DELIVERABLE 6.2.3

R&D TOPICS AND EXPECTED MILESTONES FOR HYDROGEN AND FUEL CELL TECHNOLOGIES

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

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

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

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This report is a deliverable of the Roads2HyCom project, a partnership of 29 stakeholder organisations supported by the European 6th Framework Programme. It is based on individual Roads2Hycom partners' expertise and additional contributions from hydrogen and fuel cell technology experts.

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EXECUTIVE SUMMARY

This report is a deliverable of the Roads2HyCom project, a partnership of 29 stakeholder organisations supported by the European Commission Framework Six programme. The project is studying technical and socio-economic issues associated with the use of fuel cells and hydrogen in a sustainable energy economy. Within the project, studies have been made of the status of technology development and its likely evolution in future. This report contains recommendations and milestones for future research, based upon those project studies, collation of research agenda information from around the world, and project partners' expertise.

In this document, a detailed description of issues requiring further R&D in the field of hydrogen (H2) and fuel cells (FC) is presented. The research topics are divided into six main chapters: hydrogen production, hydrogen storage, distribution and refuelling, hydrogen energy converters, and cross cutting issues. For each section, tables with an overview of international milestones, with technical targets and with R&D recommendations give a clear impression of the state of art and the technical challenges for the periods until 2015, 2020, and 2030 and beyond.

Hydrogen production: As carbon-free fuel, hydrogen has the potential for a carbon-free energy cycle provided it is produced without the emission of CO_2. This is not happening at present, as most hydrogen is currently produced from hydrocarbons. Carbon-capture, electrolysis of water with electricity from carbon-free sources, or direct production of hydrogen from such sources, creates a CO_2-free hydrogen fuel. Main research topics are industrialisation of unproven or laboratory-scale processes, and reduction of costs of equipment and electricity; while as an interim measure, reducing the carbon footprint of existing industrial processes through efficiency improvement and realisation of carbon capture is desirable. There are many potential routes, with the only "certainty" being that, in a future with more scarce energy resources, multiple routes are likely to be required.

Hydrogen storage: Efficient storage with high energy density plays a key role for hydrogen application, especially in the case of onboard storage in vehicles. Storage methods as compressed gas, cryogenic liquid, and in compounds are analyzed. Main research topics are focusing on the increase of gravimetric and volumetric energy density and reduction of costs of storage systems. This will prove challenging, as the commonly used gaseous and liquid technologies are constrained by laws-of-physics issues, and the best known state-of-the-art is around 5 times more expensive and 2 times more heavy than desired. Reduction of fuel requirement, through lighter and more efficient vehicles, must play a part in solving this challenge.

Distribution and refuelling: Hydrogen is distributed in compressed or liquid form in trailers by road, rail or ship. For the containers the same research issues as for already described tank systems in general are applicable. The use of pipelines to distribute hydrogen gas or mixtures with natural gas offers an interesting alternative. In filling stations, reduction of costs is the main aim of research.

Hydrogen energy converters: As carbon free fuel, hydrogen can be used with low or no emissions in turbines, internal combustion engines, or fuel cells; some forms of fuel cell can use existing Natural Gas supplies or other hydrocarbons as a fuel. The usage of hydrogen as an energy carrier, and/or the fuel cell as an energy converter, is discussed for stationary, mobile, and automotive applications. Fuel cells promise a clean combustion without emission at high efficiency rates, costs and weight are high though. Research recommendations focus on realising recent improvements at prototype level in lower-cost, reliable, mass-produced products. In the stationary sector (particularly uninterruptible power and co-generation at the "kilowatt to megawatt" scale), some of these products are approaching full commercialisation (meaning products that are profitable along the value chain, sold in volumes that are significant in the sector) in the next decade – the research agenda needs to ensure that the first generation is successful and the second generation is even better. Commercialising in the transport sector is more challenging, with ultimately greater rewards but the need to realise high product volumes before costs can be reduced – so the research agenda needs to support extended demonstration activity to realise these ambitions.

Cross-cutting issues: Apart from technical issues, a variety of socio-economic questions have to be addressed. Political and financial decisions, e.g. about taxes, play an important role in the implementation of hydrogen and fuel cells into the market. Safety, standards and regulation have to support technical development. And the education agenda, at all levels, has to provide the skills required in business development, product development, fuel supply and in-field operation. Studies within the Roads2HyCom project deliver recommendations on many of these issues, but further work will be required as fuel cells and hydrogen are realised in a sustainable energy economy.

Prioritisation: Based on this report the recommendations were filtered in an additional deliverable. This will be reported in document R2H6035PU (Deliverable 6.5).

R&D TOPICS AND EXPECTED MILESTONES FOR HYDROGEN AND FUEL CELL TECHNOLOGIES

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1. Introduction

1.1 Background

The landscape of technology development in Europe has been mapped by the Roads2HyCom project [97], and this exercise highlighted the continuing importance of government research grants for many stakeholders. In Europe, such support comes from a mix of Regional, National and European Commission Framework programmes; recently the European Commission and stakeholders from industry and research institutions have created the New Energy World Joint Technology Initiative (JTI) [98], a public-private partnership which aims to accelerate commercialisation of fuel cell and hydrogen technologies through stronger collaboration.

It is impossible to succinctly summarise the State of the Art in Fuel Cell and Hydrogen technologies, but in general these are often (but not always) unproven in genuine mass-market application, requiring further research to reduce costs and improve robustness in use. Roads2HyCom has created a comprehensive State of the Art encyclopaedia [99], which has provided information as a basis for the work reported here.

1.2 Methodology

The aim of this document is to develop a detailed description of issues requiring further R&D in the field of fuel cells (FC) and hydrogen (H2). The document seeks to complement existing research agenda documents such as those of the New Energy World JTI and National programmes, with an independent viewpoint developed from the project’s many studies in the sector.

This document has been produced on the basis of Roads2HyCom partners’ expertise, information abstracted from other studies in the project, and a review of comparable research agendas. Two workshops, one for project partners and one with members of the executive committee of the International Energy Agency Hydrogen Implementing Agreement, were used to develop and receive feedback on the work shown.

The research topics are divided in six main chapters, Hydrogen production, Transport and Refuelling, Hydrogen storage, Hydrogen energy converters, and cross cutting issues. After an introduction and overview, each chapter is subdivided in a number of sections. With few exceptions such as the “Cross-cutting issues”, all sections are structured in the following way:

First a short general introduction into the section is given.

As a second step, where found, expected milestones from existing strategy papers of EU, USA, and Japan are listed in a table. Outlined in particular are quantitative targets for future FC and H2 research structured in 5-years steps from 2010 to 2030 and later.

Then a table highlights the technical targets as seen by the Roads2HyCom experts. Besides the “state of the art”, possible targets are given “until 2015”, “until 2020”, and “until 2030 and beyond”.

The tables for the recommended research activities, the “Roads2HyCom recommendations for future research milestones, targets and actions” are an essential part of this deliverable. The authors tried to propose precise and focused research actions in a table where the research recommendations are divided into three time frames: What are the Roads2HyCom priorities “until 2015”, “until 2020”, and “until 2030 and beyond”. Not always all columns could be filled in, as a prognosis is sometimes difficult, especially for the period 2030 and beyond.

As the next step, the project will filter the recommendations in this report on the basis of impact and degree of challenge, using analytical information from other studies in the project. This will be reported in document R2H6035PU (Deliverable 6.5).

2. Hydrogen Production

Like electricity, hydrogen is an energy carrier that has to be produced, as hydrogen is not found in pure form. Hydrogen can be produced by a number of methods from many different sources. The amount of hydrogen globally produced equals 600 billions Nm^3 per year corresponding to about 1.5% of global energy consumption. More than 40% of the produced hydrogen comes from industrial processes where hydrogen is a by-product, like the reforming of gasoline or the production of ethene, methanol, or chlorine.

For the large-scale production of the remaining 60% the reformation of fossil hydrocarbons is widely used. The most cost-effective process is the steam reforming of short chained hydrocarbons such as methane (natural gas). The industrial production takes place in huge reactors at high temperatures. First a so called synthetic gas of carbon monoxide and hydrogen is formed. This syngas exits the reformer at temperatures around 850°C. After cooling, CO is oxidised in the shift reaction at around 400°C. Efficiencies of up to 80% can be achieved. Natural gas, water, and energy are used, the energy coming from the natural gas.

Other industrial production processes include the gasification of coal if natural gas is not available or of other fossil or biological hydrocarbons. Recently gasification of biomass and waste is under investigation. The efficiency of the gasification process lies around 50% and has to be increased. All production methods based on hydrocarbons are producing CO_2.

The production of hydrogen from water via electrolysis is free of emissions if the needed electricity is produced from renewable energy sources such as wind, water or solar energy. Main topics of research are improvement of efficiency (up to 70% at present) and reduction of equipment costs.

Upcoming technologies are expected to play an important role if efficient methods can be developed. High temperature methods for the production of hydrogen are based on solar and nuclear heat sources to split water. Biological processes like fermentation and photoelectrolysis are under investigation. Also production of hydrogen from the reaction of metals with water is a promising approach.

As hydrogen can be stored more effectively than electric energy, the vision is to produce electricity from renewable sources, use a given surplus of electricity to produce hydrogen that can be stored and used as fuel in stationary and automotive applications.

An increasing demand of hydrogen can be expected for the years to come due to the growing application of hydrogen in energy production but especially also in refinery processes. This is also due to an increasing need of hydrogen in hydrofining and hydrocracking, as the quality of the processed crude oil decreases, e.g. oil with higher contents of sulphur. In order to produce hydrogen from renewable sources but also due to the globally increased energy demand a determined expansion of alternative energy production is crucial.

MILESTONES FROM EXISTING STRATEGY PAPERS					
	2010	**2015**	**2020**	**2025**	**2030 AND LATER**
EU	22% of all electricity produced in the EU15 region coming from renewable energy systems [9] Local H_2 production at refuelling station by reforming and electrolysis [7]	H_2 produced from fossil fuels with C sequestration [7] Clusters of local H_2 distribution grids [7] 20% of hydrogen energy demand CO_2 free [39] Reduction of CO_2 emissions for fossil reforming >25% [39]	Significant H_2 production from renewables, incl. biomass gasification [7] CO_2 capture and sequestration from fossil fuel power plants is in practical use [5] 5% of new cars fuelled by zero carbon hydrogen [7] 2% of fleet fuelled by zero carbon hydrogen [7] Hydrogen production and distribution cost < current cost by factor 3 [39] Cost of hydrogen delivery at the pump 2.50 €/kg [39]	Increasing de-carbonisation of H_2 production, renewables, fossil fuel with sequestration, new nuclear [7] 25% of new cars fuelled by zero carbon hydrogen [7] 15% of fleet fuelled by zero carbon hydrogen [7]	Direct H_2 production from renewables, de-carbonised H_2 society [7] Hydrogen produced solely from renewables [5] 35% of new cars fuelled by zero carbon hydrogen [7] 32% of fleet fuelled by zero carbon hydrogen [7]
USA	Produce hydrogen (350 bar) from natural gas at \$2.50/gge [23]	Near zero emission coal plant producing hydrogen and power at \$0.80/gge at the plant gate (\$1.80/gge delivered) [23]			
JAPAN	Hydrogen demand: 1.6 Billion Nm³/year [17]	Hydrogen demand: 7.4 Billion Nm³/year [17]	Hydrogen demand: 42.5 Billion Nm³/year [17]		

2.1 Reforming Technologies

2.1.1 Natural Gas Reforming

Industrial natural gas (NG) reformers have capacities up to 300'000 Nm^3/h H_2 and generally are part of highly integrated, larger complexes, where the heat produced in a section of the plant is used in another section. There are large variations in the efficiency of reforming processes, according to the assumptions made and the consideration of heat recovery. A typical consumption "feed+fuel" of 13.5-15.7 MJ/Nm^3 H_2 is reported for some reformers, while the specific consumption "feed+fuel-export steam" varies in the range 12.6-15.1 MJ/Nm^3 H_2 [6]. For "Advanced Steam Reformers", the net energy efficiency, taking into account the export of steam, reaches 87%, with a consumption of 12.4 MJ/Nm^3 [6].

The hydrogen cost deriving from capital investment and operational costs is largely situation-specific, so there is a wide range of values in the literature. As a consequence, target values should be placed in a particular context. The wide variation in actual hydrogen costs is based on a report of the IEA/HIA 2005 [86], where hydrogen production costs 5-8 US$/GJ from large-scale reforming plants and 16-29 US$/GJ from small-scale reforming plants. A "commercial" target for hydrogen production cost is proposed at 0.3 US$/kg or 2.5 US$/GJ [86].

Reformer tubes are designed for a lifetime of 100'000 hours of operation. Tube failures generally occur during transients like start-up and shut-down or are due to operating errors [61]. The cost of industrial plants has decreased over the last decades thanks to the development of new materials for the reformer tubes, new catalysts and better control of carbon formation.

The optimisation of large scale reformers has reached such a point over the years, that no major improvements can be expected. The most important milestones for the reforming technology are related to the reduction of CO_2 emissions. In reforming plants, CO_2 is produced by the combustion of fuel and the process itself, and is mainly emitted in the flue gas from the reforming and in the off-gas from the PSA purification unit. New designs are already under study, which would allow the separation of up to 80% of the total CO_2 produced for sequestration and storage.

In the longer term, the ability to sequester will be important to this branch of the technology, meaning that its success may become more dependent on access to nearby sequestration sites and/or the transport of CO_2 to them. Findings elsewhere in Roads2HyCom indicate that this production route needs a carbon footprint some 20-30% lower in order for the total "source to user" carbon emission to be below the best future technologies that use liquid fossil fuels, especially in transport. This is consistent with the international targets collated below.

TECHNICAL TARGETS				
	STATE OF THE ART	UNTIL 2015	UNTIL 2020	UNTIL 2030 AND BEYOND
Reduction of CO_2 emissions		> 25% [39]		
Integration with CCS		10-20% CO_2 free [39]		
H_2 cost (Large scale)	7-15 €/GJ [80] 5-29 US$/GJ [86]			10 US$/GJ [56]
Overall efficiency (LHV)	70-85%	90%		
Lifetime of reformer tubes	100 000 hr [61]			
Availability (On-stream time)	99.5% [51]			

ROADS2HYCOM RECOMMENDATIONS FOR FUTURE RESEARCH MILESTONES, TARGETS AND ACTIONS		
Until 2015	**Until 2020**	**Until 2030 and beyond**
Development of new materials for the reformer tubes, new catalysts and better control of carbon formation	Reduction of CO_2 emissions by CO_2 capture and storage. R&D on CO_2 absorption/separation processes and process line-up	*On this timescale the technology may be more mature, even with CCS*
	Further development of new materials for the reformer tubes, new catalysts and better control of carbon formation	

2.1.2 Coal Gasification

Coal gasification is a mature but complex technology, composed of several steps, generally implemented in coal-rich regions without easy access to natural gas. Industrial gasifiers have capacities up to 100’000 Nm^3/h H_2. Gasification may proceed with pure oxygen instead of air, in which case an air separation unit is integrated in the plant.

The EC has set a goal for 10-20% of the hydrogen supplied for energy applications to be CO_2 lean or free by 2015. The development and implementation of carbon capture and sequestration technologies (CCS) is therefore essential for all the fossil fuel based hydrogen production pathways.

New designs are actually under study, aiming to integrate a CO_2 separation step with the water gas shift reaction, with an overall efficiency in the range 64-68 % (LHV) [46].

TECHNICAL TARGETS				
	STATE OF THE ART	UNTIL 2015	UNTIL 2020	UNTIL 2030 AND BEYOND
H_2 cost				5 US$/GJ [56]
Integration with CCS		10-20% CO_2 free [39]		
Fuel-to-hydrogen efficiency (LHV)	55% [46]	70%		

ROADS2HYCOM RECOMMENDATIONS FOR FUTURE RESEARCH MILESTONES, TARGETS AND ACTIONS		
Until 2015	Until 2020	Until 2030 and beyond
New designs for integrating the CO_2 separation step with the water gas shift reaction	Development and implementation of carbon capture and sequestration technologies (CCS)	Improvement of carbon capture and sequestration technologies (CCS)

2.1.3 Biomass Gasification

As a potential energy resource for hydrogen, biomass has the advantage of being widely available now, with known (if not fully upscaled) processes for conversion. However, there are a number of known issues with its use:

- Transportation of raw biomass is difficult due to its relative bulk, so it is often more effective in financial or carbon terms to use it locally. Local use could include hydrogen production, but the production of conventional power (or combined heat/power) is often favoured and is a mature technology

- Biomass is in high demand for production of liquid (and gaseous) biofuels, which are readily compatible with existing power devices. In the longer term, transport sectors such as air, marine and long haul trucks, where the use of hydrogen or electricity as a fuel is most challenging, will sustain a high demand for this biomass

As a result, it is unlikely that production of hydrogen from biomass will be prioritised as a mainstream route, a conclusion that was validated in the IEA workshop. However, there may be local circumstances (for example, surplus biomass stranded in an area that needs hydrogen as a fuel) where the technology is needed, and research needs to focus on those circumstances.

The thermochemical pyrolysis and gasification of biomass for hydrogen production methods are economically viable and will become competitive. The production of hydrogen from biomass is still in an early phase of development, of special interest is gasification of biological waste.

In order to evaluate hydrogen production through pyrolysis of various types of biomass, extensive experimental investigations have been conducted in recent years. In order to solve the problem of decreasing reforming performance caused by char and coke deposition on the catalyst surface and in the bed itself, fluidized catalyst beds are usually used to improve hydrogen production from biomass-pyrolysis-derived bio-fuel [64].

Further R&D is needed prior to the large scale implementation of biomass gasifiers in the fields of feedstock preparation, ash removal, gas conditioning and purification and process design optimisation [46].

MILESTONES FROM EXISTING STRATEGY PAPERS					
	2010	**2015**	**2020**	**2025**	**2030 and later**
USA		Improve global gasification yield to H_2 up to 50% [64]			

TECHNICAL TARGETS				
	STATE OF THE ART	**UNTIL 2015**	**UNTIL 2020**	**UNTIL 2030 AND BEYOND**
Integration with CCS		10-20% CO_2 free [39]		
Hydrogen production cost (BTH standalone)		< 3 €/kg [39]		
Hydrogen production cost (BTH co-gasification)		1.2 €/kg [39]		
Biomass feedstock cost (BTH co-gasification)		3 €/GJ [39]		
H_2 from biomass – mass efficiency		> 40% [39]	> 60% [64]	
Tar reforming system efficiency	90%	> 99% [64]		

ROADS2HYCOM RECOMMENDATIONS FOR FUTURE RESEARCH MILESTONES, TARGETS AND ACTIONS		
Until 2015	**Until 2020**	**Until 2030 and beyond**
Further development of the fluidized catalyst beds in order to solve the problem of decreasing reforming performance caused by char and coke deposition on the catalyst surface and in the bed itself, are usually used to improve hydrogen production from biomass-pyrolysis-derived bio-fuel	Improvements of the reliability of the syngas cleaning (especially tar reduction) [38]	*On this timescale the technology is expected to be approaching maturity, and rising demand for biomass in other applications may prevent further growth as a hydrogen source*
R&D in the fields of feedstock preparation, ash removal, gas conditioning and purification and process design optimisation	Optimisation of pressure temperature and exposure time [38]	
	High temperature gas cleaning to improve overall efficiency [38]	

2.2 Electrolysis

Producing hydrogen by electrolysis from water provides a method which is CO_2-free at the point of production, meaning that it is sustainable if electricity from sustainable sources is used. Main topics of research are improvement of efficiency (up to 70% at present) and reduction of equipment costs. Different technologies for electrolysers are used, with alkaline and PEM being most common.

Where electrolysis is applicable, alkaline electrolyser is most mature and is the current technology for most commercial systems in use. PEM electrolyser, a more recently developed technology, has higher costs and is supplied for small capacity plants only. There are many challenges in adapting this technology to meet energy-related applications in the future.

The cornerstone for hydrogen production from electrolysis is the cost of delivered hydrogen and the purity of the gas. As electricity is needed, the technology is dependent on affordable electricity preferably from renewable sources.

