European Hydrogen & Fuel Cell Technology Platform

Strategic Research Agenda

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Definitions

Demonstration: The use of the term demonstration indicates development projects. Demonstration provides evidence of the viability of a new technology that offers potential economic (and societal) advantage but cannot be commercialised directly. The act of demonstrating (i) proves the functional performance, including operability, reliability and economics and (ii) enhances public awareness and public acceptance of the applied technology.

Verification: The use of the term verification indicates research projects. Verification is the process of determining whether or not a product of a given phase in the life-cycle fulfils a set of specified performance requirements. Verification of research results is covered here. Verification may be determined by test, analysis, inspection, or demonstration.

Validation: Stage in the product life-cycle at the end of the development process where a product is evaluated to ensure that it complies with the application requirements/specifications. This evaluation also includes a techno- and socio-economic assessment framework.

Acronyms and abbreviations

AC	Alternating current
APU	Auxiliary power unit
BOP	Balance of plant (components)
CGH_2	Compressed gaseous hydrogen
CHP	Combined heat and power (generation)
DC	Direct current
DISI	Direct injection spark ignition
DMFC	Direct methanol fuel cell
DOE	US Department of Energy
DS	Deployment Strategy, Steering Panel of the European Hydrogen and Fuel Cell Technology Platform
EIHP	European Integrated Hydrogen Project, http://www.eihp.org/
FP7	Upcoming Framework Program of the European Union, the Framework Program is the main instrument for funding research and development
GATT	General Agreement on Tariffs and Trade; agreement of the World Trade Organisation
GDL	Gas diffusion layer
GHG	Greenhouse gas (emissions)
GHSV	Gas hourly space velocity
HFP	European Hydrogen and Fuel Cell Technology Platform
HHV	Higher heating value
HTFC	High-temperature fuel cells
ICE	Internal combustion engine
ICT	Information and communication tools
IG FBD	Initiative Group on Financing and Business Development
IPHE	International Partnership for the Hydrogen Economy, http://www.iphe.net
IPR	Intellectual property rights

Glossary (cont.)

JTI	Joint Technology Initiative, concept of the European commission of realising public private partnerships
JTI OA	Operational activities of the JTI
LCA	Life Cycle Assessment
LH_2	Liquefied hydrogen
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
LTFC	Low-temperature fuel cells
MCFC	Molten carbonate fuel cells
MEA	Membrane electrode assembly
NEDC	New European Driving Cycle, test procedure or the European Union for certifying passenger cars
OEM	Original equipment manufacturer
PE	Primary energy
PEFC	Polymer electrolyte fuel cells
PEM	Proton exchange membrane
PGM	Platinum group metals
PISI	Port injection spark ignition
PV	Photovoltaic (electricity generation)
RCS	Regulations, codes and standards
RES	Renewable energy sources
RTD	Research and technological development
SECA	The Solid State Energy Conversion Alliance, program of the US Department of Energy targeting SOFC development and market introduction
SME	Small and medium enterprises
SMR	Steam methane reforming
SOFC	Solid oxide fuel cells
SRA	Strategic Research Agenda, Steering Panel of the European Hydrogen and Fuel Cell Technology Platform
SWOT	Strengths, weaknesses, opportunities and threats, analysis tool
UPS	Uninterruptible power supply
WTO	World Trade Organisation

Strategic Research Agenda

0 Executive summary

This report is part of the activities of the European Hydrogen & Fuel Cell Technology Platform, which was initiated by the European Commission, as recommended by the High Level Group. Its aim? To bring hydrogen & fuel cells to market in order to exploit their outstanding environmental and economic potential. To this end, it has outlined a strategic approach for research in Europe – the Strategic Research Agenda.

The Strategic Research Agenda was compiled by a European panel of stakeholders and endorsed by the Advisory Board of the European Hydrogen and Fuel Cell Technology Platform, which itself advises the European Commission.

Hydrogen and fuel cells: effectively supplying energy

Reducing greenhouse gas emissions, improving security of energy supply and strengthening the European economy – not to mention reducing local emissions – are the main drivers for establishing a hydrogen-oriented energy economy, as outlined in the final report of the High Level Group.

Indeed, hydrogen is widely recognised as a truly environmentally friendly energy carrier which does not contribute to global warming, if supplied properly. Using more internal – i.e. renewable – energy sources is also key to optimising Europe's security of energy supply – particularly in the transport sector.

Electricity and hydrogen together represent one of the most promising ways to achieve this, as hydrogen complements electricity with enhanced storability, facilitating the integration of non-dispatchable electric power into the energy market.

Fuel cells are widely acknowledged to be the primary application technology for hydrogen. Highly efficient, these intrinsically clean energy converters are adaptable to a wide range of energy-consuming applications, including small portable devices, small and large combined heat and power, as well as road, rail, sea and air transport applications. Fuel flexible fuel-cell systems, however, do not rely on a dedicated hydrogen infrastructure and thus offer commercial appliances in the near term – for certain applications, where hydrogen may not be suitable as a fuel, even in the long term.

Crucial highlights

1. Hydrogen can be made from a variety of primary energies.
2. It is suitable for a wide range of mass market applications, including transport, portable and stationary uses.
3. Thus, hydrogen complements electric power as a second energy hub with much better storage capabilities.
4. It can be used in decentralised systems and can even be CO_2-free or lean, depending on its supply route.

In fact, hydrogen is already an integral part of today's industrial technology. Yet for energy use, the real benefits can only be exploited with innovative technologies, such as fuel cells. These, however, require further research and subsequent market introduction, supported by a deployment phase. The report therefore includes a coherent energy strategy on hydrogen and fuel cells.

The aim of the SRA

The Strategic Research Agenda is designed to:

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

A strategic research approach clearly needs to incorporate the societal requirements, the technical and economic potential – and the inherent limitations of the technologies under consideration. After all, energy touches the basic needs of modern societies – it must be widely available, affordable and environmentally friendly to justify its massive and indispensable use. The Strategic Research Agenda therefore devotes a substantial part of its considerations to societal implications and socio-economic research.

The Strategic Research Agenda also defines priorities for investment in R&D in the context of Europe's strengths and weaknesses, and later industrial exploitation, which is the focus of the Deployment Strategy. Technologies thus need to be weighed against the likelihood of their coming into effect at all, in view of the envisaged timeline and the benefit they provide.

It also takes into account the imminent seventh Framework Programme for research and subsequent programmes, plus the need to coordinate R&D with demonstration, deployment and financing. It therefore includes a prioritised, 10-year research program, a well-founded medium-term strategy up to 2030 and a long-term strategic outlook up to 2050.

Taking a medium and long-term outlook (2030 to 2050)

From today's perspective, market penetration will occur via early niche markets, where initial experience with the products is gained and first returns on investment are achieved. It is thought that small and medium-sized enterprises, in particular, will benefit from this development. Nevertheless, it will be vital to support the development of mass market applications, as only these will deliver on the primary policy targets. However, niche and early markets are expected to pave the way.

For orientation purposes, the envisaged status of hydrogen and fuel cell technology is outlined for 2030 as a medium-term outlook and for 2050 as a long-term outlook.

The long-term outlook is the basic motivation for the R&D initiative. In 2050, oil will very likely no longer be cheap and, certainly, Europe's internal reserves will be exhausted. It is inferred from today's stock assessments that an increasing proportion of primary energy production will be drawn from CO_2 lean resources that may be:

- Renewable, e.g. solar, wind, tidal, hydropower and biomass, and
- Nuclear, replacing today's energy sources, e.g. crude oil, coal and natural gas, step by step.

Hydrogen will be one of the three energy vectors, besides electric power and liquid biofuels. As it can be produced from a great variety of primary energies and consumed by an even greater variety of applications, it will form an energy hub – much like electric power today.

However, hydrogen has the advantage over electric power in that it can be stored much more effectively. By its nature, such an energy hub helps stabilise energy security and pricing, giving rise to competition among different energy inputs. It also offers great flexibility with respect to primary energy over time, as the general infrastructure is not affected by the primary energy input.

By 2050, fuel cell systems for transport, stationary and portable applications will be mature technologies produced at competitive costs. Hydrogen turbines and combustion engines will also be optimised and serve certain markets. Fuel cells are likely to predominantly consume hydrogen, but are unlikely to rely on a single fuel. Fuel flexible fuel cells are considered an important innovation that is expected to be widely available, also in combination with reformers for certain transport applications.

Hydrogen a major transport fuel by 2050

By 2050, hydrogen is expected to be widely available in industrial nations, at competitive cost. Indeed, it can realistically be expected to serve as a major transport fuel for vehicles, with a share of up to 50%.

In centralised power generation, it will serve as an energy storage medium that complements electric power from renewables to match stochastic energy generation & demand. Water electrolysis, hydrogen storage and re-conversion into power via fuel cells, gas turbines or combined cycles are the intermediate steps.

Hydrogen will also have growing importance in the distributed power generation, while an extended network of pipelines will emerge connecting new large-scale production sites. In this way, advantage can be taken of the extensive natural gas grid through technical synergy.

As a prerequisite for mass market applications, a hydrogen pipeline infrastructure will have been set up by this time. Road transport of gaseous and liquid hydrogen and on-site hydrogen production are expected to prevail to a far smaller extent in certain market segments.

There will, of course, be a considerable time lag between successful R&D and first market introduction, and a deep market penetration which may take a long time for technologies requiring such substantial infrastructural investment. Timing, however, is crucial: a hydrogen infrastructure should be set up early enough to ensure that a timely appropriate, environmentally compatible and economically viable infrastructure is made available.

Fuel cells facilitating the transition

In the medium term (2030) a significant fraction of all hydrogen will still be produced from fossil fuels. Integration of hydrogen production with carbon capture and sequestration – which is currently covered within other European R&D programmes and has not been addressed within the scope of the present Strategic Research Agenda – is envisaged.

Where renewable electric power cannot be effectively distributed through the electric grid hydrogen will be produced via electrolysis to be used locally for balancing power or – with subsequent distribution – for transportation purposes.

Before pipeline transportation will entirely penetrate hydrogen mass markets, on-site hydrogen production will play a significant role. The natural gas grid may be advantageously used for facilitating that transition. Supply routes based on centralised hydrogen production and road-based distribution of liquefied hydrogen will gradually lose the vital role it has played in supplying early adopters of hydrogen technology.

Fuel cell technology will provide the means to utilize the different fuels in the energy market by that time with high efficiency and thus significantly reduce carbon dioxide emissions. Still gaining importance in stationary power and transport sector, fuel cells will have reached a high level of maturity in portable applications.

The six key areas of research

The field of hydrogen & fuel cell technology can be broken down into five areas: hydrogen production, hydrogen storage and distribution, stationary applications, transport applications and portable applications. Socio-economic research – in terms of monitoring and forecasting – is also, however, important. Proposed budget shares for these six research areas are outlined at the end of this summary, according to their relative importance in creating an energy economy in which hydrogen & fuel cells represent a key energy vector.

1) Hydrogen production

Hydrogen production is considered crucial for the development of the entire sector. Based on fossil fuels – namely natural gas – hydrogen production is already a mature technology for the chemical industry, which can provide hydrogen for an emerging fuel cell sector. Yet for energy use with higher price constraints, additional applied research is required – particularly for catalysts and catalytic reactors. In order to provide hydrogen in the long term, increasingly 'carbon-dioxide-free' investigation of new production methods from renewables and nuclear power is important. A budget share of 22 % is recommended.

Key research issues:

- Reforming and gasification units utilising renewables, fossil or clear power, including process control, system and safety monitoring.
- Technology development of liquefaction processes with improved efficiency and system integration with hydrogen production facilities.
- Development of different electrolyser types, e.g. alkaline, proton exchange membrane (PEM) at high pressure above 700 bar and high-temperature electrolysers, aimed at higher efficiencies, cost reduction and compactness.
- Process control, system and safety monitoring

➢ *Basic research issues*: analysis and development of thermochemical processes and photo-electrolysis and biological hydrogen production routes; investigation of conversion efficiency for photobiological processes; development of catalysts, adsorption materials and gas separation membranes.

➢ *Cross-cutting issues*: major technical issues are associated with hydrogen safety in hydrogen production, hydrogen storage & distribution and socio-economics.

2) Hydrogen storage and distribution

Storage of hydrogen is of paramount importance because the energy density is fairly low for existing storage technologies, being 10 – 20 % of that of gasoline or diesel. It therefore limits the range of operation for transport applications, particularly automobiles. A great deal of research has already been done on qualifying gaseous and liquid hydrogen as the main candidates for transport applications over other well-known technologies. Beyond further applied research on these candidates, deployment projects will be appropriate.

Basic research, on the other hand, is strongly recommended for new storage principles promising higher energy densities and emerging material classes like alanates and high-surface materials. Research into hydrogen distribution needs to be carried out in a targeted way as this technology is already further advanced. A budget share of 18 % is recommended.

It is advised that an incipient hydrogen pipeline infrastructure be set-up by a number of local hydrogen supply clusters, which can be connected later. A focus should be on component development for infrastructure at the end-user side, as well as transmission and distribution. Such clusters need to be versatile with respect to the applications they provide.

They also need to be designed as a first step towards a long-lasting infrastructure that can serve a variety of projects and applications, in number and kind.

Key research issues:

- Reversible storage systems for transport need to be developed towards energy densities exceeding 1.1 kWh/l, a usable hydrogen fraction above 6 % and cost below 10 EUR/kWh. This is to be achieved under reasonable operating conditions, with long-term performance stability. Improvement of the energy density of hydrogen storage with metal hydrides also needs to be investigated; plus the use of chemical storage media and nanostructured materials.
- Core components for hydrogen management at transfer, filling and fuelling stations should be investigated. In a first stage project, it is recommended that results are evaluated on a worldwide basis.
- Reversible and non-reversible storage solutions for portable applications are crucial. Other than for transport, non-reversible chemical storage can be attractive when competing with batteries. For portable safety studies, supply chain management, plus component and infrastructure development for compressed hydrogen and metal hydrides, are important. Methanol as an energy carrier is particularly relevant to portables because of its high energy density compared to hydrogen.
- For liquid hydrogen in transport infrastructural components, boil-off and cost reduction for cryogenic hydrogen storage are key. A boil-off below 1% per day on-board which does not start before a dormancy period of at least 5 days is seen as a development target. Boil-off management – from liquefaction to the filling station – should also be optimised.

➢ *Basic research issues:* New materials for hydrogen storage and storage containers should be thoroughly investigated, along with failure mechanisms and modelling. Standardised material screening and testing procedures are crucial. Further investigation of absorption and adsorption mechanisms is also needed – in particular, for a deeper understanding of degradation mechanisms.

➢ *Cross-cutting issues:* Safety guidelines; sensors; computational methods; cost analyses and socio-economics. For reasons of prudence, it is also advised that the potential impact of hydrogen emissions is investigated.

3) Stationary applications

Stationary applications can rely on natural gas for a long time. Indeed, decentralised reforming of natural gas is an important part of fuel cell technology for decentralised power generation. Whereas polymer electrolyte fuel cell (PEFC) technology offers solutions for residential use, district and industrial cogeneration comes within the realm of high-temperature fuel cells because of the higher efficiencies and simpler reforming.

The main application will be residential cogeneration and district cogeneration in the 100 kW range for the near and medium term. Units in the MW power range are envisaged for the longer term and should be investigated. Of the high-temperature fuel cells, the solid oxide fuel cell (SOFC) is preferred over molten carbonate fuel cells (MCFC). Nevertheless, MCFC is considered important for stationary, decentralized use as well.

The PEFC operated at elevated temperatures of 120 to 180°C has a great potential to simplify stationary systems and reduce costs. It could also prove successful for units larger than required for residential use. Stationary applications are important for the early market opportunities they provide, since they are not dependent on a hydrogen infrastructure. They will also still deliver on environmental goals if fed with natural gas. A 20 % research budget share is recommended for stationary applications.

Key research issues:

- For all types of fuel cells stack design, balance of plant component development and industrial production methods are important for further advancement. Gas processing units, i.e. reforming of natural gas & biogas, middle distillates like diesel, heating oil or kerosene and propane and subsequent gas clean-up, are important for early market introduction and, in the long term, for remote applications.
- Electronic equipment for fuel cells, including hardware and strategies for operation control, will be of utmost importance in the future. This includes power electronics, sensors and tools for diagnostics and control. The idea of single cell control should be investigated, as well as the map-controlled operation of fuel cells.
- Efficient hydrogen turbine systems and internal combustion engines require further investigation – particularly for non-dispatchable power of renewable stocks. Systems that operate with hydrogen-rich fuels need a new design for burners and novel materials for proper hydrogen combustion. Peripheral systems and safety features for hydrogen operation are also required.

➢ *Basic research issues*: Integrated catalyst concepts for easy and efficient recycling of stack components have been identified. However, now and for some time in the future, stack components for high- and low-temperature fuel cells will need further advancement. Harnessing and further developing existing PEFC technology will encourage early market entry for the technology. For breaking advance in energy efficiency and cost reduction, special emphasis should be placed on high-temperature polymer membranes and the corresponding stack concepts. In general, modelling of electrode processes, cells and stacks, as well as the systems level, provides great insight into the function of fuel cells and should be increasingly exploited.

➢ *Cross-cutting issues:* It is essential to investigate pathways to the commercialisation of fuel cells and the development of materials for SOFC and high-temperature PEFC fuel cell stacks. Mass production methods for stacks and systems also have a high synergy with other fuel cell applications. On a more basic level, lifetime prediction, electronics, control and reformer technology all have high synergetic potential.

4) Transport applications

As transport applications can substantially deliver on goals to reduce CO_2, alleviate dependence on oil and improve fuel economy, they have been the major driver for hydrogen & fuel cell technology for the past 15 years and remain the single most important application. A budget share of 27 % is recommended. The clear focus within transport applications is on direct-hydrogen PEFC technology for propulsion.

Key research issues:

- PEFC needs to be optimised – in particular, with respect to power density, durability, humidification, cathodic water management and contaminant tolerance.
- PEFC operated at elevated temperature is considered a breaking technology path for future transport applications. Membranes suitable for operation between 120°C and 160°C, with favourable start-up properties at low temperatures and a good long-term stability are a prerequisite. Improvement of the other stack components for elevated temperatures is imminent. Passive humidification allows for further system simplification and should also be investigated.
- For PEFC systems, further advancements in components such as highly efficient air supply units, sensors, controls and power electronics are required. In traction applications, electric motors allow for further improvements. In order to achieve a

reasonable range of operation, new hydrogen storage systems based on 700 bar gaseous hydrogen and alternative storage options are essential.

- Reformer systems are largely dedicated to auxiliary power units which provide electric power independently of the propulsion unit. Applications currently under development are vehicles, aircraft and ships. The main energy carriers to be investigated for these applications are diesel, kerosene and gasoline, with particular emphasis on desulphurisation1.
- SOFC for auxiliary power units in transport offers great potential as reforming is easy. It is therefore expected to fit easily into the existing fuel infrastructure, which will become even more beneficial for the technology as cleaner fuels emerge. Crucial development issues include improving thermal cycling stability, robustness and reliability, plus tolerance to fuel impurities, such as sulphur. Further reduction of the operating temperature will be beneficial for mechanical integrity and is likely to reduce degradation even more.
- Although stack technology is important, systems integration and verification at an early stage is vital to the success of the entire technology. Efforts to increase systems efficiency, improve systems dynamics and decrease start-up times are particularly important. Cost reduction will rely partly on further systems simplification.
- In order to bring hydrogen to market early, it would be desirable to improve the performance of internal hydrogen combustion engines.

➢ *Basic research issues:* Development of new polymer membranes for operation at elevated temperatures, new electrocatalysts with higher activity – and, preferably, with less or even without platinum group metals – plus materials for bipolar plates and seals; investigation of degradation mechanisms; development of methods for lifetime prediction and accelerated testing for PEFCs and SOFCs, plus new SOFC materials for electrolyte sealing and interconnectors operating at lower temperatures; improvement of injection technology and combustion process for hydrogen internal combustion engines development of operation strategies for hybrid configurations, new battery concepts and supercapacitors, plus new stack control procedures; development of reversible hydrogen storage materials and fuel gas processing technology for gasoline, diesel and kerosene.

➢ *Cross-cutting issues:* PEFC stack technology applied for decentralised power generation and portable power generators; SOFC stack technology applied for decentralised power generation; fuel-gas processing technology applied for portable power generators.

5) Portable applications

Portable applications are important and it is strongly advised that they be part of future EU research programmes. They will help proliferate fuel cells via early market entry and create an early industry which will probably include a large share of small and medium-sized enterprises. As they only have a minor, though growing, impact on the energy sector and on CO_2 savings, the proposed budget share is small at 10%.

Key research issues:

- For portable applications, polymer fuel cells which consume hydrogen and their direct methanol (DMFC) consuming descendents are viable options. Improving stack efficiency and power density, reducing precious metal loading and developing low-cost

[1] Although future fuels will be thoroughly desulphurised in many countries for automotive use, this will not apply to all countries and applications.

stack components are the major issues to be solved. For the use of carbon-containing fuels, the improvement of carbon monoxide and sulphur tolerance is essential for PEFC technology. The DMFC requires most research directed at the problem of methanol crossover and reduction of the current, very high precious metal loading, which is a sacrifice for a much simpler system.

- More simplified water management for small applications – particularly the development of fluid handling components and water recovery options.
- System components for small fuel cells need to be highlighted.
- Microreformers suitable for small fuel cell systems.
- System integration, miniaturisation and verification efforts should be directed towards the improvement of system efficiency, dynamics and start-up time, e.g. by hybrid system solutions. Miniaturisation, the simplification of systems and the improvement of thermal integration will also lead to further cost reduction and efficiency improvement. As for all other fuel cell systems, novel hydrogen storage approaches are required, as well as improvements to existing hydrogen storage – either pressurised, absorbed by metal hydrides or stored-in chemically.
- Small power electronic devices with high efficiency and sensors are important – single-cell control strategies are recommended.

➢ _Basic research issues_: The development of high-temperature membranes, carbon–monoxide- and sulphur-tolerant catalysts, new membrane electrode assemblies (MEAs), flow-field design, plus seals and bipolar plates for PEFCs; new methanol oxidation and resistant cathode catalysts, and composite membranes for DMFCs; alternative options for humidification, new battery concepts and stack control procedures; storage materials for hydrogen; fuel gas processors for liquid petroleum gas and hydrocarbon fuels.

➢ _Cross-cutting issues:_ Catalysts with low precious-metal content, good methanol oxidation and oxygen reduction behaviour; new low-cost and high-temperature polymer membranes and MEAs; fuel storage with hydrogen and methanol cartridges; reformers for hydrogen production from propane, butane and methanol.

6) Socio-economic research

The proposed budget share of 3% reflects the great importance of this sector, bearing in mind that no cost-intensive experiments, verification or demonstrations are required.

Key research issues:

- The strategic assessment of technologies and pathways, with particular focus on developing, refining and using tools for strategic energy systems analyses. Input data for strategic decision-making in science, industry and policy should also be collected and disseminated for public use. Integrated studies on the potential impacts of hydrogen & fuel cell technologies are required. Within this context, analysing and defining boundary conditions for creating added value for the hydrogen transition is necessary. This includes different transition scenarios on the basis of the current technological status and its projections, market trends and policies.
- Fundamental analysis of market actors and diffusion mechanisms, together with training and education, will offer deeper insights for market development. This includes creating specific measures to facilitate the demonstration, early-market penetration and design of ‘umbrella’ measures for the hydrogen & fuel cell market.
- Public acceptance needs to be developed, based on a detailed understanding of apprehensions and obstacles. This includes a strong focus on the early education of

ever increasing numbers of the public, industrial and academic institutions, and individuals. It is strongly advised that all information be based on honesty – and shown to be complete – yet simple and relevant to the target audience.

- A strategic outlook should be created and continually updated. This includes road maps, modelling, experience curves etc. for condensing the technological state of the art. The transformation of system analyses should also be evaluated and monitored with regard to different socio-economic criteria not covered by the research areas mentioned above.

➢ *Cross-cutting issues:* Identification of policy evaluation for market development; assessment of societal, economic and environmental impacts in terms of employment effects; identification of suitable niche markets; delivery of important insights on innovation penetration and diffusion; energy systems analyses, and pathway and life cycle assessment; fostering education and public acceptance.

Dividing up the budget

All six research areas are critical to achieving a substantial contribution of hydrogen & fuel cell technologies in European political and economic targets. But because the technologies are just at the brink of field testing – and, in some cases, early market introduction – all the applications are still strongly interrelated. Indeed, they are all crucial for the economic and ecologically viable development of hydrogen and fuel cell technologies. Nevertheless, different budget allocations are appropriate to accelerate growth and are proposed in Table 1.

As hydrogen- and fuel-cell-related research is still in an early phase, many basic and cross-cutting issues are still being identified. Cross-cutting issues are a key source of synergy in hydrogen and fuel cell R&D. But as they are not specific to one area of application, there is a great overlap with basic research. Thus these two areas are closely allied to one another and are not separated in terms of budget allocation. In order to encourage an innovative approach, it is recommended that 16% of the budget for every research area, shown in Table 1, is spent on cross-cutting issues and basic research.

Table 1: Proposed Budget Shares for Hydrogen & Fuel Cell Targeted R&D

Research Area	Budget Share	Key Considerations
Transport applications	27%	Technologically crucial for environmentally friendly transport solutions and the driving force for fuel cell development
Hydrogen production	22%	Essential for the technological development of the entire sector. Increase of CO_2-lean production is targeted. Carbon capture and sequestration are of the essence, yet are expected to be covered within other European R&D programmes
Stationary applications	20%	Important for CO_2 reduction via highly efficient cogeneration. Provides an opportunity for early markets
Hydrogen storage & distribution	18%	Storage density is crucial for effective storage – particularly for transport and portable applications
Portable applications	10%	Important for early markets. Fit ever increasing market needs to fuel gadgets and small transport applications
Socio-economics	3%	Long-term guidance for technological development
Total Hydrogen & Fuel Cells	100%	

1 Introduction

This report is part of the activities of the European Hydrogen and Fuel Cell Technology Platform, which was initiated by the European Commission, as recommended by the High Level Group, with the aim of bringing hydrogen and fuel cells to the market – exploiting their outstanding environmental and economic potential.

It outlines a strategic approach for research in Europe in the field of hydrogen and fuel cells, the Strategic Research Agenda (SRA). The SRA was compiled by a European panel and adopted by the Advisory Board of the respective platform rendering advice to the European Commission.

Greenhouse gas emissions and energy security are major issues besides local emissions and economic considerations like creating employment opportunities, as already outlined in the Final Report of the High Level Group.

A coherent energy strategy is required in which hydrogen and fuel cells will play an important role. Electric power and hydrogen together represent one of the most promising ways to achieve a coherent energy strategy, since hydrogen complements electric power with enhanced storability. A strategic research approach needs to match the societal requirements mentioned above and the technical and economical potential, as well as the inherent limitations of the technologies under consideration.

This report covers these issues for the field of hydrogen and fuel cells. It is application-oriented outlining the strategy for hydrogen in two chapters: one for hydrogen production, and the other for hydrogen storage and distribution. The question of hydrogen is paramount for the whole strategy and the use of fuel cells, as hydrogen is not a primary energy but merely an energy carrier which has to be produced from existing or future sources for primary energy. This research agenda limits itself to energy conversion to electric power and does not include energy production. It thus excludes a general discussion of the primary energy carriers used, which is covered elsewhere. As hydrogen is not a primary energy carrier efficiency of the energy chains involved in conversion is of utmost importance. This includes efficient storage and effective distribution of hydrogen, which both still have notable research potential. Three further chapters deal with the application technology for hydrogen, i.e. the use of hydrogen as an energy carrier for power production. For energy conversion disparity in terms of application and technology is obvious for stationary use, transportation and for small portable devices. Hence, three chapters for energy conversion follow this primary criterion. As fuel cells offer high conversion efficiencies it is considered that they will play a major role in the future, although combustion engines and turbines are further developed at present and will probably play a notable role not only in the transition phase but also in the long run for certain applications. All of this is considered and reflected in the strategy outlined.

Energy touches basic requirements of modern societies since it must be readily available, cheap and environmentally friendly for its widespread and indispensable use. Therefore, the sixth chapter deals with the societal implications, makes suggestions and outlines the socio-economical research needed to gain further insight.

2 Technical assessment of SRA

The Strategic Research Agenda (SRA) provides a strategic outline to stimulate investment in research, provide guidance for policy options and deliver a realistic and inspirational research programme that will mobilize stakeholders and ensure that European competences are at the forefront of science & technology worldwide. It will take into account the imminent FP7 and subsequent programmes, the need to coordinate R&D with demonstration, deployment and financing.

It will provide a prioritised 10-year research programme, a well-founded medium-term strategy up to 2030 and a long-term strategic outlook up to 2050. The SRA defines priorities for investment in R&D in the context of Europe’s strengths and weaknesses and later industrial exploitation. Thus, in addition to highlighting certain technologies it also identifies those that need to be down-selected or right-sized in their budget allocation to the most effective ones. Technologies considered effective are those which help achieve the main goals in the shortest timeframe possible. Thus, from a societal point of view technologies are addressed that do not – or only to a low degree – contribute to these goals. From a technical point of view, particularly those technologies are addressed that have already been under development for a long time with limited progress.

This research agenda indicates those areas that are vital for the introduction and rollout of hydrogen as an energy carrier from now until 2050. It follows that it is not a full summary of all science and technology that could be pursued in relation to hydrogen but a selected and weighted compilation of strategic research issues.

Today hydrogen is widely recognised as an environmentally friendly energy carrier since it does not contribute to global warming if produced properly. Moreover, hydrogen has a profile ideally suiting it for a wide range of mass market applications. Crucial highlights are: hydrogen can be made from a variety of primary energies. It can be advantageously utilised in a great variety of different applications covering transport applications and portables as well as even stationary applications, which are to a large extent supplied today by natural gas. Furthermore, it can be used in decentralised systems without emitting carbon dioxide and can be carbon-dioxide-free or lean on its energy pathway if produced appropriately. It is already part of today’s industrial technology; yet for energy use the real benefits can only be exploited with novel technologies such as fuel cells. These technologies require further research and subsequent market introduction supported by a deployment phase. The research need is described in this report. For orientation purposes, the envisaged status of hydrogen and fuel-cell technology is outlined below for 2050 as a long-term outlook and for 2030 as a medium-term outlook. Each main chapter additionally provides a more specific outline.

Long-term outlook for hydrogen and fuel cells up to 2050

By this time, cheap oil will no longer be available and certainly Europe’s internal reserves will be exhausted. An increasing proportion of primary energy production will be from renewables such as solar, wind, tidal, hydropower and biomass supplemented by nuclear, natural gas and coal.

Taking the fossil resource base in its entirety, i.e. natural gas, conventional and unconventional oil and coal, there is limited pressure in terms of resource scarcity, yet there is the already conceivable problem of having appropriate and long-term secure access to

these reserves owing to their regional clustering[2]. It will be the ongoing climate change primarily owing to anthropogenic carbon dioxide emissions and the issue of energy supply security that will make societies implement alternative energy supply patterns worldwide.

Hydrogen is assumed to be one of three energy vectors, besides electric power and liquid fuels, which are desired to be bio-based. As hydrogen can be produced from a great variety of primary energies and it can be consumed by an even greater variety of applications it will form an energy hub like electric power today. Hydrogen has the advantage over electric power that it can be stored much better. By its nature such an energy hub helps stabilize energy security and pricing and gives rise to competition between different energy inputs. It offers great flexibility with respect to primary energy over time as the general infrastructure is not affected by the primary energy input.

By this time, hydrogen is assumed to be widely available in industrial nations at competitive cost. In this case it can serve as a major transportation fuel for vehicles with a share of up to 50 %. Besides, it is envisaged as an energy storage medium that complements electric power from renewables to match stochastic energy generation and demand by hydrogen electrolysis, storage and reconversion into power via fuel cells, gas turbines or gas and steam turbine combined cycles. Moreover, hydrogen is expected to have growing importance in the stationary sector while an extended network of pipelines will be emerging to connect new large-scale production sites. Comprehensive experience and the existence of an extensive natural gas grid will allow for technical synergies. An incipient hydrogen pipeline infrastructure will probably have been set up by that time. Once mass markets have been established road transport of gaseous and liquid hydrogen will lose the crucial role that they previously had in supplying early adopters of hydrogen technology, although it is still expected to prevail in certain market segments. It needs to be recognized that there is a considerable time lag between successful R&D and first market introduction and a deep market penetration, which might take decades for technologies requiring substantial infrastructural investment as hydrogen and fuel cell technology do. Timing, however, is crucial: a hydrogen infrastructure should be set up early enough to ensure its effective contribution to the political goals mentioned above.

