the approach chosen was to perform a synthesis of the policy cases analyzed by various models. Some of these models have comparable methodologies and scope, others complement each other, such as economic models and energy system models. Next, consensus among the modellers has been sought concerning the results presented and the main policy messages. The summarised policy briefs bundled in this report reflect the consensus found over different policy cases. Although all models confirm these messages, there are sometimes significant differences among individual model results, reflecting the different dynamics and assumptions and indicating the impact of uncertainties in the future energy system. The graphs presented here show projections from different models, and should be regarded as illustrative of the discussed trends, by no means the only possible paths.

As a background to the description of the model results, Table F-1: gives an overview of the models involved, classified along their methodology. Generally, energy system models have a detailed technology representation and these have been used to analyse the impact of CCS technologies. Still, a variety of methodologies, including 'hybrid' modelling approaches is represented. The equilibrium models participating in the case study have made use of the results of one of the energy system models. Note that not all of the models have participated in all policy cases. More information on the models can be found in (Uyterlinde et al, 2004).

Table F-1: Overview of the models participating in the CASCADE MINTS project

	Top down		*Bottom up*	
	Macro-economic	*Computable General Equilibrium*	*Energy System Optimisation*	*Integrated Energy System Simulation*
Global *US, Canada*		AIM NEWAGE-W PACE	DNE21+ ETP GMM MESSAGE PROMETHEUS *(stochastic)*	POLES NEMS MAPLE
Europe	NEMESIS		MARKAL Europe TIMES-EE	PRIMES

F.3 Baseline trends for Europe in a global perspective

F.3.1 Objectives and work performed

The objective of this work package was to harmonise for each of the models used the initial conditions, which are needed to define the baseline (no-policy intervention) or business as usual (BAU) case.

ECN has coordinated WP2.1. This comprised the following activities:

- Discuss and agree with project partners on which model assumptions needed harmonisation and based on which sources. The main assumptions were:
    - Use GDP and population assumptions made in the B2 scenario at world and regional levels

- Prices will be estimated either endogenously in the models or as specified by POLES, while modellers should report shadow prices for the energy resources.
- Technologies considered will differ by model but for transparency reasons each modeller should provide information on four parameters for each technology used (investment cost, efficiency, lifetime, availability factor).
- End-use sectors were not harmonized

- Coordinate the production of baseline projections by all models involved in the project.
- Collect the results, analyse the baselines, including methodological issues arising from different types of models and write a synthesis report [1]. The draft synthesis has been discussed with all modelling teams in order to achieve scientific consensus.
- Write a policy brief on the baseline results.

All project partners that participated in WP2.1 have used their model to produce a baseline projection in Part 2 of CASCADE-MINTS and have reported on this.

F.3.2 Summary of results and conclusions

Part 2 of the project has started with formulating a common baseline projection (Uyterlinde et al., 2004). Given the diversity of the models, a moderate level of harmonisation was chosen. A number of quantitative assumptions – economic and demographic developments, oil prices and current policies – have been harmonised, whereas technology-specific assumptions have not been harmonised. A consistent basis for harmonisation of a baseline scenario was provided by the SRES 'B2 marker scenario' (IPCC, 2000). Oil prices reflect assumptions of low to moderate resource availability. In the period 2000-2050, the world oil price is projected to increase from ca. 26 to 38 US$$_{95}$/barrel (4.2 to 6.2 €/GJ). Obviously there is a great deal of uncertainty to this assumption, and scenarios with higher oil and gas prices have also been explored (see Section F.7). Natural gas prices within Europe, although not explicitly harmonised among the models, are projected to increase from on average 2.3 to 5.4 €/GJ in 2000-2050. Finally, some representation of climate policy or emission trading for the region of Europe has been included, reflected in a generic carbon tax of 10 €/tonne CO_2 from the year 2012 onwards.

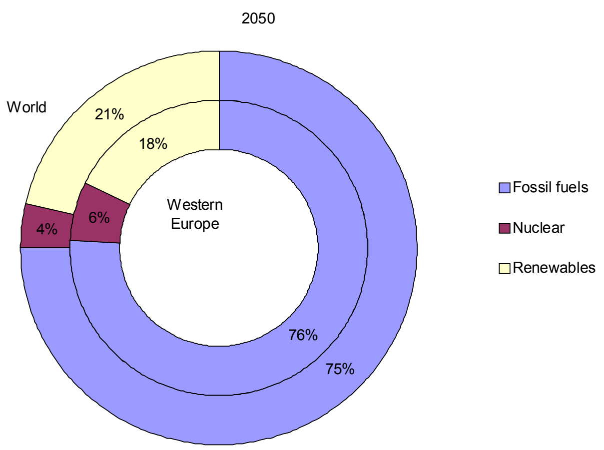
Because other important driving forces, such as technological change and average improvement of energy efficiency, were not harmonised, the set of baseline results from CASCADE MINTS is broader than the B2 group of scenarios. The added value of these variations is that they reflect uncertainty about future developments. Moreover, the diversity of the models will provide different views on the effectiveness of the policy approaches.

The overall picture arising from the synthesis of baseline projections is that in the coming decades, Europe's energy system is facing a number of challenges.

Continuing strong reliance on fossil fuels

Most of these are related to the continuing, worldwide, reliance on fossil fuels, with still a 70-75% contribution to the primary energy mix in 2030. All models indicate that fossil fuels are expected to remain dominant in the world fuel mix by supplying 65-80% of primary energy use (Figure F-1). Combined with the growth in primary energy consumption, this will result in an even faster depletion of the global natural resources than today. Although Europe's primary energy consumption shows a much slower growth than the world average - some 20% until 2030 -its reliance on fossil fuels (70-75% of the primary energy mix, depending on the model), is comparable to the rest of the world.

Figure F-1: Fuel mix of primary energy consumption in the world and Western Europe, 2050



Although the models show a consistent picture of the share of fossil and non-fossil fuels in future primary energy mix, they deviate on the contributions of individual fuels. In Europe, particularly the prospects of solid fuels and nuclear energy differ, due to different assumptions on technological development and costs. The power generation sector plays a key role in these fuel and technology choices. Coal consumption is expected to stabilise or grow. Some models expect nuclear energy to be phased out, due to high costs. There is a certain consensus on Europe's consumption of natural gas for power production, which is expected to increase significantly, and on the moderately increasing consumption of oil, mainly in the transport sector. Developments of energy prices may play a key role here.

On world level, a similar variation in projections exists. One of the models includes constraints on sulphur emissions, which induce a smaller share of particularly solids, and a substitution with nuclear and renewables.

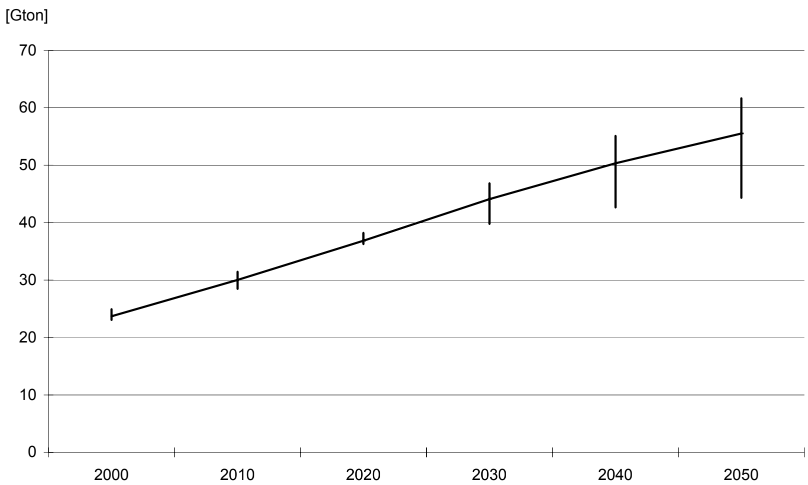
These observations have the following implications for Europe.