The question of the validity of this production route is the topic of much debate – for example it is easily argued that it is more effective to make hydrogen from natural gas and use scarce renewables to substitute obsolete coal-fired electricity supply, than it is to use the renewable electricity for hydrogen production and burn the natural gas to make electricity. In reality the situation is much more complex, with issues such as electricity price fluctuation and the strength of electricity grid infrastructure near to new renewable resources such as wind, wave and solar farms having a major impact. This topic has been the source of a major study in another part of the project, which concluded that “steady” or predictable low-carbon energy sources such as nuclear power, hydro-electricity and geothermal energy were much better suited to meeting the base loads of the existing electricity grid and its consumers; whereas more intermittent renewables such as wind, wave and solar power could find synergy with hydrogen production as a supply/demand buffer (possibly even a reversible one, re-converting hydrogen to electricity). Above all, this is a complex situation, with local factors and taxation policy very much influencing what may actually happen. Nonetheless, the ability to turn electricity to hydrogen effectively will remain important.

2.2.1 Electricity Generation

The conversion of non-electrical energy to electricity from renewable energy sources is highly promoted by the European Union. The directive concerns electricity produced from renewable energy sources such as wind, solar, geothermal, hydroelectric, biomass, landfill gas, sewage treatment gas and biogas energies [27], [34].

MILESTONES FROM EXISTING STRATEGY PAPERS PER TECHNOLOGY				
	STATE OF THE ART	**UNTIL 2015**	**UNTIL 2020**	**UNTIL 2030 AND BEYOND**
Wind	2010: 80 TWh of wind energy will be produced (2.8% of total electricity production) [26]			
	Present: 34,000 MW installed, of which 640 MW offshore [44]		180,000 MW of which 70,000 MW offshore	
	Share of wind electricity in total electricity production is 2.8% (2006). There are 47,000 turbines installed generating 83 TWh. In 2010 the share will increase to 5.5% (188TWh) [14]		Share of wind electricity in total electricity production will increase to 13.4% (523 TWh). There will be 110 GW installed onshore and 70 GW offshore	Share of wind electricity in total electricity production will increase to 22.6% (965 TWh). There will be 180 GW installed onshore and 180 GW offshore
	2010: 80 GW will be installed and 194 TWh will be produced [34]		180 GW of wind energy will be installed producing 530 TWh	
	Current (2007): 57,136 MW in Europe of which 56,535 MW in European Union [43]			
PV	2010: 3 TWh will be produced (0.1% of total electricity production) [26]			
	2010: 3.6 GWp [32]			
	Current (2006): 6.6 GW (worldwide) by which 8 TWh is produced [33]			
	2010: 8 GWp will be installed producing 7.5 TWh [34]		52 GWp will be installed, producing 55 TWh	
Geothermal	2010: 7 TWh (0.2% of total electricity production) [26]			

MILESTONES FROM EXISTING STRATEGY PAPERS PER TECHNOLOGY				
	STATE OF THE ART	**UNTIL 2015**	**UNTIL 2020**	**UNTIL 2030 AND BEYOND**
	EU-27 (2005) 8750MWth, 2010: 16,000 MWth [29]			
	2007: 850 MWe 2010: 25000 MWe [30]		39,000 MWth 6,000 MWe	
	2010: 1 GW producing 7 TWh [34]		2 GW producing 14 TWh	
Hydro	2010: Total 355 TWh (12.4% of total electricity production) of which large (incl. pumped storage) 300 TWh and small scale 55 TWh [26]			
	Current (2005) Small scale hydro power: 11 GW producing 41 TWh [36]			
		Small scale hydro power (EU-25): 12850 MW installed producing 51.5 TWh [35]		
	2010: 113 GW producing 356 TWh [34]		120 GW producing 384 TWh	
Biomass	2010: 230 TWh (% of total produced electr. is 8.0) [26]			
	2010: 25 GWe producing 138 TWh [34]		50 GWe producing 300 TWh	

2.2.2 Electrolyser Technology

The hydrogen production costs deriving from capital investment and operational costs are largely situation-specific, like for other production technologies, so there is a wide range of values in the literature [86], [80]. As a consequence, target values should be placed in a particular context. Regarding capital cost, the range is even larger, depending on technology, materials used, automatisation features, hydrogen purity and pressure, power consumption, and so on. The actual market prices of electrolysers with very different characteristics vary from 10'000 to 200'000 €/Nm^3 H_2 or 1500 to 20'000 €/kW for small units of a few kW, and from 4'000 to 15'000 €/Nm^3 H_2 or 1000 to 6000 €/kW for large units up to the MW size. Actually, there is no production of electrolysers in large series.

Some of the milestones reported are interconnected. For example, the energy efficiency tends to increase with decreasing current density. However, when a unit operates at low current density, with low operating costs, it needs a larger stack to produce the same quantity of hydrogen, increasing the capital cost.

Generally, the energy efficiency of an electrolyser refers to the stack efficiency, which is readily measurable, omitting the power losses for the power conditioning (AC/DC inverter and other regulating components) and the control of the unit. The power losses for the control and monitoring of the plants are significant for small units and tend to be negligible for large units.

An energy efficiency of 70% (LHV) is state of the art for some commercial electrolysers. For example, the alkaline, atmospheric electrolyser of the Bamag technology, operates with a specific power consumption of 3.9 to 4.5 kWh/Nm^3 H_2, corresponding to an LHV efficiency of 67 to 77%, while the pressurized (3.2 MPa) electrolyser of the Lurgi technology consumes 4.3 to 4.6 kWh/Nm^3 H_2, corresponding to an LHV efficiency of 65 to 70% [87]. However, both well established technologies operate at current densities far below 1 A/cm^2. Similar efficiencies are also reported for the commercial electrolysers by Hydro, Norway [1]. Small scale electrolysers of the PEM and conventional alkaline technology operate with an efficiency of only 40-50% (LHV).

Current densities of 1 A/cm^2 are actually used in PEM electrolysers and have also been reported for advanced alkaline electrolysers. The stack efficiency (HHV) of an advanced alkaline electrolyser of 0.5 Nm^3/h H_2 capacity had been presented as a function of the current density. The efficiency at a current density of 1 A/cm^2 was 70% (HHV) or 60% (LHV). The efficiency at 0.2 A/cm^2 was 87% (HHV) or 75% (LHV), but the hydrogen production in the same stack was 5 times lower than in the first case [25].

TECHNICAL TARGETS					
	STATE OF THE ART	**UNTIL 2015**	**UNTIL 2020**	**UNTIL 2030 AND BEYOND**	**REMARKS**
Energy efficiency (LHV basis)		> 70% [39]			
Current density		1 A/cm2 [39]			
Cost of modular system		1000 €/Nm3 [39]			
System availability		> 99% [39]			
Production flow rate		> 500 Nm3/h [39]			(2012 target)
Operating pressure		3 – 5 MPa [39]			(2012 target)
Production flow rate (PEM technology)		100 Nm3/h [39]			
Lifetime (PEM technology)		40000 hr [39]			
Hydrogen cost	25 €/GJ [80] 20-40 US$/GJ [86]			17 US$/GJ [56]	

2.2.3 On-site Electrolysis

The efficiency of commercially available alkaline electrolysers ranges typically between 48-63% based on the lower heating value (LHV) for hydrogen, being equivalent to 56-73% of the higher heating value (HHV), respectively [60]. This includes all auxiliary power requirements such as AC/DC rectification, pumps controls, etc. Thus, this technology offers a fairly high efficiency compared to the theoretical maximum of 100%, but there are still margins for efficiency increase, mainly in the field of power conversion and conditioning, in the use of more efficient activated electrodes and non-asbestos diaphragms of lower resistance, and in the optimisation of auxiliaries.

To achieve a substantial saving in the energy consumption compared to the conventional electrolysis, the temperature must be drastically increased compared to today's technology (e.g. to 800°C) and make use of the effect that thermodynamically water is split more easily at high temperature. High temperature electrolysis based on solid oxide technology was developed in the 1980s. This technology has great potential in energy savings but at the same time great challenges in thermo mechanical stresses within the functional ceramic materials.

Synthetic materials together with high pressure applied in the cell stacks on electrolysers, prove to be more capable of handling fluctuations in power input. This makes them especially suitable in combination with transient or intermittent power supply, such as is often the experience with renewable energy sources. These types of electrolysers have become available in the market during the last couple of decades, but mainly for small capacities. The future challenge for these materials will be to cope with higher pressure and larger capacity electrolysers.

Electrolysers are currently manufactured in very small quantities (almost to order). A considerable cost reduction can only be achieved through improved manufacturing techniques following a considerable market expansion (large number of units per year). In addition there is also a potential for cost reduction through system simplification.

Alkaline electrolysis is a mature technology allowing unmanned remote operation with significant operating experience in industrial applications.

The PEM electrolysers currently available are not as mature as alkaline electrolysers with relatively high cost, low capacity, poor efficiency and short lifetime. PEM electrolysers are a promising technology potentially benefiting from development synergies with PEM fuel cells. This technology has been introduced to the market recently, but mainly for small capacities. The energy consumption is high and the lifetime of the cell stack or MEA (Membrane Electrode Assembly) needs to be improved.

Attempts are currently underway to develop systems in which some of the electricity consumed by the electrolyser can be replaced with available heat from, for example geothermal, solar or natural gas, thus reducing the consumption of electricity significantly.

The major R&D challenges for the future are the design and manufacturing of electrolyser equipment at lower costs with higher energy efficiency and large turn down ratios. It is expected that the performance of PEM electrolysers can be improved significantly by material development and cell stack design.

For the solid oxide electrolyser SOEC the main R&D needs relate to materials development and thermo-mechanical stress within the functional ceramic materials, similar to the main challenges for the SOFC.

For future central hydrogen production mainly associated with hydropower, nuclear power and future offshore wind farms or thermo-solar towers, larger and more cost-effective units will be necessary. A substantial scale-up in the size of today's electrolysers will therefore be required.

MILESTONES FROM EXISTING STRATEGY PAPERS					
	2010	**2015**	**2020**	**2025**	**2030 and later**
EU		Low Temperature electrolysis: Efficiency > 70 % Current density > 1A/cm² Cost = 1000 €/Nm³ System availability > 99% [39] PEM: Production flow rate: 100 Nm³/h Lifetime: 40000 h [39]	High pressure electrolysis: Production flow rate: 500 Nm³/h Operating pressure: 5 MPa [39]		
USA	Reactive membrane separation technology for hydrogen production that meets cost targets [23].	Produce hydrogen utilizing distributed electrolysis that at $3.00/gge [23].			

TECHNICAL TARGETS				
	STATE OF THE ART	**UNTIL 2015**	**UNTIL 2020**	**UNTIL 2030 AND BEYOND**
Energy efficiency (full load)	65-70% [60]	> 70% [39]		
Capacity	Up to 485 Nm^3/h pr unit			
System availability	99%	> 99% [39]		

ROADS2HYCOM RECOMMENDATIONS FOR FUTURE RESEARCH MILESTONES, TARGETS AND ACTIONS		
Until 2015	**Until 2020**	**Until 2030 and beyond**
Material Research for Low Temperature electrolysers (alkaline & PEM) o Synthetic materials for handling fluctuations in power input; to cope with higher pressure and larger capacity electrolysers. **Component Research** (e.g. valves, sensors) **Improvement of efficiency** o Power conversion and conditioning o More efficient activated electrodes o Use of non-asbestos diaphragms of lower resistance o Optimization of auxiliaries **Increase hydrogen purity** **Cost reduction of system** o Substantial size scale-up	**Material Research for High Temperature electrolysers (SOEC)** Materials development and thermomechanical stress within the functional ceramic materials **Component Research** (e.g. valves, sensors) **Improvement of energy consumption** **Cost reduction of system** o Improved manufacturing techniques o Considerable market expansion o System simplification **Electrolyser based production synergy with intermittent renewables** – reversible or one way conversion of electricity to hydrogen as an energy buffer with capacity to "export" fuel	**Design and manufacturing of electrolyser equipment at lower costs with higher energy efficiency and large turn down ratios** **Substantial scale-up in the size** **Central hydrogen production** associated with offshore wind farms or large thermo-solar towers, then hydropower and nuclear power if surpluses of these become available

2.3 Upcoming Technologies

A number of technologies under investigation are expected to play an important role if they prove technical interesting yields at sufficient efficiency. High temperature methods for the production of hydrogen are based on solar and nuclear heat sources to split water. Biological processes comprise fermentation and photoelectrolysis. Also production of hydrogen from the reaction of metals with water is a promising approach.

2.3.1 High Temperature Methods

High temperature methods for the production of hydrogen are promising for the long term, based on solar and nuclear heat sources. The main methods are the thermal decomposition of water and the high temperature electrolysis of water or steam. In an appropriate energy policy environment (for nuclear) or geographic region (for sunshine), these technologies could show great ultimate promise.

MILESTONES FROM EXISTING STRATEGY PAPERS					
	2010	**2015**	**2020**	**2025**	**2030 and later**
EU		Large scale pyrolysis at < 3 €/kg [39]	HT processes with solar/nuclear heat sources: production cost < 2 €/kg [39]		
USA	Laboratory-scale thermochemical hydrogen production from solar reactors at \$6/gge [23].	Thermochemical hydrogen production from nuclear reactors at \$2.50/gge [23].	Thermochemical hydrogen production from nuclear reactors at \$2.00/gge [23].		
Japan	Solar light (electrolysis): Production efficiency: 10% Solar light (photo-catalyst): production efficiency: 0.01% [62]				Solar light (electrolysis): Production efficiency: 20% Solar light (photo-catalyst): production efficiency: 0.1% [62]

TECHNICAL TARGETS					
	STATE OF THE ART	**UNTIL 2015**	**UNTIL 2020**	**UNTIL 2030 AND BEYOND**	**REMARKS**
Hydrogen production cost		< 2 €/kg		10-20 \$/GJ	

		[39]		[56]	
Temperature [38]	850°C	700°C	Direct splitting >2500°C with nuclear heat (MK)		
Efficiency [38]	90%	>95%			
Electrolyte thickness [38]	50-200 μm	10 μm			
Cell size	25 cm^2	2500 cm^2			
Stack power	0.1 Nm^3H_2/h		7000 Nm^3H_2/h		
Electrode degradation	>10%/1000h		<0.1%/1000h		

ROADS2HYCOM RECOMMENDATIONS FOR FUTURE RESEARCH MILESTONES, TARGETS AND ACTIONS		
Until 2015	**Until 2020**	**Until 2030 and beyond**
Reduction of operating temperature [38]	Scale-up of processes to industrial scale in suitable applications – solar in southern Europe likely to be first	Reduction of investment cost
Increase of power density [38]		Full scale-up of processes in line with prevailing policy on nuclear and solar energy
Increase of electrical efficiency [38]		
Reduction of electrolyte thickness without degradation of lifetime [38]		
Scale-up: Increase the size of the electrolysis cells and stack		
Prevent degradation processes at the electrodes		

2.3.2 Production from Biological Sources

Biological hydrogen production processes are at a (very) early stage of development and practical applications still need to be demonstrated. Efficiencies and yields at the moment do not fulfil technical requirements. In general long-term basic and applied research is needed in these areas [47].

Biological hydrogen production can be classified into 5 different groups:

- (Direct) Biophotolysis
- Photo-fermentation
- Biological water-gas shift reaction
- Dark fermentation
- Electrochemically assisted microbial hydrogen production

Direct Photo-biological hydrogen production (biophotolysis)

In direct biophotolysis the overall reaction is the splitting of water into hydrogen and oxygen through photosynthesis by microalgae. Reductant generated by photosynthesis is used for reduction of protons to hydrogen by hydrogenase enzymes. The simultaneous evolution of hydrogen and oxygen (the latter as a by-product of photosynthesis) poses an obstacle because hydrogenases are severely inhibited by oxygen. Another issue is the occurrence of uptake hydrogenases, that consume part of the produced hydrogen.

Indirect Biophotolysis and Photofermentation

Indirect biophotolysis aims to separate (in time or space) the oxygen and hydrogen evolution stages. R&D has thus far mainly focused on green microalgae employing hydrogenases. Photofermentation is performed by anaerobic photosynthetic bacteria. Externally provided carbon compounds (such as organic acids) serve as electron donor for photosynthesis generating reductant for hydrogen production by the nitrogenase enzyme. Because no oxygen is generated, inhibition of the enzymatic reaction does not occur. Photofermentations can be combined with dark hydrogen fermentation described below. Acetic acid is one of the end products of dark fermentation, and for thermodynamic reasons further conversion of acetic acid to hydrogen requires input of energy, e.g. in the form of sunlight. Thus a photofermentation can be employed as second stage in a two-stage biohydrogen production process, where the organic feedstock is completely converted to H_2 and CO_2. An alternative approach is Bio-electrolysis of organic compounds.

Biological water–gas shift reaction

Gasification results in the formation of syngas, which contains H_2, CO_2 and CO. CO can be “converted” to H_2 by the chemical shift reaction.

$$CO + H_2O \rightarrow H_2 + CO_2$$

This reaction can also be catalyzed by microorganisms. Some microorganisms are even able to grow by that conversion. For the purification of syngas especially thermophilic bacteria seem promising.

Dark fermentation

Dark hydrogen fermentations produce hydrogen, organic acids and other metabolites from organic matter under anaerobic conditions by a wide range of bacteria employing hydrogenases. In current R&D there is considerable attention for (hyper)thermophilic fermentation at temperatures > 70°C using a variety of feedstock including agro-industrial wastes and (ligno)cellulose. Extreme thermophilic bacteria have been selected because of favourable thermodynamics and relatively high hydrogen yields. Dark fermentation produces a mixture of hydrogen, organic acids (mainly acetate) and CO_2. Acetate can be converted to hydrogen in a consecutive photofermentation stage. Alternatively, the acetate can be used for methane production.

Electrochemically assisted microbial production of hydrogen

The efficiency of dark fermentation of carbohydrate-rich waste to form hydrogen is generally less than 15%. This low yield is caused by thermodynamical limitations. Consequently, the majority of the substrate is converted to byproducts (e.g. acetate, butyrate) instead of hydrogen. Biocatalysed electrolysis (or electrochemically-assisted fermentation), a recently discovered technology that is related to the microbial fuel cell, overcomes this thermodynamical barrier by means of a small input of electrical energy [47].

MILESTONES FROM EXISTING STRATEGY PAPERS					
	2010	**2015**	**2020**	**2025**	**2030 and later**
EU		Conversion efficiency photobiological H_2 production 10% [1] Molar efficiency of sugar to H_2 conversion by dark fermentation under stable conversion conditions > 3 to 4 mol H_2/mol sugar [1] Cost of hydrogen production 2 to 5 €/kg [1]	Reduction of hydrogen production & distribution cost by a factor of 3 compared to current cost Cost of hydrogen delivery at the pump (excl. taxes) < 2.5 €/kg [1]		
USA		Demonstrate lab-scale photobiological water splitting to produce hydrogen with an energy efficiency of 5% (solar to H_2) [8]	Functional control for biological sequencing [10]		

TECHNICAL TARGETS				
	STATE OF THE ART	UNTIL 2015	UNTIL 2020	UNTIL 2030 AND BEYOND
Conversion efficiency photobiological H_2 production		5% (solar to H_2) [8] 10% [1]		
Molar efficiency of of sugar to H_2 conversion by dark fermentation under stable conversion conditions		> 3 to 4 mol H_2/mol sugar [1]		

ROADS2HYCOM RECOMMENDATIONS FOR FUTURE RESEARCH MILESTONES, TARGETS AND ACTIONS		
Until 2015	**Until 2020**	**Until 2030 and beyond**
Biomass fermentation: basic research stage at laboratory level [15]	Optimize light conversion efficiency	Search for new fermentation bacterium [15]
Biomass fermentation: basic research stage at laboratory level [15]	Enhancing H_2 yield and volumetric productivity	Search for new fermentation bacterium [15]
	Optimize H_2 volumetric productivity and production rate	
	Selection/engineering oxygen tolerant hydrogenase	
	Process optimization via physiological and genetic studies	
	Process development based on thermophilic bacteria	

2.3.3 Other Methods

Another methods to produce hydrogen include the chemical splitting of water with metals like alkaline metals. The reaction of metals (Na, K, Be, Al, Mg, Fe, etc.) with water yields hydrogen and heat. If this heat can be recovered and used to generate work these methods promise a highly efficient hydrogen production. These hydrogen on-demand production methods are also investigated as storage technology.