Fuel cells are widely acknowledged to be the primary application technology for hydrogen. Fuel cell systems for transport and stationary applications as well as portables, which are assumed to have entered niche markets first, are forecast to be mature technologies at that time, being produced in high quantities and at competitive costs. In addition, optimized hydrogen turbines and combustion engines are expected to serve certain markets as indicated above. Fuel cells will predominantly consume hydrogen but will not rely entirely on one fuel. Fuel-flexible fuel cells will be widely available in combination with reforming systems for certain transportation applications.

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[2] World energy, technology and climate policy outlook 2030, WETO, Luxembourg: Office for Official Publications of the European Communities, 2003,ISBN 92-894-4186-0, " report, EUR 20366

2.1 Hydrogen production

Hydrogen production encompasses all physical and chemical processes that are required to convert primary energy into hydrogen, to purify it and to otherwise condition it for its subsequent distribution and use. As hydrogen is a secondary energy carrier primary energy production issues are only addressed in terms of pathway energy efficiency, carbon dioxide emissions or when hydrogen production retroacts on design or operation conditions of the particular primary energy production method. Novel ways and means of making primary energy available or producing electrical power are discussed elsewhere. Hydrogen production is thus the link between primary energy resources and the fuel that is hydrogen. Most hydrogen production processes are linked to a specific energy resource. Hence, their prioritisation is assumed to vary over the different member states of the EU owing to different infrastructures and different opportunities of exploiting novel energies in the future. For these reasons there will remain a remarkable variety in the specific energy policy approaches of member states or even regions where particular energy patterns are needed or appropriate. It has been declared a goal of the European Commission to achieve a step-by-step shift toward a fully integrated hydrogen economy, based on renewable energy sources, by the middle of the century.

There exists broad agreement among the member states that the main policy aims are towards energy supply security, reduction and finally elimination of greenhouse gas emissions, specifically of carbon dioxide; bearing in mind that energy needs to be kept affordable. It has long been recognised that hydrogen can contribute to both of these policy aims, even though the level of this contribution is dependent on the production pathway.

With these considerations in mind, the emphasis given to different production pathways in this chapter is a combination of their technical potential and their potential of contributing to energy security and carbon dioxide mitigation. The main energy pathways which lead to carbon dioxide reduction are listed below:

- chemical conversion of fossil or biomass-derived feedstocks via gasification or reforming processes, with carbon dioxide sequestration where appropriate
- chemical conversion of natural gas using high-temperature heat from solar-thermal concentrators or Generation IV nuclear reactors
- electrolysis with electricity from renewable or nuclear power
- thermochemical water splitting, photo-electrolysis, biophotolysis or fermentation processes

There are notable differences in the characteristics of these pathways. Whereas renewables in general, besides hydropower and wind power, qualify for decentralised approaches and, thus, offer the specific advantages of decentralised power production, all processes involving carbon sequestration are to be considered as centralised for the foreseeable future. Nuclear power by its nature is centralised as well. As for carbon dioxide reduction, natural gas has an advantage over all other fossils due to its high hydrogen content of the predominant molecule methane. If combined with carbon sequestration it could be carbon-dioxide-free or carbon-dioxide-lean depending on the rate of carbon dioxide capture. For coal, carbon sequestration is required instead to make it an environmentally friendly primary energy carrier. It should be noted that carbon sequestration is a technology which still needs to be practically verified and accepted. Nevertheless, nuclear power is very carbon-dioxide-lean in its life cycle, although it involves a hazard potential from radiation. Therefore, it is a political decision to use it or reject it as a primary energy source, on which the EU states currently have different stances.

On the time line, hydrogen can be most easily produced by reforming natural gas, which is an established industrial process. In essence, the swift introduction of hydrogen favours central production whereas sustainable hydrogen production methods are seen to come in later. For this reason, the following chapters distinguish between centralised and decentralised production. The first exhibits more development character, and particularly fosters market introduction, whereas the latter involves more basic research thus providing great opportunities for the future.

All hydrogen production technologies need to be considered in principle by life cycle analyses that include energy pathway efficiencies and cost. For the sake of practicability and simplicity, energy pathway efficiencies and cost consideration may be sufficient in simpler cases or by complete life cycle analyses. In any case, studies need to reflect local strength, weaknesses, opportunities and threats for particular sites, areas or regions where the technology is to be applied. Life cycle analyses, energy pathway analyses and SWOT analyses are therefore strongly recommended.

2.1.1 Long-term outlook for hydrogen production up to 2050

The ultimate goal is to produce hydrogen from carbon-dioxide-lean energy sources including nuclear fission. Other energy sources like nuclear fusion might become relevant beyond the 2050 timeframe. Finally, in a world in which renewable energies and other non-fossil energy sources are dominant hydrogen is assumed to be one of three energy vectors besides electric power and liquid fuels which are required to be biobased.

Hydrogen opens up access to a broad range of primary energy sources that include fossil fuels, nuclear energy and, increasingly, renewable energy sources like wind, solar, ocean, and biomass, as they become more widely available. Thus, the availability and price of hydrogen as a carrier should be more stable than any single energy source. The introduction of hydrogen as an energy carrier, alongside electricity, would enable Europe to exploit resources that can be best adapted to regional circumstances and political or technical shifts over time. As hydrogen is also suitable for multiple application technologies it forms an energy hub like electric power.

It will serve both as a popular transportation fuel and as an energy storage medium that complements electrical power to match stochastically accruing renewable power supply and the power demand. Hydrogen as a transportation fuel will be cost competitive with liquid fuels at that time.

Renewable electricity will be the major source of renewable hydrogen. Where biomass cannot be used directly in decentralized stationary applications it might be preferably converted into liquid biofuels. Research and development is needed to promote effective systems.

From the current point of view, alternative bioroutes to hydrogen such as photolysis or fermentation require major breakthroughs to reach levels of efficiency, cost or versatility that will make them attractive for mass markets. The same holds for high-temperature thermochemical processes and photolysis. The potential of these technologies is not to be underestimated. Hence, major basic research is required.

From the perspective of carbon dioxide emissions reduction across all energy sectors hydrogen production from renewable electric power is advantageous for countries with low carbon dioxide emissions from the power sector. For grid stabilization purposes combined cycle, hydrogen-fuelled power plants will contribute to the required balancing and reserve power nearby the renewable power generation sites. Hydrogen fuel is electrolysed during the generation peaks and will be stored in the interim. This situation will occur ever more frequently as time progresses; it will occur first in isolated energy systems and is generally

brought forward in time by increases in the fossil fuel prices. Technically, as long as there is no excess of nonfossil electricity, it is more effectively deployed to phase out fossil-based power generation than to replace transportation fuels. However, the market introduction for novel fuel infrastructures in transportation will take long a long time and thus needs to be phase in parallel. Thus, hydrogen needs to be, and will be, already introduced for transportation, owing to market forces, at a time when the power market is not fully supplied by sustainable power.

Even in the 2050 timeframe, fossil fuels are expected to provide half of the EU and world primary energy consumption. Taking the fossil resource base in its entirety, i.e. natural gas, conventional and unconventional oil and coal, there is limited pressure in terms of resource scarcity, although there is an already conceivable problem of having appropriate and long-term secure access to these reserves owing to their regional clustering.

However, it is the impending climate change owing to carbon dioxide emissions that leads society to seek alternatives. Hydrogen will play a role in meeting the two main aims of energy policy, i.e. energy security and carbon dioxide or climate change mitigation. The former implies a broadening of the resources base, especially that of oil for transport fuels. Moreover, climate protection emphasises the importance of carbon-dioxide-free sources of hydrogen including carbon sequestration for fossil hydrogen production: fossil hydrogen thus becomes a carbon-dioxide-free or lean fuel; however, without it fossil hydrogen is still an efficient fuel, but not carbon-free.

The conclusion for the long term is that hydrogen has the potential to become an important, carbon-neutral energy vector that can be produced from a variety of primary energy sources. Hydrogen will meet those energy needs that cannot be satisfied with electric power. In the transportation sector, the compressed gas-based hydrogen pathway already produces less carbon dioxide when using natural gas. For transportation and for portable energy applications it will complement liquid biofuels and thereby provide essential expansion of the renewable energy resource base beyond biomass. It could additionally develop into an important energy storage medium, particularly in combination with non-dispatchable renewable energy. In this arena, hydrogen's strength is its versatility to complement a more flexible use of electric power. Hence, it will be applied where efficiency and cost targets are met.

2.1.2 Medium-term outlook for hydrogen production up to 2030

The long-term logic for hydrogen production as laid out in the preceding section is equally valid for the medium term. The main difference is that the uncertainty in make-up of the EU primary energy mix is considerably smaller[3]. Based on the EU target of doubling the electricity production from renewables from 6 % to 12 % by 2010 it can be estimated that the electric wind power capacity has to be increased to 180 GW by 2020[4]. Thus, providing reserve and balancing power will be a major task. Combined cycle power plants and fuel cells will fit into this scenario. Moreover, hydrogen will contribute to energy security if it is primarily produced from non-liquid fossil fuels, notably natural gas and possibly coal and increasingly from carbon-dioxide-lean sources. Advanced methods of gasification and reforming derived from today's technologies of hydrogen production will be applicable. Biomass will only be a minor feedstock for hydrogen production as its use for liquid transportation fuels and for power and heat generation and will take priority.

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3 See e.g. the EU "World energy, technology and climate policy outlook" report, EUR 20366.

4 EREC – The European Renewable Energy Council

Thus, in this timeframe a significant fraction of all hydrogen will still be produced from fossil fuels. Integration of hydrogen production with carbon capture and sequestration is envisaged but it is not clear at this point in time whether it will be achieved. However, hydrogen is to contribute to the objective of carbon dioxide reduction anyway, even without carbon sequestration, if produced from natural gas. Nevertheless, a technical objective should be the optimisation of the simultaneous production of pure hydrogen and of carbon dioxide qualities suitable for sequestration[5], which, though technically feasible, is not commercially practiced today. It should be noted that carbon sequestration in the form of underground storage needs societal acceptance and a legal framework for management of carbon repositories being in place in time.

Before pipeline transportation penetrates hydrogen mass markets, liquefied hydrogen (LH_2) will play a notable role for distribution and/or on-board storage (cf. Chapter 0.1). Both hydrogen production and liquefaction are energy-intensive processes, for which large-scale new infrastructure will have to be built. Integration with other existing or new industries by applying concepts of industrial ecology could significantly contribute to general energy policy goals.

In addition to the current way of production from fossil fuels using existing reforming technology, hydrogen will be produced from non-fossil electric power through electrolysis. This will take place at those sites where a temporary or structural overproduction of renewable electric power exists which cannot be effectively distributed through the electric grid. The hydrogen may be used locally for generating balancing power when hydrogen is used as an energy storage medium. Alternatively, it may be used for transportation purposes. The former strategy may typically be practised on islands; the latter may be relevant for "stranded renewables" as from remote offshore wind parks.

2.1.3 Research strategy for hydrogen production for 2005 to 2015

Basically, hydrogen can be produced via different pathways, as illustrated below, cf. Figure 2.1-1. The figure also shows the scope of the present research agenda that is focused on hydrogen production taking primary energy issues into account only if they are directly related to production.

The degree of centralisation may serve as a main criterion for a future hydrogen economy. Beyond obvious technical differences between centralised and decentralised systems, the infrastructure will certainly be at least as different for these two options. Essentially, nuclear and fossil energy input is appropriate for centralised infrastructures, whereas renewables are mostly difficult or impossible to transport. As examples, the energy-inefficient transport of biomass or thermo-solar energy may serve, respectively. Thus, decentralisation is generic to these technologies. Natural gas leaves all options open in this respect. In view of this major difference between decentralised and decentralised structures this serves as a major criterion in this chapter.

At the same time, the efficiency and cost-effectiveness of existing routes represent a major obstacle for alternative processes. This should not prevent the EU pursuing such alternatives, but it needs to be considered whether the prospects of efficiency and cost-effectiveness are bright enough in comparison to conventional technologies. The sections below discuss the five main modes of hydrogen production, at first in the context of centralised production (cf. Chapter 0) and then for decentralised production (cf. Chapter 2.1.3.2). This structure was chosen as there are notable technical differences in hydrogen production techniques.

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5 I.e. > 90 % pure and preferably at high pressure

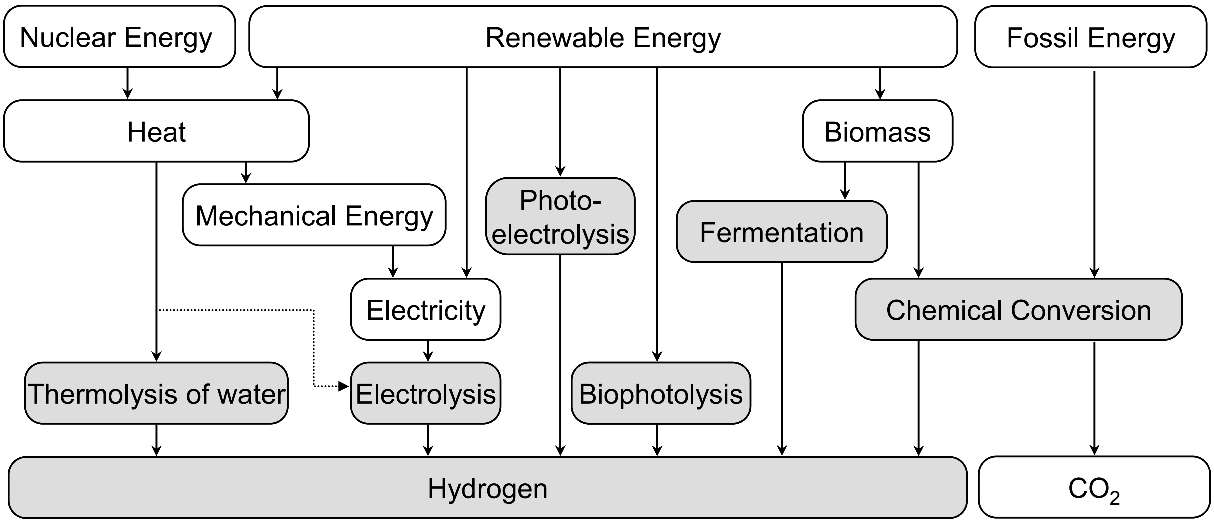

Figure 2.1-1: Hydrogen production pathways. Adapted and expanded from: John A. Turner, Science 285, 687 (1999).

2.1.3.1 Centralised hydrogen production

Cornerstones for hydrogen production are the pathway energy efficiency, the carbon intensity of hydrogen production, the cost of delivered hydrogen and hydrogen purity. At a secondary level, durability, system complexity and performance under transient or intermittent conditions should be considered.

Benchmarking efficiency and cost requires consideration of the energy chains in terms of cost and efficiency including both production and distribution. Even so, for the two commercially available classes of technology for hydrogen production, chemical conversion and electrolysis, today's production efficiencies and cost levels may serve as a useful benchmark, cf. Table 2.1-1.

Table 2.1-1: Current commercial cost and efficiency benchmark figures for large-scale natural gas steam reforming and electrolysis.

	Efficiency (LHV-basis) [--]	Non-energy cost [EUR/kg]	Energy cost [EUR/kg]	CO_2 intensity [kg_{CO2}/kg_{H2}]
Steam reforming [6]	75 %	0.2 – 0.35	0.65 [7]	9.5
Electrolysis	65 – 70 %	1.0 [8]	1.9 – 3.8 [9]	0 – 27 [10]

A crucial issue for centralised hydrogen production is transport to the point of use, cf. Chapter 2.2.

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[6] Based on natural gas steam methane reforming in D.R. Simbeck and L. Chang, Hydrogen Supply: Cost Estimate for Hydrogen Pathways – Scoping Analysis, NREL/SR-540-32525 (July 2002)

[7] Assuming a price for natural gas of around 4 EUR/GJ

[8] J. Ivy, Summary of Electrolytic Hydrogen Production, NREL/MP-560-35948 (April 2004)

[9] Assuming 0.05 EUR/kWh

[10] Zero when using renewables or electric energy, upper bound refers to a typical electricity mix emitting 0.5 kg CO_2 per kWh

2.1.3.1.1 Hydrogen production via reforming

Large-scale, industrial hydrogen production from the full range of fossil energy sources coal, oil and natural gas can be considered a commercial technology for industrial purposes, though not yet for utilities. This includes a range of gas-phase processes, referred to as gasification processes for oil and coal as well as catalytic processes, including steam reforming, autothermal reforming and various partial oxidation processes. Catalytic reactors are mostly used for processing natural gas and light hydrocarbons. Important post-processing steps include the water-gas-shift reaction, hydrogen separation and purification using pressure swing adsorption and membrane technology. Though research and development are predominantly conducted by industry, there is a need for basic research in catalytic reaction technology. The use of high-temperature primary energy systems such as Generation IV nuclear reactors or solar-thermal concentrating systems reduces the required input of carbon-containing feedstock.

Biomass gasification is technically closely related to coal gasification, with biomass units generally being smaller in size in order to limit the biomass transport distances. For hydrogen production biomass gasifiers must not be air-blown, but are either indirectly heated or oxygen-blown in order to produce a gas undiluted by nitrogen. The main development issues relate to biomass pre-conditioning, ash removal and synthesis gas clean-up, especially hot gas clean-up. It needs to be noted that biomass gasification is an R&D area shared between hydrogen production and biofuels production being done via Fischer-Tropsch synthesis or methanol-to-gasoline processes. Further important R&D issues are: heat transfer technology and suitable heat carriers for indirectly heated gasifiers (engineering, materials science), efficient and cost-effective small-scale oxygen production units for oxygen-blown gasifiers (engineering, materials science, especially pressure-swing-absorption technology), development and validation of small and medium-scale systems with 1 to 10 MW_{th} biomass input, and biomass gasification concepts which are efficient, cost-effective as well as reliable in delivering pure hydrogen in automatic operation (engineering). The combined use of biomass and domestic waste allows for larger plant capacities. By using high-temperature primary energy systems such as Generation IV nuclear reactors or solar-thermal concentrating systems the hydrogen yield can be doubled.

Capture of carbon dioxide for sequestration purposes in association with all of these conversion processes is, however, not yet fully technically and commercially proven today and requires R&D on absorption or separation processes and process line-ups. This holds for all feedstocks, including biomass. Carbon dioxide capture in coal gasification units needs special emphasis because of the carbon dioxide intensity of coal-based large-scale hydrogen production. Moreover, carbon sequestration may offer a notable potential for novel options for integration with mining, power generation and hydrogen production. However, verification of concepts for hydrogen production with carbon dioxide capture and sequestration still requires further R&D efforts. This is an area relevant to hydrogen production and power generation alike.

Further R&D needs especially relate to hydrogen purification and to gas separation. The former because PEFC specifications are much stricter than for most current industrial processes and the latter in particular for the separation of hydrogen or carbon dioxide from gas mixtures. In this area in particular, there is ample scope for improvement through R&D, exploiting advances in membrane technology but equally in exploiting new reversible adsorption materials in pressure-swing or temperature-swing processes to separate hydrogen and/ or carbon dioxide, or alternatively to exploit these materials for chemical compression.

2.1.3.1.2 Hydrogen production via electrolysis

Hydrogen generation via electrolysis in decentralised systems offers the possibility to circumvent many of the distribution problems associated with central production. Central hydrogen production is mainly associated with hydropower, nuclear power and future off-shore wind farms or thermo-solar towers. Generic R&D challenges for electrolysis are discussed for decentralised production, cf. Chapter 2.1.3.2.2. Large-scale electrolysis requires a substantial scale-up in the size of electrolysers. Today, the large electrolyser modules have a capacity of approximately 1,500 kg/day. The largest integrated electrolyser installation is located at Aswan, Egypt, with a capacity of around 71,000 kg/day.

The efficiency of commercially available alkaline electrolysers ranges typically between 62 % and 70 % based on the lower heating value of hydrogen, being equivalent to 73 % and 85 % based on the higher heating value, respectively. This includes all auxiliary energy requirements such as AC/DC rectification, pumps, control etc. Thus, this technology offers a fairly high efficiency compared to the theoretical maximum of 100 %. Nevertheless, for fossil fuels it is more efficient to convert them to hydrogen by reforming than by electricity production and subsequent electrolysis. The potential for further increasing the efficiency of alkaline electrolysers is therefore limited, whereas the potential for system simplification and cost reduction is still high.

Obvious applications for large-scale electrolysis are found in association with large renewable energy potentials at locations from which electricity transport to the consumer is difficult. Cases in point are large offshore wind parks in areas where the electric transportation capacity is limited and difficult to extend.

Energy conversion devices for renewable energy sources as well as electrolysers are currently designed and built to deliver or draw electricity to or from a power grid, which is operated at an alternate current. Moreover, systems tailored for decentralised application with integrated electrolyser subsystems promise to reduce cost and increase efficiency by eliminating the electric inverters. Research should be directed to optimising the electric integration and packaging of such systems. Advantages of integrated systems are especially expected in decentralised systems with short DC connections. An example of this is off-shore wind and wave energy installations connected through DC links to hydrogen production, which were to be considered central hydrogen production sites. Such offshore installations would benefit from the development of sea-water electrolysers that can be derived from alkali-chlorine electrolysis. Similar synergies exist for the integration of photovoltaic (PV) generators, solar-thermal and geothermal energy.

Pressurised electrolysis has the advantage of reducing significantly the power requirements for subsequent hydrogen compression or liquefaction. Pressure electrolysis up to 3 MPa is state of the art. Even higher pressures up to 14 MPa have been demonstrated in prototypes. Increasing the operating temperature of alkaline electrolysers from 60 – 70°C to 120 – 140°C would increase the thermal activation of the electrodes, and thus increase the efficiency. Alternatively, higher temperatures allow for the use of cheaper catalysts without compromising on efficiency. R&D is required to identify suitable and cost-effective materials for higher operating temperatures.

PEM electrolysers are a promising technology potentially benefiting from technological development synergies with PEM fuel cells. R&D activities in Europe are practically non-existent at present.

High-temperature electrolysis makes use of the effect that thermodynamically water is split more easily at high temperature leading to electricity savings in electrolysis if high-temperature steam generated from waste heat can be used. The heat source could either be a high-temperature nuclear reactor, a solar concentrator plant or geothermal energy. High-

temperature electrolysis based on solid oxide technology was developed in Germany in the 1980s. Then, the concept has been proven to work well. Nevertheless, serious difficulties arise from thermomechanical stresses within the functional ceramic materials. It is recommended that attention be focused on this issue.

Because of recent progress in synergetic SOFC technology and development of high-temperature primary energy systems such as Generation IV nuclear reactors and solar-thermal concentrating systems this concept may receive renewed attention.

2.1.3.1.3 Hydrogen production via thermochemical processes

Thermolytic water splitting is the generic term for multi-step thermochemical processes that use high-temperature heat to split water into hydrogen and oxygen. The interest in this route stems from the theoretical potential of such a process for converting high-temperature heat into hydrogen with 50 % efficiency, thereby outperforming the efficiency of the electricity/electrolysis pathway and offering an alternative to electrolysis for renewable hydrogen generation. Over more than thirty years an extensive search has led to the identification of a handful of process options[11]. Thermochemical processes are mostly proposed in the context of advanced nuclear reactors and feature prominently in the Technology Roadmap for Generation IV nuclear reactors[12]. Alternatively, the high-temperature heat from solar concentrators may be used. In any case, the major challenge is the capture of the thermally split hydrogen.

Direct thermolytic water splitting can be pursued at very high temperatures, exceeding 2,000°C. The hydrogen might be captured via membranes. However, it needs to be taken into consideration that other major developments applying functional materials at high temperatures, such as magneto-hydrodynamic power generation or even the SOFC, revealed notable obstacles with such materials. Circumventing this problem, hydrogen can be split at lower temperatures and captured by applying a sequence of chemical processes that in the end allow pure hydrogen to be collected. Reaction temperatures required for what is generally considered the most promising thermochemical cycle, the sulphur iodine cycle, are between 800 and 900°C for sulphuric acid decomposition, or over 1100 °C for very high-temperature processes, 20 – 100°C for the SO_2 gas absorbing Bunsen reaction and 450°C for hydrogen iodide decomposition.

Side reactions need to be investigated and minimised. It is advised to avoid the use of gaseous or liquid noxious substances in these cycles if energy-relevant mass markets are targeted. Research strategies for thermochemical processes that devise pathways to get around these issues should be pursued due to the high potential of the technology.

2.1.3.1.4 Photo-electrolysis

Photo-electrolysis, or photolysis, of water – also referred to as photocatalytic water splitting – is the combination of photovoltaic cells with in-situ electrolysis of water. In other words, the photovoltaic effect of semiconductor materials is not used to generate electricity as in photovoltaic generators, but to directly split water electrochemically. The effect has been proven on a lab scale and further basic research is needed.

It is still unclear whether the efficiency of photo-electrolysis efficiency might exceed that of an integrated system of photovoltaic generators and electrolysis. It is recommended that engineering and cost aspects should be considered at an early stage: Photo-electrolysis and

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[11] J.E. Funk, *Thermochemical hydrogen production: past and present*, Int. J. Hydrogen Energy **26** 185-190 (2001)

[12] *A Technology Roadmap for Generation IV Nuclear Energy Systems*, GIF-002-00 (DOE, 2002)

photovoltaic electricity generation are by nature dispersed and much of the cost is expected to be associated with the manufacturing of large devices. As electricity is much more easily collected than gases, which require additional cover and sealing of the device, the limit capital and maintenance cost for photo-electrolysis might remain higher than for photovoltaic electricity generation. Basic research is required in this field, but the viability of engineering solutions should be investigated at an early stage and will influence further funding.

2.1.3.1.5 Biophotolysis and fermentation

Bioprocesses for hydrogen production are at an early stage of development. Major breakthroughs are required before bioprocesses can substantially contribute to sustainable hydrogen production. Breakthroughs are needed both in relation to biological conversion efficiencies and yields, for which advances in the life sciences should provide input, but also in relation to reactor technology, specifically to design and construction of technically relevant bioreactors in terms of cost and size. It is useful to split the subsequent discussion into processes that require incident sunlight (biophotolysis and photofermentation) and processes that can be carried out in the absence of light – so-called dark fermentations.

In biophotolysis the overall reaction is the splitting of water into hydrogen and oxygen through photolysis. The reductants generated by photosynthesis are used by nitrogenase (cyanobacteria) or hydrogenase (micro-algae) to evolve hydrogen. In principle, this is an attractive option, because of the simple process inputs and because photosynthetic micro-organisms are capable of highly efficient use of sunlight up to the theoretical level of 40.7 %, which is several times higher than the efficiency associated with photosynthetic biomass production. R&D has thus far mainly focused on green micro-algae employing hydrogenases. In photofermentation by anaerobic photosynthetic bacteria, externally provided carbon compounds (as e.g. in wet biomass waste) serve as electron donors for photosynthesis generating a reductant for hydrogen production by nitrogenase.

A major challenge for these photobiological processes is to achieve a high light conversion efficiency of about 10 %, which is in between the actual level of 1 % of a lot of natural, untailored biological processes and the theoretically feasible levels of up to 40 %, combined with a high hydrogen production rate. Thus, biological routes offer a great chance since their efficiency can be high. A strong development focus should be directed towards higher throughput per time, measured as gross hourly space velocity (GHSV) in process engineering. A high gross hourly space velocity leads to a smaller reactor volume for the same hydrogen production capacity. This is essential in order to reduce land requirements and costs of photobioreactor systems. Reasonable light conversion efficiencies have thus far only been obtained at low light intensities with associated low hydrogen production rates. With more realistic, higher light intensities the efficiency is thus far restricted to below 1 %, where 10 % would be the typical minimum requirement for cost-effective hydrogen production.[13,14]. As outlined, reasonable efficiencies might be achieved, but it is also of great importance to achieve technically viable conversion rates over time. These are expressed as “gross hourly space velocity” and are between 1,000 per hour at the lowest and higher than 100,000 for low-cost processes. If those GHSV-levels cannot be met biological processes may successfully occupy the niche – yet stay limited to it – of waste and sewage conversion where low-speed processes are involved anyway and hydrogen production would offer great additional value.

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13 R.C. Prince, H.S. Kheshgi (2004, unpublished). The Photobiological Production of Hydrogen: Potential Efficiency and Effectiveness as a Renewable Fuel.

14 P.C. Hallenbeck, J.R. Benemann, 2002. Biological hydrogen production; fundamentals and limiting processes. *Int. J. Hydrogen Energy* **27** 1185-1193 (2002)

Dark hydrogen fermentations produce hydrogen along with organic acids such as acetic acid and carbon dioxide from organic matter under anaerobic conditions by a wide range of bacteria employing hydrogenases. The acetate product can be converted to hydrogen in a consecutive photofermentation stage. In current R&D, considerable attention is paid to (hyper)thermophilic fermentation at temperatures above 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. From the perspective of societal benefit, the main question that needs to be addressed concerns the relative merit of hydrogen fermentation vis-à-vis conventional fermentation processes aimed at the production of methane biogas.

2.1.3.1.6 Hydrogen as an industrial by-product

Apart from the processes described above, it has to be noted that some industrial processes intrinsically produce hydrogen as a by-product. In general, this gas is used for heating purposes by adding it to natural gas combustion processes. It may be made available in the short-term for higher-value applications such as vehicle fuels or electricity generation. However, the quality of this gas gases varies widely. Some effort is needed for hydrogen conditioning in order to meet the specifications of the individual applications, as the quality of by-product hydrogen varies widely. Easy availability and the remaining technical challenges make it interesting for demonstration projects within the Deployment Strategy. About 2.8 billion Nm^3 per year of by-product hydrogen could be made available in Western Europe, including 1 billion Nm^3 per year in Germany.

2.1.3.1.7 Plasma reforming

The pyrolysis of hydrocarbon feedstocks from natural gas, heavy fuel oil or biomass yields two valuable products, hydrogen and carbon blacks, utilised in industry. Such a pyrolysis process uses an electrically powered plasma torch in a high-temperature reactor. Plasma reforming was started in Norway in 1990, where the Kværner process was developed.

Hydrogen purity obtained without additional purification steps is 98 % when natural gas is used. Specific electricity consumption of the hydrogen production process is 1.1 kWh/Nm^3 of hydrogen. The conversion rate of the hydrocarbon feedstock is almost 100 %.

The first commercial plant located in Montreal, Québec, Canada, consists of two modules with a combined annual capacity of 20,000 t of carbon black and 50 million Nm^3 of hydrogen. The plant has been operative since mid-1999. Since then, no further developments have taken place and the commercial status of the technology is unclear.

Well-to-tank greenhouse gas emissions for this process depend heavily on the source of electric power used, and the allocation of emissions to the two products. For the European electricity mix, the emissions are 49 g/MJ for the supply of CGH_2 to 70 MPa car tanks if the emissions are entirely allocated to the hydrogen product. For renewable electricity, the emissions go down to practically zero.

Plasma reforming of hydrocarbons to hydrogen-rich gases (without formation of carbon black) for small stationary and mobile applications is in the phase of basic and applied research.

2.1.3.1.8 Hydrogen liquefaction

Hydrogen liquefaction is already a commercial process in plants with a typical capacity of 4 t/d up to 55 t/d of liquid hydrogen. Smaller units are available down to sizes suitable for laboratory supply. For a future hydrogen energy economy, liquefiers up to a capacity of around 300 t/d are considered which will profit from economies of scale and increased

efficiency. The total capacity of liquefiers built worldwide since 1957 has reached some 270 t/d. Not all of these plants are operative any more. European liquefaction capacity in three plants is 19.4 t/d.

The major cost factors of a state-of-the-art commercial liquefier are service capital (typically 50 – 55 %), electric energy requirements (~ 30 %) and maintenance (~ 8 %).