- Europe will encounter more competition on increasingly scarce fossil resources. Given the limited domestic resource base, the growing dependency on imported fuels, particularly oil and natural gas, will bring about more risks of high prices and supply disruptions.
- The differences in projections of the primary energy mix indicate that there is room for fuel switch, particularly in the power sector. The results indicate that the future development of use of energy sources may substantially be influenced by policies, such as emissions regulations and stimulating non-fossil fuels. Moreover, high oil and gas prices might accelerate changes in Europe's energy mix.

Worldwide a doubling in CO2 emissions in 2030 compared to 1990

Overall, the CO_2 emissions in 2030 are expected to be approximately twice the level of 1990, the base year of the Kyoto protocol. The largest growth of these emissions is expected to occur in the developing world, in particular in Asia. There is a large variation in emissions projections between models, related to the differences in the primary energy mix, particularly the share of fossil fuels. These differences are due to different assumptions on technological development and the associated technology costs.

Figure F-2: Range among global models in average energy related CO2 emissions projections



Although CO_2 emissions in Western Europe show moderate growth as compared to the global trend, it is not on track towards the target agreed under the Kyoto Protocol. Beyond 2012, assuming that some type of climate policy is in place in Europe, reflected in a moderate carbon tax of 10 €/ton CO_2, emissions are expected to continue their growth with ca. 0.4% per year.

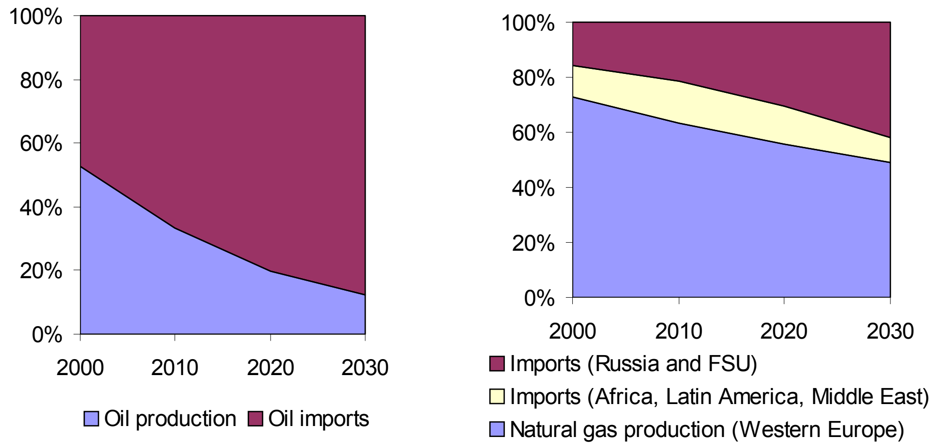
Security of supply becomes a key issue

Europe's dependence on oil from the Middle East is expected to increase up to 85%. As other world regions, such as Asia, also increasingly rely on oil from this region, this may lead to further oil price increases, which will particularly affect the transport sector.

Given the continuing global reliance on fossil fuels, an important issue in the years to come will be the increasing dependence on oil from the Middle East. Although the models show different projections of the evolvement of oil production, they agree that the contribution from the Middle East region grows, and becomes substantially larger. Given the large uncertainty on future oil price developments, confirmed by one of the models indicating that there is a substantial probability of sudden increases in the oil price, this may lead to increased concerns about the security of oil supply on the longer term, particularly in view of the present uncertain political situation in the Middle East.

For Europe, trends are in line with the global developments. Europe's oil consumption is expected to stabilise at about a third of its primary energy consumption in 2030. Domestic production however is expected to decrease due to limited reserves and high production costs, thereby introducing a greater reliance on imports up to 85% (Figure F-3).

Figure F-3: Shares of production and imports of oil and natural gas (Western Europe)



For natural gas, Europe's external dependency will also grow in the next decades. A continuing growth in gas consumption combined with a decrease of gas production in the UK, the Netherlands and Norway, will lead to a higher share of imports from the two main suppliers Russia and Algeria. Additionally, the accession of the new Member States and their heavy reliance on supplies from Russia increases the risks related to gas supply security.

There is another dimension to security of supply than dependency on imported fuels. The level of diversification is inversely related to the dependence on a few primary fuels, and is related to the correlation between the fuels in terms of costs and availability. The level of diversification may further influence the sensitivity of Europe to fuel supply disruptions.

- Europe's dependence on oil from the Middle East is expected to increase significantly in the next decades. Given the prospect that other world regions will also increasingly rely on oil from this region, this may indeed lead to further oil price increases, which will affect all economic sectors.
- An increase in diversification – for instance a growing contribution from renewables – may to a certain extent alleviate the increase in external dependence for oil and gas. In the current analysis, the models show large differences in their projections of Europe's future fuel mix, and thus in the expected level of diversification. This suggests that new policies may be required to stimulate an increased uptake of renewables or other sources.

F.4 Renewables can contribute significantly to a future sustainable energy system

F.4.1 Objectives and work performed

The objective of this work package was to analyse and assess policies imposing renewable energy.

ECN has coordinated WP2.2. This comprised the following activities:

- Propose, discuss and agree with project partners the setup of the policy cases to assess the possible contribution of renewable energy to a sustainable energy system. For WP2.2, the models were divided into two clusters (global models with a time horizon to 2050 and European models with a horizon to 2030). These clusters have analysed a global subsidy scheme for renewables and a European target for renewables in 2020 respectively.

- Coordinate the preparation of model inputs and production of policy cases by all models involved in the project. Coordinate the reporting of individual model results by providing a joint paper outline.
- Collect the results, analyse the policy cases and write a synthesis report [2]. The draft synthesis has been discussed with all modelling teams in order to achieve scientific consensus.
- Write a policy brief on the results of WP2.2.

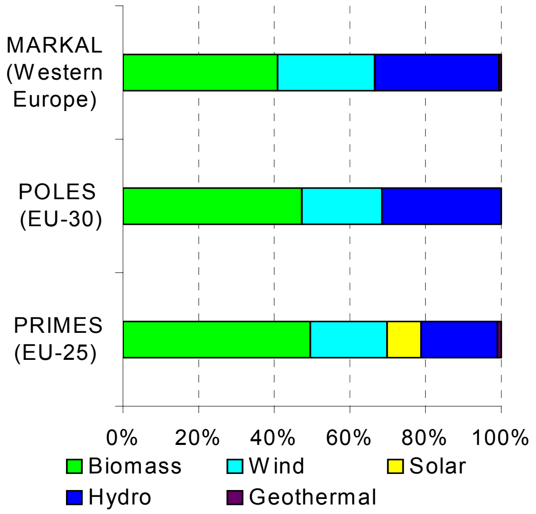
All project partners that participated in WP2.2 have used their model to calculate the policy cases and write a report on the results, including an analysis of the impact on GHG emissions and security of supply. These reports have been included as chapters in D2.2.

F.4.2 Summary of results and conclusions

In WP2.2, the role of renewables in solving global and European energy and environmental issues has been analysed (Uyterlinde et al., 2005). The feasibility of a 20% renewables target in 2020 for Europe has been assessed, and seems to be within reach, provided energy demand reductions are pursued simultaneously.

Allocation over sectors

Figure F-4: Shares of renewable technologies and resources in Europe's primary energy consumption in 2020



If renewables sub-targets for different sectors were to be imposed, the analysis shows that the power sector offers most of the technology switching options. Most of the models demonstrate that a share of 33% renewable electricity consumption is achievable in 2020 (incl. large hydro). However, this should be contrasted with the current expectation that the 21% indicative target for 2010 for the EU-25, as stated in the Renewables Directive (2001/77/EC), will only be achieved if several Member States intensify current support policies.

The transport sector is expected to play an important role for various reasons. First, this is also a sector that offers good opportunities for increased penetration of renewables, e.g. biofuels for transportation. Secondly, the penetration of biofuels has a direct impact on the import dependency for oil, and on CO_2 emissions from transportation, which makes the promotion of biofuels a strategic choice for Europe. However, there may be future bottlenecks due to the limited availability of biomass, and the competition for biomass resources that can be applied both for power generation and converted to biofuels.