3. Hydrogen Storage

After the production of hydrogen, its storage is a key issue for its widespread use. Although hydrogen has a high gravimetric energy density of 120 MJ/kg (which is three times higher than that of gasoline), since it is a very light gas its volumetric energy density is very low. Therefore hydrogen is either stored as a compressed gas at high pressures, as a liquid at very low temperatures or in a solid storage system as a physical or chemical compound. All of these storage methods involve high technical effort and sophisticated storage systems. In special cases hydrogen storage in underground caverns is also discussed.

The main research issues are the reduction of costs, weight and volume of the storage systems. Evidence collected elsewhere in the project [99] suggests that storage technologies are making less progress towards targets than the fuel cell itself, with less visible information on the roadmap to a solution. In part at least, reduction in demand for quantity of stored hydrogen will be necessary, through (for a vehicle example) improved power system efficiency, lower vehicle weight, and facilitating more frequent refuelling.

For gaseous storage the compressor technology is another issue, just as liquefaction technology is an issue for storage in the liquid phase. As there are very different demands for stationary and transportation storage systems, these are treated separately.

3.1 Gaseous Storage

For compressed hydrogen storage the gas is normally compressed to pressures between 200 bar (20 MPa) and 350 bar, though more recently storage pressures of 700 bar and even higher have been under trial. Gaseous hydrogen storage takes place in a closed system, with the result that gaseous hydrogen can be stored without losses for extended periods. At 700 bar, the density of 40 kg/m³ is somewhat 500 times higher than at ambient pressure, whilst the energy required for compression is around 15% of the fuel energy content. Such enormous pressures require consideration of questions regarding material choice, component dimensioning and safety, with such tank systems ending up quite heavy; storage weight is around 20 to 30 kg per kg of stored hydrogen. For the tank systems compliance with pressure vessel regulations is required.

3.1.1 Compression of hydrogen

Multi-cylinder piston compressors are used for the compression of hydrogen to high pressures of about 500 to 900 bar. Frequently a hydraulic system is used for the compression, which is driven by an electric pump in a non explosive area to avoid electric sparks. Important requirements for the compressors are that hydrogen compatible materials are used and that the purity of the compressed hydrogen is assured. For that the compressors have to work without lubrication. New compressor technologies involve compression with an ionic liquid instead of a piston to improve efficiency [31].

3.1.2 Stationary Applications

Most hydrogen for stationary applications is stored as a compressed gas in tanks varying from a few litres to several thousand cubic metres in capacity. These tanks are similar to natural gas storage vessels and have reached a good technical standard. Pressures in stationary hydrogen containers vary from 10 to about 350 bar. Recently higher pressures up to 700 bar have been investigated [22], [82].

An important consideration for storage containers is the fact that some gas must be retained within the storage system to maintain its operability. This so-called “cushion gas” is often 50% of the total storage volume and is not available for use. It is possible to calculate the “interest” lost on this gas, which may be as high as 25% of the total annual capital costs.

High-pressure tanks must be periodically tested and inspected to ensure their safety. Further, special seals are needed to achieve and maintain high pressure.

The main research issue is to reduce costs.

3.1.3 Transport Applications

As opposed to stationary applications, storage systems for transport applications are facing much higher demands in respect to gravimetric and volumetric storage density. The main field of application are vehicle tank systems. The question of safety plays a vital role. The main research targets are to increase the energy density and to reduce tank system costs, weight and volume.

For storing hydrogen on board vehicles, compressed hydrogen is the simplest method. Its main obstacle, however, is its low storage density which is one-tenth that of gasoline. Researchers are working on aluminium-carbon and other composite tanks to increase the storage density (pressures up to 700 bar) and to reach acceptable driving ranges for passenger cars [49].

The US Department of Energy (DoE) argues that the hydrogen-fuelled vehicle must be able to match the performance of a hydrocarbon-fuelled car at comparable cost. This has led them to establish a target for hydrogen storage capacity of 6 wt% on a system basis. A conventional steel compressed hydrogen tank achieves about 1% gravimetric hydrogen. However, recent developments of fibre-reinforced resin at 70 MPa pressure reaches a mass fraction of almost 5% [81].

Safety of compressed hydrogen tanks in proximity to vehicle passengers has been the subject of intense investigations, including crash tests and drops from considerable heights, as well as behaviour during fires, e.g., confined in long tunnels, leading traffic through mountains or under straits and other water bodies [20]. Tanks intended for use with significant hydrogen pressure should be hydrostatically tested to at least twice the intended operating pressure and equipped with a suitable pressure release device. Compressed hydrogen gas storage has a record similar to other flammable fuels. The safety level is very good but there are incidents from time to time, mainly due to the non-application of the existing codes and standards and/or the best available practices.

The efficiency of the compressed gas storage is almost 100% when checked for leaks. Only minor energy losses may be expected due to eventual venting and purging of the lines. Depending on the operating pressure of the application some of the stored hydrogen could remain in the tank.

The efficiency to compress hydrogen is greater than 85% (with respect to HHV). This figure corresponds to the measured efficiency of a hydrogen compressor compressing hydrogen from 1 MPa to 2.2 MPa in one stage. For compression to about 30 MPa, the compression energy is about 10MJ/kg or some 10% of the energy in the hydrogen stored. The further energy required for transferring the compressed gas to the tank in a vehicle is minute in comparison [84].

The total life period of the technology is 30 years, but it is a matter of debate in the case of storage tanks made of metal alloys, because it can be extended to more than 60 years with appropriate maintenance. However, compressed gas is consider to be a solution for hydrogen storage on a motor vehicle due to the relative simplicity of gaseous hydrogen, rapid refuelling capability, excellent dormancy characteristics and low infrastructure impact [18].

MILESTONES FROM EXISTING STRATEGY PAPERS					
	2010	**2015**	**2020**	**2025**	**2030 and later**
USA	On-board storage systems achieving: 6% weight capacity, 1.5 kWh/L, $4.00/kWh [23]	On-board storage systems achieving: 9% weight capacity, 2.7 kWh/L, $2.00/kWh [23]	Improve chemical hydrogen storage e.g. with alanates and sodium borohydride [74]		

TECHNICAL TARGETS				
	STATE OF THE ART	**UNTIL 2015**	**UNTIL 2020**	**UNTIL 2030 AND BEYOND**
Cost	8 €/k Wh (70 MPa) [22]			
Technology accessibility (0-4)	4	4		4
Storage Energy requirement	10 MJ/kg H2 (@ 30MPa)	-		-
Energy required to free H_2	0			
Typical Storage pressure	1 – 30 MPa	35 – 70 MPa		80 MPa
Typical Storage temperature	272 – 313 K			
Storage capacity (mass fraction)	5 wt% (kg H_2/kg storage medium)	>9 wt%		-
Efficiency	> 99.9%	> 99.9%		> 99.9%
Durability	30 years	60 years		-

TECHNICAL TARGETS				
	STATE OF THE ART	**UNTIL 2015**	**UNTIL 2020**	**UNTIL 2030 AND BEYOND**
Leakage and boil off	-			
Safety level	Very good	-		-
Refuelling capability	Rapid (< 3 min)	Rapid (< 3 min)		Rapid (< 3 min)
Infrastructure impact (simplicity) (1-5)	5	4		3

ROADS2HYCOM RECOMMENDATIONS FOR FUTURE RESEARCH MILESTONES, TARGETS AND ACTIONS		
Until 2015	**Until 2020**	**Until 2030 and beyond**
Material Research for storage tanks o Metal alloys o Lower cost fibres, and circumventing carbonfibre monopolies o Accurate prediction of life and diagnosis of condition **Manufacturing technology** o Faster winding and curing processes o Scale-up to higher daily quantities **Other cost reduction** o Sensors and safety systems o Refuelling systems	**Improved storage density** - work on aluminium-carbon and other composite tanks to increase the storage density (pressures up to 70 MPa) without creating additional safety problems **Ongoing cost reduction** **Shaped tanks –** to fit vehicle structure, cylinders of varying radius and other shape permutations	*At this point the technology is likely to be mature, unless a radical material breakthrough enables a lighter tank – higher pressures are not expected to be justified due to compression work*

3.2 Liquefied Storage

As an alternative to compression, hydrogen can be liquefied for storage at densities of 50–70 kg/m³, which is up to double the density of the compressed storage. However the very low boiling point of hydrogen at -253°C means that the production and storage of liquid hydrogen is complex and technically challenging. Liquefaction requires 20% to 30% of the energy content of hydrogen (LHV).

Containers for liquid hydrogen with high levels of insulation are used, consisting of an inner tank and an outer container with an insulating vacuum between them. The austenitic stainless steel most commonly used for such tanks retains its excellent plasticity even at very low temperature without embrittlement. The evacuated space between the nested containers is filled with multi layer insulation (MLI) having several layers of aluminium foil alternating with glass fibre matting.

Nevertheless, heat transfer cannot be prohibited completely. As a result of the inevitable inward heat leakage, hydrogen evaporates in the container leading to increases in pressure and temperature. Liquid hydrogen containers must therefore always be equipped with a suitable pressure relief system and safety valve. This lead to liquid hydrogen storage being an open system in which released hydrogen has to be dealt with by means of catalytic combustion, dilution or alternative consumption.

Evaporation losses on today's tank installations are somewhere between 0.3% and 3% per day, though larger tank installations have the advantage as a result of their lower surface area to volume ratio. With today's liquid hydrogen storage systems, the storage weight is around 20 kg per kg stored H_2.

Major drawbacks of liquid hydrogen storage are the high costs and the significant "boil-off" that could occur in the small insulated containers. Boil-off can occur because the liquid hydrogen is stored as a cryogenic liquid at its boiling point and any heat transfer to the liquid causes some hydrogen to evaporate.

Liquefying hydrogen gas also requires a large amount of electricity – as much as 30 percent of the hydrogen's original fuel energy.

3.2.1 Liquefaction

Today most of the 270 t/d of liquefied hydrogen is produced in the USA. In Europe there are four smaller plants in France (Lille, Air Liquide) with 10 t/d, one in the Netherlands (Air Products) with 5 t/d and two in Germany (Ingolstadt/Leuna, Linde) with 4.4 t/d respectively 5 t/d.

Liquefaction consumes a lot of energy, about 30% of the calorific value. New technologies are investigated to achieve an improvement in the efficiency. For example an efficiency improvement up to 30% can be obtained by using a Helium-Neon mixture as cooling agent in the temperature range between 80 K and 30 K [76], [84], [67].

3.2.2 Stationary Applications

Large stationary tanks are used to store liquid hydrogen in big amounts. This is the densest form of hydrogen storage that can be accomplished without using hydride technology. The largest liquid hydrogen storage facility in the world is the 12000 litre tank at the Kennedy Space Center.

MILESTONES FROM EXISTING STRATEGY PAPERS					
	2010	**2015**	**2020**	**2025**	**2030 and later**
USA	Processes for developing tanks for mass production [74]. Zero-loss tank for cryogenic hydrogen storage [74].		Integrated systems (storage with metering, etc) [74]		
Japan	Liquefaction technology: efficiency: 30% Capacity: 1 t/day BOG: 5-7%/day Storage without release: 0.5-1 days [62]				Liquefaction technology: efficiency: 50% Capacity: 1-10 t/day BOG: 0.5%/day Storage without release: 14 days (high pressure tanks) [62]

TECHNICAL TARGETS				
	STATE OF THE ART	**UNTIL 2015**	**UNTIL 2020**	**UNTIL 2030 AND BEYOND**
Tank mass	5 w%H2 (20 kg/kgH2)	15 w%H2 (7 kg/kgH2)	20 w%H2 (5 kg/kgH2)	
Materials	Austenitic stainless steels	Light alloys, composites		
Boil off	5 %/day	< 0.5 %/day	zero loss system	
Stand-by time	1 day	7 days		
Shape of LH_2 tank	Cylindrical tanks	Complex shape	Optimized complex shapes	
Condition of H2 aggregation	LH2	LH2, Slush		
Relative costs compared to conventional tank systems	1000	10	5	1

3.2.3 Transport Applications

For mobile use hydrogen storage, tanks need above all to be light and small. The storage of hydrogen as a liquid results in the highest storage densities, in both volumetric and gravimetric terms [45]. On a weight basis, liquid hydrogen represents the highest energy density in a chemical fuel. It is mainly for this reason that liquid hydrogen has found such a widespread application as a principal fuel in the space programmes.

The total life time of the technology may be considered as 30 years. But it is a matter of debate in the case of storage tanks made of metal alloys, because it depends on cycling and can be extended to more than 30 years with appropriate maintenance.

TECHNICAL TARGETS				
	STATE OF THE ART	**UNTIL 2015**	**UNTIL 2020**	**UNTIL 2030 AND BEYOND**
Cost	4.82 €/k Wh [12]			
Technology accessibility (0-4)	4	4		4
Storage Energy requirement	>60 MJ/kg	<60 MJ/kg		-
Energy required to free H_2	0			
Typical Storage pressure	0.6 MPa	-		-
Typical Storage temperature	20 K	-		-
Storage capacity (mass fraction kg H_2/kg storage medium)	10 wt% [39]	>12% [39]		>20% [39]
Efficiency part and full load	> 99%	> 99%		> 99%
Durability	30 years	>30 years		-
Leakage and boil-off % / day	<1			
Safety level	Very good	-		-
Refuelling capability	Few minutes	Few minutes		Few minutes
Infrastructure impact (simplicity) (1-5)	3	-		-

ROADS2HYCOM RECOMMENDATIONS FOR FUTURE RESEARCH MILESTONES, TARGETS AND ACTIONS		
Until 2015	**Until 2020**	**Until 2030 and beyond**
System design Development of novel LH2-tank systems: o Optimized, complex shaped tank systems: • Large size for HDV • Small size for bikes o Design of complex shapes by computer aided design (CAD) o Finite Element simulation	**System design** o Complex optimized shapes o Evaluation of durability and reliability o New concepts: • H2 slush: Establishment of slush-production test plants • Combination of cryogenic and compressed storage (cryo-pressure tank)	**System design** o H2 slush Evaluation of slush production and storage systems o Cryo-pressure tank Evaluation of cryo-pressure tank systems
Improvement of isolation Developments to increase standby-time to 7 days and decrease boil-off to < 0.5 %/day o CFD simulations o Tests with LH2 o New concepts (active cooling, H2 APU, improved MLI)	**Improvement of isolation** Evaluation of new concepts to achieve zero-loss tank systems: o Active cooling o H2 APU o Improved MLI	**Improvement of isolation** Evaluation of zero-loss tank systems o Development of adequate sensors and components o Tests of the integrated systems
Material Research Usage of new materials (e.g. light alloys, composites, etc.) o Material strength tests and fatigue tests in LH2	**Material Research** o Improvements regarding durability and reliability	**Material Research** Improvements regarding durability and reliability
Component Research Development of components integrated into LH2 tank systems o Improvement of sensors (mass, pressure, temperature) o Improvement of valves	**Component research** Evaluation of sensor designs o Durability o Reliability	**Component research** Improvements regarding durability and reliability
Safety and standards o LH2 detection sensors o Integrated safety concepts o Regulations for homologation	**Safety and standards** o Regulations for homologation o Standards and regulations to support a broad launch of hydrogen technology	
Cost reduction of components o Series production tools o Integrated tank systems	**Cost reduction of system** o Preparation for large scale production	**Cost reduction** o Large scale production

3.3 Solid Storage

Apart from gaseous and liquid state, hydrogen can also be stored in solid storage systems where the hydrogen molecules or atoms form physical or chemical compounds with a solid storage material.

Hydrogen combines with a variety of materials in physical or chemical binding. The important evaluation criteria for bound hydrogen storage are temperature, pressure and duration for charging and discharging the system as well as the potential number of charging cycles. Despite theoretically high storage densities, most forms of bound storage are still at the trial stage, with commercially available storage materials offering a storage weight of around 30-50 kg per kg stored hydrogen (3-5 wt%).

In the case of physical adsorption, molecular hydrogen is bound to the surface of a material, an example being deposition on carbon in the form of nanotubes. Hydrogen is also stored in microspheres.

Chemical compounds of hydrogen are known as hydrides, the most common being water, alcohol and carbon-based (e.g. petrol, diesel) hydrides. Metal hydrides, for example with light metals, are used as storage materials for hydrogen.

Further R&D is needed prior to the large scale implementation of hydrogen carriers for transport of hydrogen from production sites to distribution sites. The subject of reversible hydrogen carriers still requires fundamental material research while in the field of non-reversible hydrogen carriers the focus is on design, testing, optimization and scale-up of integrated processes [28] [73] [54] [58] [68] [16] [24] [59]. Research topics can be summarized as follows:

- Computational and analytical tools to:
  - Define and update the criteria for a cost-effective hydrogen fuel delivery infrastructure
  - Compare delivery methods and assess impact on overall system integration
  - Evaluate hydrogen carriers (storage capacity and reaction mass and heat transfer issues)
- **Materials research** to identification of suitable reversible liquid organic or hydride (possibly in slurry) hydrogen carriers. Required characteristics for the material include:
  - (De-)hydrogenation at low temp.
  - Low cost feedstock
  - Low volatility
  - Low toxicity

- **Fundamental R&D** on carbon nanostructures for storing hydrogen
- **Process Improvement** (R&D on methods) to:
  - Increase the wt% H_2 of metal hydrides;
  - Identify and develop catalysts to improve and enhance de- & rehydrogenation performance of organic liquids; cycleability; selectivity

A key issue with solid storage is the unpredictability of future breakthroughs – any recommendation should be considered with this in mind.

3.3.1 Physical solid Storage

Hydrogen molecules may adsorb not just on metal surfaces, but also on surfaces of various materials including carbon. Adsorption of hydrogen takes place some 0.1 nm above the surface, in a single (mono) layer at a suitable low temperature (but above the hydrogen liquid phase transition temperature of 20 K). It the temperature is too high, the thermal disturbance can lead to losses of the adsorbed molecules. For the only substance studied extensively so far, carbon, suitable temperatures are around the boiling point of nitrogen (70 K) and at pressures of about 10 MPa.

The maximum amount of hydrogen adsorbed is directly proportional to the carbon surface area. For thin sheets of grapheme the proportionality factor is 2 wt% (H/(C+H)) with 1.5 wt% established in practice [11]. Substances like activated carbon contain micropores that allow adsorption through surface areas 2-3 orders larger than the geometrical surface.

Predictions of room-temperature reversible 5-10 wt% H_2 have been made. If confirmed, such H-contents would surpass what is known for any reversible metal-hydride and open a new technology for solid hydrogen storage.

One form of carbon proposed for near ambient temperature H-storage applications are graphite nanofibers developed by Rodriguez and Baker of Northeastern University (USA). By a mechanism not fully understood by the developers, this form of carbon is said to be capable of condensing extraordinary amounts of molecular hydrogen within the graphite layers up to 67 wt%, but the reported measurements have been met with considerable scepticism. The measurements of Rodriguez and Baker have apparently not been independently substantiated to date. If even partially confirmed, this new form of graphite would obviously be of great interest for hydrogen storage [21].

Charging or discharging takes several hours or even days, so the concept is unsuitable for use in cars [63]. However, as always in science, time can be the resolver of this matter.

MILESTONES FROM EXISTING STRATEGY PAPERS					
	2010	**2015**	**2020**	**2025**	**2030 and later**
USA					*2050*: Develop carbon storage [74]. *2050:* R&D on nano tech storage: reliability, low cost, volume [74].
Japan	6 wt % [62]				9 wt% [62]

TECHNICAL TARGETS				
	STATE OF THE ART	**UNTIL 2015**	**UNTIL 2020**	**UNTIL 2030 AND BEYOND**
Cost				
Technology accessibility (0-4)				
Storage Energy requirement				
Energy required to free H_2				
Typical Storage pressure	10 MPa	-		-
Typical Storage Temperature	77 K	-		-
Storage capacity (mass fraction kg H_2/kg storage medium)	1.5 wt%	>5%		> 50%
Efficiency				
Durability				
Leakage and boil-off % / day	<<1			
Safety level	Excellent			
Refuelling capability	>24h			
Infrastructure impact (simplicity) (1-5)				

ROADS2HYCOM RECOMMENDATIONS FOR FUTURE RESEARCH MILESTONES, TARGETS AND ACTIONS		
Until 2015	**Until 2020**	**Until 2030 and beyond**
Develop materials that can store significant amounts of hydrogen at room temperature • Single-walled carbon nanotubes, made up of molecule-sized pore and graphite nanofibers • Stacks of nanocrystals that form a wall of similarly small pores.	**Scale-up** of first successful technologies **Further basic research** to seek better materials for physical solid storage; understanding of physics to develop models **Hybrid tanks** – material plus (optimized) pressure	**Refuelling capability** **Scale-up** of more successful technologies

3.3.2 Chemical Solid Storage

Storing hydrogen in solid materials has the potential to become a safe and efficient way to store energy, both for stationary and transport applications. A large number of metals and metal alloys can combine with hydrogen to form metal hydrides. When the hydrogen gas comes into contact with the metal (alloy) surface, often treated with a catalyst, the hydrogen dissociates into atomic hydrogen that diffuses into the metal grid.