The electricity consumption of an existing liquefaction plant with a capacity of 4 t per day is around 0.4 kWh electric per kWh of hydrogen[15]. A newly built 40 t/d liquefier would have a specific energy consumption of between 0.30 and 0.36 kWh electric per kWh of hydrogen. Conventional liquefiers have large efficiency improvement potentials without the need for technological breakthroughs. Many advanced concepts were developed in the 1960s and 1970s, but have not been implemented because of slightly higher investment costs. For very large plants consumptions of 0.23 to 0.29 kWh electric per kWh of hydrogen depending on the hydrogen input pressure can be achieved according to studies. The theoretical minimum work for hydrogen liquefaction including ortho-para conversion is 0.12 kWh per kWh of hydrogen[16].

With presently existing components plants with 150 t/d capacity can probably be built without major development efforts as one-train plants. The limiting factors for plant size are the manufacturing and transport of heat exchangers. Larger capacities than 150 t/d would have to be realised in modular form consisting of several plants or development efforts would have to be invested in larger capacities.

R&D in the area of liquefaction should focus on efficiency improvement and integration with its production. Topics for basic and applied research are component and optimised concept development for medium to very large plants as well as the validation of advanced concepts in commercial operation.

Magnetocaloric refrigeration, which is in the phase of research, promises significant efficiency improvements by a factor of 1.3 – 1.5 compared to today's best obtainable cycles. It is not clear at present whether magnetocaloric refrigeration will one day become a cost-effective, efficient and commercial-scale technology. At present, first steps towards small-scale natural gas liquefaction are being undertaken with prototype developments outside Europe. An analysis of strengths, weaknesses, opportunities and threats (SWOT) and subsequent research activities in this area are strongly recommended.

2.1.3.2 Decentralized hydrogen production

The great advantage of hydrogen production at the point of use is that it avoids the need for hydrogen transport, and can profit from locally available energies. Carbon capture and sequestration are not viable for smaller systems nor are they necessary if carbon-dioxide-free or lean energy like biomass is utilized. Operation and control of many small hydrogen production units requires cheap process control and high safety standards. These systems need to be fully automatic to be suitable for operation by untrained personnel or consumers. Thus, safety and process control are major research issues besides cost reduction and efficiency enhancement.

2.1.3.2.1 Hydrogen production via chemical conversion

On-site hydrogen production is expected to be more cost-efficient than central production during market penetration as it is more flexible and requires only incremental investment in a

[15] Based on the lower heating value of hydrogen.

[16] At a hydrogen feed pressure of 0.1 MPa.

rapidly growing market[17]. In the long run, hydrogen will be directly delivered via pipelines to filling stations or to fuel cells used in small-scale distributed power generation. Prior to this situation, decentralised hydrogen production will take advantage of the existing natural gas infrastructure by the natural gas supplied and on-site reforming of natural gas will be an important technology. Small-scale fuel cell combined heat and power plants (CHP) convert natural gas into a hydrogen-rich gas whereas the production of hydrogen for transportation at the retail site can be done by on-site reforming of natural gas.

The long-term role of on-site reforming is still undecided and will depend on future research results. It clearly has a place in the market introduction of hydrogen and in locations. Applied research and development as well as deployment activities are suggested in view of its presumably great role in market introduction. Basic research in catalysis, hydrogen purification, reactor engineering as well as in process and safety control will be synergetic with PEM fuel cell research. The main target of technological development should be the system integration of reformers and further gas processing steps for purification and conditioning with respect to unit cost and size and specific emissions.

2.1.3.2.2 Hydrogen production via electrolysis

Electrolysis has been proven to be suited for decentralised hydrogen production. Moreover, it can contribute to the stability of grids with high shares of non-dispatchable power, i.e. power which is available inconstantly and unpredictably owing to the nature of the primary energy source, like wind energy. Any power surplus can be transformed into hydrogen. This may be used as transportation fuel or for other purposes, or may be re-electrified by fuel cells, gas engines or gas turbines thus providing reserve and balancing power.

It should be noted though that water electrolysis for hydrogen production is particularly desirable when it is based on carbon dioxide lean power, as seen in Table 2.1-1. Water electrolysis is favoured for transportation fuel when produced at the fuelling station, and in general when it is coupled to remote power production from renewables. Generic research in electrolysis should be aimed at reducing cost at already high efficiencies of up to 80 % and at further improvement of efficiencies. In addition to alkaline electrolysis, PEM electrolysis should be developed. Electrocatalysis and materials are crucial. For high-pressure electrolysis functional materials for membranes and electrodes that can withstand the high oxygen partial pressure are of utmost importance. Power electronic devices are required that permit effective integration of renewable power systems avoiding DC/AC inversion which damages the electrolyser. Efficient power rectification is particularly relevant for small-scale electrolysers in off-grid applications like peak shaving.

More specific research opportunities exist for developing high pressure electrolysers and integrated renewable-hydrogen production systems exploiting synergy between renewable energy production and electrolysis[18]. Moreover, reversible fuel cells may be applied.

2.1.3.2.3 Small-scale photo-electrolysis

Section 2.1.3.1.4 already concluded that the potential of photo-electrolysis appears primarily in small-scale, stand-alone applications where the cost of electrolysers would be prohibitively high. Competition will be on the basis of energy cost and system cost will therefore be at least as important as efficiency.

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17 Market development of alternative fuels – Report of the Alternative Fuels Contact Group, December 2003, p.43

18 Examples include wind turbines in the megawatt range with an integrated electrolyser. Hydrogen could be stored in the turbine tower and only AC/DC conversion step between generator and electrolyser is needed.

The considerations on benchmarking of decentralised hydrogen production are similar to those discussed in the section on centralised production. Here as there, pathway energy efficiency, carbon intensity, cost of delivered hydrogen and hydrogen purity are the main elements. Table 2.1-2 provides figures for decentralised production as were given in Table 2.1-1 for centralised production. The differences are not so much in the efficiency, but rather in the non-energy cost elements of capital costs, operation and maintenance which depend on plant size.

Table 2.1-2: Current commercial cost and efficiency benchmark figures for small-scale natural gas reforming including gas clean up and electrolysis.

	Efficiency (LHV-basis) [--]	**Non-energy cost** [EUR/kg]	**Energy cost** [EUR/kg]	**CO_2 intensity** [kg_{CO2}/kg_{H2}]
On-site steam reforming [19]	65-75 %	1.1 – 3.0 [19]	1.3 [20]	9.5
Electrolysis	65 – 70 %	1.0 – 20 [21]	3.0 – 5.0 [22]	0 – 27 [23]

2.1.3.3 Systems analysis

The full significance of some hydrogen production pathways may only be understood if investigated in the context of the full energy pathway or at least at a subsystem level. A point in case is the controversial discussion of the relative merit of centralised as opposed to decentralised hydrogen production. Such an analysis requires complex investigations involving all processes from well to wheel, also considering the potential merits of carbon dioxide sequestration and renewables in the medium term.

Much work has already been performed in this field or is underway[24]. An important aspect of future work is to further validate the analyses with advanced and new systems to be realised in the future and to make complete regional or national scenarios. Schematic analyses should define the scenarios clearly and Life Cycle Assessment methodology according to EN ISO 14040 will prove helpful. Well-to-wheel efficiency of different conversion chains should be looked at more closely with respect to hydrogen production.

2.1.3.4 Subsystems and component development

In the case of fossil hydrogen production, the most relevant R&D topics such as gasification, carbon capture and liquefaction transcend the ‘components level’. But the key components that are amenable to continuous further optimisation and improvement are catalysts and separation membranes. In the case of small-scale reforming, additional effort

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19 Based on the natural gas case in D.R. Simbeck and L. Chang, *Hydrogen Supply: Cost Estimate for Hydrogen Pathways – Scoping Analysis*, NREL/SR-540-32525 (July 2002)

20 Assuming a price for natural gas of around 4 EUR/GJ

21 Based on data in J. Ivy, *Summary of Electrolytic Hydrogen Production*, NREL/MP-560-35948 (April 2004): lower limit is for 1000 kg/day, higher limit is for 20 kg/day;

22 Assuming 0.07 EUR/kWh; the difference from the 0.05 EUR/kWh used for large-scale electrolysis is due to additional electricity distribution cost.

23 Nearly zero when using nuclear or renewable energy which does not require fossils during production, upper bound refers to a typical electricity mix emitting 0.5 kg CO_2 per kWh

24 CONCAWE, European Council for Automotive R&D (EUCAR), European Commission Joint Research Center (JRC) *Well-to-Wheels Analysis of Future Automotive Fuels and Powertrains in the European* Context, December 2003; http://ies.jrc.cec.eu.int/Download/eh/31. The HyWays project is developing a European Hydrogen Energy Roadmap, www.hyways.de.

would be required around process control and system and safety monitoring, including sensors.

With respect to hydrogen production from electricity-producing renewable energy sources (RES), emphasis should be placed on improving the efficiency and operating characteristics of electrolysers. This includes the extension of pressure and temperature operating ranges, the improvement of the response of electrolysers to both transient and intermittent operation and the simplification of operation of small electrolysers. These improvements should be achieved for all types of electrolysers, comprising alkaline, PEM and SOFC electrolysers.

2.1.3.5 Basic research needs

The challenges within the context of a hydrogen economy are (i) to decarbonise hydrogen production through the medium-term deployment of carbon management and by increasing the share of carbon-free energy resources, (ii) to improve electrolysis efficiency and electrolyser cost and (iii) to increase the range of capacity of electrolysers and chemical conversion devices, (iv) to improve pathway efficiency through systems integration.

More specifically, the basic research needs in the area of hydrogen production are in the following areas:

- Novel approaches to efficiency improvement and system integration of hydrogen liquefaction technologies
- Development of catalysts for hydrogen production and adsorption materials and gas separation membranes for hydrogen purification and for oxygen separation
- Improvements in alkaline water electrolysis units including development of compact “on-site” and large “central” electrolysers, sea water electrolysers, high-temperature and high-pressure electrolysers, aiming for higher efficiencies and cost reduction.
- Development of alternative types of electrolysers including PEM and SOFC, as well as photo-electrolysers for small-scale applications
- Investigating the maximum achievable efficiency for biological hydrogen production processes and assessing its applications.
- Improved integration of electrolysers and stochastic renewable energy technologies, through the development of suitable power electronics, avoiding DC/AC inversion and rectification, aiming for “integrated RES-hydrogen production” systems
- High light conversion efficiency for photobiological processes, in order to achieve high hydrogen production rates to reduce land requirements and costs of such photobioreactor systems
- Pathway and life cycle analysis of hydrogen systems, including well-to-wheel and well-to-tank analysis
- Process control, system and safety monitoring including hardware development sensors for the case of small-scale reformers

2.1.3.6 Cross-cutting issues within SRA

Industrial hydrogen production as such is a known technology. The challenges within the context of a hydrogen economy are (i) to decarbonise hydrogen production through the medium-term deployment of carbon management and by increasing the share of carbon-free energy resources, (ii) to improve electrolysis efficiency and electrolyser cost and (iii) to increase the range of capacity of electrolysers and chemical conversion devices, (iv) to improve pathway efficiency through systems integration. As for electrolysis, it should be realised that the cost of the hydrogen produced is primarily determined by the cost of electricity. Hence, the commercial viability of low-carbon electrolysis routes strongly depends on progress in both carbon-free electricity production technology and electrolysis technology.

More specific basic research needs – that typically result in verification units – in the area of hydrogen production are in the following fields:

- Gasification and gas separation technologies, for hydrogen as well as for CO_2
- Catalyst and separation membrane development
- System and safety monitoring, sensors
- Electrolysis (alkaline, PEM, SOFC and high-temperature and high-pressure)
- Development of compact on-site electrolysers
- Integrated renewable energy and hydrogen production systems.

2.1.3.7 Demonstration and interaction with Deployment Strategy

It is vital that the overall strategy of energy resourcing is aligned between research and deployment strategies and is in line with an overarching view of hydrogen within the EU's long-term projections and energy policy. In the area of hydrogen production from fossil fuels, which is a mature field for chemical purposes but not yet for energy purposes, research and verification efforts may benefit from being linked to activities in the deployment field.

2.1.3.8 Appraisal of strategic benefit for Europe

Hydrogen has the potential to contribute to Europe's energy policy of becoming more resource-independent and reducing greenhouse gas emissions if produced from indigenous carbon-free or carbon-based fuels combined with carbon dioxide sequestration. At the same time, it was pointed out that this contribution is conditional on hydrogen's sensible deployment, taking the needs of the entire EU energy sector into account and realising that hydrogen is not a panacea. A joint EU energy policy which is currently the domain of the member states would help to more effectively shape a hydrogen roll-out and would thereby also help to better direct R&D.

Europe is a leader both in the fields of catalysis and process development relevant for hydrogen production via chemical conversion as well as in the field of electrolysis, the other major route to hydrogen. Support for basic and applied research in these areas will further reinforce this strategic lead.

2.1.4 Research recommendations and strategic outlook

We have argued that there are essentially five different routes for producing hydrogen (cf. Figure 2.1-1). Of these routes, chemical conversion and electrolysis are the most important. They are commercially viable today, but at the same time hold the promise for further improvement, especially with respect to carbon-intensity reduction – for chemical conversion – as well as with respect to efficiency and cost – for electrolysis. Thermochemical processes, biophotolysis and photo-electrolysis, however, will probably not be commercial for about two decades and are subject to major uncertainties regarding their ultimate relevance. Thus, the present relative budget recommendations for research and verification and the outlook are presented for these three classes.

Around 40 % of the research budget in the area of hydrogen production should be spent on hydrogen production by chemical conversion processes, including liquefaction. These processes, though highly developed today, will be the most important high volume production routes. The generic research aim should be to decarbonise hydrogen production, requiring advances especially in the area of the use of renewable energy. However, it should be noted that electrolysis development is independent of the primary energy source, as it converts electrical energy into hydrogen. Clearly, renewable energy sources are to be preferred. Nevertheless, it makes sense to already start development at a time when renewable energy is not abundantly available and fossils or nuclear energy are going to be used. Synergies

between renewable hydrogen production by electrolysis, particularly high-pressure electrolysis, and renewable energy sources for hydrogen need to be exploited.

Table 2.1-3: Research budget priorities for hydrogen production

Research issue	Year 1 – 5	Year 6 – 10
Chemical conversion	8 %	8 %
Gas separation technologies	20 %	20 %
Liquefaction processes	14 %	9 %
Electrolysis	22 %	27 %
Development of alternative production routes	20 %	20 %
Basic research and cross-cuttings	16 %	16 %

About one quarter of the budget should be reserved for electrolysis, focused on reduction of the cost of delivered hydrogen. Since electrolysis will be deployed only for hydrogen production from non-fossil electricity, the cost of energy production plus electrolysis is the benchmark, rather than electrolyser efficiency or cost in itself. Specific research aims should be the exploration of high-temperature electrolysis and high-pressure electrolysis of options for integrating electrolysis with renewable electricity generation.

Though carbon sequestration is considered to be important it is clearly understood not to be an issue to be covered by the Hydrogen and Fuel Cell Technology Platform budget. In case the carbon dioxide capture activities should not be covered elsewhere, it is recommended that hydrogen and fuel cell projects needing carbon dioxide sequestration as a prerequisite should not be funded.

About 20 % should be allocated to fundamental research into alternative production routes. Funding decisions for alternative hydrogen production research should be based on scientific quality rather than on cost or efficiency claims. At a later stage, the contours of an efficient and environmentally benign hydrogen production route will take shape.

2.2 Hydrogen storage and distribution

By definition, hydrogen storage and distribution covers the supply chain between hydrogen production sites and hydrogen consumption in all kinds of applications. This involves:

- all transportation pathways: water, rail, road, pipeline
- all storage options: gaseous, liquid and novel storage media
- all storage issues at production sites, local filling stations and transmission sites, in transport applications, stationary systems or portable systems
- all kinds of refuelling stations.

In each case, hydrogen management in terms of energy efficiency, environmental friendliness, safety, reliability, and cost is considered in this section[25].

2.2.1 Long-term outlook for hydrogen storage and distribution up to 2050

Between 2030 and 2050 increasing market penetration of hydrogen will require a dedicated infrastructure for production, storage and distribution. Road transport of gaseous hydrogen in tube trailers and of liquid hydrogen will serve to meet the demand for market introduction. Large liquefaction units will be in operation with a capacity beyond > 100 tons/day. Liquid hydrogen will be transported by road, rail or ship. For serving mass demand, a network of pipelines and related facilities will be established connecting new large-scale production sites. It will be increasingly expanded and will include decentralised production facilities also based on renewable energy sources Main stationary systems, filling centres, fuelling stations, and domestic, commercial and industrial end-users will be connected. The pipeline grid will take advantage of the existing natural gas infrastructure which will have been adapted to hydrogen.

Satisfactory solutions and processes for hydrogen storage in novel materials will have been identified and demonstrated. A dedicated industry that produces, distributes, and recycles these novel materials needs to be fostered. The main materials issues and concepts for manufacturing pipes, tanks, as well as storage media, will have been solved. Standardised technical devices will be widespread. Consequently, the research effort should evolve towards mass production and constant improvement of materials for storage systems.

2.2.2 Medium-term outlook for hydrogen storage and distribution up to 2030

After 2015 hydrogen will be supplied to the customers progressively via pipelines and decreasingly by making use of road, rail and water transport. Besides the delivery of liquefied hydrogen, also steam methane reformers (SMR) can supply hydrogen on-site at the fuelling station. In parallel with the hydrogen-adapted natural gas grid, the network of hydrogen pipelines will be significantly extended from its original base in Northern Europe and in the Ruhr area as well as the Leuna area in Germany. Liquefaction units and supply by liquefied hydrogen tanks will be established. Networks of a few thousand compressed gaseous hydrogen (CGH_2) and liquefied hydrogen (LH_2) fuelling stations coexist in the main urban areas.

[25] The most recent projects funded by the European Commission and related to hydrogen storage and distribution are HYSTORE (FP5, ending in 2005), STORHY (FP6), NATURALHY (FP6) and CUTE (FP5, ending in 2006), HYTHANE (FP6).

Table 2.2-1: Comparison of volumetric and gravimetric performances of various hydrogen storage media and tank technologies. Relative progress can be expected by 2015 in hydrogen mass fraction and also in energy density to a lesser extent. Equivalence: 1 kg H_2 ÷ 120 MJ (33.3 kWh); 1 kWh = 3,600 kJ

Type of hydrogen storage	**Intrinsic maximum volumetric energy density** [26] [kWh/l]	**Tank system energy density** [27] **2003 status** [kWh/l]	**Intrinsic maximum hydrogen mass fraction** [28] [--]	**Usable hydrogen mass fraction 2003 status** [--]	**Usable hydrogen mass fraction, 2015 perspective** [--]
Liquid H_2 1 bar, 20 K	2.4	1.2	100 %	6 %	12 %
Compressed gaseous H_2 700bar, 300K	1.3	1.1	100 %	4 %	9 %
Activated nanoporous carbon 100 bar, 300 K & 77 K	0.6	0.2	2.5 %	1 %	2 %
	1.9	0.5	8 %	4 %	6 %
Interstitial metal hydrides (AB_2, AB_5)	4.2	1.8	2.5 %	1.5 %	2 %
Complex metal hydrides (alanates)	4.2	0.7	9.5 %	5 %	7 %
Chemical hydride ($NaBH_4$)	3.7 [29]	1.4	10.8 % [29]	6 %	9 %

From experience gained with first fleets of vehicles before 2015, the storage of gaseous pressurised hydrogen in composite tanks will have been validated at 700 bar with a usable hydrogen mass fraction [30] between 4 to 6 %. Prototypes of a second generation of on-board gaseous or liquid hydrogen or hydride storage systems with a larger usable hydrogen mass fraction and volumetric energy density [31] (kWh/l), and increased safety will be available and tested on a large scale. From today's perspective, hydrogen mass fraction reaching 9 % can

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[26] Calorific power of the hydrogen content divided by the hydrogen volume (for LH_2 or CGH_2), or by the storage material volume (for activated carbon and hydrides). Theoretical data or best research results in 2003

[27] Actual best published data of prototype tanks containing 4 to 6 kg of H_2 in the case of CGH_2 and interstitial metal hydrides, and 10 kg of H_2 in the case of LH_2. The tank outer volume is taken as the inner volume of a shrunk wrap. In the case of carbon adsorption and novel complex hydrides the volume and mass figures for a tank are estimates from extrapolation of laboratory results and reasonable assumptions on tanks.

[28] Mass of hydrogen stored in the host material divided by the total material mass without tank envelope. Theoretical data or best research results in 2003

[29] Energy and mass of hydrogen normalised to the volume and weight of wet $NaBH_4$ according to the reaction $NaBH_4 + 2\,H_2O \rightarrow NaBO_2 + 4H_2$

[30] The usable hydrogen mass fraction of a tank is defined as the ratio of hydrogen mass to the total mass of the filled tank including tank wall, bosses, valves and pipes, sensors and structural elements

[31] The volumetric energy density is defined as the useful energy (kWh) divided by the maximum volume (litre) of the tank, with the equivalence : 1 kg H_2 ÷ 33.3 kWh

be expected in 2015 based on ultimate achievement for gaseous or liquid hydrogen storage on a laboratory scale. This expectation is further backed by the fact that some solid or liquid hydrides contain an intrinsic hydrogen mass fraction exceeding 10 %[32], cf. Table 2.2-1.

Besides pressurised hydrogen storage, on-board cryogenic liquid hydrogen storage may be adopted, provided solutions have been proven and optimised in terms of safety, reduction of hydrogen gas boil-off as well as prospects for the mass production of such tanks. The price level for a hydrogen tank will be higher by a factor of more than 10 compared with gasoline tanks (125 EUR/tank).

Replacing the first generation of hydride tanks already available in the early 2000s, a second generation of tanks or cartridges for stationary and portable applications will penetrate the market. This innovation will be based on novel materials.

Auxiliary technologies for safe hydrogen management will be available. This refers particularly to hydrogen management at distribution nodes, refuelling stations and filling centres and end-use applications. Critical components like hydrogen sensors, high-pressure valves, micropumps for liquid hydrogen will need further development.

2.2.3 Research strategy for hydrogen storage and distribution for 2005 to 2015

Prototypes of a next generation of on-board gaseous hydrogen or hydride storage systems with a larger usable hydrogen mass fraction and volumetric energy density [33] (kWh/l), and increased safety have to be available and tested on a large scale. From today's perspective, a hydrogen mass fraction reaching 9 % can be expected in 2015 based on the ultimate achievement for gaseous or liquid hydrogen storage on the laboratory scale.

Research should be done on gradually modifying the existing natural gas grid up to 100 % hydrogen. Hydrogen management at the refuelling or filling stations requires optimisation of components such as hydrogen dispensers and nozzles, hydrogen sensors, and sensing of hydrogen mass flows during refuelling. Moreover, basic engineering for rapid refuelling and energy management in compression and gas cooling is important. For cryogenic, liquid technology the boil-off and heat transfer are crucial issues.

Specific work has to be done in terms of safety, risk assessment and components for high-pressure and high-volume transmission, medium-pressure distribution and low-pressure infrastructure at the end-user side. Regulation and standards must be defined and questions of public acceptance must be studied.

Hydrogen in private customer use requires a new quality of handling, safety and acceptance which includes refilling procedures at special locations or in combination with fuelling stations for vehicles as well as operating small energy converters < 5 kW

2.2.3.1 Hydrogen transmission to stationary systems

2.2.3.1.1 Pipelines

The results of large existing pipeline systems in Belgium, France, the Netherlands and Germany have to be evaluated. A strategy has to be found to use these systems for initial hydrogen infrastructures and to combine today's hydrogen production stations[34] with those and new pipelines to create the first small hydrogen supply clusters. Engineering studies

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[32] L. Schlapbach and A. Zuttel, Nature, vol. 414 (2001), p. 353. The "intrinsic" hydrogen mass fraction is the mass of hydrogen atoms divided by the total molecular mass

[33] The volumetric energy density is defined as the useful energy (kWh) divided by the maximum volume (litre) of the tank, with the equivalence : 1 kg H_2 ÷ 33.3 kWh

[34] E.g. refineries or alkali-chlorine facilities

have to be done on how to make use of existing pipeline systems for hydrogen and natural gas, planning new pipelines in urban areas and distributing hydrogen from refineries and chemical plants to take maximum advantage of already existing lowest cost hydrogen sources.

After 2015, hydrogen will be supplied to the customers progressively via pipelines and decreasingly by making use of road, rail and water transport. Research should be done on gradually modifying the existing natural gas grid for hydrogen use. As biomass is envisaged to play a major role in the future there will still be the need for a methane gas pipeline grid, even in the long run. Specific work has to be done in terms of safety, risk assessment and components for high-pressure and high-volume transmission, medium-pressure distribution and low-pressure infrastructure at the end-user side. Regulation and standards must be defined and questions of public acceptance must be studied.

2.2.3.1.2 Liquid supply and/or gaseous supply

The two basic strategies supplying customers with hydrogen differ in energy demand and cost. Generally, compressed gaseous hydrogen supply is more energy-efficient especially because of the high liquefaction energy demand[35]. However, it imposes higher costs than liquid hydrogen supply when road transportation is applied. Also, energy management at the refuelling station favours liquefied hydrogen pathways. On the contrary, liquid hydrogen supply involves additional energy loss due to boil-off. Overall, the specific primary energy (PE) demand and greenhouse gas (GHG) emissions balances have to be evaluated, and will mostly be in favour of gaseous hydrogen: Hydrogen from natural-gas-based central steam reformers offers up to

- 30 % primary energy advantage,
- 20 % GHG advantage and
- 20 % cost disadvantage for gaseous hydrogen supply via bundle transport and gaseous fuelling in contrast to liquid hydrogen supply via liquid transport and fuelling at the fuelling station.

These results are influenced by regional differences in relevant boundary conditions such as energy supply patterns, transportation distances, primary energy preferences and electricity supply mixes.

2.2.3.1.3 Stationary storage

Stationary storage refers to central storage of gaseous or liquid hydrogen for industrial or further retail use. This can be secondary distribution centres, such as fuelling stations or cylinder filling centres, sites along pipelines, hydrogen production sites associated with off-shore wind parks or stationary power applications above 10 kW which need larger hydrogen supplies. In any case, the storage technology is well known. Underground and underwater storage facilities are considered to be of strategic importance to match hydrogen production and demand and to ensure energy reliability. Their deployment depends more on regulatory approval than on further research. However, more applied research is still needed to evaluate the long-term behaviour of hydrogen confinement. New procedures for regulation and standards are necessary.

For reasons of safety in the neighbourhood, stationary storage based on hydride materials needs to be investigated in terms of reactor design for relatively large hydrogen flows (several hundred or thousand Nm^3/h). Moreover, management of the supply chain of hydride

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[35] Based on the average European efficiency of electricity generation

materials, including refilling or recycling of the dehydrogenated products, needs to be addressed.

2.2.3.2 Hydrogen supply for transport systems

2.2.3.2.1 Fuelling stations

Based on the preliminary experience of the European Clean Urban Transport for Europe (CUTE) project and other national projects, the first fuelling stations have to be evaluated. New commercial standards should be derived from their non-commercial prototypes as hydrogen corridors or highways appear in some European regions. At this stage the local hydrogen demand will be met by local storage and/or on-site production. At the same time, pipeline interconnection between centralised production units and fuelling stations is expected to be starting in some areas.

A car must be refuelled with hydrogen within a few minutes and has to be safe enough for self-service operation by members of the public in various climates and operation conditions. This requires optimisation of components such as hydrogen dispensers and nozzles, hydrogen sensors, and sensing of hydrogen mass flows during refuelling. Moreover, basic engineering for rapid refuelling and energy management in compression and gas cooling (CGH_2) is important. For cryogenic liquid technology, boil-off and heat transfer are crucial issues. This should be reflected in the specific hydrogen delivery cost to the user. Space requirements of fuelling stations and scalability of their hydrogen fuelling capacity have to be optimised and anticipated. This may require scalable on-site production units, such as electrolysers or reformers, and eventually small liquefaction units. All components of future fuelling stations must be more compact to avoid complex space requirements. Underground storage must be accepted for future infrastructure. Such important developments call for an evolution of hydrogen regulations and standards and should be driven by the Deployment Strategy. Specific aspects and requirements of hydrogen fuelling stations for boats and ships in harbours should be investigated simultaneously.

2.2.3.2.2 On-board storage

Storage tanks in current hydrogen vehicles are still too bulky. The need for an increased driving range of 500 to 600 km with a fuel cell propulsion system requires an estimate of 5 kg of hydrogen. This corresponds to a liquid hydrogen volume of about 75 l, or a gaseous volume of 120 l at 700 bar and ~20 °C. In order to confine this hydrogen quantity in an overall volume smaller than 150 l, developers have to achieve a volumetric energy density for the overall tank volume larger than 1.1 kWh/l[36]. Cryogenic liquid hydrogen tanks need further research to reduce size, cost and to minimize and manage boil-off (cf. Chapter 2.4.3.3.6)

Improved storage media may be necessary to significantly improve the net volumetric energy density (kWh/l) and usable gravimetric energy density (kWh/kg) or usable mass fraction of hydrogen (% $kg_{H2}/kg_{storage}$), when the overall tank volume and weight is considered. This may be achieved by using alternative hydrogen storage media based either on hydrogen reversible physical or chemical hydrogen adsorption. Permeability to hydrogen is to be considered. Moreover, the storage system should match further criteria pertaining to automotive usage in terms of fuel stability:

- Operating temperature range from -40 °C to +60 °C

[36] The US DOE target is 2.7 kWh/l for 2015, but this net value (including the tank volume) exceeds the intrinsic value of CGH_2 at 700 bar (~1.3 kWh/l) as well as the intrinsic value for LH_2 (~2.4 kWh/l). This calls for novel hydrides provided that considerable advances will be made in tank design and engineering (cf. Table 2.1).

- Minimum and maximum hydrogen delivery temperature from -40 °C and +85 °C
- More than 1,500 cycles
- Kinetics and transient response.

2.2.3.3 Hydrogen supply for portable systems below 5 kW or below 120 kg

2.2.3.3.1 Cylinders and cartridges

Hydrogen for use by private customers requires a new quality of handling, safety and acceptance that includes refilling procedures at special locations or in combination with fuelling stations for vehicles as well as operating small energy converters < 5 kW. The storage medium either consists of compressed gaseous hydrogen cylinders, or metal-hydride tanks, or chemical-hydride tanks. In this case, refilling and recyclability of the tank or the storage medium or product are crucial.

Improved storage systems are necessary for micro or mini fuel cells < 100 W, where non-refillable cartridges can be used. These cartridges have special requirements regarding specific and volumetric energy density, kinetics, cycle life, temperature stability, interfaces, safety equipment, sensors and test procedures. Chemical hydrides or reversible adsorption/desorption systems based on metal hydrides may be preferred over gaseous hydrogen, which is basically applicable. Alternatively, reusable methanol cartridges are a solution for direct methanol fuel cells (DMFC).

2.2.3.3.2 Refilling and recycling centres

The development of a collection of specific stationary and portable applications requires the adaptation of existing industrial gas filling plants in order to manage the corresponding cylinder or cartridge logistics. This also needs engineering effort to optimise the refilling processes of reversible hydrogen adsorption/desorption systems based metal hydrides or on activated nano-porous carbon, as well as the recycling of chemical hydride by-products.

2.2.3.4 Basic research needs

2.2.3.4.1 Compressed hydrogen storage

Compressed hydrogen storage should be improved and verified in the following research areas:

- Development of novel strong, reliable, and low-cost materials for containers, i.e. fibre-reinforced composites for storage containers using high-quality fibres and new strong binders impermeable to hydrogen
- In-depth knowledge of the failure mechanisms of storage container materials, such as the atomic-level processes responsible for hydrogen embrittlement in candidate materials; this research is necessary in order to develop strategies to prevent failure resulting from long exposure to hydrogen
- Smart sensors for hydrogen leakage detection and the corresponding safety feedback systems needed to ensure safe operation of CGH_2 systems
- Miniaturised, low cost, lightweight pressure regulators for portable and transport applications.

2.2.3.4.2 Liquid hydrogen storage

Improvement of liquid hydrogen storage includes the following basic research and verification items:

- Lightweight, low-volume and low-cost materials with good heat resistivity properties, strength, integrity, leak tightness, and durability
- Improvement of liquefaction processes in terms of energy efficiency and cost, e.g. by magnetic refrigeration [37]
- Identification of fail-safe methods to handle hydrogen boil-off safely and address other safety issues associated with liquid hydrogen.