Contributions from other sectors will also be required to achieve the 20% target. Imposing a carbon cap on the emissions of the industry sector has shown that this sector does not have much room for a more renewable energy supply. The use of biomass in the industry would be possible, but suffers from competition with applications in the transport sector.

Emission reduction in 2020 up to 20%

If the share of renewables in Europe increases to (almost) 20%, the share of fossil fuels in Europe reduces roughly from 75% to 65%, which has positive implications for greenhouse gas emissions and security of supply. In 2010, energy-related CO_2 emissions are some 10% lower than in 1990 (according to PRIMES for the EU-25), indicating that Europe's Kyoto target is within range. In 2020, energy related CO_2 emissions are reduced with 9-21% compared to the baseline. The amount of emission reduction depends on the sectoral distribution of the renewables contribution and on which fossil fuels are substituted. These factors differ by model. Although the reduction is substantial, it is not sufficient for post Kyoto targets, and other mitigation measures must also be explored.

Positive impact on security of supply

As far as supply security is concerned, the impacts are positive, albeit limited. Only in case of large substitution of oil in the transport sector, import dependency is significantly reduced, as one of the models reports on a reduction of import dependency of 14% points. Regarding gas import dependency, the impact is more modest with 2-4% point reduction in 2020 compared to the baseline, which is not sufficient to counter the increasing trend in this indicator. On the other hand, the diversity of Europe's energy mix, as measured by the Shannon indicator[2], improves with 6-8% points to 76%, indicating that adding renewables helps to reduce future risks.

Economic impacts

The costs associated with the renewables targets are in the range of 0.5% of (baseline) GDP. In addition, the economic models show that the costs of renewables may lead to higher electricity prices, and to slower economic growth. On the other hand, welfare implications appear to be limited.

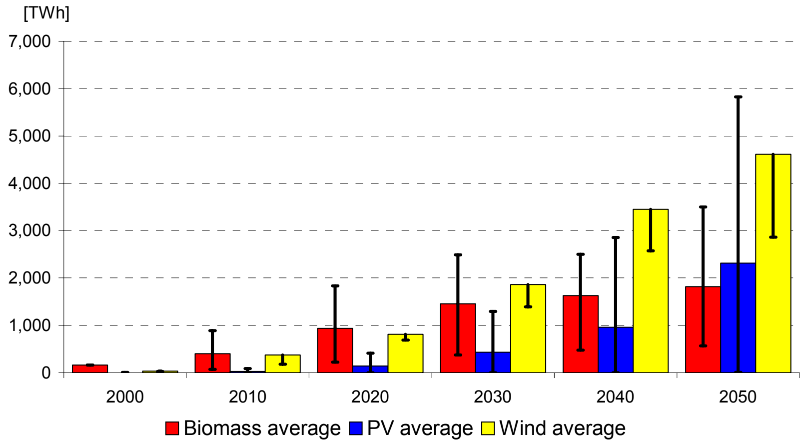
Increased penetration of renewables is often expected to lead to employment gains, because renewables energy production is more labour intensive than conventional energy production, and because it may substitute imported energy. The economic models do not agree on how the renewables target in the power sector may affect employment. One model reports a 1.8% overall increase in employment, while another model projects a 0.15% decrease for Europe. The third economic model is based on the assumption of full employment, but does report a clear shift towards employment in renewable electricity production sectors.

Some considerations should be added on how well employment effects can be evaluated with the economic models used in this project. It may be that the direct gains in employment due to the renewables targets are counterbalanced by job losses in other parts of the economy. This crowding out effect can be due to the scarcity of highly skilled labour or to the fact that the subsidies required for supporting renewable energy replace other subsidies. Therefore, net employment effects are strongly related to the structure of the labour market, wage determination and the differences in productivity in different sectors and types of labour force, and should be assessed by dedicated models that incorporate the structure of the labour markets in the different EU Member States, which is beyond the scope of the project.

Long term - the global perspective

When extending the focus to the longer term, say until 2050, a restriction of the efforts to the European Union only is unlikely to provide a realistic view on future prospects of renewable energy systems. Therefore, in the study three global models (DNE21+, GGM, and MESSAGE) have been used to analyze the long-term perspective for RES. These models show that when the industrial world takes the lead, global penetration of renewable systems may be achieved for those technologies that show an aptitude for cost decrease.

Figure F-5: Global electricity production from biomass, PV and wind under a subsidy scheme of 20 €/MWh, decreasing to zero in 2050; averages over three models and ranges



Source: MESSAGE, GMM and DNE21+

Figure F-5 presents the trends for three important options for renewable electricity production. These technologies are presented here, because the models largely differ in what they expect under the modest subsidy scheme of 20€/MWh implemented in the power sector. The assumption is made that subsidies gradually decrease, so that in 2050 the systems are no longer subsidized. This subsidy scheme reflects a situation where the policy maker is willing to provide a subsidy for market uptake, but is decreasingly willing to support systems that are not entering the market by itself.

Biomass shows the most limited growth. This is partly due to the fact that biomass resources are also used for other applications, e.g. in the transport sector. For wind power, substantial growth figures are projected by all models. Most of the capacity is installed in the industrialised world. For PV, the differences among the model results are extremely large, reflecting the uncertainties on how the costs of this technology will develop. In one of the models (MESSAGE) where it is assumed that R&D spending and direct investment in a

[2] An indicator often used to measure species diversity in a community. It reflects not only the number of energy carriers present in the fuel mix, but also the relative abundances of different energy carriers.

broad portfolio of solar technologies has contributed to important reductions of the investment cost for the PV technology, a worldwide production of over 5.000 TWh can be achieved already without additional subsidies. This corresponds to some 1700 GW capacity, which is installed mainly in Asia, Africa and South America, where the potentials are large. On the other hand, there is a model (GMM) with endogenously determined cost reductions due to learning by doing, which expects hardly any penetration of PV under the modest subsidy levels in the current case.

Conclusions

Bioenergy is one of the key renewable options because of its large potential and its different possible applications. A strong growth of biomass deployment is required for achieving ambitious renewables and climate targets. Policies in different areas such as energy, agriculture, and environment should be further streamlined in order to overcome current barriers. Efforts directed towards the transport sector combine several benefits, because the substitution of oil with biofuels improves both security of supply and reduces carbon emissions. Implementation of renewables is currently most straightforward in the power and transport sector, but to achieve further growth towards 2020, applications should involve other end-use sectors. For instance the potential in the building sector, including renewable heating and cooling options, such as solar thermal water heaters or biomass-based district heating should be further exploited. Finally, subsidy schemes should offer differentiated support and stimulate learning effects. It is important to target the subsidies correctly. If only one sector is subsidized, the renewable share in this sector will be high, but there may be 'carbon leakage' to other sectors, due to a shift in application of biomass, and the share in primary energy is only mildly affected.

F.5 Nuclear energy - one of the options to address global energy challenges

F.5.1 Objectives and work performed

The objective of this work package was to analyse and assess policies imposing nuclear energy.

As coordinator of Part 2, ECN has cooperated with the WP leader IPTS in the following activities:

- Propose, discuss and agree with project partners the setup of the policy cases to assess the possible contribution of nuclear energy to a sustainable energy system. For WP2.3, four scenarios were designed: 1) Baseline & nuclear breakthrough 2) Carbon value (tax) 3) Carbon value & nuclear breakthrough 4) Carbon value & nuclear phase-out.
- Coordinate the preparation of model inputs and production of policy cases by all models involved in this WP. Coordinate the reporting of individual model results by providing a joint paper outline.
- Collect the results, analyse the policy cases and write a synthesis report. The draft synthesis has been discussed with all modelling teams in order to achieve scientific consensus.
- Write a policy brief on the results of WP2.3.