Heat is released upon absorption (while recharging with hydrogen) and is required to free hydrogen from the grid when desorbed [48]. The amount of heat released during absorption is high, which needs to be removed during the refuelling process. This makes it difficult to meet the refuelling time criterion (<5 min). Simple calculations show that if the refuelling is to take place in this time, a typical car would require several megawatts of cooling during the refuelling process [81].

The efficiency of the hydride storage is almost 100% when checked for leaks. Only minor losses (<1%) may be expected due to venting or maintenance / replacement.

The efficiency of the auxiliary systems is variable corresponding to the efficiency of the cooling and heating energy device. For example, if waste heat is available the efficiency of the auxiliary systems may be almost 100%. If an electrical water boiler or water cooler is used, the efficiency may drop below 50%. Thus, the use of metal hydrides will probably be limited to applications where waste heat is available.

Metal hydrides are very effective at storing large amounts of hydrogen in a safe and compact way. All the reversible hydrides, working around ambient temperature and atmospheric pressure, consist of transition metals and the H-capacity of the metal hydride media is limited to below 2.5 wt%. This is unsatisfactory for on-board storage for transport applications.

Magnesium hydride is an exception with hydrogen capacity of ~8.2 wt%. However, its operating temperature, which is above 350°C, is too high for practical use [92].

It remains a challenge to explore the properties of the lightweight metal hydrides. The International Energy aims at 5 wt% hydrogen capacity with a release temperature <80°C, while the WE-NET aims at 6 wt% with a hydrogen release temperature <100°C by 2010.

R&D on metal hydrides has been going on for decades, and a large database with information about their properties exists today within the IEA HIA Annex 17 (http://hydpark.ca.sandia.gov). A summary of this database (the metal hydride "family try") is provided in Figure 6.6.1 and Table 6.6.1.

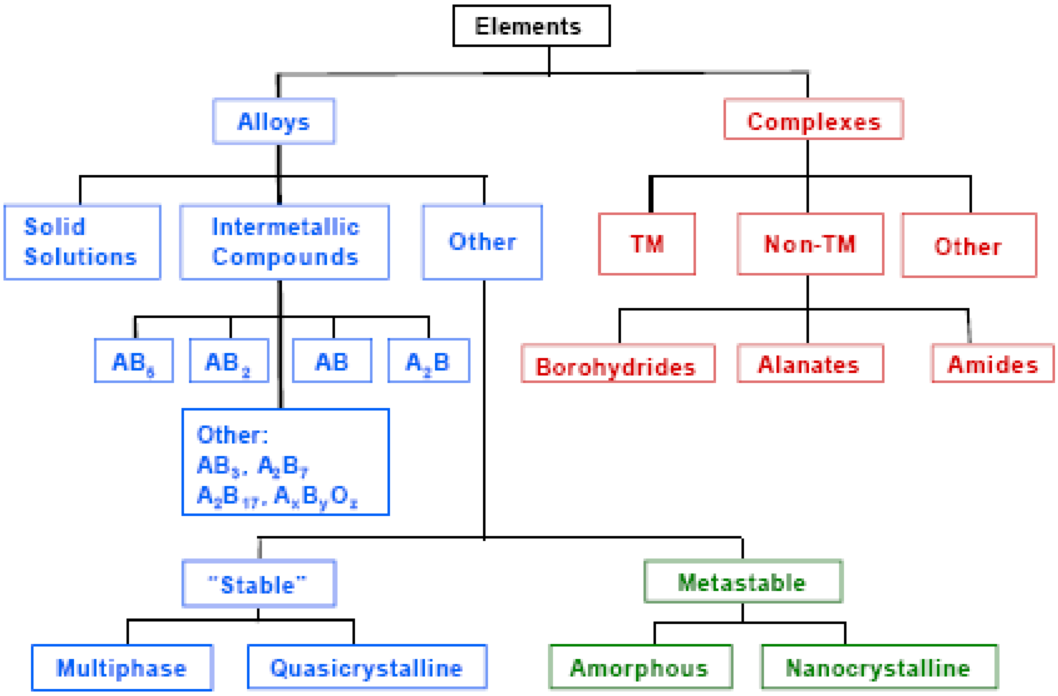

***Figure 6.6.1* – Metal hydride family tree [83]**

***Table 6.6.1* – Status and potential for metal hydrides listed in Figure 6.6.1.**

Hydrides	**Status & Potential**
Elements	Well characterized but thermodynamics unfavourable. Too stable or too unstable to use at temperatures around 0 – 100°C.
Alloys & Intermetallic Compounds	Very well studied. Mainly works well at temperatures <100°C, but gravimetric capacities are too low for vehicles (<2.5 wt% H_2). Technically suitable for stationary storage, but rather expensive.
Nanocrystalline & Amorphous	Good kinetics, but H-capacities and desorption temperatures are unfavourable.
Complex	Main hope for the future

From this it becomes clear that it is the complex hydrides that provide the hope for the future, particularly the non-transition metal types such as borohydrides, alanates and amides. Complex hydrides open a new field of hydrogen storage materials. There is a whole field of new compounds ready to be explored. The borides are especially interesting because of their very high gravimetric and volumetric hydrogen density.

The compound with the highest gravimetric hydrogen density known today is LiBH4 (18 wt%). This complex hydride could, therefore, be the ideal hydrogen storage material for transport applications [10]. However, the reversible hydrogen content is actually 13.8 % as the decomposition is given by the equation:

$$LiBH_4 \leftrightarrows LiH + B + 3/2\ H_2,$$

…and lithium hydride is far too stable to Li metal to decompose at accessible temperatures. In addition, the rehydriding process will proceed to completion under 35 MPa at 873K. Here again, current efforts are being devoted to see if the compound can be sufficiently destabilised to release and reabsorb hydrogen at lower temperatures and useable pressures [81].

The lifetime of the technology may be considered as 1 to 10 years. It is a matter of debate in the case of the external storage tanks made of metals or alloys, because it depends on cycling and may be extended to 30 years with appropriate malignance. Regarding the storage capacity of the alloys, it decreases with cycling, but may be reactivated increasing the life of the storage tank.

Safety usually centres on pyrophoricity, the tendency for a hydride powder to burn when suddenly exposed to air, for example if the tank accidentally ruptures. But the term can also include toxicity resulting from accidental ingestion or inhalation.

MILESTONES FROM EXISTING STRATEGY PAPERS					
	2010	**2015**	**2020**	**2025**	**2030 and later**
USA	Develop metal hydrides including investigations of the stability of hydrides under cyclic loading (long term studies) [74].		Develop advanced chemical hydrogen storage [74] Develop alanates (e.g. Al_xH_y) [74]		
Japan	8 wt% [62]				9 wt% [62]

TECHNICAL TARGETS				
	STATE OF THE ART	**UNTIL 2015**	**UNTIL 2020**	**UNTIL 2030 AND BEYOND**
Cost [12]	6.43 €/k Wh (chemical hydrides) 12.86 €/k Wh (complex metal hydrides)			
Technology accessibility (0-4)	2	3		-
Storage Energy requirement	>30 MJ/kg			
Energy required to free H_2	>15 MJ/kg			
Typical Storage pressure	0.06 – 6 MPa	1 – 6 MPa		
Typical Storage Temperature	> 373K	273 – 373K		-
Storage capacity (mass fraction)	2 wt%	6 wt%		> 10 wt%
Efficiency	99%			

TECHNICAL TARGETS				
	STATE OF THE ART	**UNTIL 2015**	**UNTIL 2020**	**UNTIL 2030 AND BEYOND**
Durability	<10 years	>10 years		-
Leakage and boil-off	No leakage	No leakage		No leakage
Safety level	Very good	Very good		Very good
Refuelling capability	30 -60 min	Few minutes		Few minutes
Infrastructure impact (simplicity) (1-5)	-	-		-

TECHNICAL TARGETS					
	STATE OF THE ART	**UNTIL 2015**	**UNTIL 2020**	**UNTIL 2030 AND BEYOND**	**REMARKS**
Hydrogen tank system density by weight (%) – Chemical hydrides (boro-amino hydrides and organic liquids) – Complex metal hydrides (alanates) – Metal hydrides (AB_2, AB_5) – Activated carbons, nanoporous materials	6 [39] 1.8 [39] 1.5 [39] 1 [39]	9 [39] 4.5 [39] 2 [39] 2 [39]			Reversible carriers: Liquid organic carriers and metal hydride slurries
Reforming efficiency a) (e.g. methanol b), ethanol and ammonia b))	Production process efficiency 66% [23] Costs of H_2 \$3.10/gge [23]	Production process efficiency 83% [23] Costs of H_2 \$2.00/gge [23]			Non-reversible carriers

a) Figures for reformer efficiency and cost of hydrogen apply to distributed hydrogen production via steam methane reforming. No specific targets exist for reforming of other "fuels". Costs include hydrogen production, compression, storage and dispensing to the vehicle.

b) Toxicity of methanol and especially ammonia is a severe limitation on their large-scale use as hydrogen carrier.

ROADS2HYCOM RECOMMENDATIONS FOR FUTURE RESEARCH MILESTONES, TARGETS AND ACTIONS		
Until 2015	**Until 2020**	**Until 2030 and beyond**
Material research on non-transition metal types such as borohydrides, alanates and amides.	**Complex hydrides** open a new field of hydrogen storage materials. There is a whole field of new compounds ready to be explored – select winning compounds, understand physics for modelling **Scale-up** of first promising technologies – product, processes **Hybrid tanks** – combination of material and pressure	**Lowering the cost of the processes**. In all cases, this is an energy-intensive process, need to optimize if costs can be reduced to vehicle targets **Further scale-up** of technologies and processes that appear promising

4. Hydrogen Distribution and Refuelling

Closely connected to the issue of storage is the question of how to distribute hydrogen to local users, such as filling stations for vehicles. On-site production is possible in special cases but as efficiency is better with centralized production, distribution is a key issue. Apart from distribution of compressed or liquid hydrogen in trailers by road, rail or ship, there is also the possibility to use pipelines for gaseous hydrogen.

For refuelling vehicles at filling stations, filling time is an important question. State of the art delivery for compressed gas and liquid hydrogen can be completed within a few minutes. Current solid storage systems are not suited for fast refilling. The filling support infrastructure for liquid hydrogen is especially technically demanding, with transfer pipes, filling connectors, etc. It also requires vacuum insulation and chilling to -253°C.

As with all hydrogen applications, issues of safety, codes and standards have to be addressed.

MILESTONES FROM EXISTING STRATEGY PAPERS					
	2010	**2015**	**2020**	**2025**	**2030 and later**
EU	Local clusters of H_2 filling stations, H_2 transport by road [7]	Clusters of local H_2 distribution grids [7]	Interconnection of local H_2 distribution grids [7] Distributed energy systems (< 10 MW) contribute >30% to Europe's electricity supply [5]	Widespread H_2 pipeline infrastructure [7]	
USA	Reduce the cost of H_2 delivery to < $ 1.70/gge of H_2 in 2012 [23] < $ 0.90/gge for transport from (semi-) central production sites to the refuelling station and other users < $ 0.80/gge for compression, storage and dispensing [24]	Develop technologies to reduce the cost of H_2 delivery to < $ 1.00/gge of H_2 in 2017[23			

4.1 Hydrogen Distribution

Hydrogen is distributed in compressed or liquid form in trailers by road, rail or ship. For the containers the same research issues as for already described for tank systems are generally applicable.

Apart from distribution of compressed or liquid hydrogen in trailers by road, rail or ship, there is also the possibility to use pipelines.

4.1.1 Trailer (road, rail, ship)

Trailers with compressed gaseous hydrogen bundles or tubes are carrying between 3,700 Nm^3 and 7,000 Nm^3 of H_2 to achieve a flexible supply with large and medium demands of CGH_2.

Liquefied hydrogen is used for the flexible supply of medium and large quantities with trailers carrying between 10,000 l (31,500 Nm^3) and 50,000 l (39,000 Nm^3) H2 [9].

4.1.2 Pipelines

The use of the natural gas pipeline network to deliver pure hydrogen or hydrogen mixed with natural gas (H2NG), without significant modification, may provide major cost/schedule benefits in the transition to a hydrogen economy. Mixtures of hydrogen and natural gas can also directly be burnt in gas turbines or internal combustion engines [[31]].

Due to diffusion and embrittlement, hydrogen pipelines require austenitic steel or Aluminium alloys. Hydrogen pipelines have been in use successfully for many years in Europe and the USA, installation costs are high.

Liquid hydrogen pipelines are only used for very short distances.

MILESTONES FROM EXISTING STRATEGY PAPERS					
	2010	**2015**	**2020**	**2025**	**2030 and later**
EU	3% of hydrogen in natural gas network [55]	12% of H_2 content in natural gas network [55]		25% of H_2 content in natural gas network [72]	

TECHNICAL TARGETS				
	STATE OF THE ART	**UNTIL 2015**	**UNTIL 2020**	**UNTIL 2030 AND BEYOND**
Testing NG pipelines Steels with high H_2 content	20% max			
Improve NG PE leakage				
Adjustment of gas metering and quality control systems in NG network				
Adaptation of high and medium pressure NG grid: compression horsepower, operating pressures				
Adjustment of pressure control systems and pipeline materials				

4.2 Refuelling Infrastructure

Refuelling infrastructure for hydrogen and their specific safety issues are dealt with in the EU project HyApproval.

MILESTONES FROM EXISTING STRATEGY PAPERS					
	2010	**2015**	**2020**	**2025**	**2030 and later**
EU			Cost of H_2 at pump (excluding taxes) <2.5 €/kg [39]		
USA	Reduce the cost of hydrogen fuel delivery to <$1.30/gge [23].	Reduce the cost of hydrogen fuel delivery to <$1.00/gge [23].			Reduce the cost of hydrogen fuel delivery to <$1.50/gge [23].
Japan	Number of Hydrogen stations: 169 [17] 3 wt% 17 g/L Refuelling time: 5 min [62]	Number of Hydrogen stations: 533 [17]	Number of Hydrogen stations: 2.344 [17]		Share of hydrogen stations: 5 % [17] 9 wt% 80 g/L Refuelling time: 2 min [62]

TECHNICAL TARGETS					
	STATE OF THE ART	**UNTIL 2015**	**UNTIL 2020**	**UNTIL 2030 AND BEYOND**	**REMARKS**
Cost of hydrogen delivery at the pump (centralized and decentralised) (excluding taxes) [€/kg]			< 2.5 [40]		
Filling time [minutes]		3 [39]			
Maximum storage pressure [bar]		700 [39]			
Consecutive fillings per pump [1/h]		10 [39]			
Daily sales per filling station [kg/d]		150 [39]	300 [39]		

ROADS2HYCOM RECOMMENDATIONS FOR FUTURE RESEARCH MILESTONES, TARGETS AND ACTIONS		
Until 2015	**Until 2020**	**Until 2030 and beyond**
Distribution economics – maintain databases and models of distribution costs and lifecycle impacts, develop convergence of regional policies **Pilot infrastructures** – onsite production, refuelling devices usable by the public, safety **Alternatives** – Hydrogen in Natural Gas pipelines	**Infrastructure build-up** – reduction of pipeline costs, pipeline maintenance & prognostics, reduction of power requirement for compression and liquefaction **Global commonisation** – refuelling devices for every forecourt	**Lowering the cost of a mass market Hydrogen infrastructure** - pipelines, compression, liquefaction **Permitting mass adoption** – enabling lower range through automatic smart refuelling

5. Hydrogen Energy Converters

The final element in the energy supply chain is the energy conversion of hydrogen, which can take place in two different ways, the so called hot combustion in machines like turbines or internal combustion engines (ICE) and the so called cold combustion or direct chemical conversion in fuel cells (FC).

From the application point of view, the hydrogen energy converters can be divided into transport applications (road, rail, ship, and aeronautic), stationary applications, and portable applications.

Turbines and ICE represent a reliable and relatively cheap technology with high power density and long durability. Although the conventional technology needs to be adapted to operate with hydrogen, there is not much need for the development of completely new technological approaches. Therefore there is only one chapter on combustion technology for all applications.

Fuel cells promise the direct conversion of chemical energy at high efficiency. The the chemical processes involved are quite complex and depend on the type of fuel cell and fuel being used. Therefore there is a detailed description of research topics for different applications. The main goals of research are the increase of practical efficiency and durability as well as the decrease of weight, volume, and costs of fuel cell systems.

5.1 Hydrogen Combustion Technology

With combustion of hydrogen in turbines and ICE being a proven and tested technology, there are hardly any detailed roadmaps and strategy plans for research. Besides questions of materials, the specific combustion properties of hydrogen, such as its wide ignition limits, fast burning velocity, and lower viscosity, have to be accounted for in the construction and operation of the combustion system. The main goals of hydrogen combustion research are the increase of efficiency, for example by direct injection, and the decrease of Nox emissions (e.g. by lean combustion).

The following tables include the different applications as mentioned. In the milestones table India is included with a detailed roadmap for hydrogen combustion.

Natural gas is gaining importance as a fuel. There are more reserves of natural gas than with oil and CO_2 emissions are lower due to the higher content of hydrogen. Mixtures of natural gas and hydrogen as well as hydrogen rich gas from fermentation, gasification, and waste gas will increasingly be used as fuel for ICE and turbines. The special combustion properties of such gas mixtures have to be investigated and accounted for.

MILESTONES FROM EXISTING STRATEGY PAPERS					
	2010	**2015**	**2020**	**2025**	**2030 and later**
EU Road PC	Charged H_2 PFI (Port Fuel Injection) and H_2 DI (Direct Injection) Specific Power up to 45 kW/l Specific Engine Torque 70 Nm/l	Charged H_2 PFI and H2 DI Specific Power 60-70 kW/l Specific Engine Torque 120-130 Nm/l >26% efficiency Cost = 18 €/kW	Charged H_2 DI Specific Power 100 kW/l Specific Engine torque 180 Nm/l Increasing H^2 pressure demand from 5 bar to 100 bar & up[1]		
EU Road HD		HD: 42% efficiency; cost = 1.5*Diesel powertrain costs; Lifetime 25,000-30,000 hour			
EU Air		Reduction of fuel consumption and CO_2 by 50%, noise by 50%, NOx by 80% [13]			
USA	Engine / turbine designs and controls for H_2 blends [74] Integrated H_2 storage release and engine / turbine controls [74]				

1 BMW Group Clean Energy Fuel Systems, Brussels 16 January 2008

MILESTONES FROM EXISTING STRATEGY PAPERS					
	2010	**2015**	**2020**	**2025**	**2030 and later**
India	**1.** Modification of Petrol and Diesel IC Engines for use with Hydrogen. **2.** Identification of SI/CI Engine-Genset capacities for modification for taking up demonstration projects. **3.** Hydrogen Induction system, safety system and loading arrangement. **4.** NOx emission reduction methods. **5.** Optimization of engine parameters and H_2 percentage for best performance and least emissions **6.** Demonstration plants of 1MW_{el} aggregate power generation **7.** Large scale manufacture of retrofit H_2 injecting systems into manifolds of existing engines of portable gen-sets, including modification of engines. **8.** Emission reductions with increase of H_2 percentage (in CI engines) and with pure H_2 (in SI engines). **9.** Recommendations for large scale introduction of H_2 fuelled IC engine based gensets. **10.** Developed of dedicated IC engine for Hydrogen Fuel. **11.** Demonstration plants of 9 MW_{el} aggregate power generation [71]		**1.** 20 MW_{el} aggregate power generation **2.** Large number of decentralized power generating systems with a cumulative capacity of 1 000 MW_{el} would be set up, 50 MW_{el} capacity small IC engine stand alone generators; 50 MW_{el} capacity stand alone Fuel Cell Power Packs; 900 MW_{el} aggregate capacity centralized plants. [71]		

TECHNICAL TARGETS					
ROAD	**STATE OF THE ART**	**UNTIL 2015**	**UNTIL 2020**	**UNTIL 2030 AND BEYOND**	**REMARKS**
PC: Vehicle fuel consumption in the MVEG driving cycle (MJ/100 km)	Gasoline ICE: 224 Potential 2010: 188	Hybrid potential: 163			
PC	Diesel ICE: 183	Potential 2010: 180 Hybrid potential: 148			
PC	Hydrogen ICE	Potential 168 Hybrid potential: 141			
HD application	ICE City Buses naturally aspirated and turbo-charged				
Air: H_2 combustion in propulsion systems	Technology readiness level in laboratory and demonstrator status existing	Commercial product (Turbo Prop) availability appreciated	Commercial H_2 optimised propulsion systems		
Air: Light weight LH2 storage		3kg Tank / kg LH2	2kg Tank / kg LH2		

ROADS2HYCOM RECOMMENDATIONS FOR FUTURE RESEARCH MILESTONES, TARGETS AND ACTIONS		
Until 2015	**Until 2020**	**Until 2030 and beyond**
Increased performance via turbocharged engines	Downsizing in combination with **hybrid** technology	*By this time it is possible that ICE technology will be mature, even with Hydrogen as a fuel*
More efficient internal mixture formation, combustion system with high pressure injection	**Alternative thermodynamic cycles** with efficiency approaching second-law limits	

5.2 Fuel Cell Technology

The Fuel Cell is an electro-chemical device that turns a fuel (often Hydrogen or Natural Gas, but other fuels are feasible) into Electricity. In a simple sense it can be considered as being like a battery that is re-fuelled. In stationary applications the Fuel Cell is used directly to create electricity (and often also heat) for general use. In transport applications it is used with an electric motor to drive the vehicle or vessel.