2.2.3.4.3 Novel storage materials

The development of novel materials for hydrogen storage involves many scientific and technical challenges. Fundamental research including verification is needed to understand the interaction of hydrogen in solid-state materials and identify suitable materials for hydrogen storage.

Research in solid hydrogen storage materials has to be focused on:

- Knowledge of the fundamental factors governing bond strength, kinetics, absorption and desorption behaviour, and degradation with cycling
- Applying these principles to modify the performance of known hydrogen storage materials
- Identifying new materials and new classes of materials whose properties can be tailored to meet targets required for different final uses. At present, most of the 2,000 storage materials known have not been explored yet in doped or nano form.

These experiments will require some new developments in analytical and characterisation techniques such as neutron and x-ray scattering and imaging tools. Researchers will also need to develop a comprehensive theoretical model explaining the interactions between hydrogen and its storage materials, e.g. the nature of bonding and the role of structure and nanophase boundaries.

This fundamental research should be directed in two key areas that promise to meet the goals of hydrogen storage: metal and complex hydrides and nanostructured materials.

Research will take advantage of the revolutionary new properties and capabilities offered by nanoscience to further enhance storage capacity and to improve uptake/release kinetics.

Improvements in today's metal and complex hydrides can be achieved by a careful design of two- and three-dimensional nano-architectures to improve the weight percentages of stored hydrogen and control of hydrogen storage/release. Advances in basic research also contribute to the development of intelligent storage tanks that predict and communicate performance attributes and warn of potential failure.

2.2.3.4.4 Computational approaches

Multi-scale computational approaches can be applied to model absorption and desorption in hydride storage materials. Computational approaches and experimental data should be used to identify mechanisms responsible for degradation of hydrogen storage materials, and limitation of the life spans of these materials, particularly with repeated hydrogen storage and release cycles. Experiments on model hydrogen storage systems should be benchmarked against calculations at all length scales. Taken together, this knowledge will allow the design

[37] W. Iwasaki, Int. J. Hydrogen Energy, vol. 28 (2003) pp. 559-567

of novel materials for optimum hydrogen storage and release and provide a means to control and maintain the structural properties of candidate hydrogen storage materials and improve their durability. Computational tools must be applied and developed in safety studies in order to simulate accidents and scenarios.

2.2.3.5 Cross-cutting issues within SRA

The topic of hydrogen storage and distribution is intimately linked to hydrogen production (cf. Chapter 2.1) in particular in establishing pathways for the introduction of hydrogen. Different options such as large-scale gaseous hydrogen production combined with hydrogen pipelines or with different types of liquid hydrogen transport, natural gas transport and local hydrogen production with reformers should be assessed for various applications. All of this needs to be done for different stages of market introduction of hydrogen as a fuel due to the great importance of the mass introduction phase for the success of hydrogen or alternative energies in general. An important short- and medium-term option is virtual power plants with large reformers which produce pure hydrogen for a network of interconnected stationary fuel cells, ICE power generation sets, turbo-machinery and refuelling stations.

Other cross-cutting issues are: (i) safety of gaseous and liquid hydrogen, (ii) hydrogen sensors, (iii) computational methods, (iv) cost analyses, (v) effects of hydrogen emissions on the atmosphere and (vi) thermal integration of hydride stores with high-temperature PEFC providing the required heat. Hydrogen production, storage and distribution are strongly linked to all types of applications which will determine the end-user requirements for hydrogen use in terms of cost, quality, quantity, availability, time of discharge or supply, driving range etc. Obviously, socio-economic aspects have to be taken into consideration such as safe, cost-effective and public acceptance of the operation of hydrogen storage and delivery systems, regulatory and legislative instruments or market development.

2.2.3.6 Demonstration and interaction with Deployment Strategy

The phases of research and first serial development are crucial for later successful introduction and therefore represent a major portion of the deployment strategies for all segments. Portable applications may start earlier than stationary and transport applications.

Stores and the relevant infrastructure elements for portable applications and early or niche markets applications with hydrogen cylinders need to be developed in close collaboration with the gas industry and application developers.

The ongoing improvements of liquefied and compressed hydrogen storage systems as well as eventually available alternatives need to be prepared for deployment in large-scale demonstration programmes such as Lighthouse Projects.

One urgent issue for a deployment strategy is lowering the cost of storage systems by utilising economies of scale in the production.

The results of the European CUTE project and other national or regional projects have to be evaluated. Afterwards the engineering and components as well as the hydrogen management of fuelling stations must be optimised in terms of capital costs, handling, refuelling time, boil-off solutions for liquid hydrogen, space requirements, energy demand and especially specific hydrogen delivery cost to the user. These results will be incorporated in Lighthouse Projects and in interaction with the Deployment Strategy.

The development of a hydrogen pipeline infrastructure is not so much a challenge for strategic research but it should be a main issue for the medium-term Deployment Strategy. However, engineering studies have to be done in terms of using existing pipeline systems (hydrogen and natural gas), planning pipelines in urban areas and distributing hydrogen derived from refineries and chemical plants to take maximum advantage of already existing lowest cost hydrogen sources.

The EU projections for the contribution of renewable energy sources to electricity production aim at more than 33 % in 2020, about 75 % of which is covered by non dispatchable sources. To meet these targets centralised electricity storage via hydrogen needs to be demonstrated as power generation by hydrogen-fuelled gas turbines or fuel cells will supply grid services and make a high percentage of renewable power in the grid a viable option.

Integrated cost analyses for hydrogen supply comprising production, storage and distribution which include hydrogen management at (i) distribution nodes, (ii) refuelling stations and (iii) filling centres are recommended to be done prior to starting hydrogen infrastructure lighthouse projects in the framework of a deployment strategy.

2.2.3.7 Appraisal of strategic benefit for Europe

The European Commission can play a key role in this near-term and medium-term perspective, while technologies are being developed and demonstrated in limited markets. If results of R&D programs are successful in the medium term it is suggested that public administrations act as early technology adopters enacting policies that will promote the development of an industry capable of delivering significant quantities of hydrogen to the marketplace. Industry's role will become increasingly dominant over time. This is especially important for first niche markets with hydrogen supply to vehicle fleets based on first clusters of a hydrogen infrastructure. Therefore, developing new storage systems for vehicles will be one of the important research topics.

2.2.4 Research recommendations and strategic outlook

Basic research to achieve a commercially viable hydrogen economy requires an integrated approach, connecting progress in the critical areas of hydrogen production, liquefaction, transmission, storage and use. Lower cost, lighter weight, and higher density of hydrogen storage are the key technologies needed for a hydrogen economy. A breakthrough in hydrogen storage could have a great impact on the successful introduction of hydrogen as an energy carrier especially in automotive applications. It will, however, require highly innovative materials meeting hydrogen storage requirements, and not only incremental improvements of current technologies. Investments in fundamental research to develop and examine new materials and obtain an atomic- and molecular-level understanding of the physical and chemical processes involved in hydrogen storage and release and finally to present verification units will be necessary.

The hydrogen economy implies technical challenges that require interdisciplinary approaches involving physics, chemistry, materials science and engineering. Moreover, a strong integration of experiment and theory and modelling will be necessary not only to help researchers understand the experimental data, but also to allow them to identify key parameters which will facilitate major advances in hydrogen storage technology and guide subsequent experiments. This integrated research effort will probably lead to the discovery of new hydrogen storage materials.

Pipeline systems in urban areas will play an important role for future infrastructure growth. Dispensers of hydrogen need to be self-serviceable and refuel vehicles in only a few minutes and be fully safe for operation by the public. Underground stores will have to become part of the future infrastructure and need further development, with respect to safety and sensors.

Assessment of fuel delivery costs to the user needs to consider (i) different pathways, (ii) different filling station concepts and (iii) different hydrogen sources. External factors include life cycle costs, lifetime air pollutant and greenhouse gas emissions as well as primary

energy issues and will also have to be considered in an appropriate way[38]. The European ExternE project can provide a viable methodology here[39].

Table 2.2-2: Research budget priorities for hydrogen storage and distribution

	Year 1 – 5	Year 6 – 10
Reversible storage systems for transportation	26 %	23 %
Hydrogen management at transfer, filling (cartridges) and fuelling (vehicles) stations	10 %	11 %
Hydrogen storage at production sites	10 %	10 %
Pipeline infrastructures	9 %	11 %
System analyses and network strategy	5 %	5 %
Reversible and non-reversible storage solutions for portable applications	15 %	15 %
Liquid hydrogen infrastructure components, reduction of boil-off	9 %	9 %
Basic research and cross-cuttings	16 %	16 %

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38 J. Ogden, Energy Policy, vol. 32 (2004), pp.7-27

39 *External Costs – Research results on socio-environmental damages due to electricity and transport.* EUR 20198, European Commission, Directorate-General for Research, Brussels 2003

2.3 Stationary Applications

Stationary applications comprise fuel cells, gas turbines and combustion engines. Stationary systems can be either connected to the power grid or stand alone. Fuel cell systems in particular offer early reductions in carbon dioxide emissions through their very high potential efficiencies. Such systems are likely to be fuelled by natural gas or liquid hydrocarbon fuels in the first applications, with biogas and hydrogen becoming more important as the technology matures. The primary technology development track is for decentralised combined heat and power applications with a gradual transition from fossil fuels to carbon dioxide neutral fuels. However, much early deployment will be in premium power applications where fuel cells can achieve early competitiveness. A number of important niche markets will utilise renewable fuels such as biogas at an early date. The issues important for stationary fuel cells are similar to those for larger APU units and transportable units such as those used for marine applications. In combination with wind farms and electrolyser systems, combustion engines, gas turbine systems and / or fuel cell systems can provide load levelling and responsive power supply.

2.3.1 Long-term outlook for stationary applications up to 2050

A decentralised electricity generation infrastructure powered by a broad spectrum of renewables and clean technologies with a strong fuel cell component will have been created. The power network will largely be based upon self-contained nodes, each consisting of renewable and/or fuel-cell systems. The nodes will be supported by a high-value network powered by advanced thermal nuclear systems, hydropower, and buffered wind power and fuel-cell systems. Advantages of this decentralised system can arise from higher total energy efficiency, improved energy security and lower transmission losses.

Though generally there is a tendency for decentralisation of power supply in specific sectors a reverse tendency is to be expected. Great amounts of renewable power will be generated remotely in off-shore wind farms and solar-thermal power plants. Power-on-demand – as back-up power – and base load power will be generated by fuel cells, gas turbines and combined cycle power plants. Also, coal gasification together with carbon sequestration will be deployed which is suitable for centralised power generation. Gas turbines converting hydrogen-rich gases will provide electric power.

Stationary deployment is expected to involve both high- and low-temperature fuel cells. High-temperature fuel cells will be applied where carbon-containing fuels, including less pure hydrogen, are available and also for large-scale systems, particularly when high-value heat is demanded. Low-temperature fuel cells will be applied where clean hydrogen or natural gas is available and in smaller systems. If the development of a polymer fuel cell running at elevated temperature succeeds, low-temperature fuel cells will become suitable for less clean gases and much larger and simpler systems at a lower cost level.

2.3.2 Medium-term outlook for stationary applications up to 2030

Fossil fuels such as natural gas and coal-derived gases – together with some carbon management – will still be the main options for primary energy, although biogas will have an increasing share and might be blended with natural gas, which will still be very important. Fuel cell technology provides the means to utilize these fuels at high efficiency and so significantly reduce carbon dioxide emissions. Some power production will be centralised from fossil fuels with carbon dioxide sequestration, supported by nuclear, renewables such as solar, wind and biomass and a proper mix of these options. The establishment of distributed generation and cogeneration will increase so that dependence upon central power

production will diminish as the technology becomes more competitive. Significant decentralised nodes will exist with perhaps an average of 25 % of centralised generation having been replaced. The predominant energy vectors will still be natural gas and electricity; however, some local biogas and/or coal gas networks will have been developed. One possibility considered by many is to build up a gas economy based upon mixtures of hydrogen and methane, largely from renewable resources. This would enable production from a mixture of different sources and conversion by a number of different techniques. These networks, including hydrogen-compatible natural gas, will be enriched by hydrogen from renewable and industrial sources. It is not expected that pure hydrogen will be a significant energy vector around 2030 for stationary energy conversion. Probably, most of the available hydrogen will be applied for transport applications.

Fuel-cell systems will be commercially available at price levels in the range of 1,000 – 2,000 EUR/kW$_e$ for larger systems whereas smaller systems are projected to cost between 3,000 and 4,000 EUR/kW$_e$. The costs will further decrease as the number of fuel cells increases. System lifetimes will be more than 40,000 h (cf. Chapter 2.3.3.8). Electric efficiencies with natural gas will range from 30 – 40 % for low-power-class systems up to 65 – 70 % for large-scale fuel-cell systems combined with a turbine. Reliability and availability of fuel-cell systems will be comparable or even better than today's engine- and turbine-based conversion systems; however, these technologies will also have improved characteristics by 2030.

2.3.3 Research strategy for stationary applications for 2005 to 2015

The EU research strategy in this timeframe should concentrate on the development of low-cost, reliable and robust fuel-cell stacks and fuel-cell systems, with lifetimes exceeding 40,000 h under practical operating conditions for decentralised combined heat and power generation. High-temperature fuel cells and high-temperature polymer fuel cells offer a good perspective for stationary combined heat and power generation because of (i) their fuel flexibility and contaminant tolerance, (ii) limited requirements for fuel processing of carbon-containing fuels required, and (iii) high conversion efficiencies. Therefore R&D should focus upon MCFC and SOFC materials and stack development and system integration and on high-temperature PEFC development.

Particularly for smaller systems in the kW range, PEFC technology is of significant relevance, especially if high-temperature polymer membranes with better impurity tolerances can be fully developed. Higher temperature levels have a great potential for combined systems provided with air conditioning. Advances made in the transportation and portable sector can help develop this technology although some PEFC materials at hand are of particular relevance to stationary applications[40]. Development should essentially focus on low-cost and large-scale manufacturing of the resulting technology. Specific issues that should be addressed within a first line of development are:

- Reduction of material costs through utilising less or less precious or expensive metals, [41] involving vendors of raw materials and establishing recycling strategies
- Development of more efficient stacks with (i) low electrochemical and IR losses, (ii) high fuel utilisation.
- Enhancement of fuel flexibility
- Improvement of durability, reliability, robustness and lifetime

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[40] E.g. polybenzimidazole-based proton-conducting membranes

[41] Similar to the technical target of 0.2 mg of platinum per cm^2 for automotive applications (cf. 2.4.2)

Once technical viability for market introduction has been demonstrated, emphasis should increase on further reducing system cost and size to achieve large-scale implementation of this technology:

- Development of industrial production methods and stack design to minimise production costs
- Lower cost power electronics and sensors
- Tools for in-situ diagnostics and operation control
- More efficient thermal management including reforming and gas treatment
- Standardised, i.e. exchangeable, fuel-cell stack and balance of plant (BOP) components.

Although hydrogen is not likely to be a major fuel source for stationary power generation in the period 2005 to 2015, there is a need to develop thermal generation technologies, i.e. large internal combustion engines and gas turbines to operate in more hydrogen-rich fuels. This is particularly relevant to synthesis gas produced from coal or hydrogen utilised to buffer large wind farms. Significant changes to burner design have to be made to meet the special features for hydrogen combustion like high flame velocity and to reduce NO_x generation. New materials are required to withstand the high temperatures and are more corrosion-resistant due to the high vapour content of the burnt gas. The peripheral systems and the safety features have to be adopted for hydrogen operation.

A second line of development should target early deployment in applications where fuel cells and other hydrogen converters have added value over conventional conversion technology and meaningful verifications and demonstrations can de done on an affordable scale. Identified niche applications provide such opportunities (cf. report of the Steering Panel Deployment Strategy). Moreover, the EU should emphasise the establishment of a carefully planned sequence of laboratory verification, field test, and demonstration and lighthouse projects to obtain experience from fuel cells and hydrogen conversion technology, train technical operators and disseminate information to the public outside the hydrogen and fuel-cell community. It is very important to achieve early high visibility demonstration of fuel-cell systems in operation; however, it is essential to ensure that widespread demonstration is successfully achieved. High profile failures will do major damage to the development of hydrogen and fuel-cell technology, thus the final phase of lighthouse demonstration projects must be preceded by evaluation phases to optimise the chances of success.

2.3.3.1 Decentralised power generation

Intrinsically, these applications involve long annual operation times. High efficiency and low life cycle costs are therefore very important. The possibilities of using combined heat and power (CHP) or trigeneration[42], low noise and fuel flexibility are also of great importance as well as reliability and long lifetime. Within the ten-year timescale to 2015 these applications will predominately utilise natural gas or liquefied gases like liquefied natural gas (LNG) or liquefied petroleum gas (LPG), with the later introduction of hydrogen and biogas.

2.3.3.1.1 Residential, 1 to 10 kW and community 5 to 50 kW

Similar technologies are envisaged for residential, typically single house and community systems, although the markets are different. It will require significant development to improve cost and reliability for small residential fuel cells to become competitive with conventional boiler systems for heat generation and grid-connected electricity. Low investment costs are essential and also low running costs as the competition from today's technology is fierce.

[42] Provision of power, heat and cooling

Safety issues and easy maintenance are important. Synergies with the automobile fuel cell technologies exist in stack development. Stand-alone units working on liquefied gases, or diesel oil, can offer a particularly important application in remote areas and especially outside the developed world where grid isolation is the norm. For much of the third world fuel cell units of less than 1 kW could be particularly enabling, providing household needs such as communications, lighting and refrigeration using fuels such as liquefied hydrocarbons or for groups of such households using gas from fermentation of biomass or renewably generated hydrogen.

CHP and trigeneration will be important in the developed world. High efficiency fuel-cell micro-CHP appliances for residential and small commercial use could reduce the consumption of fossil fuels by up to 50 % and hence the emission of carbon dioxide by up to 50 %[43]. Such fuel-cell micro-CHP appliances in the 1 – 5 kW class have already shown the validity of the concept. But all project teams are faced with big challenges concerning the cost and the design of key components, as well as the robustness, durability and reliability of the entire system. In a broad variety of sectors technological breakthroughs are necessary in the near term to achieve competitive components and products for worldwide mass-markets. A virtual power plant would be created by combining a large number of such units.

A community with a large number of households and also some common use of electricity and heating/cooling is well suited for a fuel-cell installation. This may be achieved either via integration of residential systems or via larger systems. The operation time will be longer than for residential fuel cells and the peaks will be more evened out. Grid parallel operation would give better handling of load variations. Some synergies with automobile and portable fuel cell technologies exist in stack and balance of plant development. In this power class, fuel-flexible fuel-cell systems fuelled by methane produced by fermentation of agricultural waste could provide an opportunity for early introduction and demonstration, generating valuable information for further development.

2.3.3.1.2 Public and commercial buildings and industrial, 50 kW to 500 kW

This application is an important market for fuel cells in terms of volume and revenue. Several European companies are developing plants of these sizes or even larger. Long operation times are an essential performance target and there will generally be a strong requirement for some type of combined heat and power operation. High efficiency and the use of alternative fuels such as waste gases from industry or biogas or fermentation gases from sludge can in many cases be very important. For these applications high-temperature fuel cells will probably be most competitive as they offer high efficiency and high-value heat especially for industrial processes. The combination with e.g. gas turbines begins to become promising for this power range.

2.3.3.1.3 Large scale, 1 MW and above

Large fuel cell plants above one megawatt are still far away. A combination with gas turbines or other equipment to increase plant efficiency can be of great importance or even mandatory to exceed the efficiency of state-of-the-art large combined cycle power plants. More research in this field is needed. The demand for highest efficiencies particularly favours high-temperature fuel cells in this power range. Multi-megawatt systems will be built by integrating stack modules of a few 100 kW_e. The modular approach will facilitate cost reduction by high stack production volumes. Basic research will be necessary in the areas of materials and stack design in order to improve power density and durability. Also, custom system engineering will remain necessary. For the development of large plants experience

[43] The UNEP Fuel Market Prospects and Intervention Strategies report, 2002

from field trials of single module systems is essential. Low-temperature fuel cells may be deployed where large volumes of hydrogen are available, for example as a by-product from the chemical industry or – at a later stage – as a deliberate product.

2.3.3.1.4 Benchmarking to conventional and forthcoming systems

Today the fiercest competition in Europe comes from the existing infrastructure: the power grid in conjunction with conventional heating. Fuel cell technology represents the keystone of a new decentralised energy economy. Up to 100 kW, the competing technologies are internal combustion engines, Stirling engines and micro-turbines in combined heat and power systems. Fuel-cell technology offers the next generation of CHP and trigeneration product providing significantly higher fuel to electrical conversion efficiencies, lower emissions and lower noise operation. Indeed these competing technologies could be viewed as facilitating market entry for fuel-cell CHP units. Above 100 kW, the competing technologies are diesel and natural gas engines as well as gas turbines. Fuel cell technology offers clear advantages in terms of lower maintenance, higher efficiencies and lower emissions. Above 100 MW, fuel-cell systems face significant competition from highly dynamic gas turbines, with investment costs of 900 EUR/kW_e combined cycle power plants at predicted electrical efficiency of up to 60 %[44 & 45].

2.3.3.2 Renewable fuel cell applications

Fuel cells can enable the introduction of renewables on a larger scale. They will play an essential role in the conversion of biofuels to electricity at a high efficiency and low emissions. There are many different kinds of gaseous and liquid biofuels. These can be obtained from waste or deliberately produced by agricultural crops. Biofuels can be used directly in high-temperature fuel cells at a high efficiency benefiting from the fuel flexibility of these systems. Biogas from gasification will be produced at a high temperature and the most efficient process will be to feed it directly into the fuel cell, without cooling down. A high degree of integration is important for achieving the highest efficiencies and lowest cost of investment. Impurity tolerance and high-temperature fuel clean-up are key aspects for developing these systems.

Biomass fermentation produces mainly methane at a low temperature. Emphasis of the development should be on direct internal reforming in high-temperature fuel cells and contaminant tolerance. The alternative process combines low-temperature fuel clean-up to high-purity fuel gas with low-temperature fuel cells. Fermentation gas needs low-temperature clean-up, high-temperature reforming, CO removal and additional clean-up before it can be fed into the low-temperature fuel cell.

Excess electricity produced by renewable sources can be used to produce hydrogen by electrolysis that can be used either for transport or for production of electricity on demand. Reversible fuel cells can provide an efficient conversion technology to use with intermittent renewables and hydrogen as energy storage. Fuel-cell technology can be applied to build better electrolysers. Preferably high-temperature electrolysers can be developed which have higher electrical conversion efficiencies if high-temperature heat is available (cf. Chapter 2.1).

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44 http://www.ieagreen.org.uk/sr1p.htm

45 *Rolls-Royce Fuel Cell Systems – Power Systems for the Future.* G.D. Agnew, A. Spangler, C. Berns, P.D. Butler, Rolls-Royce Fuel Cell Systems, UK, 8th Grove Symposium, September 2003

2.3.3.2.1 Benchmarking to conventional and forthcoming systems

Generally biogas is converted to electricity by gas engines. The advantages of fuel cells are the significantly higher efficiency and the lower emissions of carbon dioxide and other emissions detrimental to the environment like nitrogen oxides and sulphur oxides or others.

2.3.3.3 Niche and premium power applications

Fuel cells offer an attractive high technology product to provide flexible, low environmental impact solutions to quality power needs. The requirements for premium power include quick response time, flexibility and safe utilisation by non-experts, availability and reliability. The units should have moderate investment cost. In many premium power applications, the system and running costs are not sensitive as the units are only in full operation for a short time of the year. Early market availability is important; hence, development to achieve high conversion efficiency and long durability is not a primary need.

2.3.3.3.1 UPS and back-up systems

Uninterruptible power supplies (UPS) – also in grid parallel operation – require an instantaneous response to a power failure to ensure continuity of supply over a fairly short timescale. Back-up systems provide electrical supply during extended periods of power outage. The demands for UPS and back-up systems are quick start-up time, high load-following capabilities, high reliability and availability. Also, fuel storage issues including safety aspects need to be considered. The fuel cost is not sensitive nor is efficiency of prime importance. A high system cost is tolerable. This can either be achieved using a hybrid system with a storage device or with a fuel cell operating in standby mode. A polymer fuel cell operated on hydrogen offers advantages in terms of responsiveness especially for UPS applications with integrated batteries. Improved start-up times for SOFC and high-temperature PEFC would benefit the technology.

2.3.3.3.2 Quality power

Fuel-cell systems offer the potential of very high quality, stable and reliable power supply for applications that have an extremely low tolerance of frequency or voltage variations such as precision engineering or secure data systems. This is of particular and growing importance in areas where the grid is unreliable.

2.3.3.3.3 Leisure

For leisure applications such as camping, wilderness hostels, holiday cottages, luxury boats and caravans the easy and secure handling of both system and fuel are of great importance. Safety and reliability issues are very important, as non-skilled persons will in general handle the systems. The investment costs are probably more sensitive than the running costs so efficiency and fuel flexibility are of less importance. Product image and packaging are very important, as are weight and size. It is essential to have transportable fuel sources, probably involving direct hydrogen or methanol low-temperature fuel cells (PEFC or DMFC) or high-temperature fuel cells (SOFC) utilising more complex fuels such as propane.

2.3.3.3.4 Defence

In defence applications, particularly for generation at temporary or semi-permanent installations, the possibilities of using logistic fuels are of great importance (jet fuels, diesel etc). Also robustness, reliability and safety are extremely important, as the units must be able to work under severe conditions. Low noise and thermal radiation are highly desirable, giving

significant advantages to lower temperature fuel cells in certain modes of application. Size and weight are also very important. A high-temperature PEFC would probably be advantageous here. Nevertheless, MCFC and SOFC are likely to be better solutions as they still have much better tolerance of contaminants in fuel, thus simplifying fuel treatment especially when the primary fuel is diesel.

2.3.3.3.5 Benchmarking to conventional and forthcoming systems

Current technologies for this range of applications are dominated by internal combustion engine generators and batteries and other energy storage systems. The main advantages of fuel cells over internal combustion engines are high efficiency especially at small sizes and partial load operation, low noise, easy maintenance, stability of output and, of course, low emissions. The advantages over batteries will relate to improved cost, improved energy density and extended duration of operation.

2.3.3.4 Budget estimates and allocation

Carbon-containing fuels will be most relevant, probably even after 2050, for stationary energy conversion. High-temperature fuel cell technology is favoured especially for larger-scale applications due to (i) high efficiency, i.e. low carbon dioxide emission in the energy chain, (ii) high-value heat for CHP or trigeneration and (iii) fuel flexibility. It is highly likely that higher-temperature PEFC technology developed for mobile and portable applications could also be advantageously utilised for stationary applications where such technology might be appropriate. Significant investment is required by the EU, similar to that for e.g. the US SECA programme. This investment should be matched by both European Industry and national governments.

Table 2.3-1: Research budget priorities for stationary applications
HTFC: high-temperature fuel cell, LTFC: low-temperature fuel cell,
GT: Gas Turbine, ICE Internal Combustion engine

Issue	Year 1 – 5	Year 6 – 10
HTFC stack: materials and design Cells Interconnects Seals Modelling and diagnostics Other stack issues	22 %	20 %
HTFC fuel use	9 %	5 %
HTFC system Design BOP components	11 %	8 %
HTFC demonstration Feasibility studies Verification	4 % -	5 % 8 %
Total high-temperature fuel cells, 37 % SOFC; 10 % MCFC	**46 %**	**46 %**
LTFC stack High-temperature polymer membrane Catalysts Other stack issues (incl. recycling)	12 %	10 %
LTFC system Design BOP components	9 %	7 %
LTFC fuel processing	5 %	5 %
LTFC demonstration Feasibility studies Verification	 1 %	 - 5 %
Total low-temperature fuel cells	**27 %**	**27 %**
Hydrogen turbine systems	**7 %**	**7 %**
Hydrogen combustion engines	**4 %**	**4 %**
Basic research	**16 %**	**16 %**
Total	***100 %***	***100 %***

2.3.3.5 Systems and components R&D

Today the fuel-cell stack represents 30 – 50 % of the cost of a fuel-cell plant. The remaining share comes from the balance of plant. In many cases the components in the BOP are custom-made for each project. Significant lowering of the costs of the BOP, e.g. power conditioning, blowers, valves, sensors and compressors, is an important area for research. It is of prime importance to develop components that are standardised so as to become exchangeable. This would lower system costs in the long term by fostering competition among component suppliers worldwide.

Intelligent communication equipment and services must be developed for decentralised power systems and cheap and robust grid connectors and inverters must be developed for small-scale systems in particular. The possibilities of combining a gas turbine with high-temperature fuel cells can significantly increase the efficiency of the process. The interface between the gas turbine and fuel cell still needs research and development as does pressurisation.

2.3.3.6 Basic research needs

The research challenges for stack development can be broadly grouped as relating to temperature, fuel flexibility, durability and reliability, cost and system optimisation. Single cell performance is already sufficient for most applications; however, this must be transformed into stable long-term operation of stacks. Lifetimes of 40,000 h and costs of less than 1,500 EUR/kW or 4,000 EUR/kW are essential for large- and small-scale applications, respectively, to significantly penetrate the market and extend market penetration (cf. Chapter 2.3.3.8). Improved stack performance needs to be facilitated by increased power density, better system design especially to enable enhanced heat energy utilisation through CHP, trigeneration and through combined cycle, pressurised operation with gas turbines. Verification of the respective research results is essential. Specific stack, peripheral component and system development issues targeting costs, reliability, robustness, lifetime, fuel flexibility, tolerance for impurities for each of the relevant fuel cell technologies are:

- PEFC
  - Higher operating temperature
  - Dry operation
  - Higher CO tolerance
  - Lower Pt catalyst loading or alternative catalysts
  - Recycling of stack components
  - Low-cost fuel processors
- MCFC
  - Reduced degradation and carbonate depletion
  - Corrosion of bipolar plates
  - Increasing power density
  - Internal reforming
- SOFC
  - Reducing operating temperature (corrosion and degradation)
  - Redox stability
  - Alternatively, development of more robust high-temperature systems to achieve maximum efficiencies
  - Mechanical reliability and robustness, particularly of cells
  - Thermal cycling stability
  - Cheaper and less materials
  - Internal reforming and direct utilisation of methane
  - Fuel impurity tolerance
  - Sealing materials
- For all three technologies
  - Modelling of degradation and failure mechanisms for identifying the critical deterioration mechanisms and for reliable lifetime predictions
  - Temperature-compatible fuel cleaning, particularly related to biogases from gasification and fermentation

For thermal technologies such as Stirling engines, internal combustion engines and gas turbines the main development issues are:

- Adaptation of combustion technology to hydrogen-rich fuels
- Higher-temperature more corrosion-resistant materials
- Minimisation of NO_x production
- Safety engineering

Fuel processing and direct utilisation of hydrocarbon and biofuels is of high priority. On-site gas processing is a key aspect requiring desulphurisation of natural and biogas feedstocks, removal of impurities and addition of air for partial oxidation of hydrocarbon fuels such as methane or propane. Where proton exchange membranes are to be utilised in decentralised PEFC plants, more stringent gas purification will be required to provide high-purity hydrogen, reducing carbon monoxide to a very low level. Integrated catalyst concepts are clearly needed as, for example, there are questions as to whether there is sufficient platinum to meet the demands of an extensive global fuel-cell economy. Recycling of stack components is an important research task.

2.3.3.7 Cross-cutting issues

An important cross-cutting issue is the fact that fuel cells for different applications are a prerequisite for bringing about a hydrogen economy. Their rapid commercialisation is therefore an important objective. Niche markets for fuel cells should be identified which have a potential for rapid market introduction such as small kilowatt size, high allowable cost per kilowatt and short lifetimes. Examples are applications for defence, leisure, UPS, marine applications, portable applications, etc. This could initiate mass production, which will reduce fuel-cell cost and facilitate market introduction for other applications. In parallel, socio-economic studies should explore the possibilities of subsidies for fuel cells, which reflect avoided external costs.