All WP2.3 participants have used their models to calculate the policy cases and write a report on the results, including an analysis of the impact on GHG emissions and security of supply. These reports have been included as chapters in D2.3.

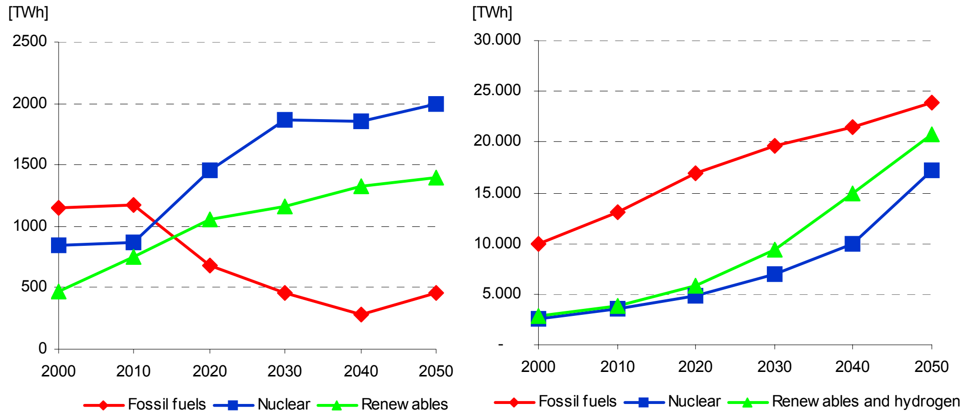
F.5.2 Summary of results and conclusions

Nuclear energy is a controversial subject for policy making on energy and environment because of arguments concerning radioactive waste, reactor accidents, nuclear proliferation, economic competitiveness and public opinion. The issues of climate change and supply security have provided a new rationale for its reappearance on the international political agenda. In the CASCADE MINTS analysis, two distinct, rather opposite scenarios have been considered (Uyterlinde et al., 2006a). They highlight the consequences of either following a strict phasing-out path of nuclear power generation capacities, as opposed to the situation where nuclear technology exhibits a 25% investment cost drop. In this Renaissance case, the assumption is also made that improved safety characteristics lead to an increased acceptance of nuclear power. Both scenarios have been analysed in combination with a rather strong CO_2 policy, reflected in a CO_2 price (carbon value - CV) rising from 10 to 50 and 100 €/tonne CO_2 in 2010, 2020 and 2030 respectively.

Impacts of a nuclear renaissance

Nuclear power technologies may be instrumental at achieving strong climate policies at acceptable costs, provided that a breakthrough in costs occurs. In that case the growth in the use of nuclear power can be substantial, and the annual average increase in installed capacity may surpass the height of the nuclear era in the early seventies. At the same time the realisation of the cost reduction may require substantial R&D expenditures. Still, it is evident that nuclear energy can constitute no panacea to the problem of global warming. Even with a massive expansion, nuclear energy can at best only be part of the solution, and should be complemented by drastic fossil fuel decarbonisation and a massive development of renewables, preferably in combination with far-reaching efficiency and savings measures. Until 2050, a substantial increase in nuclear energy use does not represent an acute threat to the cumulative uranium reserves if the speculative - and to date undiscovered- resources are considered. However, the cost of nuclear fuel supplies might increase.

Figure F-6: Electricity generation by fuel in Europe and the world for the Renaissance & CV case



Source: MARKAL and GMM.

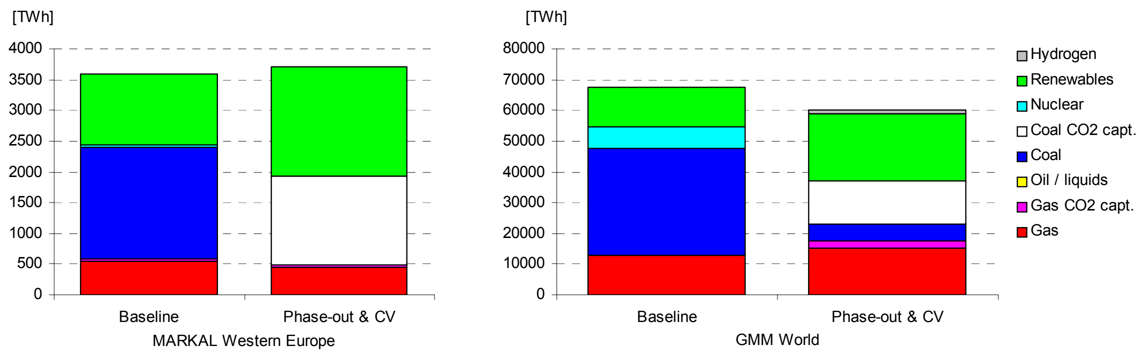
Additional obstacles that are associated with the competitiveness of nuclear energy are the public acceptance, disposal of spent fuel and radioactive waste, proliferation, and risks of severe accidents. These issues might to some extent be addressed by the introduction of new nuclear technologies. Advanced nuclear reactors might see substantial higher reactor efficiencies, lowering the use of nuclear fuel. Alternatively, these may enable the use of alternative fuels such as thorium. Reprocessing may reduce the amount of dangerous waste as well as decrease the demand for raw nuclear resources. Finally, yet more unconventional concepts such as breeder technology or the combination with accelerator technology might address the resource problem and the waste issues at the same time. However, all of these require developments that go beyond the current state of affairs, and have not been analysed in this study.

While today not being a sustainable energy resource, nuclear energy - along with other presently available energy options- could play a transitional role towards establishing sustainable energy systems.

Impacts of a nuclear phase-out

If all industrialised countries follow a strategy to retire their nuclear sites at the end of the economic lifetime, it is more difficult to achieve ambitious emission reduction targets, as one of the carbon-free options is removed from the energy system. The phase-out of nuclear generation capacities will partly offset the emission reduction achieved by increasing CO_2 prices. Renewables, natural gas and coal with CO_2 capture and storage are key options in a future without nuclear power plants. Natural gas consumption may increase, and can be up to 15% higher in 2030 compared to the baseline, causing Europe to be even more dependent on natural gas imports until 2030. In the long run, due to the limited gas reserves, this might not be a sustainable situation. The phase-out has negative impacts on the GDP and welfare that are slightly stronger than the impacts of the carbon value alone. Higher electricity generation costs will lead to higher input cost for electricity intensive production, and countries characterized by higher shares of nuclear in their power generation will face electricity price increases of 10-30% by 2030.

Figure F-7: European and global power generation mix in 2050; Phase-out & CV case



Source: MARKAL and GMM.

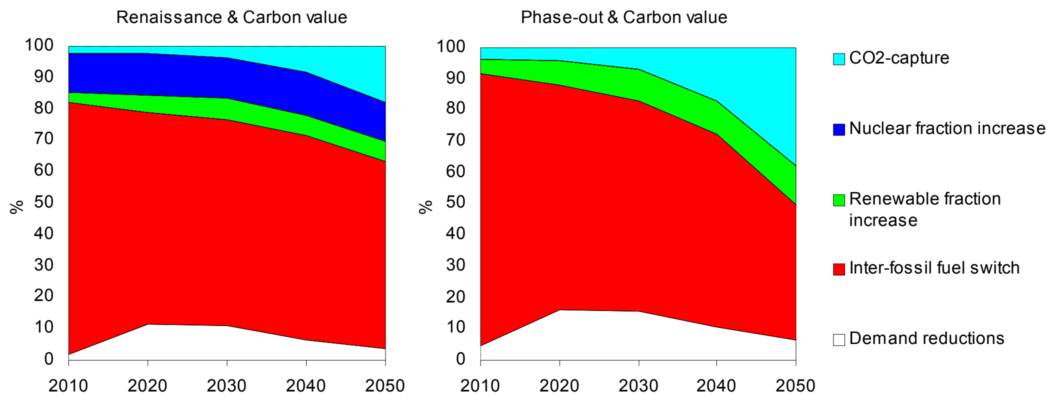
Although a nuclear phase-out in Europe appears to be feasible even in a Post Kyoto scenario, it is more difficult and costly to achieve strong CO_2 emissions reductions, and it requires a large penetration of renewables and advanced sequestration technologies. Moreover, although the impact of the phase-out in Europe seems to be relatively modest in the time frame until 2030, it might lead to more serious problems later.