The main issues of the Fuel Cell are durability, size, operation in extreme heat and cold, and the ability to manufacture it cheaply. Issues effecting the "balance of plant" are the air compressors, fuel reformers (to turn other fuels into Hydrogen), pumps and cooling systems, which are developed technologies that need significant adaptation for use in fuel cells. Whereas, for the electrical systems power control, batteries and motors, are all important, especially in transport, and tend to be costly today.

MILESTONES FROM EXISTING STRATEGY PAPERS					
	2010	**2015**	**2020**	**2025**	**2030 and later**
EU	-	Commercially competitive Fuel Cells > 1 GW capacity [39]	-	-	-
USA	Catalysts with 50% better performance and 50% cost reduction [74]	120°C PEM [74]. 500°C ionic conductors [74].	400°C ionic conductors [74].	-	-
Japan	Efficiency: 50 % Output density: 1 kW/L [62] FCV Introduction stage			-	Efficiency: 55% Output density: several kW/L [62]

5.3 Transport Fuel Cell Applications

The use of fuel cells for transport is the ultimate goal because, if fuelled with hydrogen, the vehicle will produce no emissions except for water. This will enable zero tailpipe emissions for the transport sector.

Detailed information follows on both passenger car and commercial vehicles relating to fuel cell applications.

MILESTONES FROM EXISTING STRATEGY PAPERS					
	2010	**2015**	**2020**	**2025**	**2030 and later**
EU	10 000 H_2 vehicles in the EU. [3] 13 demo sites for road vehicles: 150 passenger cars 50 buses 9 refuelling stations [39] 4 Maritime demonstrations: > 250 kW power 1 ship per project [39] 3 rail demonstrations: 1 vehicle/site [39] Demonstration of fuel cell powered vehicles in captive fleets [9]	500 000 H_2 vehicles in the EU. [3] 30 demo sites for road vehicles: 3000 vehicles <2.5 €/kg [39] 15 maritime demonstrations: > 500 kW power 1 ship per project [39] 10 rail demonstrations: 3 vehicle/site 45% efficiency 500 €/kW 50 000 hours lifetime [39] Road application: > 40% efficiency 100 €/kW 5000 hours lifetime [39] [9] Road application (auxiliary power unit): 35% efficiency < 500 €/kW 5000 h lifetime [39] Air-application: (with reformer): 60% efficiency 500 €/kW 30 000 h lifetime	4M H_2 vehicles in the EU. [3] Annual production of hydrogen vehicles with FC or ICE > 400 000 [39]. Series production of fuel cell powered vehicles for fleets (1st generation on-board hydrogen storage) [9] Small scale commercialization of H_2 Fuel Cell powered rail cars. [78] 1 – 3% H_2 vehicles (share in vehicle stock) [9]	16M H_2 vehicles in the EU. [3] Series production of fuel cell powered vehicles in broad application (2nd generation hydrogen on-board storage and low cost high-temperature fuel cell systems) [9] 8 – 25% H_2 vehicles (share in vehicle stock) [9] Small scale commercialization of H_2 Fuel Cell powered rail cars. [78]	Fuel cells become dominant technology in transport [9] 25 – 50% H_2 vehicles (share in vehicle stock) [9] 2050: 40-75% H_2 vehicles (share in vehicle stock) [9] Higher power Rail locomotive commercialization [90]

MILESTONES FROM EXISTING STRATEGY PAPERS					
	2010	**2015**	**2020**	**2025**	**2030 and later**
		[39] ICE propulsion: 40% efficiency 18 €/kW [39]			
USA	Mine loco in service Shunting loco – ongoing CARB ZEV mandate for bus fleets: 15% of all vehicles [95] H_2 vehicles with +250 miles range and + 2000 hour FC durability [79] Storage capacity of 8% by weight [74]	Validate H_2 vehicles with +300 miles range and 5,000 hour FC durability [79]. Polymer electrolyte-membrane auto-motive fuel cells that cost < $45 /kW and deliver 5,000 hours of service [23].	Storage capacity of 6% by weight [74].		
Japan	2 rail demonstrations: 1 vehicle/site 1 in passenger service				
India	Pure hydrogen combustion in ICE	Fuel Cell in hybrid electric vehicles	-	-	-

5.3.1 Road Transport

Road transport is the most technically challenging application, but the latest generation vehicles are realising the efficiencies that the fuel cell has always promised. Hydrogen storage remains a critical topic for transport-application research, as improvements are critical to developing vehicles with attractive operating range, interior space and price.

The road transport applications can be divided into two main sectors Passenger Cars (Light Duty) and Heavy Duty. Passenger cars have the bigger challenge due to the autonomous nature of drivers and wide variety of operating modes and driving styles requiring flexible use of the vehicle. Heavy duty applications are more generally controlled fleets such as buses and haulage applications, which have a more prescribe operating regime. This brings about different requirements for the two sectors such as refuelling infrastructure, weight, cost and durability of the fuel cells.

Electric Drive Technologies

Boundary conditions for FC system development following the goals for Electric Propulsion System for 2010 (Freedom Car Goals – April 2004):

Freedom Car Goals	
Peak power	55 kW for 18 seconds
Continuous power	30 kW
Lifetime	> 15 years (150,000 miles)
Cost	< 12$/peak
Technical targets	
Specific power at peak load	> 1.2 kW/kg
Volumetric power density	> 3.5 kW/l
Efficiency (10 to 100% speed, 20% rated torque)	90%

Approximate Technical targets for major components of a Series Electric propulsion System (Freedom Car Goals – April 2004)

Power Electronics (inverter/controller)	
Specific power at peak load	> 12 kW/kg
Volumetric power density	> 12 kW/l
Cost	< 5$/kW peak
Efficiency (10-100% speed and 20% torque of the drive)	> 97%
Traction motor	
Specific power at peak load	> 1.3 kW/kg
Volumetric power density	> 5 kW/l
Cost	< 7$/kW peak
Efficiency (10-100% speed and 20% torque of the drive)	> 93%

Passenger Cars

The application of Fuel Cell and Hydrogen technologies to the passenger car is seen by many as the “holy grail” in the field. There are good rational arguments for this. The Passenger Car sector offers a large greenhouse-gas abatement potential if the hydrogen is sourced from low carbon or carbon-free energy chains. Using hydrogen as a fuel gives rise to near-zero tailpipe emissions, taking the product itself out of the environmental equation and concentrating the control of greenhouse-gas emissions upon a few hydrogen fuel producers. The automobile manufacturing sector possesses mass-production expertises that can leverage lower costs, with potential benefits that could spill into other sectors

PEM is the technology universally employed for the fuel cell powertrain in the passenger car sector. These fuel cells run on pure hydrogen.

The system can be configured in different ways either as a fuel cell hybrid or a range extender for an electrical vehicle. The fuel cell can generate electric power, which is used to drive the wheels via one or more electric motors. The fuel cell power is varied directly according to drive requirements.

For Fuel Cell Hybrid systems, a battery is used to store the electricity generated by the fuel cell, thus de-coupling fuel cell output and drive power, and allowing re-generative braking. This gives an efficiency advantage as with any Hybrid vehicle.

As for a Fuel Cell Range Extender the vehicle is essentially an electric vehicle (EV). A small fuel cell is used as an onboard generator to extend the operating range. The vehicle can be refuelled with both electricity and hydrogen.

As yet there are a very limited number of fuel cell or hydrogen products on the market but there has been substantial prototype demonstration and evaluation activity worldwide since the mid 1990s. Some of these prototypes have been loaned or leased to selected users under carefully controlled conditions.

MILESTONES FROM EXISTING STRATEGY PAPERS					
	2010	**2015**	**2020**	**2025**	**2030 and later**
EU	-	Efficiency on a NEDC > 40%	5% of new cars fuelled by zero-carbon hydrogen 2% of fleet fuelled by zero-carbon hydrogen 2	-	25% of new cars fuelled by zero-carbon hydrogen 15% of fleet fuelled by zero-carbon hydrogen
EU	1 light house project [38]	Up to 2015: max. 4 light house projects [38]	General mass market roll out (main powertrain) [57]	**-**	Main type of powertrain

2 EC – Hydrogen Energy and Fuel Cells: a vision of the future; [89] JTI-information, April 2008

MILESTONES FROM EXISTING STRATEGY PAPERS					
	2010	**2015**	**2020**	**2025**	**2030 and later**
USA	CARB ZEV mandate for bus fleets: 15% of all vehicles [95] H_2 vehicles with +250 miles range and + 2000 hour FC durability [79] Storage capacity of 8% by weight [74]	Validate H_2 vehicles with +300 miles range and 5,000 hour FC durability [79]. Polymer electrolyte-membrane auto-motive fuel cells that cost < $45 /kW and deliver 5,000 hours of service [23].	Storage capacity of 6% by weight [74].	-	-
USA	Efficiency improvements of H_2 FCV respect to a gasoline ICE (USDOE) -15%		-	-	Efficiency improvements of H_2 FCV respect to a gasoline ICE (WBCSD) -46% (USDOE) -66%

TECHNICAL TARGETS					
	STATE OF THE ART	**UNTIL 2015**	**UNTIL 2020**	**UNTIL 2030 AND BEYOND**	**REMARKS**
Efficiency (NEDC)	37% [40]	> 40% [39]	-	~ 45% [41]	-
Specific Cost	> 4000 €/kW [40]	100 €/kW (>150k u/a) [39] [41]	H_2: 4 €/kg FC: 100 €/kW Tank: 10 €/kWh	60 €/kW [41]	-
Lifetime	< 2000 h [40]	> 5000 h (Bus: >10000 h) [41]	-	-	-
Ambient conditions	-	-25°C/+45°C +freeze start [41]	-	-	-
Operating Range	-	> 400 km [41]	-	> 600 km [41]	-
System Volume	3.0 l/kW [40]	1.5 l/kW [40] [41]	-	2.5 l/kW [41]	-
System Weight	-	1.5 kg/kW (without e-drive and storage) [41]	-	3 kg/kW (including e-drive and storage) [41]	-

TECHNICAL TARGETS					
	STATE OF THE ART	**UNTIL 2015**	**UNTIL 2020**	**UNTIL 2030 AND BEYOND**	**REMARKS**
Number of Vehicles	-	3000 [40]	-	0.4 – 1.8 million/a[1] [40] [39]	[1] figures for 2020
Energy consumption (typical vehicle)	-	-	-	< 3 litres of diesel equ. [41]	-
Pt-Loading mg/cm**2	0,5	-	Factor 2-5 lower than state of the art	-	-

ROADS2HYCOM RECOMMENDATIONS FOR FUTURE RESEARCH MILESTONES, TARGETS AND ACTIONS		
Until 2015	**Until 2020**	**Until 2030 and beyond**
Introduce early applications for hydrogen & FC premium niche market to stimulate the market, improve public acceptance and gain experience	Cost reduction to meet FC-system, drivetrain and tank targets	H_2 technology is fully competitive by 2030 H_2 technology is fully sustainable by 2050
Obtain significant cost and size reduction of the H_2 drive train and hydrogen system through optimisation and integration	Focus on pre-commercial applications (market preparation, system integration, continued cost reduction)	Focus on commercialization (switch from modified conventional vehicles to purpose-built vehicles; verify hydrogen safety and reliability; build consumer confidence)
Ensure that state of the art in durability and temperature envelope can be realised in production	Development of international regulation, codes and standards	Mass market maturing
Assure safe and reliable hydrogen applications. Impurity tolerance	Recycling of raw materials	New generation technologies displacing first mass-market generation – realisation of basic research and prototypes into production
Comply with long-term sustainability requirements	Methods and processes for the highest volumes of mass production	-
Further reduction of costs and improvement of performance of components for stacks and BoP; precious metal thrifting	Realisation in prototype of new concepts e.g. precious metal free	-

Heavy Duty Vehicles

The operating and market characteristics of heavy-duty vehicles are substantially different from the light-duty vehicles operated by the general public. The performance and cost aspects of the heavier vehicles make them in some aspect more conducive to early use of fuel cell and hydrogen technology. These operating and market characteristics present new opportunities and challenges for the fuel cells and hydrogen.

Heavy duty vehicle is an inhomogeneous category of vehicles with disperse requirements and where the advantages and competitiveness of fuel cell and hydrogen technologies differs considerably.

Goods handling vehicles (forklift trucks, airport vehicles, etc.) are likely to become the first market, albeit with limited scope for global environmental impact. They often work in areas with air quality issues, or indoors where toxic emissions are unacceptable. A key advantage is faster refuelling than a battery-powered equivalent.

City buses and city distribution trucks are commonly recognised as promising candidates for early adopters and demonstration projects of fuel cell propulsion. This is due to the fundamental characteristics of their operation within a defined area with possibility for central refuelling and defined drive cycles. They are often used in environmental sensitive areas. Their intensive use gives maximum experience in a short period of time as well as high public exposure.

Long haulage trucks on the other hand are driven over long distances crossing the continent. These vehicles are dependent on well established fuel infrastructure and require a fuel with very high energy density. This makes it difficult for fuel cells and hydrogen to compete in this sector in the short and mid term.

On the other hand the increasing demand for electrical power on-board long haulage trucks, especially when stationary, leads to an increasing need for an on-board highly efficient and low emissions Auxiliary Power Unit (APU). The EPA has estimated the emissions from US long haulage trucks, while idling, to be:

- NOx: 180 000 tons per year
- PM: 5 000 tons per year
- CO_2: 11 million tons per year

A fuel cell based APU, with a diesel fuel reformer, is regarded as the most interesting option since it combines high efficiency with low emissions and uses the same fuel as the main engine. By using a fuel cell APU instead of idling the main engine to produce electricity for when the truck stands still will considerably reduce emissions and fuel consumption.

For propulsion of the heavy-duty vehicles the environment and use are similar to that for light-duty vehicles and consequently the R&D needs are comparable, with some variation in priority. The main differences are that in heavy duty applications the vehicle is used more frequently and for longer periods, which leads to higher demand for durability. The vehicles are driven and serviced by professionals and are used in a predictable way.

For the powertrain, direct hydrogen PEM fuel cell systems are approaching some of the goals. Several issues remain and the primary barriers are:

- Cost
- Durability
- Size and weight
- Operational conditions (ambient temperature, humidity, shock vibration).
- R&D aiming at cost reduction and reliability should have a high priority.

For APU applications with use of a fuel processor both PEM fuel cells and SOFC are promising candidates. For this application there are similarities and common R&D needs with those for small stationary fuel cell systems as well as to other transportation modes such as aviation and maritime use. Technical challenges include:

- Reducing components and systems cost
- Reducing precious metal requirements
- Reducing volume and weight
- Increasing component and system durability
- Reducing start-up time
- Increased cycle life.
- Developing high-efficiency air management subsystems

The research challenges for stack development are related to temperature, fuel flexibility, durability and reliability, cost and system optimization. Stable long-term operation of stacks with lifetimes of 20,000 hours and costs of less than 200 €/kW are needed for significant market penetration. Stack performance needs to be enhanced by increased power density, improved system design.

For the two relevant fuel cell technologies development is targeting reducing costs, improving reliability, robustness and lifetime, making the system fuel flexibly and increasing tolerance to impurities. The development issues associated with the stack, reformer, peripheral component and fuel cell system are:

- PEMFC
    - Higher operating temperature

  - Dry operation
  - Higher CO tolerance
  - Lower Pt catalyst loading or alternative catalysts
  - Recycling of stack components
  - Low-cost fuel processors
- SOFC
  - Reducing operating temperature (corrosion and degradation)
  - Redox stability
  - More robust high-temperature systems to achieve
  - Mechanical reliability and robustness, particularly of cells
  - Thermal cycling stability
  - Cheaper and less materials
  - Internal reforming
  - Fuel impurity tolerance
  - Sealing materials

PEMFC is the more mature of the two technologies under consideration but the major issues are still cost and reliability. Focus should be given to research on cost reduction, investigation of degradation mechanisms, and development of high-temperature membranes and membrane electrode assemblies (MEAs) that do not require hydration and have a higher CO tolerance. Balance of plant components and system optimisation are also important.

MILESTONES FROM EXISTING STRATEGY PAPERS					
	2010	**2015**	**2020**	**2025**	**2030 and later**
EU	13 demo sites for road vehicles including captive fleets, 200 vehicles, 9 refuelling stations [39]	30 demo sites, 3,000 vehicles. Cost 100 €/kW, durability 5,000 h. [39]	0.4 – 1.8 million per year [39]	-	-
	1 light house project, 3 regional applications of bus fleets started. APU: 1st niche markets	Up to 2015: max. 4 light house projects (PC) and up to 10 regional applications of bus fleets finished. First market introduction APU. Mass market roll out	General mass market roll out (main powertrain & APU)	-	Main type of powertrain
USA	CARB ZEV mandate for bus fleets: 15% of all vehicles [95] H_2 vehicles with +250 miles range and + 2,000 hour FC durability [79] Storage capacity of 8% by weight [74]	Validate H_2 vehicles with +300 miles range and 5,000 hour FC durability [79]. PEM automotive fuel cells that cost < $45 /kW and deliver 5,000 hours of service [23].	Storage capacity of 6% by weight [74].		
Japan	50,000 vehicles	5,000,000 vehicles			40% total share (2050) [41]

TECHNICAL TARGETS				
	STATE OF THE ART	**UNTIL 2015**	**UNTIL 2020**	**UNTIL 2030 AND BEYOND**
Efficiency (NEDC)	37% [40]	> 40% [39]		~ 45% [41]
Specific Cost	> 4000 €/kW [40]	100 €/kW (>150k u/a) [39] [41]		60 €/kW [41]
Lifetime	< 2000 h [40]	(Bus: >10,000 h) [41]		
Ambient conditions		-25°C/+45°C +freeze start [41]		
Operating Range		> 400 km [41]	-	> 600 km [41]
System Volume	3.0 l/kW [40]	1.5 l/kW (without e-drive and storage) [40] [41]	-	2.5 l/kW (including e-drive and storage) [41]
System Weight		1.5 kg/kW (without e-drive and storage) [41]		3 kg/kW (including e-drive and storage) [41]
Number of Vehicles			-	0.4 – 1.8 million/a[1] [40] [39]

[1] figures for 2020

Roads2HyCom Recommendations for future research milestones, targets and actions		
Until 2015	**Until 2020**	**Until 2030 and beyond**
Bus and LD delivery vans: Introduce early applications for hydrogen & FC premium niche market to stimulate the market, improve public acceptance and gain experience	Bus and LD delivery vans: Cost reduction to meet FC-system & drivetrain & tank: 100 €/kW (Tank: 10 €/kWh)	Bus and LD delivery vans: H_2 technology is fully competitive by 2030 H_2 technology is fully sustainable by 2050
Goods handling equipment: Support this early market through improved durability and robustness		
APU for HD-vehicles: early applications and niche markets (on and off road)	-	-
Cost reduction of stack and BoP components	Market availability of standard BoP components	Fuel cell systems as energy supply for fully electric HD powertrains
Improved durability to meet target values	Manufacturing techniques and methods for low cost mass production incl. QA	-
See more details stationary applications	Diagnostics and life time prediction techniques	-
Fuel reformers for liquid fuels for APU systems: long term stability; higher efficiency; low maintenance; desulphurisation (synergy with residential usage)	Fuel reformers for liquid fuels for APU systems: continuous desulphurisation w/o cartridges (synergy with residential usage)	-
Higher CO tolerance of PEM stacks – HTPEM technology	-	-
Higher thermal integration of SOFC APUs for fast warm-up	Simplified low cost SOFC systems for APU	-
Efficiency improvements of BoP components such as compressors	-	-

Refer also to the recommendations for passenger cars above.