As for fuel-cell types the PEFC is most close to market but cost and reliability are still major barriers for all applications. High priority should therefore be given to research aimed at cost reduction, degradation mechanisms, high-temperature membranes and membrane electrode assemblies (MEAs) which do not require hydration and have a higher CO tolerance. Improvement of system components and balance of plant considerations are important as well. A key issue is here suitability for mass production.

In parallel to longer-term basic research, pragmatic, short-term strategies should be developed which minimises degradation. In addition, cross-cutting R&D is needed on lifetime prediction and development of accelerated lifetime testing methods, electronics and control for fuel-cell systems and networks. Reformer technology for hydrogen production in particular for filling stations and virtual power plants can bring about a synergy for transport and stationary applications.

For tubular SOFC and MCFC, which have demonstrated long life potential, the current cost of 6,000 – 8,000 EUR/kW_e should be reduced to 1,000 – 1,500 EUR/kW_e; applications are expected in cogeneration, power generation and marine applications. Planar SOFCs for transport and stationary applications will still require much long-term research to achieve satisfactory reliability and to solve sealing problems. Both for SOFC and MCFC, the problem of long cold start-up times and the limited number of thermal cycles should be addressed.

There is a strong synergy between R&D on SOFC and SOFC-based high-temperature electrolysers, which have a 30 % lower electricity consumption. Furthermore, a wide range of other socio-economic issues should be addressed such as regulatory instruments, public awareness, safety and market development.

Transport applications will take advantage of SOFC and PEFC technological development as there are partly coherent development targets such as a high system efficiency and low

cost. Differing operational requirements need to be considered though: durability, system dynamics and power density.

2.3.3.8 Demonstration and interaction with Deployment Strategy

It is important to find niche markets that will tolerate high entry costs for the early introduction of stationary fuel cells to engage industry. Here, residential fuel-cell applications need to achieve a price level of approximately 4,000 EUR/kW and a stack lifetime of approximately 10,000 h to enter the market, allowing for replacement during this period. For larger-scale systems different criteria will be needed for market entry, Figures 2.3-1.

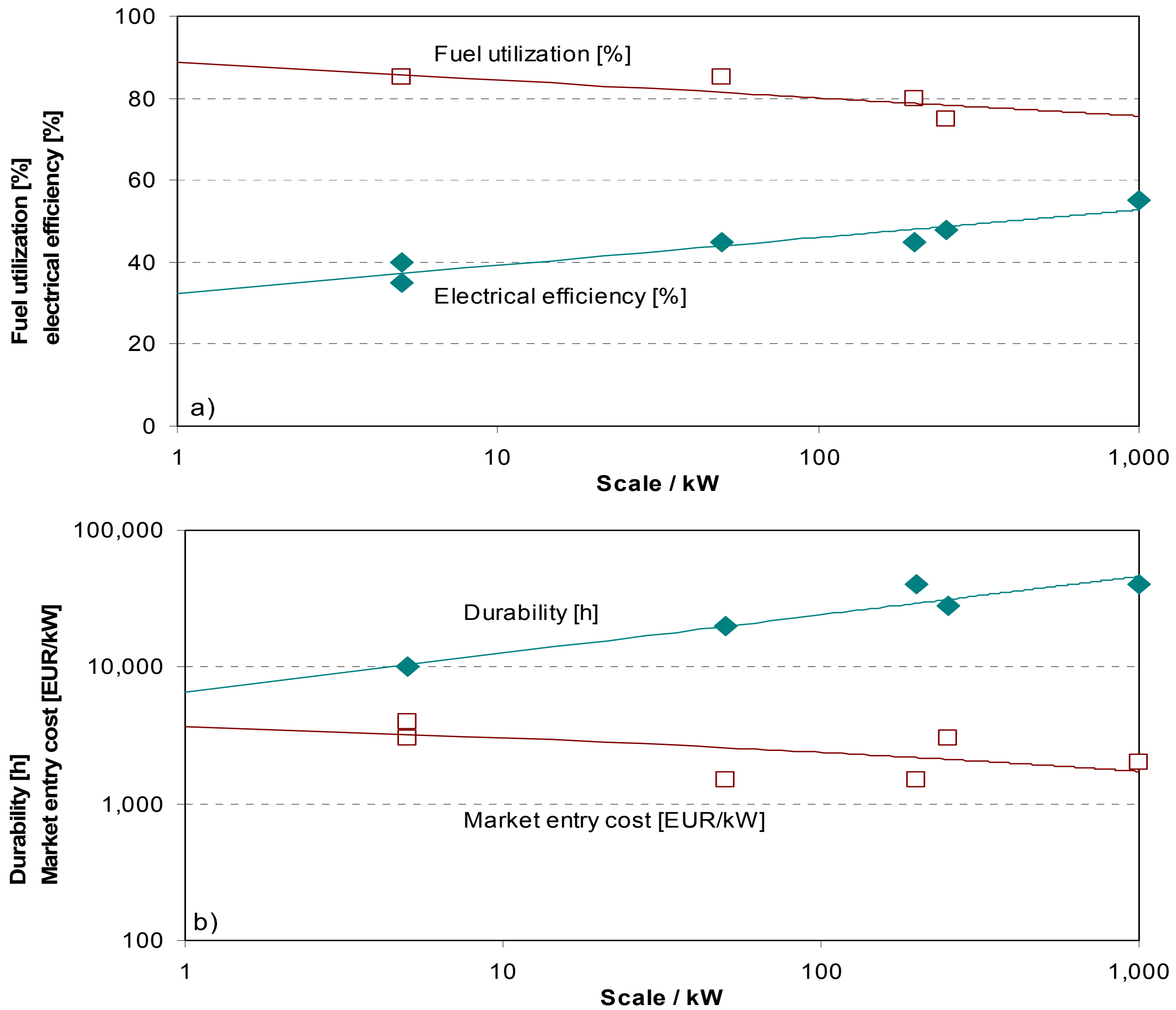

Figure 2.3-1: Target EU fuel cell industry specifications as a function of development system size for market entry in about 2008 [46]

An aggressive demonstration and deployment programme is mandatory, including public buy and incentive programmes for early pilot series to encourage and justify private investments. R&D and demonstration will go hand in hand for the next 3 to 6 years to accelerate the exchange of experience between science and engineering as well as demonstration and field tests by means of which the technology needs to prove its competitiveness. A big Lighthouse Project for residential fuel-cell systems could be a very powerful tool to encourage all stakeholders to contribute to the process; however, field tests

[46] Data from EU Industry individual assessments, July 2003

and smaller demonstrations are more important for technology development. Specific incentives for R&D should be envisaged, such as fiscal abatement harmonised at a European level. This is necessary to sustain an investment effort that must last for the next 20 to 30 years since no traditional market mechanism can help an industry that must invest for such a long period of time.

Table 2.3-2: Targets and quality criteria for different mileposts along the R&D road
BOL: beginning of life

	Early field tests	Demonstration	Lighthouse and deployment
Stationary applications 1 –10 kW (residential)			
Timeframe	2006 – 2008	2007 – 2010	2009 – 2012
Electrical efficiency @ BOL, including DC/AC conversion [--]	30 %	32 %	34 %
Total fuel efficiency BOL; @ best point [--]	> 70 %	75 %	80 %
System cost [EUR/kW]	20,000	10,000	4,000
Stack durability (90 % BOL performance) [h]	3,000	5,000	> 10,000
Number of low-temperature start-ups from 15 °C [1/a]	20	35	50
Stationary applications ~100 kW (community/industrial)			
Timeframe	2006 – 2008	2007 – 2010	2009 – 2012
Electrical efficiency @ BOL, including DC/AC conversion [--]	45 %	50 %	60 %
Total fuel efficiency BOL; @ best point [--]	75 %	80 %	85 %
System cost [EUR/kW]	12,000	4,000	1,500
Stack degradation [1/1,000 h]	< 1 %	<< 1 %	<< 1 %
Validated reference data for large-scale stationary applications ~1MW cannot be expected within the time frame considered here			

2.3.3.9 Appraisal of strategic benefit for Europe

It is urgent that Europe regains its leading position in fuel-cell technology as we develop the future energy environment. Europe should aim for more independence from the import of essential fuels and should be competitive worldwide in fuel-cell technology. Europe must build international partnerships from a position of strength. This can best be achieved by establishing a European industry for fuel-cell systems and components that is globally leading. To do this strong industry/academia collaborations must be enabled through public funding. Furthermore, small and medium-sized enterprises (SMEs) should be involved and their roles enhanced through the implementation of appropriate instruments. The establishment of a decentralised European Laboratory of Excellence in fuel-flexible fuel-cell technologies bringing together the capabilities of current European national centres in

stationary and some allied transportable and mobile technologies would be a particularly important development. Such a centre might usefully be mirrored by hydrogen and hydrogen fuel cell centres.

The high efficiency of fuel-cell technology offers a means to significantly reduce carbon dioxide emissions and allows a smooth transition phase to carbon-dioxide-neutral and zero-carbon-dioxide emission energy economies. Fuel cells are the ideal systems to utilise both biofuels and hydrogen. Stationary fuel-cell systems offer an entry point to carbon dioxide emission reductions and therefore must be a main pillar of fuel cell and hydrogen development.

2.4 Transportation applications

This section considers ground transportation as well as air and marine transportation. The focus for ground transportation is on propulsion for passenger cars and city buses. Moreover, auxiliary power units for passenger cars, light-duty vehicles, buses and heavy-duty trucks are considered. As a very high power level is required in air and marine propulsion the primary focus is on auxiliary power units in these cases. Hydrogen systems and systems operating on the basis of reformed liquid fuels are being considered.

On a well-to-wheel basis, however, vehicle development needs to be considered in conjunction with fuel production pathways. When compressed hydrogen from natural gas is being used, fuel-cell vehicles can achieve well-to-wheel greenhouse gas emissions equal to or slightly lower than advanced conventional hybrid vehicles. The lowest greenhouse gas emissions for transport applications will be achievable when renewable energies are being used.

The potential of fuel-cell technology for higher efficiency and zero emission has already been demonstrated worldwide by various vehicles using hydrogen as fuel, both from on-board storage and from hydrocarbon reforming. It underlines the perspective of this technology as a long-term solution towards sustainability of the rapidly growing transport market. However, major technological breakthroughs are required with respect to robust operation, sufficient lifetime and competitive cost by research and development before this new and promising technology can enter broad markets.

Hydrogen internal combustion engines could be envisaged as an intermediate step if hydrogen fuel is readily available before this breakthrough in fuel-cell technology has been achieved. However, in the long term the fuel-cell option is regarded as the ultimate solution, due to its inherently higher efficiency and ability to achieve zero emission. Fuel cells running on hydrogen from renewable sources are seen as the long-term solution.

An essential technology especially for high power and/or long range is the onboard fuel processing of liquid fuels to hydrogen using today's fossil fuels until liquid renewable synthetic fuels and biofuels are available. This especially allows highly efficient and clean direct electricity generation by auxiliary power units based on fuel cells.

2.4.1 Long-term outlook for transportation applications up to 2050

In industrialised countries, hydrogen will be widely available as a transportation fuel, at competitive cost, with up to 50 % of the primary energy demand covered by non-fossil and renewable sources.

Optimised fuel-cell propulsion systems will be mature technology and will be produced at competitive cost. The technical performance achieved by 2030 will have been further refined and advanced. However, the main improvement will have been achieved in the area of cost reduction, by mass production and technical innovations as well as by basic research and development. Experience gained from hybrid vehicle commercialisation will still be used to optimise the energy management of electric propulsion.

Hydrogen fuel-cell passenger cars will have achieved a dominant market share. Auxiliary power systems based on fuel cells fed by liquid hydrocarbon fuels and integrated reformer concepts will be commonly used in long-haulage trucks, ships and aircraft. Their high-power propulsion systems are likely to use these fuels made from fossil resources or from biomass. The rationale behind this assumption is constraints with respect to (i) energy storage density and (ii) specific power and (iii) lifetime derived from long-range and low-cost operation requirements which favour liquid fuels over hydrogen.

The achievements in hydrogen & fuel-cell technology will have a high impact on developing countries also for modernization of the energy infrastructure and of the means of transportation.

2.4.2 Medium-term outlook for transportation applications up to 2030

Fuel-cell hybrid propulsion systems are available at 50 – 300 kW net power in mass-produced passenger cars and buses. Typical data for a complete 100 kW propulsion system are: cost 60 EUR/kW; specific volume, weight: 2,5 l/kW, 3 kg/kW including electric drive and hydrogen storage system. Compact-class fuel-cell passenger cars have a typical fuel consumption of less than 3 litres of diesel equivalent per 100 km or 45 % drive-train cycle efficiency in the New European Driving Cycle (NEDC) and zero emissions. Typical range is above 600 km due to new hydrogen storage technology.

Other special and niche markets are occupied by fuel-cell solutions at more favourable cost and performance requirements.

The advances in fuel-cell technology are based on new membrane electrolyte assemblies (MEAs) with high-temperature proton-conducting membranes operating at temperatures of up to 120 °C or more and freezing tolerance. The platinum loading of the cells is reduced to 0.2 mg/cm². Catalysts allow up to 1,000 ppm CO content and cell power densities are near 1 W/cm². This also enables the realisation of compact APU systems based on liquid hydrocarbons with energy efficiencies of 30 – 40 % for various applications, such as ships, aircraft or military vehicles. Here also high-temperature fuel cell technology (SOFC) can be used.

2.4.3 Research strategy for SRA for 2005 to 2015

The short-term objectives are to advance fuel-cell technology towards a commercially viable solution by R&D on materials, components and subsystems and integration of the subsystems into fully integrated and compact fuel-cell systems. For many components in fuel-cell systems new and improved materials and technologies suitable for cost-efficient production in very large series have to be introduced.

The R&D will be guided by application-oriented requirements in competition with conventional or future solutions. This way technologies and materials can be selected that have the potential to fulfil the applications requirements; however, it is important to have challenging but realistic targets also for short-term development.

In addition, progress already achieved in certain subsystem areas should be verified in suitable applications in order to gain practical experience and feedback for further development. This includes, for example, hybrid power-train configurations.

Advances in hydrogen-fuelled internal combustion engines could be used to promote the use of hydrogen in certain areas and for local emission reduction.

2.4.3.1 Systems for propulsion applications

2.4.3.1.1 Hydrogen fuel-cell vehicles

High power density and high dynamic response in combination with short start-up times are essential for most propulsion applications. For hydrogen and air operation of the different fuel-cell types low-temperature fuel cells with high stack power density are the most appropriate.

Nevertheless, propulsion of passenger cars is probably the most demanding application of fuel cells regarding cost, size, ambient conditions and dynamic response. If the requirements for this application can be reached, it will open up an enormous market for fuel cells.

Today's fuel-cell propulsion systems, successfully demonstrated cars that are safe to operate and comfortable to drive, are still characterised by system costs above 4,000 EUR/kW, lifetime below 2,000 h and a system power density of about 3 l/kW.

It is necessary to guide further improvements of key subsystems and components (cf. Chapter 2.4.3.3). For example, the cost of MEA material must decrease by a factor of 5 to 10 to be suitable for series production with an overall cost reduction effect of a factor of 50 to 100 due to manufacturing processes. System analyses have to deliver a consistent definition of component requirements according to future market needs.

The short-term targets (2015) for the second generation of fuel-cell systems are:

- Operation under all ambient conditions including freeze start from -25 °C / +45 °C
- Maximum overall efficiency above 40 % (NEDC) by high performance MEA, low-pressure air supply, low humidification and hybrid systems architecture using small electrical storage devices, e.g. advanced batteries or supercapacitors for recuperation and optimal operational conditions.
- Operating range of vehicles above 400 km
- Cost reduction down to 100 EUR/kW, projection for >150,000 units per year
- Lifetime of at least 5,000 h
- Compact fuel-cell systems with 1.5 kg/kW and 1.5 l/kW for 100 kW systems, without electric drive and hydrogen storage

For buses with more moderate system dynamics a lifetime of over 10,000 h has to be achieved. By using hybrid architectures, lower hydrogen consumption compared to advanced diesel city buses can be expected.

2.4.3.1.2 Other fuel-cell applications

Special applications with early market opportunities may be suitable to make use of improved fuel cell technologies developed for other applications before large-series products are fabricated. Examples are the clean propulsion of small ships or even of mining vehicles. Other applications like forklifts, scooters or sport boats and even wheelchairs are already under development. The power range is 100 W – 5 kW. It is a fast-growing market that requires noise- and pollution-free drive trains and power generators.

Even for these small applications propulsion of vehicles is challenging with respect to energy density, power density and system dynamics required. Also a short start-up time and operation under different ambient conditions are crucial. Low prices and mass production are also required for the robotic market.

In order to obtain high energy and power densities new dedicated components and subsystems have to be developed.

Rough targets for short-term goals of a 1 kW wheelchair vehicle system are

- Operation under all ambient conditions incl. cold start from -10 °C
- Compact systems with energy densities of 5 kg/kW and 5 l/kW
- Overall efficiency above 30 % to be obtained by (i) high-performance MEAs and (ii) low-pressure air supplies, (iii) internal fuel-cell humidification, (iv) hybrid system architecture with battery or supercapacitors for high-power supply during acceleration.
- Cruising range of 50 – 100 km

2.4.3.1.3 Vehicles with hydrogen ICE

If hydrogen fuel is available, it can already be used with adapted internal combustion engines in the near future. Main development targets are: (i) Improved refuelling and storage systems for hydrogen (cf. Chapters 2.4.3.3.6 and 2.2), (ii) engine efficiency of at least 22 % (NEDC) for an acceptable vehicle range and (iii) low NO_x production.

2.4.3.1.4 Benchmarking to conventional and future systems

Benchmarks for the upcoming fuel-cell electric vehicles are performance, energy consumption and emissions of advanced ICE or ICE-hybrid vehicles.

For the customer system cost, life-cycle cost and operational features like manoeuvrability, maximum velocity, comfort and safety are the dominating features.

Fuel-cell cars must have similar or better operational features than conventional cars. They have (i) no regulated emissions, (ii) lower noise and (iii) significantly better efficiency above 40 %. Estimate figures of vehicle efficiencies are shown in Table 2.4-1 for comparison. In addition to the current status and the improvements achievable by 2015, the potential of hybridisation with batteries is also shown in the table. Hybrids allow the recuperation of braking energy, fuel saving during idling and the operational optimisation of the power train. In this way, an increase of the tank-to-wheel efficiency by about 25 % can realistically be achieved.

Table 2.4-1: Vehicle fuel consumption in the MVEG driving cycle [MJ/100 km][47]
Gasoline engines: Current status as PISI (port injection spark ignition), Potential 2010 and Hybrid Potential 2010 as DISI (direct injection spark ignition)

[MJ/100 km]	Gasoline ICE	Diesel ICE	Hydrogen ICE	Hydrogen Fuel Cell
Current status	224	183	-	-
Potential 2010	188	180	168	94
Hybrid Potential 2010	163	148	141	84

A significant reduction of running costs for fuel-cell cars apparently results from the lower energy consumption, if an energy price for hydrogen is assumed at similar a level to the current diesel price. However, fuel-cell propulsion system costs of 100 EUR/kW are considered to be finally the upper limit for broad markets. Higher prices can only be competitive under subsidised or specially regulated conditions, e.g. zero-emission legislation for cities or regions.

When comparing hydrogen ICE vehicles with conventional power trains, the reduced operating range due to similar system efficiency, but decreased hydrogen storage density has to be taken into account. Beneficial in this case is the lower effort necessary for emission reduction compared e. g. to diesel engines.

2.4.3.2 Auxiliary power applications

Fuel-cell APUs are mainly discussed in the context of transportation applications using conventional liquid fuels like diesel, gasoline or kerosene. In all these cases a compact onboard reforming and cleaning device is necessary in order to produce hydrogen that is delivered to a fuel-cell operating independently of the propulsion system. This is interesting

[47] Source: CONCAWE [2003], well-to-wheel study

for transportation applications of high-power and/or high-operating range like ships, planes and trucks and also for conventional vehicles in the medium term without a new hydrogen infrastructure. Since liquid hydrocarbon will also be available in the long term, APU systems will have a long-term perspective as well (cf. Chapter 2.4.1).

Depending on the power level and the dynamic requirements, PEFC or advanced SOFCs can be used. High-temperature PEFC and SOFC both facilitate the reforming process for their much higher CO tolerance.

The short-term objectives are to advance fuel cell and reformer technology towards a commercially viable solution by R&D on components and subsystems and to integrate them into compact systems. The system targets depend on the special applications and the rated power.

2.4.3.2.1 APU for vehicles

Rough target data (2015) e.g. for a 10 kW diesel vehicle APU system are:

- Durability — 5,000 h – 40,000 h, depending on application
- Ambient temperature range — -25 °C / +45 °C
- Efficiency @ full load — > 35 %
- Low temperature start-up — < 30 s
- Emission level — < SULEV [48]
- Weight and volume — < 50 kg, < 50 l

APUs are especially attractive for avoiding idling of trucks and for various comfort functions independent of engine operation for all vehicles. In this way, a high percentage of fuel consumption and emissions caused by these functions due to the unfavourable point of engine operation can be saved.

Commercial attractiveness very much depends on the specific application and must be defined carefully by individual system analysis. An important issue is the fuel quality. Considerable effort with R&D and additional equipment is necessary to deal with a high sulphur content that is extremely detrimental to lifetime.

2.4.3.2.2 APU for defence systems

Electricity supply with low or no thermal, acoustic and magnetic signature is of great interest for certain military installations such as mobile command centres and APUs for light duty vehicles. This can be an interesting application for fuel-cell systems with an early market entrance at higher system cost. The system experience gained can also be beneficial to other commercial applications.

2.4.3.2.3 APU for marine applications

For ships liquid fuels with a high volumetric energy density are essential. Ship fuel-cell systems are in the power range of several hundreds of kilowatts and need to be designed for long endurance.

Growing demand for on-board electricity and the increasing request for clean power generation in harbours can be satisfied by this fuel-cell APU technology. Again PEFC or SOFC systems can be used. System requirements are similar to those of stationary power applications. Dynamic response demands are lower and also the ambient temperature changes are more moderate. This offers an early market for fuel-cell APUs, if the cost and life-time targets can be achieved. More specifically, environmental conditions that are different compared to ground transportation like the salty air need to be taken into account.

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[48] According to California Zero Emission Legislation (Super Ultra Low Emission Vehicle standard)

2.4.3.2.4 APU for aeronautic applications

Also for aircraft, there is a tendency to develop more and all-electric systems in the medium and long term. Fuel-cell APUs can at least partially replace a conventional aircraft APU and produce electricity with high efficiency. Since water is produced as a by-product, this could be an important benefit during long-distance flights to fulfil on-board demands. This perspective has led all major aircraft companies to start research programmes in this field.

With respect to operating conditions, space requirements, specific power and lifetime the application of APU onboard an aircraft is particularly challenging. System analysis work on fuel-cell systems with the special ambient pressure and temperature conditions of long-distance flights has to be first done on the basis of existing fuel-cell technology. Thus, specific requirements can be developed for fuel-cell systems and fuel-cell hybrid systems and their components for power units between 100 kW and 1 MW.

2.4.3.2.5 Benchmarking to conventional and future systems

Comparisons with APUs based on conventional ICEs, turbines or Stirling engines have to be used for benchmarking with respect to (i) fuel efficiency, (ii) regulated emissions, (iii) noise, (iv) cost as well as (v) weight and volume.

2.4.3.3 Key subsystems and components

2.4.3.3.1 PEFC stacks

Further research on PEFC stacks has to simultaneously address the following targets: (i) cost reduction, (ii) efficiency increase, (iii) reliability and lifetime improvement, (iv) operating range extension, and (v) system simplification by avoiding liquid water.

The MEA is the most important subsystem influencing the performance of PEFC systems and is responsible for 70 % of the projected future PEFC stacks cost[49].

Platinum catalyst loading of demonstration systems has been reduced partially to less than 1 mg/cm². In order to meet the future cost goals and to become competitive with internal combustion engines, the activity of fuel-cell electrocatalysts has to be increased by at least a factor of 4. This means the realisation of power densities of 1 W/cm² at cell efficiencies above 50 % and at a total noble-metal loading of less than 0.3 mg per square centimetre of MEA. Alternatively non-noble catalysts, e.g. RuSe oxide, have to be improved dramatically to reach similar performance and cost targets as MEAs with platinum-based catalysts. A reason for that is the limited availability of ruthenium compared to platinum.

An even more fundamental approach is the necessity for membrane improvement for future needs. In order to get proper heat rejection onboard fuel-cell electric vehicles an increase of the membrane operating temperature to at least 120 °C is required without additional humidification and with increased efficiency compared to today's systems. This stiff challenge requires membranes with excellent proton conductivity of more than 100 mS/cm at 120 °C allowing a relative gas humidity of less than 10 %. On the other hand, the membrane must also work in the presence of liquid water, e.g. during start-up or at low-power operation as in urban driving. Today, no membrane material can meet this goal.

For mass production there is an absolute need to improve the lifetime performance to at least 5,000 h in real use and reduce the membrane cost significantly below 20 EUR/m². Stack development also requires new ionomers of the membrane material for electrode development and manufacturing. The bipolar plate and seal technology must also be able to

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[49] ADL [2001], E.J. Carlson, S.A. Mariano and R. Kumar, *Cost analysis of fuel cell systems for transportation – 2001 system cost estimate.* Ref. 49739 SFAA-no. DE-SCO2-98EE50526, Arthur D. Little Inc., August 2001

operate in the desired temperature range from -25 °C to 120 °C, which will require additional effort on these components.

The aforementioned targets are essential for fuel-cell systems simplification enabling (i) operation without liquid water, (ii) better heat rejection and (iii) the direct use of hydrogen-rich gases from reformers dispensing with further gas clean-up.

The key research objective is to create such a new generation of PEFCs by interrelated development of new materials and technologies for the preparation of active and non-active components by their integration into systems based on the following:

- Development of new high-temperature ionomers, polymers and membranes as well as catalysts for high-temperature operation
- Development and assembly of electrodes and MEAs as well as high-temperature stack design and construction of vehicle demonstrator systems with a peak power of at least 30 kW
- Series manufacturing and recycling aspects for all such new technologies.

2.4.3.3.2 PEFC system components

New improved air supply systems at moderate pressure for all operating conditions are required to (i) maximise the system efficiency, (ii) assure dynamic response and (iii) limit the acoustic noise. This includes the development of compact, high-performance, low-noise solutions with longer lifetime and higher efficiency over an ample range of operating conditions, for example electrically driven dynamic air compressors.

For system simplification and to avoid freezing of liquid water under winter conditions, according to the stack improvements, the humidification has to be reduced to a minimum. Thus passive humidification systems must be developed for the whole operating range of stacks.

2.4.3.3.3 Reformer systems

Reformer systems for different liquid hydrocarbon fuels have to be developed according to the requirements of different applications. Today, they still must be integrated with desulphurisation devices to allow operation using common fuel qualities.

Autothermal reformers allow a very compact design; the reforming heat is produced via partial oxidation of the fuel with air.

Higher efficiencies can be achieved by steam reforming of hydrocarbons at elevated pressure using high-pressure fuel and water injection. Subsequent hydrogen separation via diffusion membranes allows the provision of very pure hydrogen to the fuel cell. If this is not applicable the development of shift reactors with follow-up selective partial oxidation processes for PEFC or the use of advanced SOFC stacks with inherently simpler fuel gas processing can be appropriate.

For reformer applications in aeronautic and marine systems, e.g. as part of an APU, the fuel qualities are particularly challenging due to the high sulphur content. Methods of desulphurisation have thus a special importance.

Technical targets for the development of reformer systems are:

- Efficiency: above 75 %, defined as lower heating value of hydrogen produced divided by the lower heating value of the fuel processed and multiplied by the hydrogen utilisation of the fuel cell
- Exhaust: has to comply with emissions standards [48]
- Start-up time: less than 20 s until 30 % of the nominal gas flow can be delivered with required hydrogen purity and exhaust gas standard

- Power density: > 1,5 kW/l and kg
- Lifetime: > 6,000 h
- Freezability: the process water system has to be freeze-tolerant

2.4.3.3.4 SOFC stack for APU

SOFC systems allow direct conversion of hydrogen and carbon monoxide mixtures into electricity, which is a considerable system advantage over PEFC. On the other hand, existing high-temperature stack technologies are not yet mature enough for thermally cycled operation over extended time periods.

For transportation applications flat plate cell concepts with high power density are most promising. A key issue is R&D on cell interconnection materials and technologies which are stable under thermomechanical cycling conditions. On the stack and system level the stiff requirements of aeronautic and marine applications with respect to operating conditions as well as specific power – comparable to passenger car drive trains – and lifetime demand for substantial progress in reduced degradation, high system and stack power density and system integration.

2.4.3.3.5 Hydrogen internal combustion engines

Further improvements of injection technologies with high-pressure direct hydrogen injection and optimisation of the combustion process as well as its operational strategy are necessary to achieve the efficiency and performance goals in compliance with low NO_x emissions.

2.4.3.3.6 Hydrogen storage technologies

High-energy density storage of hydrogen is essential for transportation applications. The existing liquid hydrogen storage technology has the highest available energy density but disadvantages with respect to high energy consumption for liquefaction and boil-off losses. The development of highly pressurised gas bottles made of composite materials for up to 700 bar of storage pressure is of utmost importance.

However, the desired energy density of more than 2 kWh per litre and per kilogram at reasonable cost may only be achieved by entirely new concepts preferably by reversible solid-state compounds (cf. Chapter 2.2.3.2.2). This technology could also alleviate safety issues, which have always to be taken into account with pressurised or liquefied hydrogen storage in case of crash, leakage in confined locations or refuelling failures.

2.4.3.3.7 Fuel-cell system integration

Essential for reliably operating fuel-cell propulsion systems is integration with efficient, low-cost [50] electric drive trains comprising (i) DC/AC conversion, (ii) an electric machine and (iii) the electric power management system. Integration of electricity storage devices such as batteries or super-capacitors plays an important role for maximising the overall system efficiency. Fuel-cell stack control devices for important thermodynamic and electric parameters are needed to extend lifetime.

2.4.3.4 Basic research needs

Despite the progress that has already been achieved by fuel-cell developments for transportation applications, this technology is still in its infancy and much basic research including the presentation of verification units is needed before fuel cells can compete with

[50] Specific cost of around 15 EUR/kW can be defined as a target for the development

the well-established thermomechanical energy conversion technologies developed over more than one hundred years.

Very important are the following research fields:

- Development of new highly conductive ionomers for membranes which can operate at temperatures of at least 120 °C and at a low or zero water content
- High-activity and cost-reduced electrocatalysts based on ultra-low platinum loading or non-noble metal compositions that allow higher contaminant tolerance
- Investigations into failure and ageing mechanisms of MEAs for PEFC, including catalyst support stability, lifetime prediction and lifetime testing
- Fundamental understanding of transport mechanisms in the fuel cell, resulting in microscopic and macroscopic models
- Screening of materials and their qualification for fuel-cell applications, including bipolar plate materials, durable coatings e.g. for thin, cheap metal plates and diffusion media
- Novel analysis techniques for quality control of stacks, e.g. magnetic resonance imaging
- Strategies and equipment for stack control: e.g. voltage, humidification and temperature
- Low-cost hydrogen separation membranes for reformate gases and gas processing lines that include shift and preferential oxidation reactors
- Interconnection materials and technologies for advanced high-power SOFC stacks
- Compact liquid-fuel reformer technology including desulphurisation units, heat exchangers and evaporators for APU and propulsion which are long-lasting
- Solid state compounds for hydrogen storage with substantially higher storage density
- Supercapacitors and high-performance batteries for efficient electricity storage that allow for improved dynamic response, reduced start-up times and efficiency-optimised system operation

2.4.3.5 Cross-cutting issues within the SRA

Compared to the stationary sector, fuel-cell applications for propulsion of passenger cars have the advantage that shorter lifetimes are required for which reliability can be more easily achieved. It should further be noted that if the target cost of 50 – 100 EUR/kW can be reached, fuel cells will also be competitive for other applications with a higher allowable cost, such as buses, trucks and cogeneration and decentralised electricity production; provided that the problem of longer lifetimes can be solved.

As for fuel-cell types the PEFC is closest to the market and R&D aiming at cost reduction and reliability for up to 5,000 h for passenger cars and up to 40,000 h for buses, trucks and stationary applications should have a high priority.