Finally, improving international safeguards and institutions should have high priority, whatever the future share of nuclear energy in power production. The importance of the International Atomic Energy Agency (IAEA) in this is fundamental, as proliferation risks will remain even if the civil use of nuclear power were phased out entirely.

Emission reduction induced by carbon tax

The importance of nuclear energy as compared to other options within the carbon mitigation strategy is illustrated in Figure F-7, where a breakdown of different CO_2 reduction components is provided. In general, an inter-fossil fuel switching, e.g., substitution from coal to natural gas, plays the dominant role in the global CO_2 abatement process in all CO_2 constrained cases. However, important differences are observed for the role of nuclear energy, CO_2 capture and renewables. In the Renaissance & CV scenario, nuclear energy contributes by about 13% to the overall mitigation between 2010-2050 and is the second most important player in the cumulative carbon abatement. Exclusion of nuclear energy from the portfolio of abatement options in the Phase-out & CV scenario results in a rapid increase of the contribution of CO_2 capture (38% in 2050[3]). Similarly, the fraction of renewables and demand-reductions is higher as compared to carbon-taxed cases allowing for utilization of nuclear power. Implication of this result is that the policies in favour of nuclear power can shift the need to invest in other capital-intensive technologies, e.g., CO_2 capture or renewables, towards later decades.

Figure F-8: Breakdown of CO2 reduction components



Source: GMM.

Impacts on security of supply mainly for natural gas and coal

For European models, the shifts in power generation mix visible in the renaissance case do have some impacts on the Europe's import dependency for coal, which is significantly reduced, and for natural gas, which slightly decreases in most of the models. The import dependence for oil is hardly affected. Of course, the growth in nuclear capacity in this scenario would require imports of uranium, but these would likely come from other world regions than the Middle East, relieving the dependence on this region. Similarly, a nuclear phase-out in Europe would not affect the import dependency for oil, while it could lead to a small increase in the dependence on imports of natural gas.

Conclusions

Two main conclusions can be drawn. First, the analyses have shown that a nuclear phase-out in Europe is feasible, even in a future with a strong climate policy. However, in this case, renewables, natural gas and advanced coal-fired plants with CCS are key options, and achieving climate goals is more costly. Consequently, the dependency on natural gas imports would increase even further than already expected in a business as usual scenario. Secondly, nuclear energy could be an important component of carbon mitigation strategies, under the condition that the risks related to reactor safety and proliferation are dealt with or accepted, and that long-term solutions for the disposal of radioactive waste are found. With the assumption that carbon prices reach a level of 100 €/tonne CO_2 in 2030, nuclear power plants could somewhat reduce

[3] In the Phase-out scenario, the cumulative amount of CO_2 captured and stored in the period 2010-2050 is 132 Gton CO_2. This corresponds to about 13% of the global cumulative storage-potentials in depleted oil and gas fields estimated by IEA (2004).

the import dependency of natural gas, and could contribute to up to 50% of Western Europe's power generation mix.

F.6 Impact of CO2 capture and storage (CCS)

F.6.1 Objectives and work performed

The objective of this work package was to analyse and assess policies imposing CCS.

As coordinator of Part 2, ECN has cooperated with the WP leader IIASA in the following activities:

- Propose, discuss and agree with project partners the setup of the policy cases. The case studies compared policy schemes concentrating on technology standards, emission caps and investment subsidies for CCS technologies.
- Coordinate the preparation of model inputs and production of policy cases by all models involved in this WP. Coordinate the reporting of individual model results by providing a joint paper outline.

All project partners that participated in WP2.4 have used their model to calculate the policy cases and write a report on the results, including an analysis of the impact on GHG emissions and security of supply. These reports have been included as chapters in D2.4.

F.6.2 Summary of results and conclusions

CO_2 capture and storage (CCS) is increasingly mentioned as one of the options in the portfolio to mitigate climate change. Two policy approaches are compared in order to address the question how to achieve significant CO_2 emission reductions through the application of CCS technologies (Uyterlinde et al, 2006b).

- Case 1: 'CCS standards' requires that from 2015 onwards, all new power plants have to be equipped with a CO_2 capture facility. These standards are not applied to peaking plants with a utilisation rate of 20% and small CHP-plants.
- Case 2: 'CO_2 emission cap' takes the emission level from the Standards case as an upper bound for the overall emissions. No other policies are assumed.

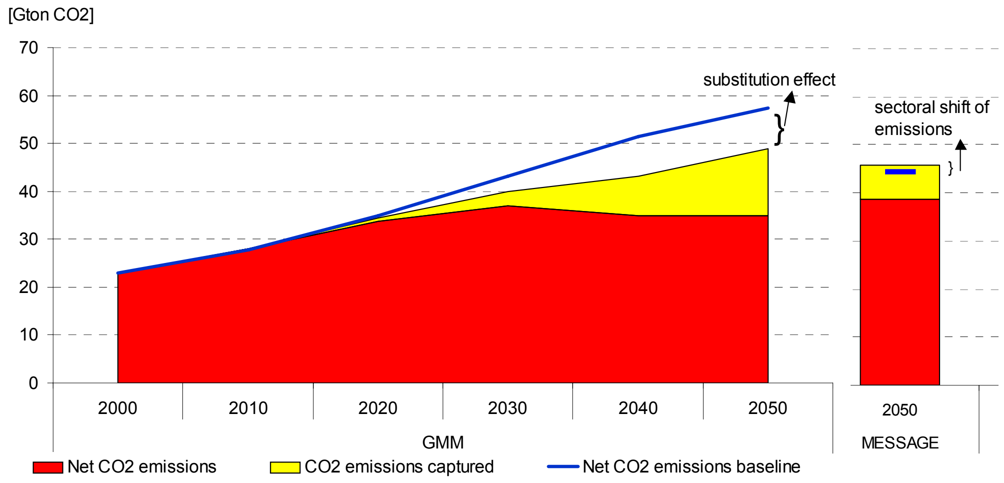
Most models have applied approximately the same set of capture technologies. Post-combustion systems, that separate CO_2 from the flue gases after combustion, are generally coupled to supercritical pulverised coal (PC) plants, or to natural gas combined cycle power plants (NGCC). Pre-combustion systems, which extract the CO_2 and combust or use the resulting hydrogen, are used in combination with an integrated coal gasification combined cycle plant (IGCC), or with a biomass gasification plant. Oxyfuel combustion, which is still in a demonstration phase, has not been modelled. Some models have also included CO_2 capture in hydrogen production processes (gas steam reforming or coal partial oxidation) and in industry, in the production of cement, cokes, and ammonia. The models do not take into account non-economic aspects of CCS that may inhibit the deployment, such as public acceptance, risks and safety regulations and upstream environmental impacts. There are differences in how transportation and storage of CO_2 is modelled. Some models have a wide array of storage options with capacities whereas others have a generic storage technology with infinite capacity. This does have an effect on the results, since for some models, the revenues related to hydrocarbon recovery greatly contribute to making CCS viable. The modelling of transportation costs also varies.

Regulatory CCS standards compared to a global CO2 emission cap

Under the assumption of the regulatory CCS standards, 16% to 30% of global CO2 emissions can be captured in 2050, as illustrated in Figure F-9. According to the different global models used, this corresponds to a range of 7 to 19 Gton CO2 captured and stored in 2050. For Europe, due to a more limited growth of the power sector than in some other world regions, this would amount to some 21%-23% of total CO2 emissions. One of the factors underlying this range is the large variation in emissions projections among the models, which is related to the differences in the projected primary energy mix, particularly the share of fossil fuels. Other important explanatory factors are the assumptions related to technology learning and future costs of CCS technologies and renewables, as well as the growth constraints or potentials of the main carbon-free energy sources, nuclear and renewables.