5.3.2 Rail Application

During FP6, the UIC HyRail project [89] delivered a position paper summarizing hydrogen as an energy carrier, and its potential for application in the rail sector.

Three successful rail applications have been completed. In Japan the JRE and RTRI rail companies have each developed fuel cell trains that have run in non-passenger trials. Further demonstrations of fuel cell trains in passenger service are understood to be planned. In USA, Vehicle Projects have successfully built a fuel cell mine locomotive, with hydrogen stored in a metal hydride system, which has completed trial and continues in operation.

Currently Vehicle Projects are building a shunting locomotive with 250 kW PEM fuel cell from hydrogen in compressed gas storage. Batteries will supplement the mean power from the fuel cell, delivering >1MW peak power.

In France, SNCF are building a hybrid demonstration locomotive which incorporates a SPACT80, 80 kW fuel cell and hydrogen gas storage.

A European passenger train trial is proposed for FP7, in which European consortium members from countries including Spain, Denmark and UK will demonstrate a PEM fuel cell powered train in branch line passenger operation in Denmark and England.

At present the density of on-vehicle hydrogen storage is seen as a restriction that will limit PEM fuel cell vehicle power and time between refuelling. This can be overcome where high power vehicles operate in a restricted local environment such as a freight depot in shunting operation. However, in situations where high power is required throughout a long route, electrification is likely to continue to be justified.

Lower powered vehicles operating on branches from the electrified core route will continue to be required. In these cases hydrogen fuel cell trains can offer advantages over existing diesel technology.

Future fuel cell and storage development will increase the traction efficiency, time between refuelling and time between maintenance. Reduction in the component external dimensions and weight will enhance train performance and maximize passenger capacity.

After solid oxide fuel cells are developed in other sectors, they may allow development of high powered traction packages for use on core routes in high speed passenger service or long haul freight use.

In both light/medium power, and high power rail traction, fuel cell technology is expected to dominate over internal combustion engine technology (ICE). ICE technology for long range rail applications is not expected to continue developing due to the lower efficiency of the ICE compared to the fuel cell and the need to reduce emissions. [78]

MILESTONES FROM EXISTING STRATEGY PAPERS					
	2010	**2015**	**2020**	**2025**	**2030 and later**
EU	3 rail demonstrations: 1 vehicle/site [39]	10 rail demonstrations: 3 vehicle/site 45% efficiency 500 €/kW 50,000 h lifetime [39]	Small scale commercialization of rail cars. [78]	Small scale commercialization of rail cars. [78]	Higher power Rail locomotive commercialization [90]
USA	Mine loco in service Shunting loco – ongoing	Not known	Not known	Not known	Not known
Japan	2 rail demonstrations: 1 vehicle/site 1 in passenger service	Not known	Not known	Not known	Not known

TECHNICAL TARGETS				
	STATE OF THE ART	**UNTIL 2015**	**UNTIL 2020**	**UNTIL 2030 AND BEYOND**
Power [kW]	300 (H_2)	500 (H_2) 1000 (SOFC)	600 (H_2) 1000 (SOFC)	2000 (long haul)
Durability [hours]	12,000 (PEM)	50,000 (SOFC) [1] 20000 (PEM)	50,000 (SOFC) [1] 20000 (PEM)	30 – 40,000 (PEM). [78]
Cost [€/kW]	1,600	500 [1]		
Net Efficiency [%]	45%	55% (PEM) 60% (SOFC)	60% (PEM) 60% (SOFC)	
Storage Gravimetric Capacity [kg H_2/kg system]	0.045 [91]	0.09 [91]		
Storage Volumetric Capacity [kg H_2/Litres of system]	0.036 [91]	0.81 [91]		
Ambient conditions [°C]	-5 to 30			-40 to 45
Range (refuelling frequency)	Daily			Every 3-4 days

ROADS2HYCOM RECOMMENDATIONS FOR FUTURE RESEARCH MILESTONES, TARGETS AND ACTIONS		
Until 2015	**Until 2020**	**Until 2030 and beyond**
Creation of common Technical Specification for Interoperability (TSI) (Railway acceptance criteria within EU)	Higher power density of the powertrain (see above)	
Application specific testing (such as vibration and shock resistance under specific load conditions)	Improvement in Fuel Cell durability, within the railway operating environment	
Establishing maintenance procedures and periodicities within the railway operating environment	*Reduction in cost of fuel cells and balance of plant*	
	Achieving passenger acceptance of hydrogen based technologies in rail transport	
Remark: Elimination of limitations of range due to limited storage density – see Chapter 7		

5.3.3 Ship Application

Fuel cells for maritime applications can be used for propelling ships or for onboard power supply. Fuel cells offer the possibility of emission-free ship operation, which can be important for ports and inner-city traffic. Further, the higher gravimetric energy density of hydrogen compared to current hydrocarbon fuels offers the possibility to increase the payload of ships (subject to volumetric constraints, which remain more challenging).

Solid Oxide Fuel Cells may be the preferable type of fuel cell for maritime transport in the near future, because it has high fuel flexibility due to its internal reformation ability.

In 2003, MTU equipped a sailing yacht with four 4.8 kW PEM fuel cell stacks from Ballard. With compressed hydrogen on board the ship has a hydrogen-powered range of 225km. However, the use of fuel cells to supply "hotel loads" (and to power dockside vehicles) in port remains the most promising application.

MILESTONES FROM EXISTING STRATEGY PAPERS					
	2010	**2015**	**2020**	**2025**	**2030 and later**
EU	Synergies with stationary FC	500-1000 kW units as APU and propulsion	-	-	-

TECHNICAL TARGETS					
	STATE OF THE ART	**UNTIL 2015**	**UNTIL 2020**	**UNTIL 2030 AND BEYOND**	**REMARKS**
Efficiency [%]	-	> 55	-	-	-
Costs [€/kW]	-	< 1000	-	-	-
Lifetime [hours]	-	>50,000	-	-	-

ROADS2HYCOM RECOMMENDATIONS FOR FUTURE RESEARCH MILESTONES, TARGETS AND ACTIONS		
Until 2015	**Until 2020**	**Until 2030 and beyond**
Demonstration of small vehicles with FC propulsion	Naval applications for lakes and inland waterways	-
Demonstration of APU units and auxiliary propulsion (several tens of kW)	-	-
Seawater corrosivity	-	-

5.3.4 Aeronautic Application

Fuel cell application

There are potential applications for fuel cells on aeroplanes. The partial replacement of the conventional main engine power generator capacity through the implementation of a FC system has potential benefits. In order to gain full advantage of these benefits, the level of integration of the fuel cell generator system is as such that nearly all systems and cabin systems are adapted. This means that all three energy systems, hydraulic, pneumatic and electric are to be converted into an AC and DC electric power network.

In order to balance the weight penalty of the fuel cell technology the by-products need to be used on-board the aircraft. For example, the water can be condensed and used as fresh water. The remaining exhaust gas from the fuel cell has a low oxygen content and could, possibly, be used in the fire extinguishing/prevention system. Heat generated by the fuel cell system could be used for the replacement of conventional heating systems. In this case the operation temperature of the fuel cell system should be close to 180°C. Operation temperatures above 70°C are as well mandatory for system cooling.

Further potential for system simplifications are the deletion of the complete APU (auxiliary power unit), the RAT (ram air turbine) and some AC-DC converters.

Adding all the advantages and disadvantages together leads to the result that fuel cell technology has a high potential to increase the overall efficiency of an commercial passenger aircraft, while lowering the production costs and the operational costs by reducing the complexity of traditional aircraft systems. Even higher energy specific costs of the hydrogen would be balanced by the higher tank to user efficiency.

Hydrogen as a fuel for propulsion of commercial passenger aircraft

The EU funded FP5 funded “Cryoplane System Analysis” project was the last project to work on LH2 fuelled Aircraft. The result has shown that hydrogen could be a suitable alternative fuel for the future aviation. Nevertheless, due to the missing materials, parts, components and engines further R&D work has to be performed until hydrogen can be used as an aircraft fuel. According to estimations made during this project the earliest implementation of this technology could be expected in 15 to 20 years, provided that research work will continue on an adequate level.

From the operating cost point of view hydrogen remains unattractive under today’s condition, with kerosene is much cheaper as hydrogen and production/infrastructure is completely missing.

Assessments based on conservative calculations and today’s understanding have confirmed that the use of hydrogen would reduce aircraft emissions. It needs to be validated that the water emission of hydrogen-fuelled aircraft has low impact to the atmosphere as predicted.

Due to low interest from the market side further work on a concept of a LH2 fuelled aircraft received low priority. Consequently no time planning for next steps have been established.

MILESTONES FROM EXISTING STRATEGY PAPERS					
	2010	**2015**	**2020**	**2025**	**2030 and later**
EU	-	-	To reduce fuel consumption and CO_2 by 50% To reduce perceived external noise by 50% To reduce NOx by 80% To make substantial progress in reducing the environmental impact of the manufacture, maintenance and disposal of aircraft and related products [13]	-	-

The Joint Technology Initiative in Aeronautics “Clean Sky” was launched early 2008. Further 20-40% CO_2 reductions are targeted in Clean Sky as incremental impact.

Clean Sky will demonstrate and validate the technology breakthroughs that are necessary to make major steps towards the environmental goals sets by ACARE - Advisory Council for Aeronautics Research in Europe - the European Technology Platform for Aeronautics & Air Transport and to be reached in 2020:

- 50% reduction of CO_2 emissions through drastic reduction of fuel consumption
- 80% reduction of NOx (nitrogen oxide) emissions
- 50% reduction of external noise
- A green product life cycle: design, manufacturing, maintenance and disposal / recycling

TECHNICAL TARGETS				
	STATE OF THE ART	**UNTIL 2015**	**UNTIL 2020**	**UNTIL 2030 AND BEYOND**
Fuel Cell Operating Lifetime @ similar maintenance costs to traditional components	-	20,000 h	40,000h	-
Fuel Cell Electrical Efficiency @ part load 60%	-	50kW	-	-
The intension to use the product water requires to develop the components of the fuel cell system in a way that the water quality and quantity meets the relevant requirements	-	50kW	-	-
Fuel Cell System weight (depending on level of system integration)	-	0.5kW/kg to 1kW/kg	-	-
Because of the temperature range of the environment (- 40°C to + 50°C) and due to the intension to use the thermal energy for WIP a HT PEM System or MT PEM would be highly appreciated.	-	50kW	100kW	-
In case of using an on board reforming process (VIP aircraft; mission aircraft) a fuel processing system needs to be in developed. This simultaneously require more research work on HT and MT PEM technology		50kW	100kW	
Light Weight LH2 Tank System – This depends on standards of design requirements, which are to be derived from existing requirements for hydrocarbons, but also on the qualification of FRP material in cryogenic environment	-	3kg Tank / kg LH2	2kg Tank / kg LH2	-

ROADS2HYCOM RECOMMENDATIONS FOR FUTURE RESEARCH MILESTONES, TARGETS AND ACTIONS		
Until 2015	**Until 2020**	**Until 2030 and beyond**
Increase FC lifetime	Further increase of FC lifetime	
Increase FC electric efficiency		
Decrease FC system weight		
Develop FC system components in order that the water can be further used.		
Development of a HT PEM system or MT PEM system	Further improvement of a HT PEM system or MT PEM system	
Development of a fuel processing system for on-board reforming	Further improvement of a fuel processing system for on-board reforming	
Development of a light weight LH2 tank system	Further weight reduction of the light weight LH2 tank system	

5.4 Stationary Fuel Cell Applications

Stationary applications of fuel cells and hydrogen can be found in the main areas of combined heat and power production (CHP) at scales from 1 kW to several 100 kW, power generation (multi-MW) and uninterruptible power supply. A special case of these is the use of hydrogen as a storage medium for renewable energies. The re-conversion of the hydrogen to electrical energy can also be considered as a stationary application. Generally, fuel cells will be regarded as the predominant conversion technology. Nevertheless, similar to the transport sector, the use of internal combustion engines (in CHP) or gas turbines (in power generation) are also imaginable, although little technical development is currently going on in this sector.

This sector contains some very significant early markets for fuel cells (if not hydrogen – they all use natural gas as a fuel), namely un-interruptible power supply, and heat-power cogeneration in the 1kW–1MW range. Both these sectors passed the milestone of forward orders for over 10,000 units in 2008.

In the very long term (commonly meaning a future with very restricted use of fossil fuels), some argue that the future for these applications is less promising, as electricity from sustainable sources may become the universal energy vector. However, there is great significance to their energy saving capability in the transition period (which will span decades), and these technologies could make use of hydrogen (or bio-gas) as a fuel where this makes sense.

MILESTONES FROM EXISTING STRATEGY PAPERS					
	2010	**2015**	**2020**	**2025**	**2030 and later**
EU	-	-	1% total share of households, 0.3% of commercial demand [9]	4% total share of households, 1% commercial demand [9]	8% total share of households, 3% commercial demand [9] 2050: 10% total share of households, 3.5% commercial demand [9]

5.4.1 Classification

Stationary applications of fuel cells can be divided into four main areas:

- Micro-Combined Heat and Power (μ-CHP) with 1 or 2 kW_{el} for single family homes
- Mini-CHP (m-CHP) up to 10 kW_{el} for multi-family homes
- Industrial CHP up to several 100 kW_{el} (also including 'commercial' applications up to few 100 kW_{el})
- Power generation over 1 MW_{el}

The first two categories are combined into one in the HFP Deployment Strategy [40] and Implementation Plan [39]. In this report the last two categories will be joined, also, in order to avoid redundancy and overly detailed tables. The Strategic Research Agenda [41] has an altogether different categorisation (residential & community 1-50 kW, public and commercial 50-500 kW, large scale >1 MW), which is by now outdated and has been replaced by the above structure.

Uninterruptible power supply (UPS) also falls under the category 'stationary' but due to the niche market character no strategy goals or technical specifications in development programmes and roadmaps are known to us. Nevertheless, they will constitute a first market.

The fuel for stationary fuel cells is generally methane, in the form of natural gas (NG) in most cases, but also as (fermentation) biogas from biomass digesters (energy crop, farm manure, sewage, etc.) or synthesis gas from biomass (wood, household wastes, etc.) or even coal gasification. All three require clean-up from fuel impurities, depending on the composition of the gas. Only in a few cases will hydrogen be the fuel, i.e. when industrial surplus hydrogen is converted or hydrogen is used as a storage medium for renewable energy sources.

All types of fuel cell are being considered for stationary operation, apart from the alkaline and direct methanol types (AFC and DMFC). In the research agendas relevant today, the main role is played by the high temperature variants MCFC and SOFC, since these are capable of internal reforming, thus making direct use of natural gas (with minor pre-treatment for sulphur and higher hydrocarbons) or bio- and synthesis gases. The sensitivity of PEM FC to carbon monoxide in the fuel gas (besides the reforming unit to produce hydrogen) necessitates an elaborate clean-up in several steps. This not only incurs cost but also reduces the overall system efficiency. High temperature PEM FC (HT-PEFC) operating up to as much as 180°C are one way of increasing the CO tolerance. PAFC have been recently re-introduced to the market, but are not anymore included in the strategic and funding programmes.

The competing technology to stationary fuel cells is micro to regular scale gas and diesel engine CHP units. These units reach total electrical efficiencies of 30-40% (depending on size and mode of operation). This is the benchmark fuel cell systems have to pass. Fuel cells will principally have the advantage of a higher electricity to heat ratio, thus reducing the problems of summer-time (low heat demand) operation of CHP units. Nevertheless, they have to prove more efficient to engine CHP units in order to justify investment and environmental benefits. Stirling and ORC engines are not considered competition due to extremely low efficiencies that only allow their use with waste and excess heat.

MILESTONES FROM EXISTING STRATEGY PAPERS					
	2010	**2015**	**2020**	**2025**	**2030 and later**
EU	29 MW_{el} cumulative installation in LHPs [40] (*)(**) 100 MW_{el} installed [39]	>600 MW_{el} cumulative installation in LHPs [40] (*)(**) 1 GW_{el} installed [39]	1% total share of households, 0.3% of commercial demand [9] 100,000 to 200,000 units p.y. (2-4 GW_{el}) [40] 400,000 to 800,000 units cumulative (8-16 GW_{el}) [40]	4% total share of households, 1% commercial demand [9] Market introduction and growth [40]	8% total share of households, 3% commercial demand [9] 2050: 10% total share of households, 3.5% commercial demand [9]
Japan			10 GW_{el} installed [40]		

(*) LHP = Lighthouse Projects

(**) There is an inconsistency between the Deployment Strategy text (sections 2.3 and 5.3) and Table 15 with the LHP implementation overview, probably due to errors in transferring the information to the table. The information contained in the text was adopted here.

5.4.2 Cogeneration (> 10 kW)

The application of Fuel Cell and Hydrogen technologies to the industrial and commercial markets takes the form of co-generation or tri-generation systems. Systems available today have total powers in the range 100kW to 2-3MW (higher power, modular, systems are possible but have not been installed) and produce electricity, heating and, sometimes, cooling. Most quoted efficiencies are 70-80% overall and 45-50% electrical, suggesting that co-generation using Fuel Cells will yield significant reductions in GHG emissions. In developed countries the existing industrial and commercial power/heat sources are responsible for approximately 20-25% of the total GHG emissions, making these sectors prime targets for Fuel Cell system introduction.

MILESTONES FROM EXISTING STRATEGY PAPERS					
	2010	**2015**	**2020**	**2025**	**2030 and later**
EU	23 MW_{el} installed in LHPs [40]	400 MW_{el} installed in LHP's Transition to commercialisation [40] 1500-5000 €/kW 1 GW_{el} installed 2600, 10kW-1MW units in industrial use 50 units of 1MW or more in industrial use [39]	Growth of FC markets, FC system cost target: 1000-1500 €/kW [39]	-	Significant growth in distributed power generation with substantial penetration of FCs [52]

MILESTONES FROM EXISTING STRATEGY PAPERS					
	2010	**2015**	**2020**	**2025**	**2030 and later**
USA	Distributed stationary generation natural gas / propane 50-250kW fuel cell developed: 40,000 hours durability (equivalent to service life between major overhauls), at a cost of less than 340-634 €/kW [53] Distributed generation PEM FC system operating on natural gas or LPG that achieves 40% electrical efficiency and 40,000 hours durability at 578 €/kW.	Fuel cell / turbine hybrid operating on coal developed at a cost of 400 €/kW with a system efficiency of 50% HHV (75% with natural gas) with carbon sequestration (90%). Validate stationary fuel cell system that co-produces hydrogen and electricity at 40,000 hours durability with 40% efficiency at a cost of $750/kW or less. [53] Deliver 10 to 50 MW of SOFC (FutureGen), >25,000 h lifetime, 50% efficiency [93]	Demonstrate 100 MW_{el} class fuel cell / turbine hybrid system fuelled by coal gasification. [53] With 60% efficiency [69]	n.a.	n.a.
Japan	Installed stationary fuel cell capacity of 2 100 MW_{el} [7] 40% electrical efficiency, 80% total efficiency, degradation <0.25%/1kh for systems 10-20kW; start-up < 1 hour >50% electrical efficiency, degradation <0.25%/1 kh for 200kW systems [65]	Installed stationary fuel cell capacity of 10,000 MW [7]	n.a.	n.a.	n.a.