Research should be aimed at (i) cost reduction, (ii) degradation mechanisms, (iii) high-temperature membranes and MEAs which do not require hydration and have a higher CO tolerance, (iv) low platinum loading of below 0.3 mg/cm^2 and (v) improvement of other system components etc. A key issue is here suitability for mass production. In parallel to longer-term basic research, pragmatic, short-term strategies should be developed which minimise degradation, such as voltage, temperature and hydration control and operating the PEFC at favourable load levels, e.g. through the application of fuel cell & battery hybrid systems. In addition, cross-cutting R&D is needed on lifetime prediction and development of accelerated lifetime testing methods, electronic control systems for fuel-cell systems and networks, reformer technology for hydrogen production in particular for filling stations and virtual power plants which can bring about a synergy for transport and stationary

applications. Other cross-cutting issues are system components such as highly efficient and compact air supply systems and passive humidifier systems.

Planar SOFCs for APUs in transportation and stationary applications will still require research to achieve a satisfactory reliability and to solve problems related to sealing, long start-up times and the limited number of thermal cycles. Important here are a new stack design as well as the development of new materials for interconnectors and sealing.

Compact storage of hydrogen in particular with innovative, reversible and preferably solid-state storage technologies and related safety issues are a key to both transportation and portable applications. Hydrogen purity is essential for direct use in fuel cells and in metal-hydride storage systems. Hydrogen purification and separation technologies are important issues for hydrogen production and for liquid-fuel onboard reforming processes, e.g. for APUs.

Finally, socio-economic studies must explore the needs of initial subsidies for fuel cells which, for example, reflect avoided external costs. Furthermore, a wide range of other socio-economic issues should be addressed such as regulatory and legislative instruments, public awareness, safety and market development and others.

2.4.3.6 Demonstration and interaction with Deployment Strategy

Advanced fuel-cell system achievements should be verified and demonstrated with high priority in projects with high visibility.

Despite noncompetitive cost, early deployment of fuel-cell vehicles that offer a convincing driving experience will greatly promote public acceptance of fuel-cell solutions. Zero emission combined with high drivability and low-noise operation will stimulate the public to demand alternatives to conventional cars. Bus fleet demonstration, for example, has an immediate impact on the public's perception.

Market entry can be promoted either by applications in niche markets, where the cost requirements are less stringent or – in the case of vehicles – in fleet applications for environmentally sensitive areas with enabling technical and economic boundary conditions such as the presence of central hydrogen fuelling stations, subsidies or preferential tax conditions.

More options for early market application are micro-electric vehicles and specialist vehicles and APUs for marine and rail application.

2.4.3.7 Appraisal of strategic benefit for Europe

For the following reasons innovative technologies for the transportation sector are of great importance for the European industry, economy and society:

- A considerable 20 – 30 % of the automotive and transportation system industry is in added-value generation and exportation of innovative technical solutions
- Technical leadership in alternative drive systems and fuels is of high relevance for the competitive position of our European industry
- Transport applications have a huge market of several hundred gigawatt per year
- Many of the pioneering research and engineering innovations have been realised in Europe, e.g. the first fuel-cell cars or first series fuel-cell onboard submarines. An excellent basis of specific know-how and relevant scientific expertise and technical experience is available within European institutions and companies.
- Low-emission propulsion systems and a clean environment are of high value for European society. Therefore, high societal acceptance can be expected for fuel-cell technologies that ensure a clean environment.
- Depletion of their own oil resources are forcing the European countries to invest in technologies with high efficiencies and non-oil-based fuels. This is especially desirable

for stack production within the EU as a core technology of fuel cells that is needed for reasons of economic and ecological foresight.

2.4.4 Research recommendations and strategic outlook

The highest impact of novel fuel-cell technologies in the long term can be expected for the European automotive industry with its production of drive trains at an accumulated power of several hundred gigawatts per year. A breakthrough with respect to lifetime and cost of fuel-cell systems within the next 10 years is essential to successfully introduce the fuel-cell technology in at least a part of this huge market. Therefore, R&D and verification efforts targeted at improved PEFC stacks and their key components, which are mainly responsible for the high cost, is of the highest priority. The substitution of perfluorinated membranes and higher operating temperatures is a fundamental research task.

The improvement of the electrocatalyst activity of platinum or non-noble metal electrodes is of similar importance to reduce material cost and simultaneously increase power density of the stack. Basic research work on new materials and manufacturing technologies has to be done in close cooperation with development of improved system components and subsystems. This should be realised by cooperation with this industry on the part of research institutes who are responsible and knowledgeable about the system specifications and applications. Successful results should be demonstrated in visible projects also to gain practical experience under conditions of everyday life and to promote this new technology.

For basic research and development of PEFC stacks, at least 50 % of the research budget should be concentrated on achieving the breakthroughs described above. R&D on this key subsystem will have positive effects, also on portable and stationary applications of fuel cells.

For the overall timing of R&D and the parallel deployment strategy other enabling technologies such as improved hydrogen storage systems (cf. Chapter 2.2.3.2.2) for an acceptable vehicle range and the availability of hydrogen infrastructure (cf. Chapters 2.1 and 2.2) are of great influence.

Table 2.4-2: Research budget priorities for transportation applications

	Year 1 – 5	Year 6 – 10
PEM stack Membrane Catalyst Other stack issues	40 %	18 %
SOFC for transportation	4 %	5 %
Reformer systems	7 %	6 %
PEM system components Air supply E-drive	12 %	8 %
System integration Verification	16 %	14 % 8 %
Verification programmes	-	20 %
ICE	5 %	5 %
Basic research and cross-cuttings	16 %	16 %

Fuel-cell reformer systems based on liquid fuels – mineral-oil-based or in future renewable, synthetic or biofuels – are the other option; however, these systems are ranked only second when comparing the progress with respect to overall efficiency, emissions and complexity. However, they are essential for APUs of high-power and long-endurance applications like ships. They are independent of a new infrastructure and will have a better range of operation presumably also in the long run. Furthermore, these applications could be introduced earlier into niche markets. Therefore, component R&D for highly efficient and compact fuel-cell systems using integrated fuel processors and reformers also has high priority. This includes SOFC stacks that are resistant to thermal cycling and have a long lifetime at reasonable cost.

A framework of a research budget planning for the next 10 years is proposed in Table 2.4-2, taking the most relevant and promising issues into account.

2.5 Portable applications

Fuel cells for portable applications will be the first systems to be used in niche markets and in consumer applications. Therefore they will play a crucial role for gaining experience, trust and acceptance, both among consumers and industry. Portable fuel cells can replace batteries and combustion engines thus improving the energy efficiency and ecological balance of millions of devices.

The early development and introduction of fuel cells in portable applications might be the nucleus for a strong European fuel cell and electronics industry. Portable applications can therefore ensure that a fuel-cell industry for other applications will emerge in Europe as well.

In this section, portable applications are defined by a maximum power of 5 kW and the property of portability of the device. There are chiefly two classes of applications: systems below 50 W, represented mostly by portable electronic or electric devices and high-power systems below 5 kW represented by products such as portable power generators. Portable applications are attractive for fuel-cell systems because the volume of possible units is high and cost limitations are easier to meet compared to fuel cells in mobile or stationary applications. The modular design makes it easy to adjust fuel cell power to the application as required.

Portable power generation has already been playing a great role in the market introduction of fuel cell technology and creates business opportunities for small and medium-sized enterprises which are active in high technology. For the relatively high allowable prices per power unit and high-value propositions portable fuel cells give rise to early adoption markets in which customers will buy down early costs. In this way, fuel-cell technology can be made tangible for a great variety of people through application in portable devices. Polymer electrolyte fuel cells (PEFCs) and direct methanol fuel cells (DMFCs) that directly convert hydrogen or methanol into electric power are at the focus of research and development. The use of presently available liquid fuels like liquid propane gas and middle distillates as diesel fuel would be beneficial for early commercialisation. However, this requires the application of fuel reforming and gas purification.

2.5.1 Long-term outlook for portable applications up to 2050

In 2050, most electronic devices and portable applications will rely on fuel cells, not on batteries or combustion engines, resulting in less hazardous waste from batteries and reduced carbon dioxide emissions. The European research and industry structure develops and produces fuel-cell components and systems for portable, stationary and automotive applications, also increasing the competitiveness of other sectors such as the electronics or automotive industries.

An infrastructure for hydrogen and liquid fuels such as methanol with a widespread distribution network will be established worldwide. Handling and transport regulations, legal issues and standardisation of fuel containers are agreed upon and are being followed globally. Recycling concepts for fuel cells as well as reuse systems for fuel containers have been proven and are available worldwide. Significant cost reduction of fuel cells and fuel has been achieved. Synergies with other applications will have facilitated cost reduction efforts and market introduction. Fuel taxation for hydrogen and methanol will have been started. The following table provides an outline of the characteristic data that will be achieved by this time.

Table 2.5-1: Typical specifications for a low-power consumer electronic device below 50 W and for improved high-power systems of 500 W – 5 kW

Specification	Unit	Low-power system	High-power system
Gravimetric power density	W/kg	300	500
Volumetric power density	W/l	200	400
Energy density	Wh/l	1,000	-
Electrical efficiency (ratio electrical power to HHV)	%	-	> 35
Cost (defence/industry)	EUR/W	-	3
Cost (commercial)	EUR/W	1 – 2	0.5
Lifetime (defence/industry)	h	-	5,000
Lifetime (commercial)	h	5,000	2,000
Start-up time (hybridised with battery or supercapacitor)	s	instantaneous	instantaneous

2.5.2 Medium-term outlook for portable applications up to 2030

In 2030, fuel cells will have been broadly accepted by customers as a reliable, cost-effective and attractive device to power many electronic devices such as chargers, laptops or camcorders. Industry, trade and consumers will have gained experience with fuel cell technology and the fuel supply. The European fuel cell and electronic industries will have established a leading position in developing and producing integrated fuel cell systems for portable applications. This success will have prepared the market introduction of fuel cells in stationary and automotive applications.

Fuel-cell systems for portable applications converting hydrogen or liquid fuels are available in commercial quantities at competitive prices. Fuel cells based on liquid fuels are still somewhat more expensive compared to the hydrogen systems.

Hydrogen and liquid fuels are widely available in industrialised countries. The constraints regarding the use and transport of fuel-cell systems and fuel containers are entirely eliminated. Durability and reliability issues of fuel-cell systems are resolved for operating times of roughly 3,000 h. Safety and regulatory issues are resolved. Transport of fuel-cell system and fuel container is unrestricted. Fail-safe handling is warranted by appropriately implemented standardised practices and procedures. The technological achievements can be described as follows:

- Gravimetric power density: 80 – 200 W/kg
- Volumetric power density: 80 – 150 W/l
- Energy density: 500 – 1,000 Wh/l
- Production cost: 3 – 5 EUR/W
- Durability of systems: 1,000 – 5,000 h

For the higher-power systems ranging from 500 W to 5 kW the specifications of a typical system in 2030 are comparable to those for the long-term perspective. However, further improvements in power density, costs and BOP components are expected. In the long run, simultaneous development of fuel cells for transport and stationary applications may lead to further reduced cost and improved technical performance.

2.5.3 Research strategy for portable applications for 2005 to 2015

Fuel cells will be found in first applications with a clear value proposition in niche markets, such as emergency and defence services, and for consumers of premium devices.

The short-term research strategy must create the conditions for early market introduction of portable fuel cells. One R&D focus has to be components and subsystems that are to be integrated into autonomously working and compact fuel-cell systems. Important aspects are (i) miniaturisation, (ii) compatibility, (iii) simplicity and (iv) cost-effectiveness. Standardisation regulations and consumer safety need to be considered.

Mainly three different fuel-cell system configurations are relevant for portable applications and have to be looked at individually [1]:

- PEFCs converting pure hydrogen
- PEFCs converting hydrogen-rich gases from hydrocarbon reforming
- DMFCs directly converting methanol into electric power.

Main research and development challenges are (i) the development of microreformers, (ii) fuel cells with high carbon monoxide tolerance or low cross-over of methanol and (iii) simple water and heat management as well as (iv) hydrogen storage solutions that can be widely and safely distributed.

2.5.3.1 Portable power generators (500 W – 5 kW)

2.5.3.1.1 Back-up power generators

Back-up power generators range from a few hundred watts to several kilowatts. High energy and power density as well as a short start-up time are essential. Such systems are to be operated at ambient conditions. When used in uninterruptible power systems a wide power range in combination with highly dynamic operation are required. PEFC systems including DMFC are suitable solutions. Hybrid configurations may be appropriate if the load-following capabilities of the fuel cell are not adequate. Consequently, R&D efforts need to address PEFC materials development as described in part 2.4.3.3.1. In particular, research topics include:

- Alternative catalysts with reduced precious metal loading
- Sulphur-tolerant catalysts and/or sulphur removal strategies
- CO-resistant MEAs for reformate gas
- MEAs with a simple thermal management
- Novel membranes with improved humidification and methanol permeation properties
- BOP components that enable short start-up and high system dynamics, e.g. batteries and supercapacitors.

For back-up power generators it may be foreseen that the low power range will mainly be covered by DMFCs. PEFC systems for high-power applications will either be fuelled by hydrogen or by other hydrocarbons such as diesel, kerosene, gasoline, LPG, or methanol through a reformer system. DMFC systems are considered to be effective in the very low kW range as well. Systems with higher power suffer from reduced efficiency of DMFC stacks owing to methanol permeation. If this problem is solved and platinum loading of DMFC membranes were lowered to about 2 mg/cm^2 the DMFC is expected to play a vital role in the portable high-power sector.

Today, a first generation of back-up power generator systems is being successfully demonstrated in prototypes. They are characterised by system costs of around 10 EUR/W with a lifetime below 1,000 h. Power densities of fuel cell systems are currently in a range of

10 – 100 W/l. Proper system components need to be developed as high power densities of cells and stacks are spoilt in the system by a lack of availability of proper system components.

Technical goals for the next generation of back-up power generator systems are

- Short start-up time below 20 µs for UPS and appropriate load-following capability systems applying hybrid system configurations with batteries or supercapacitors
- Stable and reliable operation at all ambient conditions
  - Temperatures from -20 °C to 70 °C
  - Variations in relative humidity
  - Trace contaminants in air
- System efficiency above 30 % requiring
  - New high-performance MEAs
  - Low-pressure stacks and fuel supplies
  - Simplified internal fuel cell humidification
  - Dedicated BOP components in integrated system configurations
- New highly efficient and compact reformers for different fuels
- New high-performance MEAs for DMFCs with low methanol permeation
- Compact systems with power densities in the range 100 W/l
- Lifetime and durability better than 2,000 h in 5 years
- Cost reduction for compact power generators to 2 EUR/W for mass production above 10,000 units/year
- Cost-effective high power electronics

2.5.3.1.2 Defence applications

Power range and performance characteristics of defence applications are mostly similar to those of back-up power generators and APUs. The acceptable cost in this market is much higher compared to other portable applications. Special emphasis in systems development needs to be put on a low thermal or acoustic signature. Low-temperature PEFC and DMFC technology may thus be favoured. The use of today's logistic fuels again involves the development of liquid fuel reformers and desulphurisation units. Also here ambient conditions must be considered for defence applications that need to be applicable all over the world.

2.5.3.1.3 Off-grid applications

At present, a variety of off-grid applications use batteries as power sources leading to short replacing or recharging intervals. Examples are sea buoys, lighthouses, weather stations. Fuel-cell systems ensuring long durable operation by adjusting the storage size to the application standard may significantly improve this situation. Even at today's cost fuel-cell systems may be applicable as soon as robust systems are technically available.

2.5.3.1.4 Benchmarking to conventional and forthcoming systems

Fuel-cell systems have to be compared to advanced lead-acid batteries and to advanced internal combustion engines which presently dominate the market for portable power generators. Advanced batteries need to be included in the surveys although they are not yet competitive owing to their high prices. Technical performance, weight & volume, consumption, emissions, and cost of these technologies are setting the performance targets. Benchmarking is also necessary to forthcoming systems like the Stirling engine or microturbines that are currently at the development stage.

2.5.3.2 Power supply for electronic devices (consumer electronics)

Fuel-cell system types with DMFC, hydrogen-fuelled PEFC and PEFC converting hydrogen-rich gases may be used as power generators for device-integrated units. Battery chargers, cellular phones and notebooks are examples of this application. Weight and volume constraints lead to the major development challenges. Research and development should thus emphasise miniaturization of systems. Considering low-power applications below 20 W the fuel-cell system needs to be integrated into the portable device. Configurations that better correspond to a charger design with separate energy converter and portable device and are suitable for applications with higher power, e.g. notebooks, power tools or professional camcorders.

Notebook demonstrators based on a hydrogen-fuelled PEFC with metal-hydride storage systems power have achieved a power density of 55 W/l and a specific power of 95 W/kg [2]. An energy density of about 120 – 140 Wh/l has been accomplished. A commercially available 25 W DMFC system with a power density of about 40 W/l and 30 W/kg offers an operating time of 12 h.

The overall target of further developing power generators for electronic devices can be seen in the miniaturisation of systems by improving durability and efficiency as well as operational reliability. Keywords are system simplification, water and effluent management and fuel handling.

Air supply should be accomplished without active means of air movement like fans. Regarding the stack design, reaction rate limitations due to oxygen diffusion have to be avoided by improved flow-field and distribution layer design.

Substantial improvement needs to be achieved in water management. This includes fuel concentration control, membrane humidification and water recovery. The ultimate goal should be passive operation of fuel-cell systems, which also supports systems reliability and cost reduction.

Special attention needs to be given to the thermal integration of power generators. Compared to battery-operated devices fuel-cell systems produce substantially more heat[51]. The integration of fuel cells with metal hydride storages that require heat for hydrogen release is one example of integrated heat management. Compact and highly efficient thermal barriers are also related to this issue.

For fluid handling, miniaturised components like valves, sensors and controls, liquid/gas separation units, humidifiers and heat exchangers including the appropriate materials needs will be the focus of future R&D.

Gas-processing systems that include reformers and gas-cleaning units as well as power electronics need further development. In order to meet the peak power demand of portable devices the application of hybrid configurations may be necessary. Key components that need to be developed include small batteries and supercapacitors.

For the sake of operational safety any leakage of noxious or inflammable substances is to be prevented under any operation or handling conditions even by untrained personnel and unintended misuse. Systems research addressing these issues comprises the substances hydrogen, methanol, formic acid and CO including fuel containers.

As described above, progress in materials development for liquid-fuelled systems like DMFC is intimately related to power density improvement. Materials' research will include electrocatalysts, electrode structures and membrane-electrode assemblies with

- Improved catalyst utilisation
- Advanced methanol oxidation catalyst
- Methanol-resistant cathode catalyst

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[51] 50 % electric efficiency of fuel cells compares to 80 % efficiency of batteries

- Improved carbon-monoxide tolerance
- Manufacturability
- Improved membranes without fuel and water crossover by maintaining conductivity, improved humidification properties, operation over wide temperature range

The integration of single cells to the stacks will also require new sealing concepts ensuring gas tightness and stack durability. A general aspect of all materials development is applicability of mass production utilising low cost materials in order to reach a cost level that is suitable for the mass market.

Finally, standardisation of fuel containers requires special attention and is of utmost importance for an early market introduction.

2.5.3.2.1 Benchmarking to conventional and forthcoming systems

Various demonstrators and published information infer that specific energy densities of pre-commercial fuel cell systems in the power regime below 20 W are comparable to Li-ion battery technology, with a reported energy density of 250 Wh/l for a system including a tank as of 2004. However, PEFCs that run on reformate fuel gas as well as DMFC have the potential for much higher energy densities.

For low-power applications below 20 W Li-ion batteries will serve as benchmarking fuel cells since this type of battery dominates the market for electronic devices at present. The status of Li-ion batteries in 2004 according to [4] is:

- Specific power: 350 W/kg
- Power density: 600 W/l
- Energy density: 160 Wh/l
- Specific energy: 110 Wh/kg
- Lifetime: 500 cycles

Power sources to be replaced by fuel cell systems with higher power output between 20 and 100 W are the nickel metal hydride battery and the Li-ion battery. Therefore, the most advanced batteries of these types should be taken as a basis for benchmarking.

2.5.3.3 Subsystems and component development

2.5.3.3.1 Fuel-cell stack components

Fuel-cell systems with DMFC, hydrogen-fuelled PEFC and integrated systems with reformer and PEFC are being developed at present. As a consequence, component development exhibits considerable differences depending on system configuration and application-specific system requirements. In the following, R&D priorities for fuel-cell system components will be identified.

2.5.3.3.1.1 Direct methanol fuel cell

Key issues of membrane materials development are high current densities, low methanol diffusion and low water diffusion. For example, this can be achieved through the development of composite membranes. Also non-fluorinated membrane materials offer good cost effectiveness and are suitable for portable applications due to the lower lifetime requirement in comparison to automotive applications. Existing electrocatalysts are to be improved with respect to electrochemical activity. Moreover, alternative catalysts will be investigated. Power density and efficiency need to be improved to achieve medium- to long-term technical targets. Alternative stack designs for even more compact systems will be needed to meet the high requirements of size reduction for specific applications.

In view of reducing the number of active components, such as pumps and blowers, in fuel cell systems water and gas management are crucial for small portables. This can be achieved, for example by improving the functionality of the gas distribution layer and bipolar plate materials, as well as by optimising the system layout.

2.5.3.3.1.2 Hydrogen- and reformate-fuelled PEFC

The development of membrane materials and MEA concepts for portable applications primarily aims at improving gravimetric and volumetric power densities. Moreover, PEFCs run on reformate need a high CO tolerance. As for membrane development for automotive applications, membranes that allow dry operation are relevant to portable applications in order to reduce system complexity and cost. Dry operation in this sense may be defined as free of liquid water and not necessarily free of water vapour. Both CO tolerance and dry operation can be achieved with high temperature membranes.

The fact that the required lifetime is shorter for portables compared to other applications may be exploited for cost reduction of membrane materials specific to portable applications. High temperature membranes would be of great advantage in simplifying systems.

Catalysts and materials for gas distribution layers have to be improved and adjusted to dry and eventually to high-temperature operating conditions. Again, better catalyst performance is necessary to reduce total platinum use. Especially for PEFCs that run on hydrogen-rich gases from reformers the focus has to be on catalysts with high CO tolerance.

2.5.3.3.1.3 General aspects for all fuel-cell stack components

New solutions for bipolar plates, seals, end plates and cooling installations have to be developed considering gastightness, chemical and physical stability, cost targets, and manufacturability. Performance characteristics such as degradation and lifetime of any stack component need to be developed in accordance with application requirements.

Interdependent aspects of component mass production, cost and recycling need to be considered during the entire development processes. The expected production volumes are to be considered. New production methods and recycling concepts will have to be developed. The same is true of the manufacturing of membrane-electrode assemblies and stack assembly.

2.5.3.3.2 Fuel storage units

A portable power generation system also contains all means of fuel storage, fuel supply to the fuel cell and the fuel-gas processing. As a cross-cutting issue, the research requirements for hydrogen storage and distribution are defined in Chapter 2.2.3.3.

2.5.3.3.3 Control and management systems

Inexpensive control and management systems including simple and compact sensors are needed for portable power supplies. Important factors to control are:

- Water management
- Operating temperature
- Mass flow
- Voltage homogeneity

2.5.3.3.4 Fittings

Standardisation of physical interfaces for portable systems as well as fittings in portable systems is required in order to achieve cost effectiveness. As the unit numbers of individual manufacturers will be low during market introduction standardisation efforts are essential for increasing the total unit volume of jointly used components. Development of highly reliable connectors is important.

2.5.3.3.5 Power conditioning and power management

Rapid load changes of electronic devices present a stiff challenge for the load-following capability of the power supply. Also cold start must be possible under diverse ambient conditions. Hybrid system configurations with small batteries or supercapacitors will be needed in order to improve dynamic response characteristics. Also cost-effective and fuel-cell-specific power electronics are needed. Currently power electronics contribute significantly to overall system cost. Further research in the direction of cost reduction and system simplification is required and will contribute to systems reliability and durability.

2.5.3.4 Basic research needs

Despite the progress achieved, basic research needs remain that have to be addressed for an efficient development of portable fuel cell systems. The basic research and verification needs can be differentiated into R&D needs of general importance for fuel cell technology and R&D areas of specific importance for portable applications:

R&D needs of general importance for fuel cells:

- Novel electrocatalysts with high activity and lower cost
- Novel inexpensive membranes with superior conductivity, durability and reduced humidification requirements
- MEAs enabling a more cost-effective reformate gas purification e.g. by increasing the CO tolerance through higher operation temperature
- MEAs enabling a more cost-effective, simple heat management, e.g. through higher operation temperature
- Understanding of degradation mechanisms and investigation of operation failures
- Inexpensive interconnects
- Novel hydrogen storage technologies, e.g. catalysed alanates

R&D needs of specific importance to portable systems:

- Miniaturisation of fuel-cell systems and components
- High specific power at ambient conditions
- Cathode catalysts with lower methanol sensitivity for DMFC
- Improved liquid/gas handling and separation for DMFC
- Functional integration of system components
- System simplification
- Improved fuel/water containment and management
- Thermal management
- Miniaturised sensors and controls
- New membranes with reduced permeation
- Low-power and efficient miniature electronics
- Compact reformers for hydrocarbons
- Simple gas purification for reformate gases

2.5.3.5 Cross-cutting issues within SRA

Fuel cells for portable applications have the advantage that the systems have a high allowable cost per kW and shorter lifetimes are required. This makes them very suitable for a rapid market introduction, which might facilitate market introduction for other applications.

General cross-cutting issues are:

- Catalysts with low precious-metal content, high reactivity and reduced ageing
- New low-cost membranes and membrane-electrode assemblies should be developed which will allow reliable operation with simple reformate gas purification and water and thermal management.
- Furthermore, a wide range of other socio-economic issues should be addressed such as regulatory and legislative instruments, public awareness, safety, market development, etc.
- High-temperature polymer membranes need to be developed

Cross-cutting issues for DMFC

- Special methanol oxidation catalysts and catalysts for oxygen reduction which are not methanol-sensitive.
- The high catalyst cost of 800 EUR/kW, assuming 2 mg Pt/cm^2 and 0.05 W/cm^2, needs to be considerably reduced
- Reduction of methanol and water cross-over

Cross-cutting issues for reformate-fuelled PEFC

- Fuel storage with hydrogen and methanol cartridges and with new chemical hydrides with a high hydrogen storage density. Clear synergy with hydrogen storage in transport sector.
- Reformers suitable for the production of hydrogen from a wide variety of fuels such as propane, butane and methanol. Synergy with transport and stationary applications.

2.5.3.6 Demonstration and interaction with Deployment Strategy

Implementing a deployment strategy which would integrate stationary/portable power and transport systems will be crucial to successfully move fuel cell technology from the prototype stage through demonstration to commercialisation. Pathways for increasing infrastructure availability and production volume will be identified. Also education and training as well as strategies for improving public awareness should be integrated into this effort.

This approach should create early market opportunities and reduce early product costs. In this way, technical and market barriers can be overcome. Visibility of this new technology to the public is of utmost importance to reach a high level of acceptance of the new technology and to convey the benefits. Possibly a fuel cell bicycle fleet within the European Commission, national or federal governments, mail companies and others could offer an opportunity here. Such a “portable lighthouse project” is likely to have great public outreach and to create sufficient critical mass to establish a general standard for further expansion and is strongly recommended.

Exploring potential niche markets for fuel-cell systems will be of utmost importance. One option for portable fuel cell systems with elevated power can be seen in auxiliary power units delivering electric power to sailing boats, caravans or telecom stations. Also back-up power generators open up a considerable first market for PEFCs. Once established, it will have considerable impact on fuel-cell development for related applications. Both types of applications can be characterized by lifetime and cost requirements that are easier to meet compared to transport and stationary applications.

2.5.3.7 Appraisal of strategic benefit for Europe

In particular the portable application shows that fuel-cell systems have the potential to specifically contribute to customer benefit while making the transitional step from conventional energy sources to hydrogen and also to liquid fuels. In this way fuel cell systems can open up a way to integrated "open energy systems" that address major energy and environment challenges while having the flexibility to adapt to the diverse and intermittent renewable energy sources in the near future.

Fuel-cell-based power generators that replace batteries as a power source for electronic devices allow longer operational times and improved performance. Consequently, a higher cost level might be possible. Thus, fuel-cell systems for portable devices are seen by many experts as the first commercial application of fuel cells. Such systems can be used in a wide spectrum of consumer products, ranging from very small fuel cells in medical applications, through electronic devices like cellular phones, chargers and notebooks to larger units like auxiliary power units and back-up power generators.

A considerable share of pioneering research and product engineering has been carried out in Europe, where excellent technical expertise and experience in both R&D institutions and industry are available. Successful development of portable fuel cell systems can therefore provide Europe with highly efficient power generation units for converting a variety of fuels into electricity. By supporting cross-disciplinary strategic and industrial R&D in portable applications, Europe can build up a new strong industry with business opportunities for small and medium-sized enterprises. Also, fields of technological research will be addressed that are relevant to a wide spectrum of technical developments.

North America and Japan consider fuel cells to be core technology of the 21st century important for industry, economic prosperity and quality of life. It is therefore crucial for Europe to keep its leadership in developing and manufacturing fuel cell systems for portable applications. This would ensure the creation of high-quality business and employment opportunities ranging from strategic R&D to industry.

2.5.3.8 Research recommendations and strategic outlook

Though recognising the considerable progress that has been made in fuel-cell technology, substantial technological and economic barriers still have to be overcome for large-scale market introduction. The long-term funding of research and verification is one of the building blocks on which a successful commercialisation can be achieved. Breakthrough innovations as well as a cost level that is comparable to competing technology routes will be crucial. Public funding that addresses a broad spectrum of research areas is necessary on different levels of generic and applied research:

- Basic funding is required to enable breakthrough innovations e.g. in the area of catalysts, membranes, hydrogen storage materials
- Demonstration and lighthouse projects are necessary to obtain results under practical conditions to (i) improve systems design, (ii) identify further basic research needs and (iii) illustrate the benefits of the new technology to the public.
- Subsequent to the demonstration phase, continuing R&D funding will be highly beneficial for sustaining the pace of technological development.

It is recommended that fuel cell technology for portable power supplies should receive backing on all of these levels to ensure early market success. Numerous verification and demonstration efforts of portable systems will be needed to enable competition between different innovative design concepts and system configurations. A benchmark procedure needs to be established in order to clearly expose benefits and shortcomings of concepts that are under development.

Table 2.5-2: Research budget priorities for portable applications

	Year 1 – 5	Year 6 – 10
PEFC, DMFC stack Membranes New catalysts Membrane-electrode assemblies	30 %	30 %
Simplified water management in low-temperature systems	4 %	6 %
PEFC system components Sensors, pumps Fuel storage systems	13 %	9 %
Microreformers	13 %	11 %
System integration and miniaturisation Verification	16 %	12 % 8 %
Verification programme	8 %	8 %
Basic research and cross-cutting issues	16 %	16 %

Literature:

A. Heinzel, Ch. Hebling, "Portable PEM Systems", "Handbook of Fuel Cells – Fundamentals, Technology and Applications", (Eds. Vielstich, Gasteiger, Lamm), John Wiley & Sons Ltd, Chichester, 2003.

D. Geppert, Gun-Tag Kim, "Brennstoffzellensysteme für Laptop-Computer und andere elektronische Geräte", Proceedings f-cell 2002.

"Fuel cells for portable power" Workshop Proceedings, Phoenix, Arizona, January 2002, p. 10

2.6 Socio-economic issues

To manage the transition towards a hydrogen-oriented energy system it is central to take into account the social and economic factors that surround the new technologies. Apart from an intrinsic motivation to achieve scientific excellence for technical R&D described in the sections above it is necessary to deliver innovative solutions and end-use products that contribute to a successful market introduction of hydrogen and fuel cell applications. Market success, however, depends strongly on the surrounding policy framework, e.g. in terms of policy targets and resulting legislation, regulation, institutional settings etc. The policy framework in turn forms an important part of the overarching socio-economic system of society that influences the science system as well as the economy by factors such as societal demand, socio-cultural preferences, norms and values (Figure 2.6-1).