The CCS standards not only induce the large-scale introduction of CCS systems in the electricity sector, but they also accelerate the penetration of nuclear and renewable energy sources. This 'substitution effect' is due to the fact that the application of CCS makes electricity generation more expensive and therefore other options become more competitive. For this reason, the emission reduction compared to the baseline is even larger, up to 40%, in most models. Generally, it more than compensates the 'energy penalty', e.g. the energy use and related emissions due to the additional energy needed for the CO_2 capture and storage processes themselves. However, one of the models (MESSAGE) points out that imposing CCS standards within the power sector may lead to a considerable shift ('leakage') of emissions to other sectors. The increase of biomass use for power production, for instance, induces more use of fossil methanol instead of bio-ethanol in the transport sector.

Figure F-9: Global net CO2 emissions and amount of CO2 captured in the CCS Standards case compared to net CO2 emissions in the baseline



A global CO_2 emission cap results in a lower penetration of CCS technologies, but reaches the same emission reduction at lower costs. Generally, this policy instrument induces a stronger increase in the contribution of renewable energy sources and nuclear power. There may also be a shift towards natural gas power plants instead of coal capacity. There are clear differences between the models concerning the timing and extent of CCS penetration, related not only to the differences in projected fuel mix, but also to the severity of the CO_2 cap, which is derived from the emission reduction realised in the CCS standards case.

Sufficient storage capacities towards 2050

There is an ongoing scientific debate on how the CO_2 storage capacity should be estimated. Any site needs a detailed geological survey in order to make a reliable estimate of the suitability of the reservoir for storage of CO_2. Although acknowledging the controversies in the scientific literature on this issue, the CASCADE-MINTS project used conservative estimates in line with the IPCC Special Report, and arrives at the conclusion that the availability of storage capacity does not impose limits to the amount of CO_2 stored in the time frame to 2050.

Figure F-10: Cumulative amount of CO2 stored in 2020-2050

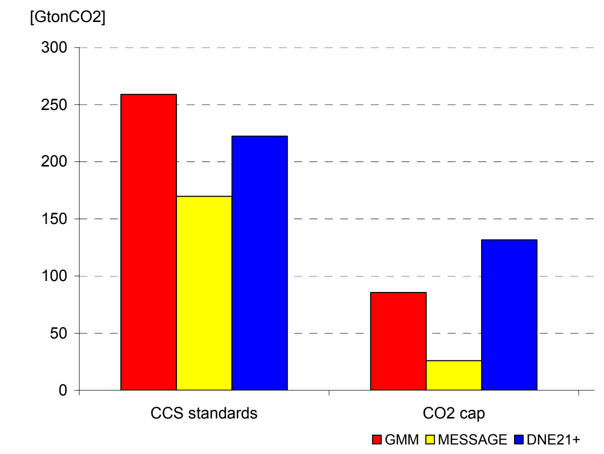


Figure F-10 presents the cumulative amount of CO2 stored under the different policy cases, for three world models. These models report that under the CCS standards policy for new fossil power plants, the global, cumulative amount of CO_2 captured and stored in 2020-2050 is in the range of 170 - 260 $GtCO_2$. Acknowledging that the power plants built towards 2050 will need enough storage capacity for the decades to come, this still seems well below IPCC estimates (IPCC, 2005) of 675-900 $GtCO_2$ of cumulative potential for CO_2 storage in global gas and oil fields. Also in Europe, storage potentials appear to be sufficient. There are differences among the models in what kind of reservoirs are used. These differences are closely related to the uncertainties in storage potentials as a result of the huge variety in local geological circumstances.

Conclusions

From a comparison of the policy cases, a number of conclusions can be drawn. The most general observation is that the models investigated are broadly in agreement: they confirm that CCS is likely to play a role in cost-effectively reducing CO_2 emissions. However, the actual deployment of CCS not only depends on its technical and economical characteristics, as taken into account by the models, but also on several other important aspects, such as the importance of the availability of reservoirs near a point source of CO_2 was already mentioned. The potential and characteristics of CO_2 storage reservoirs remain uncertain, although several studies aim at reducing this uncertainty. Furthermore, several legal and regulatory issues, related to risks and liabilities still need to be dealt with, and not much is known yet about public acceptance. Finally, CCS has not yet established itself in the climate change negotiations, and it needs an accepted accounting methodology in the Kyoto regime.

The first policy instrument analysed, which obliges new fossil power plants to install CCS technologies as of 2015, shows that 16% to 30% of global CO_2 emissions could be captured in 2050. These amounts could be regarded indicative of the maximal CCS penetration achievable by 2050, as the more flexible global CO_2 emissions cap induces a much lower CCS uptake, while at the same time there are several mechanisms limiting the effectiveness of any policy focusing exclusively on CCS. First, the inertia in the power sector will slow down the penetration of CCS technologies, as plants built before the introduction of the standards regime are allowed to operate until the end of their lifetime. Secondly, imposing a strict standard requirement on one sector alone leads in some cases to moving the carbon intensive fuels to sectors where no such requirements are imposed. Third, it is difficult to target such a policy well, as it may easily provide an incentive for fossil-based technologies not covered by the standard, such as peak-load gas plants. Finally, the introduction of a CCS standards policy is often much more costly than imposing a CO_2 cap that reaches the same emission reduction.

F.7 Trade offs and synergies

F.7.1 Objectives and work performed

The objective of this work package was to analyse and assess trade-offs and synergies between policies aiming at CO2 capture/storage, renewables, nuclear or hydrogen.

ECN was WP leader for WP2.5 and has therefore performed the following tasks:

- Propose, discuss and agree with project partners the setup of the policy cases. The case studies have analysed the effect of (additional) technological progress against a background of ambitious climate policy and/or high oil and gas prices.
- Coordinate the preparation of model inputs and production of policy cases by all models involved in this WP. Coordinate the reporting of individual model results by providing a joint paper outline.

Achievements:

- Consensus on policy case setup
- Quantitative model results
- Synthesis report and policy brief

All project partners that participated in WP2.5 have used their model to calculate the policy cases and write a report on the results, including an analysis of the impact on GHG emissions and security of supply. These reports have been included as chapters in D2.5.

F.7.2 Summary of results and conclusions

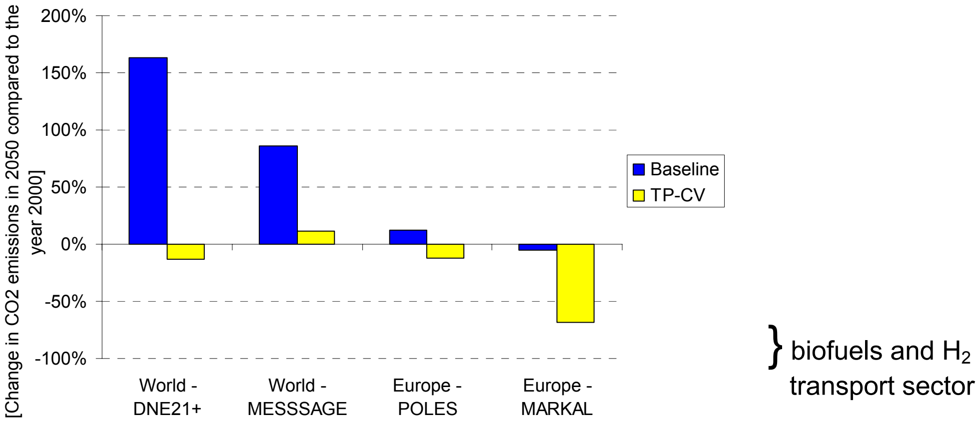
In order to analyse the trade-offs and synergies between the various technologies for which particular policy measures were investigated previously in the project, this case focuses on the possible role and impact of technology progress in the energy system. At the same time, a close relationship to the policies of the EU is desired, and particularly to those related to greenhouse gas emissions or security of supply. Therefore, a set of policy cases has been designed, based on assumptions on enhanced technological progress, combined with CO_2 values and high oil & gas prices (Uyterlinde et al, 2007a).