MILESTONES FROM EXISTING STRATEGY PAPERS					
	2010	2015	2020	2025	2030 and later
India	**1.** Agree rating of individual PEM FC and AFC power packs and fuel choice (Bottled or piped H_2 / on-site reformer fuel with CNG, LPG, Methanol). **2.** PEM FC-R&D topics: indigenous, low cost proton exchange membranes; low-cost bipolar plates (graphite based, high conductivity, impervious), preferably with flow grooves incorporated; higher CO tolerant anode catalyst; cheaper cathode catalysts; electrode support substrate (graphite paper). **3.** AFC R&D topics: compact, low-power electrolyte re-circulating system; low-cost, regenerative CO_2 scrubber, alkali-water heat exchanger; low-cost catalysts (Ni-Co spinel, MnO_2/C); ensure availability of low-cost, resin based mono-polar plates/cell enclosures; generation of long term performance data & operational experience **4.** Finalize suitable design for stand-alone operation of the power packs including C&I and inverter systems. **5.** Optimize design of various components (bipolar plates, MEAs etc for PEMFC and electrode frames, seals, CO_2 scrubbing / electrolyte re-circulating systems for AFC). **6.** Integrate AFC and PEM FC stacks with other subsystems. **7.** Demonstration of 2 MW_{el} aggregate capacity PEM FC, AFC and PAFC power packs for decentralized applications, including performance evaluation [71] **1.** Development of SOFC (5kW) and MCFC stacks (10kW): Agree SOFC technology (Planar or Tubular); develop, optimize and freeze component and stack design for SOFC and MCFC. Identify fuel to be used. **2.** Development & demonstration (5 MW_{el} aggregate capacity) of		Set up decentralized demonstration of PEM FC, AFC & PAFC power packs of 8 MW_{el} aggregate capacity. [71] Demonstration (45 MW_{el} aggregate capacity) of SOFC and MCFC stacks and conduct long-term testing, compile & analyze performance. Expanded demonstration (450 MW_{el} aggregate capacity) of SOFC and MCFC. [71]		n.a.

MILESTONES FROM EXISTING STRATEGY PAPERS					
	2010	**2015**	**2020**	**2025**	**2030 and later**
	SOFC stacks with the topics: electrode, electrolyte, seals development, interconnects, mechanical systems (clamping/stacking arrangements), stack assembly & testing procedures. Integrate the complete system and test; design C&I and inverter systems and incorporate safety systems; design skid mounted sub-assemblies/systems for easy of transportation to site. **3.** Install, Commission & test the integrated system. [71]				

TECHNICAL TARGETS					
STATIONARY FUEL CELL POWER SYSTEMS (10-250KW) OPERATING ON HYDROCARBONS [A]	**STATE OF THE ART**	**UNTIL 2015**	**UNTIL 2020**	**UNTIL 2030 AND BEYOND**	**REMARKS**
Electrical energy efficiency [b] @ rated power [%]	45 [39]	50 [39]	-	65-70 (hybrid systems) [41]	-
Combined Heat and Power (CHP) energy efficiency [cd] @ rated power [%]	80 [39]	90 [39]	-	-	-
Cost [e] [EUR/kW$_e$]	8.000 – 12.000 [39]	1.500 – 5.000 [39]	1 000 – 2 000 [41]	-	-
Transient response time (from 10% to 90% power) [sec]	n.a.	n.a.	-	-	-
Cold start-up time (to rated power @ -20°C ambient) [hours] Continuous use application	< 6 (SOFC/MCFC) <30 min. (PEFC)	< 4 (SOFC/MCFC) < 15 mins. (PEFC)	< 30 min. [75] (SOFC/MCFC) < 5 min. (PEFC)	-	-
Thermal cycles from ambient [number]			250 [75]		
Operating hours up to 10% rated power loss [hours]	10 000 – 20 000 [39]	2012: >30 000 [39] >50 000	>40 000 [41] <100 000	>100 000	-
Degradation rate [%V/1 kh]	0.5	0.25	0.1	<0.1	
Loss of power from beginning of Life to End of Life	30%	25%	20% [75]		
Power density			300 mW/cm² [75]		
Noise [dB(A)]	<60 @ 10 m	<55 @ 10 m	-	-	-
Emissions (combined NO_x, CO, SO_x, hydrocarbon, particulates) [g/1000 kWh]	<8	<1.5	-	-	-

[a] Includes fuel processor, stack and all ancillaries.

[b] Ratio of AC output energy to the LHV of the input fuel (natural gas or LPG) value at rated power at beginning of life (BoL) of power plant.

[c] Ratio of AC output energy plus recovery thermal energy to the LHV of the input fuel (natural gas or LPG) value at rated power at beginning of life (BoL) of power plant.

[d] For LPG, efficiencies are 1.5 percentage points lower than natural gas because the reforming process is more complex.

[e] Includes projected cost advantages of high volume production (2,000 units/year). Current cost does not include integration auxiliaries, battery and power regulator necessary for unassisted start.

ROADS2HYCOM RECOMMENDATIONS FOR FUTURE RESEARCH MILESTONES, TARGETS AND ACTIONS		
Until 2015	**Until 2020**	**Until 2030 and beyond**
Focus on system durability, fuel processing, system electrical efficiency	Focus on performance of stack, balance trade off between performance and efficiency, reduce costs Exploit possibilities of stabilising decentralised grids with fuel cells (supply of grid backup and reactive power)	Reduce costs, improve robustness, install rules and codes for recycling and refurbishing of FC systems Extensive use of fuel cells in stabilising decentralised grids
DURABILITY		
Increase of stack and system efficiency, enhancement of fuel flexibility, improvement of durability – reliability – robustness – lifetime (including understanding and modelling effects), accelerated lifetime testing routines	• Further improved durability of fuel cell stacks • Tolerance to impurities, both in stacks and fuel processing equipment (BoP) • Mechanical integrity • Full understanding of cell/MEA, stack and BoP component degradation and failure mechanisms, development of effective mitigating strategies • Lifetime exceeding 80 000 operating hours achieved • Standardized routines for lifetime and robustness testing	Lifetime exceeding 150,000 operating hours achieved
COST		
Reduction of materials and manufacturing (processing) costs, reduction of cost and increase in performance of balance of plant components Low-cost, efficient power electronics and DC/AC converters	Reduce costs to 1,000 to 1,500 €/kW_{el} (system) Low-cost, high-volume manufacturing processes	
PERFORMANCE		
High-performance, low-cost power electronics and DC/AC converters	System (net) electrical efficiencies above 50%	Electrical efficiencies of 65 to 70% in hybrid systems with (micro) gas turbines
SYSTEMS & BALANCE OF PLANT		
Development of diagnostic and non-invasive tools and integration into system controls, Standardized components and interfaces in systems Exchangeability of components Stack modules (incl. hot box) for up to 100 kW_{el} per module	Standardised BoP components and system interfaces Stack modules (incl. hot box) for several 100 kW_{el} per module	Stack modules (system sub-modules) > 1 MW_{el} per module
START-UP		
Strategies to lower start-up time		-

5.4.3 Residential Use

Residential applications of fuel cells refer to micro combined heat and power units (μ-CHP) in the class of 1 to 10 kW_{el}. They are traditionally expected to serve as heating appliances for residential buildings – foremost single (rated at 1 to 2 kW_{el}) and multi-family (>2 kW_{el}) housings. As such they also produce electricity that is used in the building, feeding any excess into the grid. This concept builds on the situation in most Central European countries, where feed-in tariffs generally encourage the domestic use of the electricity produced and only the remainder is fed into the grid.

Since the average maximum electrical power consumption of a household is around 1 kW_{el} most systems display a corresponding power rating.

From 10 kW upwards the boundary to commercial and industrial CHP is not very clear and the definitions of residential, commercial and industrial CHP differ throughout the documents evaluated and even in the various EU strategy papers.

MILESTONES FROM EXISTING STRATEGY PAPERS					
	2010	**2015**	**2020**	**2025**	**2030 and later**
EU	6 MW_{el} installed in LHP's [40]	1. 80.000 units installed 2. ~150 MW_{el} installed [39] 1. 200 MW_{el} installed in LHP's 2. transition to commercialisa tion [40]	Market growth [40]	-	-
USA	Demonstrate 3-10kW fuel cells at $400/kW with target efficiencies of 40-60%. [23]	n.a.	n.a.	n.a.	n.a.
Japan	1.2m 1 kW_{el} fuel-cell cogeneration units deployed in homes across Japan – a total of 1.2 GW_{el} of distributed generating power. 2% penetration of the country's 47 million households. [88]	n.a.	n.a.	n.a.	n.a.

Technical targets depend very much on the application. In this case the use for residential heating at first glance appears sufficiently defined. Nevertheless, project results from the Real-SOFC project [75] indicate that under the boundary conditions of various European electricity grids very different technical operation regimes follow with strongly divergent technical requirements. On one hand the German, Austrian, Benelux and British markets require units that offer a high number of operating (and grid feed-in) hours and therefore use a hot water tank to buffer thermal energy during times of low heating demand. The electricity produced has a high value for emission abatement. On the other hand, the French market is more interested in heating since the CO_2 footprint of grid electricity is inherently low (nuclear and hydro; a similar situation is true for Norway, Sweden and Switzerland). No buffer tanks are foreseen and fuel cell units need to continuously cycle, following the heating demand. The table therefore states different values for residential µ-CHP units operated continuously or in demand following mode.

TECHNICAL TARGETS					
	STATE OF THE ART	**UNTIL 2015**	**UNTIL 2020**	**UNTIL 2030 AND BEYOND**	**REMARKS**
System cost [€/kW]	20,000	6,000	3,000 – 4,000 [40]	-	-
Electrical efficiency @ BOL, including DC/AC conversion	30-40% [39]	34-40% [39]	> 50% [75]	> 55%	-
Total fuel efficiency BOL; @ best point	> 70%	80%	90% [75]	>90% [40]	-
Stack durability (90 % BOL performance) [h]	5,000	>12,000	> 40,000	-> 80,000	-
Degradation rate [%V/1 kh]	0.5 [75]	0.25 [75]	0.10 [75]	-	-
Allowable loss of power from Beginning of Life to End of Life			30% [75]		
Power density [kW/litre ; kW/kg]	0.25 ; 0.25		0.5 – 1 ; 0.25 [75]		
Sulphur tolerance	0	10 ppm [75]	> 10 ppm [75]		
OPERATION PRIMARILY FOR ELECTRICITY PRODUCTION					
Start-up time, ambient to operating temp. (800°C) [hours]	6 – 8 [75]		30 minutes [75]		
Start-up time, 200°C to 600°C (first power delivery) [hours]	3 – 4 [75]		15 minutes [75]		
Number of low temperature start-ups from ambient [number]	40 [75]	250 [75]	500 [75]		
Redox-cycles [number]	10	250 [75]	500 [75]		

TECHNICAL TARGETS					
	STATE OF THE ART	UNTIL 2015	UNTIL 2020	UNTIL 2030 AND BEYOND	REMARKS
HEATING DEMAND FOLLOWING OPERATION					
Start-up time, ambient to operating temp. (800°C) [hours]	6 – 8 [75]		5 – 15 minutes [75]		
Start-up time, 200°C to 600°C (first power delivery) [hours]	3 – 4 [75]		5 minutes [75]		
Number of low temperature start-ups from ambient [number]	40 [75]	4,000 [75]	15,000 [75]		
Redox-cycles [number]	10	4,000 [75]	15,000 [75]		

ROADS2HYCOM RECOMMENDATIONS FOR FUTURE RESEARCH MILESTONES, TARGETS AND ACTIONS		
Until 2015	**Until 2020**	**Until 2030 and beyond**
Focus on system durability, fuel processing, system electrical efficiency	Focus on performance of stack, balance trade off between performance and efficiency, educe costs Exploit possibilities of stabilising decentralised grids with fuel cells (supply of grid backup and reactive power)	Reduce costs, improve robustness, install rules and codes for recycling and refurbishing of FC systems Extensive use of fuel cells in stabilising decentralised grids
DURABILITY		
Increase of stack and system efficiency, enhancement of fuel flexibility, improvement of durability – reliability – robustness – lifetime (including understanding and modelling effects), accelerated lifetime testing routines	• Further improved durability of fuel cell stacks • Tolerance to impurities, both in stacks and fuel processing equipment (BoP) • Mechanical integrity • Full understanding of cell/MEA, stack and BoP component degradation and failure mechanisms, development of effective mitigating strategies • Lifetime > 50 000 operating hours achieved • Standardized routines for lifetime and robustness testing	Lifetime > 80,000 operating hours achieved

ROADS2HYCOM RECOMMENDATIONS FOR FUTURE RESEARCH MILESTONES, TARGETS AND ACTIONS		
Until 2015	**Until 2020**	**Until 2030 and beyond**
COST		
Reduction of materials and manufacturing (processing) costs, reduction of cost and increase in performance of balance of plant components Low-cost, efficient power electronics and DC/AC converters	Reduce costs to 2 500 to 2 000 €/kW_{el} (system) Low-cost, high-volume manufacturing processes	Reduce costs to 1,500 to 800 €/kW_{el} (system)
PERFORMANCE		
System (net) electrical efficiencies > 40%	System (net) electrical efficiencies > 45%	Electrical efficiencies > 55%
SYSTEMS & BALANCE OF PLANT		
Development of diagnostic and non-invasive tools and integration into system controls, Standardized components and interfaces in systems, exchangeability of components Tri-generation concepts for residential buildings	Standardised BoP components and system interfaces Tri-generation concepts for commercial units	Fully functional, automatic systems outperforming conventional heating boilers
START-UP		
Strategies to lower start-up time Start-up from ambient temperature to 50% of rated power < 60 minutes	Start-up from ambient temperature to 50% of rated power < 30 minutes	Start-up from ambient temperature to 50% of rated power < 15 minutes

5.5 Portable Fuel Cell Application

Portable Fuel Cell systems tend to use either DMFC or PEM technology. However there are a few companies working on novel fuel cell solutions such as Direct Liquid Fuel Cells powered by a borohydride salt.

Many of the fuel cell companies in the Portable sector are also developing on-board fuel storage solutions and refuelling systems. For PEM FC systems run on pure hydrogen, the hydrogen tends to be stored as a gas or in a metal hydride canister. A few players in this sector are researching alternative solutions for transporting and storing the hydrogen, such as using ammonia borane tablets.

Military applications are a key area for Portable Fuel Cells. Several countries, such as USA, UK and Germany, are investing in the development of Fuel Cell products to support their Infantry. It is estimated that the future infantryman power requirements could be 10 times higher that what is currently used today. This is driving defence forces to seek alternatives to conventional battery packs in order to meet these future power requirements within an acceptable weight and package volume.

MILESTONES FROM EXISTING STRATEGY PAPERS					
	2010	**2015**	**2020**	**2025**	**2030 and later**
SMALL PORTABLE & HAND-HELD & PORTABLE GENERATORS					
EU		1. 200 MW rated capacity by 2012 2. 20,000 units sold by 2012 3. Establish distribution channels for fuel containers, including regulatory approval, 4. Military standards, ruggedised, no signature, light weight [39]	1. Small portable and hand-held: ~ 250 million units sold p.a. 2. Portable power: ~ 100,000 units sold p.a. (1 GW_{el}) (600,000 cumulative sales, 6 GW_{el}) [40]	-	-
USA	Fuel cell system for consumer electronics (<50W) with an energy density of 1,000Wh/L. [23]	-	-	-	-

TECHNICAL TARGETS				
	STATE OF THE ART	**UNTIL 2015**	**UNTIL 2020**	**UNTIL 2030 AND BEYOND**
SMALL PORTABLE & HAND-HELD				
Average power	-	-	15 W [40]	-
Cost target system [€/W]	-	3 – 5 €/W [39]	1-2 €/W [40]	-
Energy density [Wh/l]	-	500 – 1,000 [39]	-	-
Specific energy [Wh/kg]	-	150 – 200 [39]	-	-
Volumetric power density [W/l]	-	80 – 150 [39]	-	-
Gravimetric power density [W/kg]	-	80 – 200 [39]	-	-
Lifetime [hours]	-	1,000 – 5,000 [39]	-	-
Operating temperature range [°C]	-	-20 to 60 [39]	-	-
Start-up time (hybridised)	-	Instant [39]	-	-
PORTABLE GENERATORS				
Average power	-	-	10 kW [40]	-
Cost target system	-	-	500 €/kW [40]	-

ROADS2HYCOM RECOMMENDATIONS FOR FUTURE RESEARCH MILESTONES, TARGETS AND ACTIONS		
Until 2015	**Until 2020**	**Until 2030 and beyond**
Identification of technical safety-related topics (including testing) as an input for Regulations, Codes and Standards (RCS) for handheld devices (strong interface to regulating bodies such as ISO, etc. – definition of RCS not part of research)	Low cost – “simple” fuel cell for commodity products	*This sector is likely to be mature by this point unless there are further enabling breakthroughs in fuel cells at the material level*

6. Cross-Cutting Issues

6.1 Finance and business development

The EU FC&H2 industry has a strong presence of well-financed, economically successful multinationals and SMEs (corporates): auto, chemical, materials, precious metals and energy companies, which are very much in evidence. However, the emerging industry is numerically dominated by independent micro companies, universities and research institutes.

In addition to their own internal resources the corporates have access to many external sources of capital to finance their FC&H2 activities, including government and EU subsidies. The academic sector acquires most of its funding from public authorities and to varying degrees from contract research activities.

The major finance problems lie with the independent developers, which for the most part rely on their own resources, family and friends and/or venture capitalists. However, relative to the USA the European venture capital market is less dynamic and considerably smaller. Indeed, Europe is institutionally fragmented in terms of finance market regulation, national tax regimes, has a high degree of cultural and linguistic barriers and is characterised by a relatively high level of risk aversion. In addition, independent European technology developers appear to be relatively unaware as to how, and from whom they could most efficiently seek financial support. In short, they appear to be less financially literate compared with their North American competitors, which may in part help explain the huge discrepancy noted above between the funding raised by European and North American independent developers.

Finally, when considering the following recommendations it is important to bear in mind that much FC&H2 innovation displays disruptive characteristics, defined as an innovation once commercially successful leads to fundamental changes in the way goods and services are both produced and consumed. Further, the development of FC&H2 technologies, particularly components, are not burdened by scale effects, as witnessed by the plethora of capital poor micro independent developers and academics.

Given these considerations, combined with, in some cases obstacles unique to Europe, we propose the following recommendations be considered to maximise Europe's chances of becoming a major developer and producer of FC&H2 technologies.

ROADS2HYCOM RECOMMENDATIONS
1. EU Provision of Equity: A European Trust Fund for Future Generations In an effort to address the critical shortage of equity finance the Commission should investigate the feasibility of establishing a European Trust Fund, along the lines of the Carbon Trust[3] established by the UK government, thereby leveraging investment in emerging companies whilst at the same time leaving the lead investment and technology decisions to the market. Where national governments seek to leverage their own investments in new companies, they act on the basis of promoting national and not European interests and as such do not necessarily promote the best European technology. [These funds may partly be financed through energy taxation revenues or carbon permit auctioning.]
2. Favourable tax legislation to enhance investment in high risk enterprises The UK, widely regarded as the 'best practitioner' in finance matters provides both income tax and capital gains tax relief to private individuals investing in UK-based smaller "high risk" companies. Meanwhile, in 2007 the French government introduced wealth tax relief allowing investors to offset their tax liability when investing in early-stage companies anywhere in Europe. While we recognise that the EU cannot legislate for Member State tax arrangements, the EU should proactively support the deployment of such schemes in all member countries. In addition, the EU and its member states should fully implement the principle of internalizisation of negative externalities via instruments such as taxation and emissions trading.
3. Easier access to non-equity funding While many countries and regions provide a variety of grants and subsidies to companies within their own jurisdictions, we were unable to identify any specifically allowing the funding to be used for bilateral projects between companies and/or research institutes/universities outside of their jurisdictions. Thus we recommend that both member states and regions investigate methods of extending financial support schemes to small bilateral R&DD partnerships. At the same time, effort should be dedicated to lowering the administrative burden faced by particularly smaller, micro companies when applying for government / EU support programmes. In short, the burden should be proportionate to the nature and size of the applicants.
4. Joining up the policy dots The Commission is often unfairly accused of being unaware of the financing difficulties faced by corporate and small private companies alike. However, the EU is well aware that European fragmentation negatively affects investment and fundraising[4]. Nevertheless, it is widely held that finance initiatives relevant to innovation are not communicated across all necessary departments, which in turn conveys the impression of fragmentation with the Commission itself. Hence the often repeated appeal for "more joined up thinking". Specifically, the Commission should seek to improve communications between directorates with the aim of ensuring for example financial issues and opportunities, above and beyond framework grants are given more prominence in R&DD events and its literature. The JTI for its part should also consider this recommendation, not least in order to avoid similar criticisms in the future.