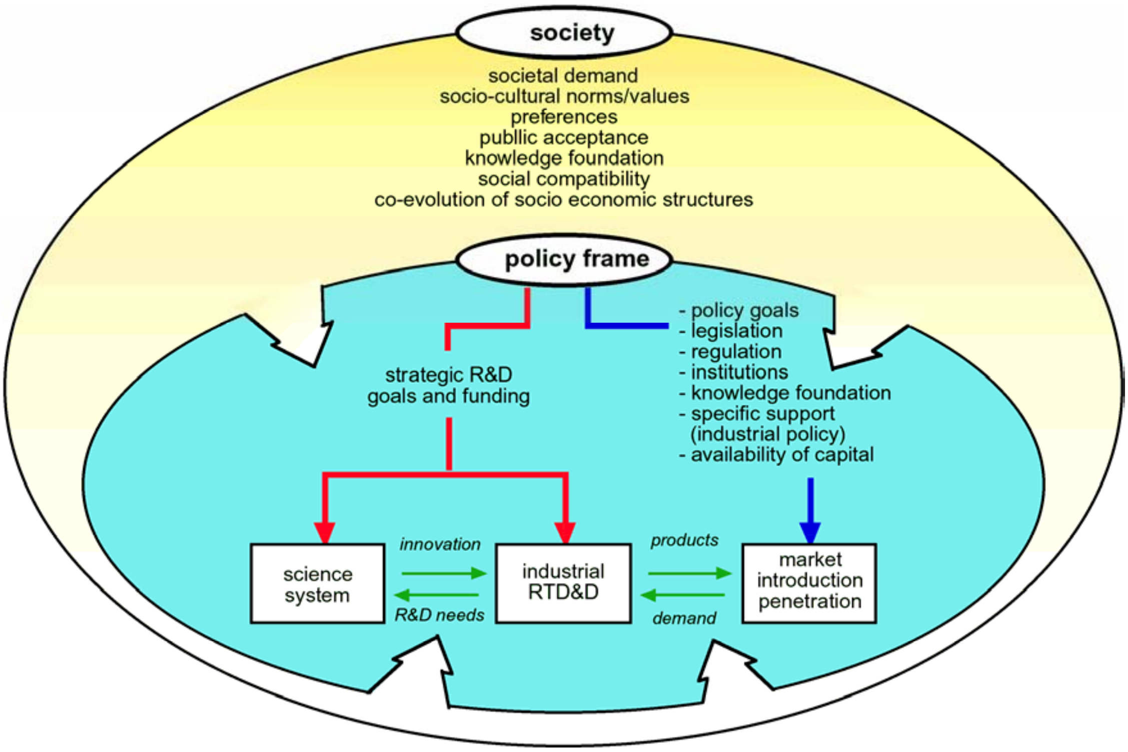

Figure 2.6-1: Impact of socio-economic parameters on RTD and market development

Keeping these fundamental interdependences in mind, this division of the Strategic Research Agenda will consider the key questions arising from the field of socio-economic research as it relates to the set-up of a hydrogen society in Europe. It includes the full range of social, economic, environmental and political questions that result from the integration of hydrogen and fuel-cell technologies into the energy system. In this context socio-economic research

- Provides the analytical framework for assessing the future role of hydrogen in a sustainable European energy system, especially with regard to compatibility with the long-term energy, climate and environmental policy goals
- Investigates the technical, economic and social aspects of infrastructure set-up and transformation in order to avoid lock-in situations at sub-optimal intermediate stages
- Specifies the preconditions for an economically feasible, environmentally sustainable and socially acceptable path towards a hydrogen system

- Derives strategic orientation for the management of research and demonstration activities in science and industry by specifying benchmarks and future requirements for market success
- Analyses the impact mechanisms that foster or hinder the market penetration of hydrogen and fuel cell applications and, thereby, offers the means to alleviate these obstacles in good time through targeted market transformation activities
- Specifies the role of the policy framework for a successful introduction of hydrogen as a new energy vector and identifies areas of action, including the need for a co-evolution of socio-economic institutions and subsystems such as education, professional training etc.

Considering the ambitious scope of the European Hydrogen and Fuel Cell Technology Platform to launch a successful transition towards a future full-scale hydrogen system in Europe, socio-economic research is an indispensable complement to technical RTD. EU-wide research projects already underway include[52]; HySociety (non-technical barriers), EIHP (codes and standards), and AcceptH2 (public acceptance of hydrogen buses) .The recent publication of the HyNet results, preface to the first European Hydrogen Roadmap (HyWays) constitutes the first step towards an *integrated* socio-economic analysis of the challenges facing the transition to hydrogen.

2.6.1 Long-term outlook for socio-economic issues up to 2050

In the long term, it is the role of socio-economic research to pave the way for further dissemination of hydrogen technologies and the related consolidation of mass markets, including targeted market research. In this context, the central expectations comprise a streamlining of regulations as well as the exploration of synergies with other policy areas and markets. Moreover, a strong focus should be put on policy evaluation for market development and the assessment of social, economic and environmental impacts of hydrogen, e.g. in terms of employment effects. Lastly, public attitudes and education are pivotal topics to be addressed in order to achieve a spread of hydrogen applications to the broader public.

The successful introduction of hydrogen solutions in the EU offers new opportunities for strategic benefits in terms of sustainable development both inside and outside the EU. Regarding global effects, there is a clear chance for technology transfer to global markets, especially in less developed countries. Socio-economic research hence also faces new challenges in terms of policy analysis, capacity building, adaptation of technologies, etc.

2.6.2 Medium-term outlook for socio-economic issues up to 2030

The *medium-term* outlook is characterized by two core tasks of socio-economic research. First, strategic orientation is needed to guide technology R&D towards the most promising pathways and to avoid a lock-in of undesirable intermediate solutions. This requires holistic and dynamic energy systems analyses in order to derive benchmarks and evaluation criteria for research management and technology assessment. Second, suitable niche markets have to be identified that allow an early demonstration and commercialisation of hydrogen and fuel cell applications. Here, socio-economic research delivers important insights on innovation penetration and diffusion, both with regard to markets and policies. Short-term policy will be reviewed and refined to cater for development-induced changes. The results of learning-by-doing will lead to greater and more efficient infrastructure build-up, market development

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[52] For more information: www.hysociety.net; www.eihp.org; www.accepth2.com; www.hyways.de; www.hynet.info.

policies and enhanced public awareness and public acceptance. Drawing on the HyNet project, critical actions and milestones up to 2020 are depicted in Fig. 2, mapping the timing for the start of these and other medium-term research and policy efforts. Quite obviously, socio-economic research is closely linked to deployment strategies.

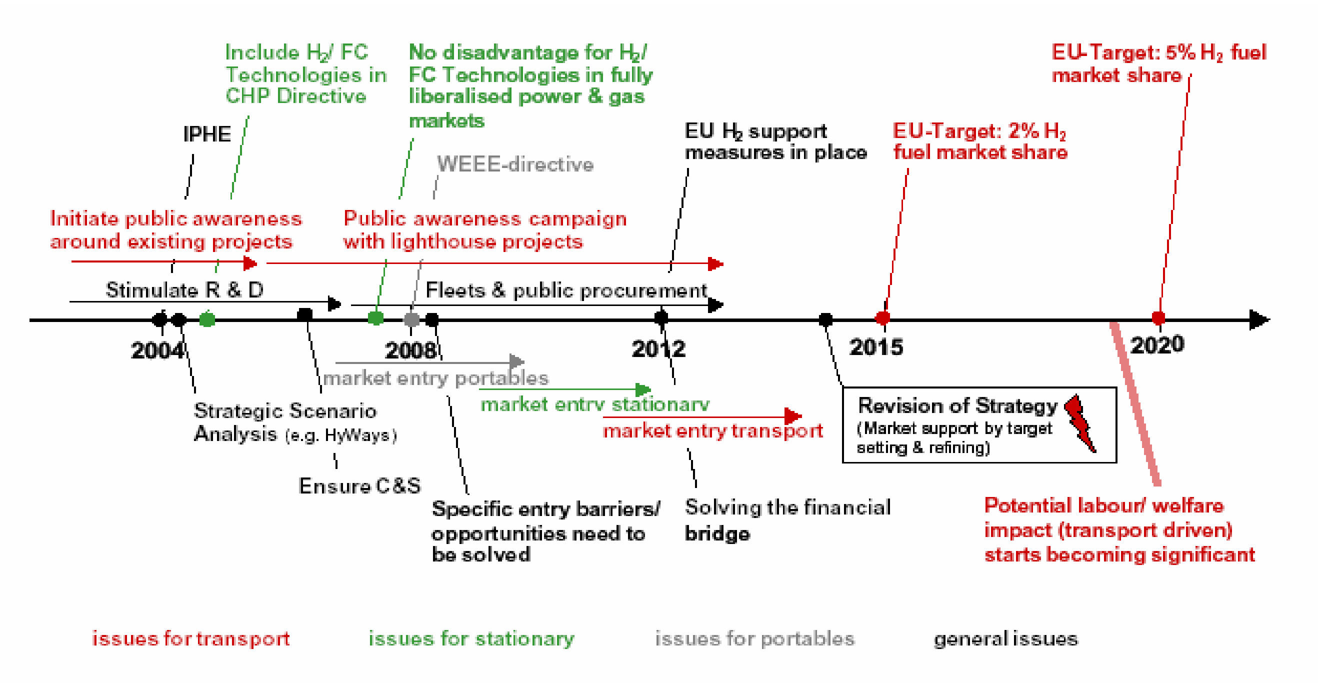

Figure 2.6-2: Critical policy and socio-economic issues identified by HyNet [53]

2.6.3 Research strategy for socio-economic issues for 2005-2015

Socio-economic research will address three interlinked key questions emerging from the transformation of a European Hydrogen System. In these core areas, socio-economic research focuses on the development and/or refinement of research tools as well as on the provision of input data for strategic decision-making in science, industry and policy:

5. **Strategic assessment of technologies and pathways:** What are robust hydrogen technology options and long-term development trajectories towards a sustainable hydrogen economy?
6. **Market development:** What parameters and mechanisms determine the penetration and broad diffusion of hydrogen and fuel cell applications in economy and society – what are the possibilities and limitations for enhancing the market transformation and co-evolution of the socio-economic context?
7. **Socio-economic impact assessment:** What are the effects of a transition to a hydrogen economy with regard to the EU's social targets, employment and economic growth and competitiveness, esp. concerning the Lisbon Process – how can possible benefits be strengthened e.g. in terms of export performance of technology transfer?

[53] HyNet Executive Report; http://www.hynet.info/publications/docs/HYNET-roadmap_Executive_Report_MAY2004.pdf

2.6.3.1 Strategic assessment of technologies and pathways

Socio-economic research generates information on hydrogen technologies that is necessary to design, implement and evaluate RTD strategies. This aspect includes a basic knowledge of the techno-economic performance of technologies as well their environmental impacts as a mandatory precondition to make sustainable policy and business choices. Moreover, the information on specific technology paths must be put into the overall context of the energy system. Hydrogen strategies will be successful only if they are compatible with prospects and restrictions resulting from other necessary energy system structures, e.g. in terms of availability of clean primary energy sources for hydrogen production or in terms of infrastructure requirements. For this reason, the further use and development of tools for qualitative and quantitative strategic energy systems analyses is a vital part of the short- and medium-term research agenda as it reveals probabilities and restrictions for growth and the related timescales for action.

2.6.3.1.1 Technology and process chain assessment

Complementary to the technical research areas, the socio-economic research field should provide an integrated assessment of the potential impacts of hydrogen and fuel cell technologies, esp. with regard to environmental effects. Focusing on the single technology, Life Cycle Assessment (LCA) will play a prominent role by delivering the comprehensive analysis of the environmental impact caused by a product during its life cycle, comprising its production, use and disposal (including recycling).The life cycle of hydrogen involves the analysis of material flows, energy flows and emissions resulting from hydrogen production, transport and storage within the supply infrastructure, up to the end-use application appliance, e.g. as well-to-wheel analyses. In this respect, end-of-life issues (disposal of all equipment, toxic residues, recycling) are an area that is currently neglected. Furthermore, LCA has to cope with a number of difficulties such as the data being uncertain, inconsistent or unavailable (some of the technologies considered are still under development). The adoption of the LCA approach to research lines can also be extended to the analysis of the historical evolution of the data itself (meta-analysis), which can indicate areas with potential for further research.

Technology and process chain assessment applied to energetic vectors helps our understanding of energy systems and provides some orientation in the search for more sustainable and/or optimised solutions as it can provide input for a feasible means of comparing different options. This is a precondition for the strategic energy systems analyses described below. They may also be used to convey environmental information about hydrogen and fuel cells to the public.

2.6.3.1.2 Analysis of techno-economic boundary conditions and prospects

Closely related to energy system analysis (cf. Chapter 2.6.3.1.3), this area also entails the assessment of the techno-economic conditions and desirability of the transition towards a hydrogen society. Any future political and economical success of hydrogen technologies will depend on the fact that hydrogen technologies are directed to the most economically and environmentally efficient applications. On the contrary, barriers with regard to social and political acceptance will be erected if hydrogen and fuel cells are enforced at high costs although alternative, potentially superior solutions are available at equal or lower cost.

In this context, the focus of research should be on the definition, analysis and review of boundary conditions to specify the added value of the transition to hydrogen. The prospects will depend on a few important conditions that can either be intrinsic or extrinsic to the properties of hydrogen and fuel-cell systems.

Intrinsic characteristics are those which a system has by its very nature, regardless of its situation or circumstances, e.g. the physical properties of hydrogen. Some of the intrinsic conditions are the rate of learning, cost reductions, the dates of commercial viability of different technological options and their impacts. Analyses built on tools such as experience curves, LCA etc. should provide insight concerning performance benchmarks while taking dynamic interdependences with competing technologies and a changing context of the energy system into account (cf. Chapter 2.6.3.1.3).

Extrinsic characteristics are those which a system has solely in relationship to others, e.g. oil prices will influence the development of hydrogen markets These conditions relate to the necessity of proving that the future hydrogen society actually solves the problems that we are facing (current and post-Kyoto greenhouse gas reduction targets, reduction of other pollutants, and, importantly, security of supply issues). They will arise from, for instance, investigating the development of competing and complementary technologies and policies and analysing the effects of the course of action of other leading economies (e.g. US, Japan and increasingly China).

2.6.3.1.3 Strategic energy systems analyses

For the design, timing and implementation of any hydrogen RTD roadmap and deployment strategy, a sound understanding on the future role of hydrogen in the energy system is absolutely necessary. Only an integrated assessment of the manifold chances, but also of the limitations of hydrogen, in our future energy system will provide the basis for sustainable policy decisions and business strategies. (A pivotal example of this is the planning of required infrastructure). Whereas the environmental and techno-economic analyses depicted above provide fundamental knowledge, these insights need to be put into the dynamic context of energy systems analysis in order to cope both with growth effects as well as with changing interdependences.

For this reason, a key part of short- and medium-term socio-economic research is evaluating the plausible hydrogen transition scenarios on the basis of current technological status, market trends and policies. In the absence of any solid scenario for hydrogen penetration in the EU[54] one focus should be the exploration of the *long-term outlook* for the social, economic and environmental impacts of hydrogen strategies within an EU-wide modelling framework.

Moreover, there are a number of important questions that need to be addressed by specific approaches, e.g. simulation-based or of a more heuristic nature. Topics include:

- The dynamic assessment of availability of primary energy sources (focusing on the interactions over time that reflect the competition of various end-uses for currently limited clean resources such as biomass and other renewables that are still not taken into sufficient account.
- The interlinkages of hydrogen strategies with other core areas of sustainable development, especially enhanced energy efficiency and the resulting possible changes in demand/end-use patterns (e.g. potential of enhancing electricity savings through demand-side management and regulation as a means to reveal RES electricity potentials)
- The infrastructure requirements and an in-depth discussion of niche markets and temporary solutions (technology bridge concepts) with regard to their long-term viability and the potential risk of technology lock-in (2.6.3.2.1).

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[54] The 2003 "*European Energy and Transport Trends to 2030*" report lacks any mention of hydrogen.

- Possibly emerging resource risks due to increased global consumption of precious materials (noble metals etc.) and related issues of recycling, material flow management, eco-efficiency (cf. the EU IPP directive) etc.
- The still unknown climate and atmospheric impacts of large-scale implementation of hydrogen systems
- The systems analysis of carbon management on a large scale in Europe and its viability as a decisive precondition for fossil-based hydrogen production, and the socio-economic context of such a massive carbon disposal scheme (e.g. in terms of infrastructure needs, public acceptance etc.)
- A discussion of future sustainable mobility concepts that go far beyond "clean cars" and assessment of resulting requirements for transport technologies as benchmarks for technical RTD

These aspects are of direct importance for the timing of hydrogen solutions (what technologies make sense and can be realised in the energy system, at what quantitative level and at what point in time?). Moreover, energy systems analysis provides the essential information for political strategy building and justification of RTD strategies and expenses.

Finally, it provides the ground for policy analyses addressing future areas of synergies as well as potential conflicts with other EU policy areas (energy, climate, transport, environment, regional development, agriculture, etc.).

2.6.3.2 Market development

Linking the spheres of technical RTD and deployment, the area of socio-economic research on market development provides tools and concepts to facilitate the market introduction of hydrogen and fuel-cell applications. The research aims at providing the methodologies and basic knowledge needed for designing effective and efficient market introduction policies, covering, for example, the whole range of parameters triggering public acceptance, the crucial area of codes and standards as well as public technology procurement schemes, innovative financing mechanisms and others. Following the experiences of lighthouse projects, these policies will be designed in the short-medium term (up to 2030) with the goal of effectively managing those future markets. The investigation of areas for synergy between hydrogen promotion and other initiatives is essential. In this context, socio-economic research should not only contribute to the toolbox but provide instruments for the monitoring of transition processes and evaluation of market transformation policies as well.

Starting from a fundamental analysis of market actors and diffusion mechanisms we can distinguish five overlapping lines of research in market development:

1. *Basic R&D policy*: research for best practice in supporting the early stages of development. This includes the need for training and education efforts to build the necessary human resources to lead research.
2. *Strategic niche management*: research focused on learning-by-doing leading to cost reduction so the technology can break from its niche, with specific measures for the demonstration, early-market, mid- and late-market phases.
3. *Wider market management* through economic or legislative instruments: outcome-based targets, obligations or financial incentives. Due to the complex nature of the hydrogen energy chain, for the purposes of designing these ‘umbrella’ measures the hydrogen and fuel cell market must be understood as a composite system of markets.
4. *Developing codes, standards and regulatory tools*: as an indirect incentive to investment by lowering risk. Related to these is the development of technical skills in the hydrogen supply chain.

5. *Breaking down socio-cultural barriers*: dissemination, public acceptance and public participation in the transition. Note that this field is conventionally seen as separate from market development.

2.6.3.2.1 Analysis of market actors and socio-economic systems

In order to make sound decisions on specific technology paths, the full range of opinions needs to be taken into account.

Whilst investigating such a range of options, specific strategic tools are to be developed and applied in order to substantiate and distinguish between the various interests, such as economic and political interests, underpinning preferences for specific technological paths. By doing so effective communication can be vested and rational decisions then lead to shorter learning curves.

From a policy point of view, as well as from an industry and market point of view, lock-in situations are to be prevented since these and their the obstructing effects decelerate the process of the transition. Specifically, in situations where policies are based upon consultancy results provided by major players in the market and strong political movements such lock-in situations existing in the market or in politics may easily be transferred to the hydrogen policy makers. Building on the insights from the energy systems analysis, socio-economic research should provide methods that identify in advance lock-in situations which have been prevented or eliminated. The attainment of the necessary level of political and economic transparency should be pivotal in developing and applying such strategic tools. In particular, it is vital to understand public opinion and society's concern for issues such as the environment, emissions, noise and recycling. Such concerns may not be as great as policy makers or single issue campaigners believe so there is a need for scientific support to identify future societal demand in order to prevent overreaction by moving too far ahead of public opinion.

In addition, socio-economic research should transfer approaches from innovation and diffusion research to the topic of hydrogen in order to gain knowledge about important issues such as the role of (regional or topical) networks, the co-evolution of institutions e.g. with regard to education etc.

2.6.3.2.2 Basic R&D policy:

To date, research efforts have focused on basic R&D and strategic niche management. For the former, R&D has received strong backing from private and public funding, but a coherent R&D strategy is still under preparation for the EU. Future research into the R&D needs of hydrogen must elucidate the best system for efficient use of resources, e.g. by avoiding duplication and by allowing a steady stream of trained scientists and technicians to develop the area. A proposed ERA–NET (European Research Area Network) on Hydrogen and Fuel Cell research could become the channel for these efforts. In this context, socio-economic research should deepen the understanding of the appropriate design and effective implementation of research and technology policies.

2.6.3.2.3 Strategic niche management

The research strategy regarding niche management is one of the most important contributions to the deployment strategy and the intended launch of large-scale lighthouse demonstration projects. As already mentioned in the technical sections, niche markets allow a market introduction of hydrogen and fuel-cell applications at favourable but still commercially viable conditions. This offers the opportunity to demonstrate and to refine technologies while at the same time generating first revenues. Socio-economic research has

to investigate the appropriate conditions and the necessary incentives for taking demonstration efforts to the next phase of early-market penetration, thereby providing guidelines for the conceptual design of deployment strategies. Socio-economic research should facilitate the gradual expansion of "limited niches", e.g. sailing boats or light traction, where hydrogen and fuel cells bring added value, even if costs are higher than the reference technology.

In this context, another topic of crucial importance relates to the role of capital markets in financing the hydrogen and fuel cell businesses especially during the critical stages of market introduction and establishment after the innovation has left the sphere of the laboratory. Although various modes of financing exist, there is further need for research on and demonstration of innovative and flexible schemes of private and public funding. Closely related to this, novel service and finance concepts foster the diffusion of innovations in early market segments, e.g. with the help of leasing models. Socio-economic research should provide background knowledge and evaluation methods to refine these approaches.

2.6.3.2.4 Wider market management

There is no experience with wider market management policies targeted directly at hydrogen and fuel cells, but the experience gathered in similar complex markets such as the renewable electricity generation or emissions trading systems can provide a basis for this section of policy research. Given a sufficient availability of technically mature products, at this stage the policy framework gains importance. Incentives should be designed to be legally or economically enforceable. Financial incentives include capital subsidies, tax credits or hypothecated revenues. Their suitability for encouraging the different actors and sections of the hydrogen chain is to be studied. Lastly, an appropriate mix of legal, informational, behaviour-orientated and economic instruments will need to be found for markets among the EU members states, as the needs and opportunities may vary widely across regions and applications.

2.6.3.2.5 Developing codes, standards and regulatory instruments

Codes and standards is an emerging area of research where the EU is lagging behind the US. The present research strategy will emphasise the need for coordinated efforts across the energy chain in this respect. One particular aspect of codes and standards is the development of the appropriate market regulation (related to "Wider market management" above). Due to the international character of the topic, research work needs to be embedded in already running initiatives such as the IPHE as well as in the context of EU legislation, e.g. in terms of energy market regulation.

2.6.3.2.6 Breaking down sociocultural barriers

Public opinion and consumer preferences based on sociocultural norms and values are major factors influencing market development. The underlying mechanisms of opinion-forming and decision-making and the approach of user groups and customers with respect to new technologies are areas considered to need more research. First, it is important to identify practical issues, i.e. what is the awareness, perceptions and pros and cons regarding the convenience, costs, safety, performance, and environmental aspects of a technology, compared to the conventional one, and consumer expectations *vs.* industry perspectives. EU research has been limited to the AcceptH2 project. There is a need for monitoring the attitudes towards hydrogen and the introduction of educational programmes.

Second, methods and instruments for information, dissemination and awareness-building need to be established, e.g. in the context of dedicated public-private social marketing campaigns. This includes the evaluation of the social impacts with respect to potential

problems associated with the perceived poor safety image of hydrogen and the level of knowledge of the different market actors (policy makers, industry, educational entities and general public) on the subject.

As another supportive aspect, there is room for investigating the role of public participation techniques in order to involve the public in the transition process. The existing legislation for public consultation in Environmental Impact Analysis (the EIA directive) is a starting point for developing the mechanisms necessary to involve users in the decisions that will affect their energy systems.

2.6.3.3 Socio-economic impact assessment

Considering the vital importance of the energy system for Europe's economies, there is a need for the appraisal of the socio-economic impacts of the transition to a hydrogen economy. Although the full impacts will only be visible in the medium-to-long term, related analyses should be prepared and started early enough by elaborating suitable methodological tools and concepts. In addition, an on-going appraisal of RTD policies is necessary in order to monitor the performance of EU activities with regard to other international competitors such as the USA or Japan. The change to hydrogen as an energy vector will involve a major transition that is likely to have very significant socio-economic impacts. The need to understand the nature and magnitude of these impacts relates to the anticipated changes in, for example, the transport sector, urban settlements and the centralised *vs.* decentralised generation of power. We can distinguish two dimensions in which impacts can be evaluated:

2.6.3.3.1 Appraisal of strategic socio-economic benefits within Europe

This constitutes the evaluation and monitoring of the transformation of energy chains with regard to different socio-economic criteria not covered by the aforementioned research areas such as employment, job creation and job migration, changing industrial structures, international trade, regional development, quality of life, gender issues or qualification-related aspects of a knowledge-based society. Projects such as HyNet, HySociety and HyWays have begun to identify the issues that need to be addressed. These issues include:

2.6.3.3.2 Exploitation of external benefits related to international competitiveness, partnerships and technology transfer

Hydrogen and fuel-cell technologies will gain increasing importance as high-value export goods on a global scale. Besides leading industrial economies such as Europe, the USA and Japan, markets in emerging economies such as China, India and Brazil offer a tremendous strategic potential for trade and technology transfer. From the very beginning, therefore, socio-economic research should investigate opportunities and means to secure strategic partnerships and potential markets. This includes both the assessment of specific market requirements in these regions as benchmarks for technology and product development as well as cooperative approaches for capacity and institution building.

Moreover, with regard to less developed countries, hydrogen and fuel cell technologies may offer certain opportunities for "leap-frogging", i.e. for accelerating the catch-up process by implementing the latest system designs without replicating intermediate development stages. Socio-economic research should explore these possibilities further.

In line with the ongoing consolidation of hydrogen and fuel cell activities, several supra-national initiatives emerge such as the US-lead International Partnership for a Hydrogen Economy (IPHE). Comparable to the climate policy regime, policy science has to make contributions to an effective design, implementation and administration of these institutions

that may gain increasing influence on hydrogen global markets (e.g. in terms of standardisation).

2.6.4 Recommendations and strategic outlook

Socio-economic research

- provides the analytical framework for assessing the future role of hydrogen in a sustainable European energy system, especially with regard to compatibility with the long-term energy, climate and environmental policy goals
- investigates the technical, economic and social aspects of the infrastructure set-up and transformation in order to avoid lock-in situations at sub-optimal intermediate stages
- specifies the preconditions for an economically feasible, environmentally sustainable and socially acceptable path towards a hydrogen system
- derives strategic orientation for the management of research and demonstration activities in science and industry by specifying benchmarks and future requirements for market success
- analyses the impact mechanisms that foster or hinder the market penetration of hydrogen and fuel-cell applications and, thereby, offers means to alleviate these obstacles in good time through targeted market transformation activities
- specifies the role of the policy framework for a successful introduction of hydrogen as a new energy vector and identifies areas of action, including the need for a co-evolution of socio-economic institutions and subsystems such as education, professional training etc.

The specific questions and strategic outlook that arise from the preceding points are detailed below regarding four main overlapping objectives

1. activities for condensing the state of the art, e.g. concerning life-cycle and well-to-wheel analysis, road mapping, energy system modelling, experience curves etc. in Europe; this includes a transfer of experience and methodologies from other policy areas to hydrogen and fuel cells, e.g. examples from IT innovations and diffusion research, renewables;
2. evaluation and monitoring of the transformation of systems analyses with regard to different socio-economic criteria not covered by the aforementioned research areas such as employment, job creation and job migration, changing industrial structures, international trade, regional development and quality of life
3. investigation of opportunities and means to secure strategic partnerships and potential markets; this includes both the assessment of specific market requirements in these regions as benchmarks for technology and product development as well as cooperative approaches for capacity and institution building
4. accompanying socio-economic research as a mandatory element of technical R&D and especially of deployment activities, in this case more specifically designed but still reflecting the overarching structure of the research area.

Many institutions are working in the area of Life Cycle Assessment (LCA) and provide guidance through relevant data and tools like GEMIS, ETH-ESU and others[55]. A meta-analysis of worldwide well-to-wheel data would be beneficial and has been suggested by the International Partnership for the Hydrogen Economy (IPHE). An assessment of the existing

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[55] More examples are: IKARUS by German governmental institutions, GREET model by Argonne National Laboratory, USA, E3 Database by LBST, Germany, related reports by Massachusetts Institute of Technology, USA)

tools including a comparison of the outcomes, a choice of the best models and how they can be integrated is essential. In the case of the E3 Database, the determination of the indices used to express the emissions and impacts associated with the hydrogen energetic system is used to evaluate, in economical and environmental terms, the hydrogen energetic chains and the regional differences. These indices are then used in comparing different options, as in the case of the GREET Model or the recent JRC/CONCAWE/EUCAR well-to-wheel study, where well-to-wheel analyses were carried out in terms of energy demand, emissions and costs. These analyses need to be integrated with Life Cycle Costs studies, which have been conducted e.g. by J. OGDEN (Princeton University USA).

A particular interest is bridging the results from the HyWays Roadmap to the development of specific research activities targeting the 2050 range.

The European HySociety project has identified barriers in the different dimensions and stakeholder groups involved in hydrogen demonstration projects. Moreover, demonstration projects such as CUTE (hydrogen bus demonstration project) have provided an unprecedented opportunity to encourage niche markets in real-life conditions and gather experience in their management.

2.7 Cross-cutting issues

Of the topics described in Chapters 2.1 to 2.6, Chapter 2.6 on socio-economics is cross-cutting by nature and interacts with all the other chapters on issues such as market development, impact assessment and hydrogen pathways for the short, medium and long term. Socio-economics also has a strong link with the deployment activities in the Platform. Chapters 2.1 and 2.2 on hydrogen production and hydrogen storage and distribution are intimately interlinked, in particular by the way a hydrogen infrastructure will gradually be built up. Key issues are here cost, safety, hydrogen purity, public awareness, etc. The three Chapters 2.3 to 2.5 have many common challenges and synergies in the development of fuel cells (PEFC, DMFC, SOFC and MCFC) for different applications. A major issue is the fact that fuel cells for different applications are an important element in bringing about a hydrogen economy. By linking hydrogen technology to a specific application or unproven technology the broad market introduction might fail. There is a danger that the hydrogen economy will not come about; major barriers are cost, lifetime and reliability. Short- and medium-term actions are therefore needed to come to a rapid commercialisation of a hydrogen-related energy technology for the mass market. Niche markets for fuel cells should be identified which have a potential for rapid market introduction (small kW size, high allowable cost per kW and short lifetimes); examples are applications for defence, leisure, UPS, marine applications, portable applications, etc. On the other hand, ways of large-scale, sustainable hydrogen production with concomitantly efficient logistics have to be developed and installed. This could initiate mass production, which may reduce fuel cell cost and ease market introduction for other applications. In parallel, socio-economic studies should explore the possibilities of subsidies for fuel cells, which reflect avoided external costs. As for fuel cell types, the PEFC is closest to the market and R&D aiming at cost reduction and reliability for up to 5.000 h for private cars and up to 40,000 h for buses, lorries and stationary applications should have a high, short- and medium-term, priority for stationary, transport and portable applications. Research should be aimed at cost reduction, understanding degradation mechanisms, high-temperature membranes and MEAs which do not require hydration and have a higher CO tolerance, low Pt loads (0.3 mg/cm2), improvement of other system components, balance of plant, etc.; a key issue is here suitability for mass production. In parallel to longer-term basic research, pragmatic, short-term, strategies should be developed, which minimise degradation such as keeping voltage, temperature and hydration at constant levels and operating the PEFC at part load (e.g. in fuel cell/battery hybrids for transport, limit start-up and shut-down of stationary fuel cells in networks in virtual power plants). For DMFCs, the problem of methanol cross-over needs to be solved and the high catalyst cost per kW needs to be reduced by at least one order of magnitude for DMFCs to become attractive for other than portable applications. As for high-temperature fuel cells, tubular SOFCs and MCFCs have demonstrated long life potential, the current cost of 6000 – 8000 EUR/kW should be reduced to 1000 – 1500 EUR/kW; applications are expected in cogeneration, power production and marine applications. Planar SOFCs for transport (APU) and stationary applications will still require much long-term research to achieve satisfactory reliability and to solve sealing problems. Both for SOFCs and DMFCs, the problem of long cold start-up times (hours) and the limited number of thermal cycles should be addressed. There is a strong synergy for R&D on fuel cells and related electrolysers (e.g. PEFC and SOFC). Lifetime prediction and accelerated lifetime testing, electronics/control, hydrogen storage, reformer technologies for hydrogen production and development of virtual power plants are important cross-cutting issues. An overview of cross-cutting technologies and their relevance for different R&D areas is given in Table 2.7-1.