Impact of a strong climate policy

The primary aim of a strong carbon policy is to reduce the emissions of CO_2 so as to minimize the effects of the enhanced greenhouse effect. In the case study considering such a policy, an increasing carbon value has been assumed, rising to 100 €/tCO_2 in 2030 and beyond. The models are unanimous about the decreasing share of oil and particularly coal in the primary energy consumption as a result of the policy, although there is some uncertainty over the size of the reduction. The potential role for natural gas in a world with a strong carbon policy is strongly linked to the success of its competitors: renewables and nuclear. At world level, the emission reduction ranges from a mere 40% to as much as 67% by 2050, relative to the baseline. It is important to notice that the baseline projections for CO_2 emissions in 2050 among models differ substantially, as shown in

Figure F-11, due to different estimates for the role of renewable technologies, in particular learning effects for wind energy and biomass. At European level, the shift to renewables, coal with CCS, and possibly nuclear power allows CO_2 emissions to be reduced with 21%-54% in 2050. When the possibility of enhanced technological progress is added, the transport sector, thanks to the breakthrough of fuel cell cars, may contribute with up to 10% additional emission reduction.

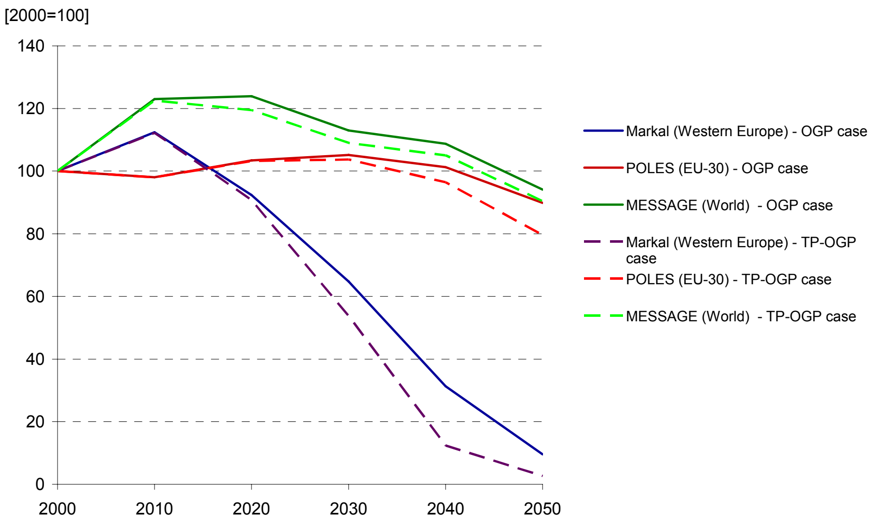
Figure F-11: Change in CO2 emissions in 2050, relative to the year 2000, under baseline conditions and with ambitious climate policy combined with enhanced technological progress.



High oil and gas prices: the return to coal?

If the price of oil increases up to 110 $/barrel in 2050, and natural gas prices also rise substantially above the baseline level, as is projected in the high oil and gas price (OGP) scenario, the contribution of oil to the primary energy consumption is substantially reduced, as well as the consumption of natural gas. The transport sector is most sensitive to increases in oil prices, and to some extent, gas prices. In Europe, according to POLES, by 2050, the consumption of oil-based automotive fuels (diesel and gasoline) could be reduced by more than a quarter (compared to baseline developments) and substituted mainly by hydrogen. The MARKAL model expects an even faster adjustment of the transport sector and shows a large penetration of biofuels, which could replace virtually all oil in 2050. The passenger car fleet consists largely of ICE cars on biofuels and some 10% CNG cars. The enhanced technological progress gives momentum to the hydrogen based passenger cars, mainly fuel cells cars. Thus, in the TP-OGP case, models estimate 20-95% of the European passenger car fleet in 2050 to be based on hydrogen.

Figure F-12: Consumption of oil in the transport sector relative to the year 2000; cases OGP and TP-OGP



Enhanced technological progress

In this case study, *enhanced* technological progress in terms of investment cost reductions has been modelled to reflect the impact of additional R&D policies on top of the considerable technological progress already represented in the baseline and policy cases. It should be stressed that this case set-up does not cover all possibilities for progress in the techno-economic characteristics of technologies. Looking more closely at the role and contribution of this enhanced progress, it appears to have the most significant impacts on hydrogen production, storage and consumption and on the use of renewables (wind and solar PV) for power generation. This may lead to a reduction of Europe's dependence in electricity imports. All energy system models indicate that the enhanced technological progress leads to a decrease in overall costs of a few percent, both for the carbon policy as well as for the high oil and gas price scenario.

Furthermore, models with endogenous technological learning show the most sizeable impacts of enhanced technological progress, because the impacts of the other drivers (carbon value, high oil and gas prices) are reinforced by the stronger cost reductions as a result of higher volumes of carbon-free technologies. Since this reflects the effect of learning-by-doing, it indicates that the impact of enhanced technological progress may in reality be stronger than what has been shown by most of the models in this case study. However, it remains a challenge to design R&D policies that actually achieve these stronger cost reductions.

Hydrogen can play a significant role in meeting challenges posed by the introduction of climate policies or increasing oil and gas prices. Enhanced technological progress in general does not necessarily lower the barriers for hydrogen, as competitors may also profit from increased research efforts, but if the effort is aimed specifically at hydrogen technologies, enhanced technological progress will considerably speed up the uptake of hydrogen in the energy system.

Different policy objectives

Climate policies do not necessarily result in increased security of supply – depending on the role of natural gas. The changes largely take place in the power sector, where the contribution of coal remains uncertain, as it depends on the estimates for costs and potential of CCS. Security of supply policies do not automatically lead to CO_2 emission reductions. The implications of high oil and gas prices for Europe are not necessarily environmentally favourable, as there is a tendency towards coal, even though renewables also benefit. In principle, nuclear power is an alternative to gas in the power sector, its expansion, however, depends on political decisions.

The combination of a strong climate policy and high oil and gas prices is a strong incentive in a sustainable direction. As illustrated by the 'combined case', Europe could introduce a carbon value to counter the adverse environmental impacts of high oil and gas prices. This would specifically provide opportunities for renewable energy technologies, which have shown to possess a large potential for learning and associated cost reductions. Alternatively, the prices of oil and gas could be decoupled, to prevent the undesired shift to coal without CCS.

F.8 Overall conclusions

F.8.1 Objectives and work performed

The objective of work package 2.6 was to communicate the project results with policy makers and disseminate the results.

ECN was WP leader for WP2.6 and has therefore performed the following tasks:

- Discuss the overall conclusions with partners and with the Commission's project officer
- Prepare a final report in which the results of all simulation exercises are compared, conclusions are drawn and further topics for modelling research are suggested + preparation of an executive summary for wider dissemination
- Translate the conclusions from model results into an accessible policy brief for each work package
- To compile, in cooperation with project partners, an E-mail list of policymakers in Europe for which the project results may be relevant
- Use this E-mail list for announcing the publication of project reports and to distribute policy briefs
- Distribute the policy brief through other relevant E-mail fora (i.e. climate-l)
- Actively seek opportunities to present the results of the project to policymakers and researchers

Achievements:

- Synthesis reports and policy briefs
- Dissemination

Contractors involved: All project partners have contributed in commenting on the policy briefs and have written overall conclusions based on their models. Furthermore, all project partners have undertaken dissemination activities or intend to do so.

F.8.2 Summary of results and conclusions

A more sustainable energy system requires a portfolio of technological options. The problems faced by Europe and the world are of a magnitude for which no single technology is the solution. Some of the options benefit both the climate problem and security of supply, and thus provide synergies, while others represent trade-offs for the policymaker (Uyterlinde et al, 2007b).