3 The Carbon Trust was set up, and is financed by Government in 2001 as an independent company with the aim of accelerating "the move to a low carbon economy by working with organisations to reduce carbon emissions and develop commercial low carbon technologies." To this end the Carbon Trust also act as a co-investor in early stage companies including independent H2&FC developers, managing both venture capital and seed funds. See http://www.carbontrust.co.uk/investments

4 See presentation given by Per-Ove Engelbrecht, Head of Unit Financing Innovations and SMEs, at the EASY Summit, London June 26 2008

ROADS2HYCOM RECOMMENDATIONS
5. Education and Training We may not be able to address the cultural issue of relatively high levels of European risk aversion amongst European investors and entrepreneurs alike. Nor can we resolve the problems of institutional fragmentation. But we could address the lack of awareness European H2&FC developers exhibit in the area of finance: • Promote practical financial courses with credits specifically for scientists from undergraduate level through to PhD. Such courses could specifically deal with issues in finance related to company building and technology development. Since FC&H2 are a disruptive technology, core elements of microeconomics such as market development, competition and innovation are relevant too, while macroeconomics seems of less importance for this target group. Europe's science & technology students could be academically rewarded for taking such financial and economic courses. • Promote similar (free or at least low-cost) courses for independent H2&FC developers.
6. Increased and sustained public procurement programmes At the outset we propose that the EU investigate the feasibility of establishing a European Public Procurement Agency for promising near-commercial technologies. There are many calls within the FC&H2 industry for a clear policy of public procurement, not least to compete with the effective FC&H2 procurement programmes of the US DoD and DoE. Indeed, in the case of FC&H2, the EU could take the lead by installing FC&H2 equipment in high profile locations in Brussels and Strasbourg. The following list offers some of the more pertinent reasons for the EU, member states and the regions to introduce such programmes: • To bridge the gap between R&D and demonstration on the one hand, and full scale commercialisation on the other • To facilitate the acquisition within local markets of the skills and expertise required of integrators, installers, maintenance personnel, distributors and recyclers. Fostering 'home grown' expertise will not only lead to enhancing local employment opportunities, but will render obsolete the need to import such skills once the technology has become more globally established. Currently the US has a fuel cell installed base estimated at two to three times larger than Europe. This in turn indicates that the US is acquiring the new skills demanded by the technology more rapidly than Europe. European and member state public procurement, widely used in the US, would go some way to redress this imbalance. • To leverage industry investment in the new technologies, and at the same time assist industry in utilising existing facilities and provide a degree of product visibility.
The EU should increase the funding for FC&H2 in regionally focused support schemes on intelligent energy and eco-innovation (CIP) as well as on CO_2 reduction in buildings via CHP/HFC.
Interconnected infrastructure: The EU may therefore set up a programme designed as private public partnership to connect regional networks such as the emerging Scandinavian one in the post 2013 period. The EU funding for the partnership could for example partly be covered by the Trans-European-Transport-Networks (TEN-T) budget as well as by structural funds.
Use the EU structural funds for eligible regions. Any such support should be subject to the condition that the less innovative region in question disposes of some other success factors (e.g. hydrogen production infrastructure) which promise to make the investment a rewarding one.

6.2 Socio-economic costs

MILESTONES FROM EXISTING STRATEGY PAPERS					
	2010	**2015**	**2020**	**2025**	**2030 and later**
EU	20% of EU-population with local hydrogen access. [3]	25% of EU-population with local hydrogen access. [3]	50% of EU-population with local hydrogen access. [3]	85% of EU-population with local hydrogen access. [3]	
USA	California's Hydrogen Highway Network: 150 to 200 hydrogen-fuelling stations throughout the State, one station every 20 miles on the State's major highways [19].				Create a public demonstration hydrogen village [74].

ROADS2HYCOM RECOMMENDATIONS
Investigations about technological learning rate in the FC&H2 sector. Improve two-factor learning methodology. Connection between learning rate and RTD investment (including possible diseconomies of scale)
Monitor tech progress: If you see too low tech progress rates you need to change processes, put in more RTD. Progress ratios of nearly 20% for many years
Early and niche market investigations: Investigate discontinuations in market growth. Investigate series of early markets and how technologies jump from one early market to the other. Tech. performance, end-user needs, tech. requirements; e.g. batteries. In FC&H2 today: Portable applications, material handling vehicles, road vehicles, leisure sector, military usage. Study ramp up of those market developments.
Investigations into regional strategies for FC&H2, sustainable energy and growth. Any support for regional initiatives should take the specific regional cluster structure and the general stage of market development into account.
Develop tools for benchmarking across regions and across differing technologies. With growing development of FC&H2 activities and clusters, these tools should be refined and causal relations for success should be investigated as soon as data for time series analyses are available.

ROADS2HYCOM RECOMMENDATIONS
EU Policy support for regional activities (such as HyRaMP) needed: • Joint procurement and 'green public procurement': a group of regions can purchase certain products together. The supplier may thus realize economies of scale whereas the regional purchasers will get a lower price for the demanded product. Joint procurement is especially interesting for independent producers, SMEs and start-ups that need to reduce uncertainties about demand. • Producer-user networks: If a producer supplies a relatively great number of regions with the same FC&H2 product s/he will benefit from the feedback of users in different communities and geographical settings. As a result he can improve the product and better respond to market demands. The regional users of the product can also benefit from such a network for they can exchange information on how to best deal with technical problems or combine the product with other applications. • Cooperation among regions can lead to a valuable exchange on how to scale up production and/or applications. A platform of regions such as HyRaMP will not only lead to a better understanding of the size of niche markets in Europe and enable actors to take well informed investment decisions, but also prepare the ground for full deployment and mass market development. • Interconnected infrastructure • Create a level playing field for applications all over Europe • Barrier: Different tax systems (hydrogen should be exempted from taxation). Harmonisation on European level needed. Member States not interested. Use ETS auctioning mechanism for financing purposes. Long term perspective for climate policy beyond 2020 needed.

6.3 Safety, Standards and Regulations

MILESTONES FROM EXISTING STRATEGY PAPERS					
	2010	**2015**	**2020**	**2025**	**2030 and later**
USA	Technical codes and standards to Co-AUTHOR regulatory standards [23]. Product safety standards for mobile and stationary applications [74]. Safety standards for H2 fuels and fuel quality [74]	Harmonize codes and standards, technical expertise, data access and testing/evaluation procedures to assure cost effective standards and system compatibility [74].			

ROADS2HYCOM RECOMMENDATIONS
Perception of risk: 100% safety is not possible. Safety issues with hydrogen must be seen objectively as for other technologies / fuels.
Safety regulations are not fitted on consumers, since most FC&H2 technologies are not through the design stage.
Harmonisation of regulations across Europe. Non-bureaucratic introduction of new technologies into regulatory, certification and standardization processes. This is not only relevant for technologies (where the EU principle of mutual recognition should apply) but especially for distribution systems, refuelling stations and their permission processes. Such harmonization will lower costs and business risks.
Many current hydrogen standards and regulations are general for high pressure and industrial gases and very restrictive (e.g. refuelling of hydrogen). Should be appropriate for hydrogen energy applications. Regulations currently not fit for purpose, especially for consumer applications.

6.4 Public Perception, Acceptance and Consumer Preferences

MILESTONES FROM EXISTING STRATEGY PAPERS					
	2010	**2015**	**2020**	**2025**	**2030 and later**
EU	20% of EU-population with local hydrogen access. [3]	25% of EU-population with local hydrogen access. [3]	50% of EU-population with local hydrogen access. [3]	85% of EU-population with local hydrogen access. [3]	
USA	California's Hydrogen Highway Network: 150 to 200 hydrogen-fuelling stations throughout the State, one station every 20 miles on the State's major highways [19].				Create a public demonstration hydrogen village [74].

ROADS2HYCOM RECOMMENDATIONS
Consumer preferences: Today it is not known, if consumers will be willing to pay for the new technologies; a few analyses have revealed a willingness to pay (e.g. in London) if a tangible benefit can be obtained (e.g. lower noise or lower pollution). Today most customers are not willing to pay only for technology, if there is no direct advantage.
Launch of huge demonstration project in centrally located area in order to be able to study user preferences
Study producer – user networks and stakeholder participation to learn about changing preferences and demand.
Organize stakeholder dialogues and public participation along with scenario analysis in regions with large-scale applications of FC&H2 technologies
Concern in future may be if fuel cell or hydrogen technologies are linked to contentious issue such as hydrogen production from nuclear energy.
Education of public of benefits of FC&H2 technologies to support technology commercialization.
Encourage niche markets. E.g. simple gadgets or consumer goods to promote the technology

6.5 Human Capital (Education and Training)

The number of people with workforce skills in hydrogen technologies should be available in time in order to be properly prepared for the development of hydrogen technologies. To support this development some education policy suggestions are:

- Continue to support basic and applied research
- Support post-graduate professional development training
- Develop of an EU network of graduate courses
- Develop a EU wide national curriculum integration programme for FC&H2
- Encourage human capital investment in adults by the private sector
- Develop educational package to increase the connection between universities and the private sector

Several real or perceived obstacles of different quality may impede the access of citizens to a technology or a service. To support the removal of some of the obstacles some policy recommendations are:

- Develop information packages about fuel cell and hydrogen technologies for citizens
- Support early adopters

Since the development of hydrogen technologies will depend of the development of other technologies support multi-technology projects where hydrogen, CSS, battery, wind energy technology projects are demonstrated together. The multi-technology skills of the projects member could be useful in the future.

ROADS2HYCOM RECOMMENDATIONS
University programmes to train developers in financing issues: What are the right financing programmes, how to talk to financial investors, etc. For students and for scientist who might found spin off companies.
Education the public of benefits of hydrogen technologies to support technology commercialisation
FC promotion at schools. Not on the curricula today (compared to wind energy, etc.) as it should be. Supply education material to schools (including FC and electrolyser equipment).
Cross-disciplinary courses to train tomorrows technicians on new technologies such as FC&H2 technologies
Programme of public education and outreach in established FC networks. (e.g NRW, Northeast of England, London, etc) and in Hydrogen communities as identified in Roads2HyCom WP3.
Teaching and qualification modules for different target groups

In general it must be stated for the cross-cutting issues that on a policy level, the EU discussions are too vague, too much about methodologies not about “actions”. The EU is not at the same speed as the USA and Japan.

Anyway it is important that certain technologies are not “legislated” into the market, if they are not yet ready for legislation.

Finally, a good management of the expectations of different stakeholders (industry, public authorities, consumers) is needed.

6.6 Public Policy Framework

The current EU policy framework does not hinder hydrogen development. Yet it does not constitute a strong push factor either. The screening of existing EU policies unfolds some inconsistencies in the macro-framework for hydrogen promotion. The EU is strongly committed to reduce GHG as shown by its role in the Kyoto Protocol framework and the Council conclusions. Fuel cells and hydrogen are conceived as an instrument to reduce GHG. The EU therefore strongly supports research and development in this field through its Framework Programmes. However, the EU policy framework for the promotion of hydrogen is not as strong and coherent as its commitment to these technologies may suggest.

First, the **EU lacks a clear mid to long term strategy beyond the year 2020** explaining the desired role of different energy sources and carriers. In view of avoiding lock-in effects, this absence of technological preferences is understandable. Yet, biofuels, which are unlikely to be a sustainable long term solution for the global energy challenge and may even be competing with hydrogen, are promoted by EU policies too. It is not clear whether the EU conceives biofuels as an instrument for transition management or whether biofuels are understood as a potential long term solution. If the latter were the case, hydrogen technologies would directly compete with biofuels. Since energy supply is under responsibility of member states, the EU should use and strengthen the Lisbon method to develop a coherent strategy together with Member States that also embraces policy for the long term ramp-up of carbon-free energy sources from which to make hydrogen.

Second, changes in EU policies must closely be analyzed with regard to their effects on hydrogen and fuel cell development. A case in point is the current **taxation of hydrogen** utilization in some member states which could deter the uptake of hydrogen-based technologies, especially if the taxation level becomes unreasonable relative to the comparative environmental credentials of hydrogen as a fuel. Furthermore, in a communication of January 2008, the Commission proposes to extend the ETS to all major energy emitters. A reformed **ETS** should push towards more investment in low GHG emitting technologies. Yet, the current proposals may also deter from investment in hydrogen technologies given that transitional hydrogen production from natural gas would be part of such a new ETS (and perhaps also chemical production), and would therefore be required to pay the full cost of its carbon emissions. Exemption would assist a transitional phase, but needs to be linked to the ramp-up of zero carbon hydrogen production so that hydrogen production is not seen to enjoy “unfair advantage” beyond a managed transition period.

Third, the EU lacks **competences** necessary to reach its ambitious energy policy goals. The Treaty of Lisbon would confer the EU level stronger legal competences in the field of energy. However, other matters of relevance for energy and climate change policy will remain at national level such as taxation. Stronger coordination of national policies is therefore needed; more competences at the EU level, for example on energy security and energy distribution is an option that ought to be considered.

Fourth, the overall policy framework must be aligned with the challenges ahead. Otherwise, different policies might neutralize each other. Improvements in energy efficiency and the liberalisation of the electricity and gas markets may either reduce the share of energy expenses in household or firm budgets or lead to higher demand for energy. Such impacts may lead to higher energy consumption that can over compensate for the initial gains in EE ('rebound effect'). Hence, not only a coherent policy framework is needed but also a **clear link between the energy objectives of GHG reduction targets, deployment and roadmaps on the one hand and instruments on the other. Coherency thus is not only a matter of today's policy but a matter of long-term dynamic development in the EU.**

In can be concluded that hydrogen and fuel cells will require a special support scheme as well as an alignment of other policies.

ROADS2HYCOM RECOMMENDATIONS
Develop long term GHG reduction targets beyond the year 2020 in line with other EU energy objectives and the hydrogen deployment strategy at EU level.
Maintain taxation on energy with the credible aim to internalize negative externalities while revising any current taxation of hydrogen.
Incentives to comply with the targets (see above) should be market based. Instruments may be combined: • Feed-in systems for producers of hydrogen and fuel cells • Permits for early adopters / purchasers of hydrogen vehicles • Dynamic standard setting and visible label (and monitoring) of full life cycle carbon missions for energy-intensive products including vehicles
A Pan-European network of agencies for energy efficiency to coordinate efforts (analogy to European Energy Regulatory Agencies)
Strengthen Regional funding towards a EU cluster policy on FC&H2

7. Discussion and Conclusion

The driving forces of environmental concern and security of energy supply mean that there is undoubtedly strong mid-term to long-term potential for Fuel Cell and Hydrogen technologies, if they can be developed into appropriate market offerings. This means that the functional performance and total ownership cost must be attractive in the context of the future energy economy; which in turn means that the research agenda must enable this to be so.

It is almost impossible to construct a general conclusion about such a diverse and complex topic. However, the following broad patterns emerge from the 100 pages of this document:

- Early markets that are in the process of establishing themselves right now, need to have the support required to realise ramp-up of volume and development of a satisfied user base. It is especially critical that some of these early applications – namely UPS and domestic CHP, which have five-digit forward orders for the first time – establish a good product reputation, as they are both operating in fields which have high visibility to the public (homes, telecommunications). Research in these sectors, and in fuel cell power for goods handling, needs to focus first on realising mass-production with low cost and high reliability; then on supporting a better second-generation product with more mass appeal – probably through lower cost and higher efficiency.

- The next set of markets are slightly less mature in terms of readiness of product that can be sold profitably all the way along the value chain – however, factors like future legislation or civic purchasing can promote the development of markets such as low power portable devices, truck APUs or niche Fuel Cell / Hydrogen vehicles – in the latter case either electrified bicycles, city buses or internal combustion engine vehicles may fall into this category. In these cases, prototypes and demonstration products have been used successfully, but there remains a mismatch with customer expectations in a number of areas – cost, durability / robustness, and fuelling issues in particular. Research needs to address this mismatch through improvements of the whole system (including the fuel tank and to some extent the fuel supply chain), while validating the technologies through extended fleet trials or public demonstrations where necessary.

- The highest volume products, passenger car propulsion units, offer the greatest reward but are most challenging to implement. Analysis in projects such as HyWays has shown that high product volumes, comparable to mainstream internal combustion engines, are needed to realise low costs; and unlike niches such as buses, a widespread refuelling infrastructure is needed. The synergy of public demonstrations and ongoing product research must strike the right balance of product improvement, feedback and public interest; and the technology (and primary energy supply) behind the energy chain must allow the new fuel, hydrogen, to be seen as truly “green” – and affordable. The option of producing hydrogen via steam reformation – certainly not the ‘truly green’ vision and not aimed for by many regions trying to become greener – should be seen at least as a transitional pathway of balancing a variety of goals. Finally, it is worth noting that, as with the Hybrid car, leading OEMs promoting this technology will have to endure a long period – ten years or more – of marginally profitable or loss-making niche products before the rewards are reaped. So policy support needs to remain consistent over this period and promote long-term consistent sustainable development in the EU.

- In the complex field of technologies and applications, it can be hard to find technical synergies but some repeated themes are:

  - Hydrogen storage in vehicles – here, a “task force” approach could be beneficial to continually bring together best practise and manage research resources efficiently

  - Realising mass-production processes for fuel cells – although the detail of technologies varies, sharing best practise in processes, process control, cost reduction and quality improvement could prove beneficial

  - Reducing the cost and carbon footprint of Hydrogen supply – through integration into future energy policy, and putting in place the right market mechanisms to allow desirable solutions to prevail

  - Development of skills at all levels, to ensure that shortages do not become a barrier to uptake

In addition to this report, the research recommendations were filtered on the basis of expected impact and degree of challenge, using also analytical information from other studies in the project. The outcome of this work was published in document R2H6035PU (Deliverable 6.5), and may adjust or add depth to the conclusions presented above.

8. Abbreviations

AFU	Alkaline Fuel Cell
APU	Auxiliary Power Unit
BOG	Boil Off Gas
BoL	Beginnig of Life
BoP	Balance of Plant
BTH	Biomass to Hydrogen
CAD	Computional Aided Design
CCS	Carbon Capture and Sequestration Technologies
CFD	Computational Fluid Dynamics
CGH2	Compressed Gaseous Hydrogen
CHP	Combined Heat and Power Production
CI	Compression Ignition
DI	Direct Injection
DMFC	Direct Methanol Fuel Cell
FC	Fuel Cell
FCV	Fuel Cell Vehicle
FC&H2	Fuel Cell & Hydrogen
H2NG	Hydrogen Mixed with Natural Gas
HD	Heavy Duty
HDV	Heavy Duty Vehicle
HHV	Higher Heating Value
HT	High Temperature
HTPEM	High Temperature Polymer Electrolyte Membrane
ICE	Internal Combustion Engine
LD	Light Duty
LHP	Lighthouse Project
LHV	Lower Heating Value
LPG	Liquefied Petroleum Gas
MCFC	Molten Carbonate Fuel Cell
MEA	Membrane Electrolyte Assembly
MLI	Multi Layer Insulation
MVEG	Motor Vehicle Emission Group
NEDC	New European Driving Cycle

NG	Natural Gas
PAFC	Phosphoric Acid Fuel Cell
PC	Passenger Car
PEFC	Polymer Electrolyte Fuel Cell
PEM	Polymer Electrolyte Membrane
PEMFC	Polymer Electrolyte Membrane Fuel Cell
PFI	Port Fuel Injection
PSA	Pressure Swing Adsorption
PV	Photovoltaic
R&D	Research and Development
RCS	Regulations Codes Standards
SI	Spark Ignition
SOEC	Solid Oxide Electrolyser
SOFC	Solid Oxide Fuel Cell
TSI	Technical Specification for Interoperability
UIP	Uninterruptible Power Supply
ZEV	Zero Emission Vehicle

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