Solid fuels
The case studies have shown that high oil and gas prices induce a shift towards solid fuels, as coal is a cheaper and more abundant alternative to other fossil fuels (oil and gas), with more and more applications, not only for power generation, but through a gasification process also for synthetic fuels that can be used for transportation. Given the fact that coal resources are relatively abundant and well spread over different world regions, European security of supply definitely improves with an increased share of coal. However, the use of coal potentially is a threat to the environment, and it needs clean technologies such as CCS to prevent environmental drawbacks. Furthermore, coal mining is also not always done in a sustainable way.

Nuclear power
The role of nuclear power largely depends on the public and political acceptance of this option. The scenarios analysed in this report have shown that, when this acceptance is no limiting factor, and investment costs drop with 25%, nuclear energy could have a share up to 50% in the European power generation mix, and 30% in the global power mix, as it is attractive in terms of costs and hardly generates polluting emissions. Europe's security of supply would benefit from a larger penetration of nuclear, as uranium resources are mainly found in Australia, Canada and Kazakhstan. However, the trade-off with other options here involves questions of safety, proliferation, and nuclear waste storage for many centuries to come. Conditions for increased acceptance would therefore comprise the development of inherent safe reactor systems, better utilisation of fissile material and shortening of waste lifetime. The scenarios also show that a nuclear phase-out is feasible, even under a strong climate policy, but does increase dependency on natural gas, CCS, and renewables.

Hydrogen
Hydrogen can certainly play a role in meeting challenges posed by climate change and scarcity of fossil fuels. Hydrogen is mainly used to substitute oil in private transportation, where the main competitors for fuel cell cars are biofuels (in case of climate policy) and fossil methanol or CtL (in case of high oil prices). The models have shown considerably different penetration speeds. To some extent, this is due to the difference between simulation and optimisation models, and this illustrates the difference between incremental and radical innovation. For hydrogen, which needs strong cost reductions, and imposes new infrastructure requirements, strong policies with a long-term vision will be particularly important, because incremental innovation will probably not be sufficient to lower these barriers. High oil and gas prices seem to provide a stronger incentive for hydrogen use in the transportation sector than ambitious climate policy, while the application of CCS is essential for successful market introduction of fossil-based hydrogen in a carbon constrained world.

Biomass
In many of the scenarios analysed, particularly those on renewables, the key role of biomass has become clear. An increasingly important trade-off will be where to apply the scarce biomass resources, in view of competing applications in the power, transport and heating sectors, apart from the non-energy uses such as food production. Security of supply might be a stronger driver than greenhouse gas emission reduction, because of the lack of alternatives for oil in transport sector, and because biomass is not carbon-free but rather carbon neutral. Other sustainability issues, such as land use, biodiversity, emissions due to fertiliser use, and water requirements are also becoming increasingly important. It is expected that in the future, most biomass will be used in gasification processes with many different applications.

Natural gas
From the range of fossil fuels, natural gas fits best in a carbon constrained world. Although in the baseline, gas demand grows faster than total consumption, this level is usually not achieved in the policy scenarios, where its prospects depend on the success of competitors such as renewables or nuclear in the power sector, or biofuels in the transport sector. Natural gas has a key role when it comes to security of supply. A strong climate policy may induce an increasing role for natural gas, which can further increase Europe's dependency on gas imports. However, in case of higher CO_2 prices than the 100 €/ton CO_2 assumed in this project, the role of natural gas will probably become more marginal.

CO_2 capture and storage
Finally, as already alluded to, CO_2 capture and storage (CCS) appears to be essential for the perspectives of hydrogen in a carbon-constrained world, while it is also vital for the prospects of coal. According to the scenarios assessed in this project, CCS on coal-based power plants, notably IGCC, is preferred over gas-fired plants. This implies that especially for countries with a booming demand for cheap (often coal-based) energy, CCS could still allow for a low-carbon energy supply. The application of CCS could lead to an increased reliance on coal, thus increasing security of energy supply.

However, there is still a large uncertainty on the potential for CCS and when it will become available, while legal issues, risks and public acceptance also play a role. The only incentive for CCS is in climate policy, but here it can complement other technologies in a useful way. Moreover, if the world is moving towards a more coal-intensive energy system, it is crucial to stimulate the timely development of affordable CCS technologies in order to counter the climate effects.

Synergies

Energy efficiency

One of the most robust options is energy efficiency as it provides a significant contribution to reducing both import dependency and mitigation of CO_2 emissions at negative or low cost. None of the policy cases in the CASCADE MINTS project has focused on the possible contribution of energy efficiency. There are indications (Uyterlinde et al, 2007a) that high oil and gas prices may induce energy intensity improvements that counterbalance the increase in carbon intensity resulting from the expected shift to solid fuels.

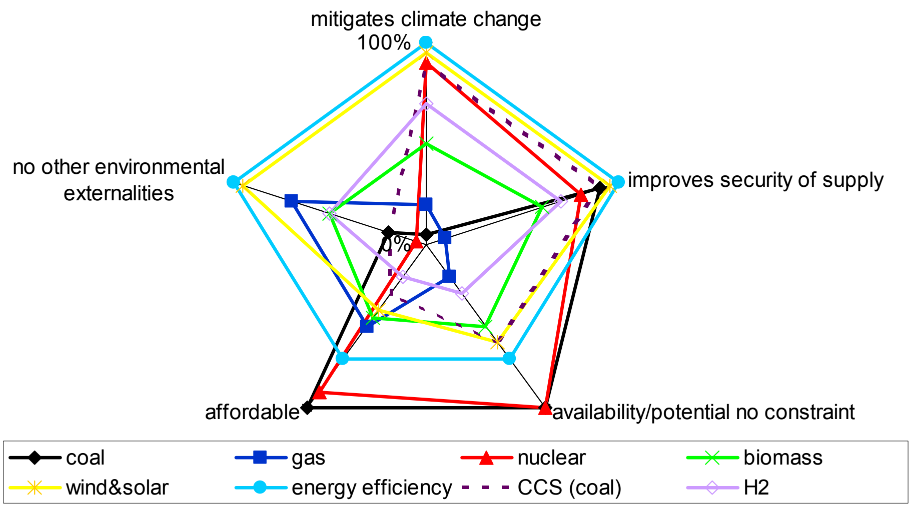
Renewable energy

Another apparent option for a sustainable energy system is renewable energy, as most renewable sources – with the exception of biomass – are both indigenous and emission-free, thereby benefiting both climate objectives and security of supply. The main barriers are in terms of high costs and limited potentials. For most technologies, large cost reductions are still possible. The case study has shown that enhanced technological progress, which can be operationalised through R&D and increased deployment, can make a difference for wind and solar PV. Furthermore, a combination of high prices for oil and gas, and ambitious climate policy provides a strong incentive for renewable energy, although coal with CCS can be a serious competitor. A high penetration of renewables imposes additional challenges due to their intermittent nature, and may take time.

Transport sector

Finally, a synergy can be found in policies targeting at the transport sector, as these can achieve both emission reduction and increased security of supply, when the dependence on oil is significantly reduced. The case studies have shown that major shifts in the structure of the transport sector are technically possible, up to completely phasing out petroleum based fuels in Europe by 2050. However, is conditional on the success of the 2nd generation of biofuels, as these have a larger energy density per hectare of land, and on a strong cost reduction of fuel cells.

Figure F-13: Illustration of trade-offs and synergies



Finally, Figure F-13 provides an overview how the different technological options perform against the most important policy objectives and criteria. Options should ideally mitigate climate change and improve security of supply, while being affordable, available, and without other environmental externalities. It demonstrates that while energy efficiency, intermittent renewable resources, nuclear and CCS (with coal) are robust in that they serve both objectives, they are no 'silver bullet', and a portfolio approach should be used to employ mixes of options, also depending on regional potentials and preferences.

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