Table 2.7-1: Cross-cutting technologies

	H_2 Production	H_2 Distr. + Storage	Stationary Applications	Transport Applications	Portable Applications	Problems to be addressed
Reformers, compression, liquefaction	x		x	x	x	Cost, reduction of impurities in reformate gases, efficiency.
H_2 purity	x	x	x	x	x	Hydrogen purification and separation methods.
H_2 safety	x	x	x	x	x	Technological and socio-economic R&D.
CO_2 management	x					Socio-economic studies.
H_2 pathways	x	x	x	x	x	Short-, medium- and long-term options and their technical and nontechnical barriers and incentives; virtual power plants; well/wheel analysis; subsidies.
H_2 environmental impact	x	x				Environmental impact of hydrogen economy (e.g. hydrogen leakage), H_2 sensors.
H_2 storage		x	X	x	x	Cost-effective storage with a high H_2 weight-%, good cycling properties and low energy losses.
Fuel cell, electrolysers, general	x		X	x	x	Lifetime prediction, accelerated lifetime testing, electronics/control.
PEFC/low-temperature electrolysers	x		x	x	x	Cost, reliability (degradation), tolerance for impurities (e.g. CO, S), water management, high-temperature membranes and MEAs, balance of plant.
DMFC			x	x	x	Cost, low power density, high Pt load, membranes (e.g. methanol cross-over), water management.
SOFC/ high-temperature electrolysers	x		x	x APU		Cost, cold start-up time and thermal cycling, power density (tubular), degradation and sealing (planar), balance of plant.
MCFC			x	x ships		Cost, low power density, cold start-up time and thermal cycling, corrosion, balance of plant.
Turbines	x	x	x			Advanced materials for high-temperature operation
Combustion engine						
Socio-economics[1]	x	x	x	x	x	Hydrogen pathways, market development, impact assessment and monitoring.

[1] Socio-economics is by nature cross-cutting for the five other topics and is therefore not included as a separate column.

3 Managerial appraisal – from strategy to implementation

The work of the steering panels Strategic Research Agenda (SRA) and Deployment Strategy (DS) resulted in the formulation of an integrated research and deployment strategy. The *Snapshot 2020* of the DS report, the *Long-term strategic outlook* (2050) and the *Medium-term strategy* (2030) of the SRA report define milestones of the transition towards a hydrogen-oriented energy economy and underline the enabling role of commercialising hydrogen and fuel-cell technologies. However, besides the technological challenges that have been assessed within the reports a variety of factors for success need further consideration in order to provide a more holistic view of this transition and to identify managerial interventions that will become necessary:

- *Market entry*: focuses actions facilitating early market entry and the corresponding infrastructural efforts that will be required
- *Industrial structure*: uses the supply chain analysis to identify the role of small and medium-sized enterprises (SMEs) and original equipment manufacturers (OEMs)
- *Intellectual property rights*: makes recommendations on additional needs in the field of knowledge sharing, patent issues and model contracts for project participants
- *Human resources*: outlines actions that are necessary in order to provide industry and the scientific sector with properly qualified human capital
- *Regulatory matters, legal and insurance issues*: includes answers on the question of how to create a regulatory environment that supports hydrogen and fuel-cell technology
- *Coordination & networking*: gives recommendations to effectively (i) acquire R&D results and (ii) translate these into successful demonstration projects and early market products
- *Societal support*: outlines public and private support instruments and presents timeline-oriented requirements for supporting hydrogen and fuel-cell technology
- *Joint Technology Initiative*: is being presented as the evolutionary instrument of the HFP that manages future activities in the field of hydrogen and fuel-cell technology

In view of the envisaged timeline the goal here is the identification of (i) instruments that will be needed and (ii) stakeholders and actors that will have to be addressed for facilitating commercialisation of hydrogen and fuel-cell technologies and for monitoring progress with regard to milestones and performance goals. Several assessment methods will provide the framework for strategically prioritised activities addressing policy, industry and science as suggested in the *Socio-economics* chapter of the SRA report.

All managerial actions that will be taken require the commitment of all major private and public stakeholders to the transition process. This applies in particular to policy makers for their outreach to (i) public financing, (ii) regulatory adjustment (iii) the education sector and (iv) fiscal incentives. Besides this, the existence of a coherent European energy strategy is essential that balances national or regional policy goals and preferences, on the one hand, and supporting and regulating actions by the EU, on the other hand, which agree with the main drivers for a transitional change – (i) greenhouse gas emissions, (ii) security of energy supply and (iii) the European economy.

3.1 Market entry

The assessment of today's technological and infrastructural limitations, i.e. (i) hydrogen storage, (ii) performance characteristics of complete systems and (iii) hydrogen availability, allows the definition of product specifications for early market products. Aspects where managerial actions can specifically facilitate early market entry are (i) the regulatory market environment, (ii) the supply chain situation and (iii) infrastructural evolution, the latter being a particularly important factor that will be discussed separately. Supporting and managerial actions should be limited to applications with strategic relevance that have to compete in particularly difficult market environments.

3.1.1 Early market entry

Identifying and opening up early markets is a promising strategy in order to bridge the gap between the demonstration phase of the new technologies and their applications in self-sustaining markets. Gaining manufacturing and operational experience creates the basis for cost-effective learning effects and provides input for further technological development. Moreover, demonstrating the new fuel and key applications (cf. report by the Deployment Strategy steering panel) in early markets enhances public awareness and strengthens consumer confidence.

In order to actually accelerate early market entry the shaping of the market environment is essential. Here in particular regulations and standards are seen as a major barrier for market introduction – or even demonstration – and thus need substantial adjustment. From the customer's perspective any incentive that targets reduced cost of ownership is desirable due to the higher cost level of the technology and of the fuel. Tax preferences may be suitable here. On the other hand, regulations may also be used for preferring hydrogen and fuel-cell technology over conventional ones. One example is a zero emissions regulation for inner-city road traffic or for airports and harbours with high pollution levels. Currently such a regulation can only be met by electric vehicles with fuel cells converting pure hydrogen or by battery vehicles.

Fostering the demand side and specifically addressing public procurement, the following examples represent early market products: (i) hydrogen-operated vehicle fleets with fuel cells or internal combustion engines, (ii) demo fuel-cell equipment for educational purposes and (iii) defence applications. Buyers pools that are not limited to public procurement may offer another option for effectively introducing higher unit volumes to the market at lower cost levels. Some platform is required here for coordination. Other networking activities including regional and transregional networks are described within *Coordination and networking* (cf. Chapter 0).

In the area of manufacturing hydrogen and fuel-cell devices and their components actions with respect to the supply chain are crucial. Industrial structure analysis as an assessment tool may provide guidance to companies that have the technological know-how for the manufacture of components or for systems integration. Strategically this issue is important for securing complete supply within the EU (cf. Chapter 0).

3.1.2 Infrastructural management

In the long run, the combined use of hydrogen and electricity will play a major role in the energy market: Hydrogen and electricity are mutually convertible, thus allowing higher flexibility in the energy supply system by stabilising the energy supply provided by central and decentralised units. Both energy carriers can be produced on a fossil, non-fossil and sustainable, regenerative basis. At the same time, liquid fuels, synthetically produced on the basis of natural gas or biomass, will also be of importance. Infrastructures will have to be established or adapted to existing systems (see "NaturalHy").

Apart from the technological progress induced by R&D, the infrastructural tasks of the future have to be solved by a consortium of different energy suppliers (refineries, power stations, chemical plants and gas suppliers) in accordance with the European energy market transformation policy. The tasks are the following: (i) identifying customer requirements, (ii) elaborating systems analyses and assessments (see HyWays, HyCom, Database of IPHE), (iii) creating a transition management and (iv) assessing major incentives for motivating suppliers, end users, industry and politics.

The energy suppliers will have to agree on a common approach (methodology, database, demand and availability, benchmarking) in order to assess near- to long-term hydrogen supply infrastructures: (i) starting with existing facilities, (ii) including hydrogen derived from refineries or chemical plants, (iii) integrating decentralised small units, (iv) building large-scale hydrogen production units, (v) developing the necessary infrastructural units.

The European energy suppliers and fuel-cell industry will have to meet the requirements to make these technologies applicable in long-lasting regional, national and European projects (see HyCo, "Propositions", Chapter 1 and 1.1): (i) combining at least at one site all the different applications and production pathways, (ii) building application clusters and (iii) increasing the number of sites with new hydrogen sources offering the possibility of connecting different European hydrogen clusters via linking corridors.

3.2 Industrial structure

The effects of hydrogen and fuel cells on the industrial structure need to be assessed within the framework of an economic and job impact analysis. By analysing the industrial structure additional input for future coordination and networking actions (cf. Chapter 6) is achieved with the intention of identifying the right industrial stakeholders. With respect to the funding of industrial R&D, the economic policies of the EC emphasise the support of SMEs, where SMEs are defined as independent enterprises employing up to 249 persons and having a maximum annual turnover of EUR 50 million[56]. Hence regarding hydrogen and fuel cells, the role of SMEs, OEMs and raw material and component supplier needs to be briefly described. However, the contents of this chapter are not yet conclusive since a detailed industrial supply chain analysis is an outstanding cross-cutting issue between the two Steering Panels and the IG FBD. Further aspects that need consideration are the potential creation of new industry sectors such as required for a recycling infrastructure build-up for precious material used as catalysts for fuel cell membranes.

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[56] Commission Recommendation of 6 May 2003 concerning the definition of micro-, small and medium-sized enterprises [Official Journal L 124 of 20/05/2003]

3.2.1 Role of SMEs

While SMEs can be play a favourable role in the supply chain for automotive applications they have a high potential to for a substantial role of their own in portable and stationary applications (cf. report of the Deployment Strategy steering panel, Chapter 2.3.1). This should be decisively fostered in order to exploit niche markets at an early stage and help to build up production capabilities that are likely to stay in Europe thus creating job opportunities in the fields of:

- Manufacturing devices for portable and stationary applications (as OEM)
- Materials suppliers (e.g. catalysts)
- Component suppliers (in particular automotive), SMEs are considered to be highly innovative in the field of balance of plant components that are crucial for cost reduction.

In addition, it is recommended to support partnerships among SMEs or between SMEs and OEMs in order to facilitate business opportunities for SMEs and innovation transfers to OEMs that lead to a "win-win" situation for both partners. As a concrete medium-term action, public support for this issue should be provided within large-scale demonstration projects (cf. report of the Deployment Strategy Steering Panel, Chapter 5.6). In this context it needs to be stressed that at present SMEs are only weakly represented within European H_2 and fuel cell strategy projects[57] and hence it is recommended to address the concerns of SMEs in future EU strategies and projects to a greater extent than is currently the case. Major obstacles to smaller companies becoming involved in EU projects need to be removed such as particularly:

- Complex information about EU projects that is hardly to comprehend without full-time staff dedicated to governmental project funding. Easier access to information and support for SMEs newly involved in EU projects should be provided.
- The language barrier has to be addressed, particularly since SMEs operate internationally to a lesser degree than large-scale industry.

3.2.2 Role of OEMs

Transport applications are dominated by large industrial OEMs since mass production and global market presence exceeds the financial and human resources of typical SMEs by far. However, due the fact that on average only 25% of the vertical integration of manufacture is performed by the OEMs[58] there is a complex structure of suppliers and sub-suppliers involved in the manufacturing process. Hence many new business opportunities arise for existing and potential future suppliers in the field of hydrogen and fuel-cell technologies.

Concerning stationary applications the most promising opportunities for fuel cells will arise for micro-CHP systems and industrial systems up to 500 kW (DS Report 2.3.1). Regarding micro-CHP systems in the range between 1 kW_e and 5 kW_e large OEMs and SMEs compete, leading to a variety of different applications and technical solutions. The market for larger fuel cell systems above 200 KW is mainly dominated by a small number of large OEMs (cf. report of the Deployment Strategy steering panel, Chapter 2.3.2).

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[57] Example HyWays: out of 19 industrial partners only 3 partners fulfil the SME-criterion of the EC (source: www.hyways.de)

[58] Vertical range of manufacture for the German manufacturer according to VDA (VDA Jahresbericht 2002)

3.2.3 Role of raw materials and components suppliers

Key raw materials such as catalysts (e.g. Pt) and MEAs (e.g. Nafion) are a crucial success factor for the establishment of a competitive European fuel cell industry. A first rough supply analysis (cf. report of the Deployment Strategy steering panel, Chapter 3.3.3) indicates that especially on the field of MEAs for low-temperature fuel cells Europe is at present in a weak position. Public support is hence recommended for this issue within the framework of FP7 and large-scale demonstration projects.

The field of component suppliers consists of a broad spectrum ranging from mechanical (e.g. valves, compressors) to electrical/ electronic (electric motors, control systems) parts and chemical engineering subsystems (e.g. small-scale reformers). Hence specific actions and recommendations can only be derived after a detailed industry structure and supply chain analysis.

3.3 Intellectual property rights

Intellectual property rights (IPR) are crucial for implementing a new technology and protecting investment in R&D. However, they should not be so open as to encourage broad claims. IPR regulations should therefore be considered in the context of internal – particularly American and Japanese – patent practices. They include the handling of knowledge sharing, patent issues and the development of model contracts for project participants forming a consortium.

3.4 Human resources

The provision of human capital is of great importance for the aim of strengthening the European position in the development of hydrogen and fuel cells in the world market. Initiated by the Initiative Group “Education and Training” essential operational approaches and procedures stimulating the development of human resources at different levels of education and in all areas of the hydrogen and fuel cell technology were proposed. The target groups for updated education and training procedures on different levels involving hydrogen and fuel cells as redefined new energy technology are instructors and teachers from schools, universities, universities of applied sciences, research institutes, trade, industry and government. The trainers should later educate individual trainees. Suitable instruments for bringing about the necessary changes in the education portfolio if adjusted are the Marie Curie and the Leonardo programmes as well as the Thematic Networks of Europe. As a great challenge, Europe-wide qualification guidelines significant for the trade and industry area have to be established.

3.5 Regulatory matters, legal and insurance issues

The initiation of a hydrogen- and fuel-cell-friendly framework is major task for all HFP bodies and operations. In this context, the following issues need to be addressed from a transition management point of view:

- Development of regulations, codes & standards (RCS) with the aim of European harmonisation and international coordination (DS Report 3.3.1).
- Utilising local restrictions with the opportunity of privileging hydrogen and fuel cell applications in selected regions.
- Development of fiscal incentives including excise duty relief, road tax exemptions and income tax advantages for potential investors in hydrogen and fuel cell technologies (cf. report of the Deployment Strategy steering panel, Chapter 3.2.5).
- Applying emissions rules including the transport sector, leisure applications and local restriction for areas with high pollution levels (e.g. harbours, airports) that foster the market penetration of hydrogen and fuel-cell applications such as forklifts, utility vehicles or APUs for aircraft.

Concerning emission rules for road transport, the tool of zero-emission legislation needs to be carefully examined. Neglecting electric vehicles with their limited range, only hydrogen fuel-cell vehicles can fulfil such legislation and hence this option seems to be attractive. On the other hand, the Californian experience shows that over-ambitious targets and a subsequent delay of enforcement involve the danger of weakening the confidence of manufacturers, suppliers and potential customers.

Moving the European framework and RCS development for hydrogen and fuel cells ahead, it is recommended to provide public support under the next framework research programmes and in parallel to draft the necessary legislation as a supporting action for the large-scale demonstration projects.

3.6 Coordination & networking

Coordination and networking activities are required to accelerate the technology as well as market development by an interchange of know how, to measure basic knowledge on the global scale and to achieve approaches for the internationally required standards of hydrogen and fuel-cell technology. A prerequisite leading to cooperative international research is the definition of rules on intellectual property. Emphasis of the coordination and networking activities is placed on the encouragement and facilitation of intra-EU as well as international cooperation taking into consideration regional and national activities in the field of hydrogen and fuel cells, ongoing FP6 project activities e.g. ERA-NET, HyWays and HY-CO and initiatives of the International Partnership for the Hydrogen Economy (IPHE). Research and development for defence applications should be integrated into the coordination and networking activities. In order to develop appropriate technologies, products and services for widespread markets, it is necessary to introduce a strategy for building international cooperation with both developed and developing countries with a view to cooperating and networking on technology bottlenecks, codes and standards as well as technology transfer. For the coordination of a shift towards hydrogen and fuel cells the establishment of a centre for consolidating and disseminating information is of major significance. In addition to this, the designation of a number of strategic European virtual centres of excellence acting as focal points for critical research is recommended. The

coordination and networking of all future RTD activities is essential to increase the work efficiency, to heighten the value of the RTD efforts and to avoid double work.

3.7 Societal support

Societal support is very important for novel technologies at the stage of market entry as companies try to minimize stranded investment in technologies which never might come into effect. Moreover, public support brings technology into the limelight and eventually leads to a discussion which might help prevent stranded investments because of public protests later on.

Public support and particularly governmental support comprises funding, but just as important is security of planning for companies and consumers and legislative endorsement through regulations which provide an advantage to these more benign technologies. Moreover, endorsements and support by initiative groups and NGOs is important. Such broad support also stimulates the stock market for smaller, novel companies and offers those enterprises easier access to a variety of financing instruments.

3.7.1 Private support

In a very early stage when only little money is needed business angels play a role in investment particularly in start-up companies. Later venture capital comes into play when a greater amount of capital is needed. Since venture capitalists take a great risk they require a high payback in a foreseeable timeframe. Thus, venture capital cannot be cheap and often requires additional sources of equity or loan capital. Venture capitalists, though, frequently provide management experience which other stakeholders will not or could not furnish.

Yet, a significant particularity of fuel-cell investment should be mentioned in comparison to the less, or not at all production-oriented, companies. Fuel-cell companies already at the development stage need considerable investments. This may reduce venture capital to the function of providing management experience, but only a relatively small share of the capital needed. A further challenge surfacing at later stages of development and early market entry is the supposedly short timeframe in which venture capital is invested. There is a gap in financing towards market entry for small and medium-sized enterprises that is recommended to be investigated.

One example is the field test stage at which multiples need to be tested to get operational and production experience. Big industry will not become involved in such an undertaking if public support is lacking, nor will or can small and medium-sized enterprises do it without a positive climate for investment and strategic capital availability. Details on financing can be taken from the report of the Initiative Group Financing & Business Development (IG FBD) within the European Hydrogen and Fuel Cell Technology Platform.

3.7.2 Public support

Besides classical governmental funding there are multiple important approaches which should be pursued:

- Regulatory issues that facilitate market entry
- Information about and backing for novel energy technologies via print media, internet and TV or radio
- Nonfinancial incentives for end-users of novel, benign technologies; e.g. usage of bus/taxi lanes for fuel-cell cars in inner city areas.
- Education of stakeholders in risk assessment and prevention.

- Fostering a close cooperation between institutional research and industrial research and vice versa.
- A coordinated European research effort in a virtual institute for fuel cell research is recommended in order to strengthen and over time align the European research. This should be should be part of the Joint Technology initiative and be in line with the – for a fuel cell institute very appropriate – concepts of the EU for virtual institutes as listed below:
  - Strong scientific and technical consortium with a wide range of industrial contacts
  - Strong management structure with a “project champion”
  - Good business plan with a sound legal structure
  - Efficient use of ICT tools which go further than an internet website
  - Personal contacts with potential customers in order to establish the trust necessary for good business relations
  - Such a virtual institute should be pan-European and be based on strong existing research institutions forming the core with significant industrial involvement and aligned university research activities.
  - The virtual institute should help bridge the gap between existing institutional research and commercialisation. In particular it should be a research base for small and medium-sized enterprises during development and the early stages of market entry.

In the realm of funding, there are several measures that are intended to facilitate development and market introduction

- Appropriate fiscal measures and subsidies which are just at the level of providing enough incentive for using or applying the technologies and still leverage considerable private money from the consumers or producers.
- Expedite investment in a long-lasting infrastructure that is still highly versatile, and support planning through short lead times and high dependability on governmental decisions over long periods of time.
- Public R&D contracts for authorities
- Reduction of lead time for publicly funded projects from currently over 1 year to less than three months in order to put companies in a position to take windows of opportunity.
- Enhancing the funding tools to achieve a statistical probability for fully submitted proposals to be granted; e.g. via multistage funding which requires increasing effort in line with an increasing chance of getting the project granted or other appropriate approaches or tools.
- Public procurement of advanced technology at the brink of market entry or in an early market entry stage that is proven to foster a new technology via publicity, return on investment for the producer and the opportunity of technical optimisation during early fleet operation.
- Procurement in the defence area helps early market entry since for defence application often smaller series of products at higher prices are acceptable, which is beneficial for market entry.

Novel funding methods should be sought which increase the efficiency or even sometimes the level of funding beyond 50% and which still conform to the WTO and GATT treaties.

- It is strongly recommended that the funding level for small and medium-sized enterprises should be increased to 75%.

- At the same time, it seems the definition of small and medium-sized enterprises as having a maximum of 200 employees is no longer appropriate in a global world economy. Thus, it is suggested to extend funding according to SME rules to bigger companies which still are to be considered small or medium-sized according to conditions of the world economy, at least for novel technologies.

It is suggested to precisely shape a tool matrix for funding and non-financial support to remove existing impediments for a free flow of idea and inventions through systematic research in universities, research facilities and companies towards development and later a market entry. Particularly, the handover from universities and research facilities to development often fails at the moment, as well as the transfer from development to early production in small series in order to test the waters for mass production.

- Appropriate research grants including development in the defence area are recommended.
- The profile of the European Investment Bank can be enhanced as a financial supporter of hydrogen and fuel cells.
- The availability of venture capital is recommended to be further facilitated.

3.8 Joint Technology Initiative

The scale and ambition of the recommended actions of both the SRA and DS will require the mobilisation of very high public and private investments. Since the existing instruments of European RTD funding do not seem to be sufficient, new dimensions are required. One potential tool for managing these different actions under a single umbrella could be the concept of a "Joint Technology Initiative" (JTI). This JTI can basically be seen as a large-scale public-private partnership.

Regarding the deployment-oriented operations of the JTI, a strong industry lead including the commitment to providing sustained high levels of resources (financial, human, prototypes, …) is desired in order to accelerate the commercialisation of hydrogen and fuel cells. The additional inclusion of all related FP7 activities (no H_2 & fuel cell RTD in the other parts of FP7) and the desired coordination of national programmes will lead to one focused European Programme that could be named a "Super JTI". A reinforced, ring-fenced budget and probably simplified financial regulations as well as more flexible management could be expected as advantages. On the other hand, the very ambitious and complex set-up process of this "Super JTI" must be listed as potential drawback. Additionally, the acceptance of a "Super JTI" by the Council and the European Parliament cannot be taken as given. As an alternative a "hybrid" concept could be foreseen, featuring a JTI, which would still be large compared to today's implementations, to carry out a significant part of the RTD and deployment but giving space for "traditional" collaborative research instruments both on the EC as well as on the member states level.

In order to facilitate the different actions recommend by the SRA and DS, a project structure broken down into goal-oriented JTI Operational Activities (OA) is recommended. At present, a range of few – e.g. up to 10 – distinct but linked research and demonstration themes covering all fields of portable, stationary and mobile applications seems appropriate. Each OA can be implemented by one large "project" operated by a few "core" industry partners based on a competitive call for proposals. Possible themes identified under the frame of the SRA and DS are:

- European fuel-cell systems
- hydrogen production – renewable routes
- hydrogen delivery and storage

- hydrogen safety and testing
- lighthouse project (HyCOM) – transportation focus
- lighthouse project (HyCOM) – stationary focus
- hydrogen production from fossil fuels with CO_2 capture and storage (HyPOGEN)
- cross-cutting issues – socio-economic research, supply chain development and niche market support actions, education and training, dissemination, …

In this context, the inclusion of early and niche markets in selected OAs as a "door opener" for the commercialisation is seen as crucial since the usage of VC requires solid business plans (ref. 7.2.). In addition to private seed and VC financing the establishment of large-scale integrated demonstration projects (cf. report of the Deployment Strategy steering panel, Chapter 5.6) also requires significant public funding as described in 7.1, especially in their early phases.

4 Proposition for a research strategy

Hydrogen is seen as a main energy vector along with electricity and liquid fuels which will be increasingly based on biomass. In 2050 hydrogen is envisaged to exceed a share of more than 50% of fuels for automobiles. For stationary applications the natural gas supply will prevail for a long time to come. However, for fuel cell applications natural gas needs to be reformed, thus hydrogen is produced. Hydrogen energy pathways are very energy-efficient in combination with fuel cells. Fuel cells are energy-efficient electrochemical converters which need hydrogen, or synthesis gas in the case of high-temperature fuel cells, in the actual electrochemical process. Notwithstanding, fuel cells do not depend on a widespread hydrogen infrastructure, as reforming of natural gas and other carbon-based fuels like diesel and methanol might be used. This leaves some degree of freedom for the market introduction phase of fuel cells but a hydrogen infrastructure would certainly prove to be advantageous. Hydrogen, on the other hand, can also be used in combustion technology after some adaptation research rendering again some freedom in the market introduction phase. In conclusion, hydrogen and fuel cells are strongly linked to each other and these two technologies need to be viewed together for effective research and development which must be in line with a deployment strategy. The drivers to move forward with hydrogen and fuel cells are:

- Climate change, i.e. CO_2 reduction
- Energy supply security, i.e. less dependence on oil imports
- Strengthening the EU economy
- Local emissions

The following Strategic Research Agenda considers the issues mentioned above and proposes a strategic approach. Its purpose is to outline realistic, yet inspirational pathways for research and development that will mobilise stakeholders and ensure that European competences are at the forefront of science & technology worldwide. The SRA will provide a strategic outline to stimulate investment in research and provide guidance for policy options. It will take into account the imminent FP7 and subsequent programmes, the needs for coordinating R&D with demonstration, deployment and financing. In particular, it will provide a prioritised 10 years research programme, a well-founded medium-term outlook up to 2020 and a long-term strategic outlook up to 2050. The SRA defines priorities for investment in R&D in the context of Europe's strengths and weaknesses and later industrial exploitation. This research agenda is intentionally selective by highlighting important technological pathways.

Stationary applications will rely on natural gas for a long time. Decentralised reforming of natural gas is an important part of fuel cell technology for decentralised power generation. Whereas PEFC offers solutions for residential use, district and industrial cogeneration is the realm of high-temperature fuel cells because of the higher efficiencies and simpler reforming. The main application will be residential cogeneration and district cogeneration in the range of some 100 kW for the near and medium-term. MW units are investigated and are envisaged in the longer term. Of the various high-temperature fuel cells, the SRA prefers the SOFC to MCFC, which is considered important, nevertheless, for its higher power density, proven electrochemical longevity and synergy with transportation APUs. PEFCs operated at elevated temperature have a great potential for simplification of stationary systems and their cost reduction. It could also prove useful for units larger than those in the residential area.

Portable fuel cell applications will contribute to proliferating fuel cells at an early stage, due to their comparatively high allowable specific cost. They will facilitate the market introduction of other fuel cells. Secondly, they are important for the role they may play in

industrial development. Small and medium-sized enterprises contribute substantially to the development of portable fuel cells.

The six areas of research need different budget allocations in consideration of their importance for creating an energy economy in which hydrogen and fuel cells represent an important energy vector. As this research area is still at an early stage. a lot of basic and cross-cutting research issues are being identified. Cross-cutting issues are an important source of synergy in fuel cell R&D. As they are not specific to one area of application they have a great overlap with basic research. Thus, these two areas are very close to each other and are not separated in terms of budget allocation. In order to provide an innovative approach 16% of the budget for every section is recommended to be spent on cross-cutting issues and basic research.

Table 4-1: Proposed Budget Shares for Hydrogen & Fuel Cell Targeted R&D

Research Area	Budget Share	Key Considerations
Transport applications	27%	Technologically crucial for environmentally friendly transport solutions and the driving force for fuel cell development
Hydrogen production	22%	Essential for the technological development of the entire sector. Increase of CO_2-lean production is targeted. Carbon capture and sequestration are of the essence, but expected to be covered within other European R&D programmes
Stationary applications	20%	Important for CO_2 reduction via highly efficient cogeneration. Provides an opportunity for early markets
Hydrogen storage & distribution	18%	Storage density is crucial for effective storage – particularly for transport and portable applications
Portable applications	10%	Important for early markets. Fit ever increasing market needs to fuel gadgets and small transport applications
Socio-economics	3%	Long-term guidance for technological development
Total Hydrogen & Fuel Cells	100%	

4.1 Hydrogen production

Hydrogen production is considered as being crucial for the development of the whole sector. Based on fossil fuels, namely natural gas, hydrogen production is a mature technology for the chemical industry, from which hydrogen can be provided for an emerging fuel-cell sector. However, for energy use with higher price constraints additional applied research is needed, particularly for catalysts and catalytic reactors. In order to provide hydrogen in the long run in an increasingly CO_2-free manner, the investigation of novel production methods from renewable and nuclear power is important.

Recommended R&D areas

- development of basically known reforming and gasification methods, also with regard to high-temperature primary energy systems such as Generation IV nuclear reactors and solar-thermal concentrating systems.
- gas separation technologies, for hydrogen as well as for carbon dioxide and oxygen
- development of carbon dioxide sequestration systems and pathways with special emphasis on working hydrogen-production from fossil energies
- efficiency improvement of hydrogen liquefaction technologies and system integration with hydrogen production facilities
- improvements in alkaline water electrolysis units including development of compact “on-site” and large “central” electrolysers, sea water electrolysers, high-temperature and high-pressure electrolysers, aiming for higher efficiencies and cost reduction.
- development of alternative types of electrolysers including PEM and SOFC, as well as photo-electrolysers for small-scale applications
- improved integration of electrolysers and stochastic renewable energy technologies, through the development of suitable power electronics, avoiding DC/AC inversion and rectification, aiming for “integrated RES-H_2 production” systems
- development of compact on-site electrolysers
- process control, system and safety monitoring including sensors for the case of small-scale reformers

Recommend basic research areas

- analysis and development of thermolysis processes in compliance with available heat sources
- analysis and development of photo-electrolysis
- investigation of conversion efficiency for photobiological processes to achieve high hydrogen production rates in order to reduce land requirements and costs of such photobioreactor systems
- development of catalysts, adsorption materials and gas separation membranes for the production and purification of hydrogen

Recommend cross-cutting areas

Hydrogen production is closely linked to hydrogen storage and distribution. In particular, the role of centralised and decentralised production can only be properly assessed by an integrated approach of the two groups. Pathways for introduction of hydrogen production and distribution should be addressed within the socio-economic context, which also includes regulatory and legislative instruments, public awareness and safety. Different options such as large-scale gaseous hydrogen production combined with hydrogen pipelines or with different types of liquid hydrogen transport, transport of natural gas and local hydrogen production with reformers, etc. must be assessed for the different stages of the build-up of a hydrogen infrastructure. Specific cross-cutting areas of research and development are:

- development of cost-effective on-site natural gas reformers for both refuelling stations and stationary applications
- applying SOFC technology to high-temperature electrolysis that offers 30 % energy savings compared to low-temperature electrolysis
- applying PEFC technology for low-temperature electrolysis
- hydrogen safety with both technical and socio-economic aspects.

Table 4.1-1: Research budget priorities for hydrogen production

Research issue	Year 1 – 5	Year 6 – 10
Chemical conversion	8 %	8 %
Gas separation technologies	20 %	20 %
Liquefaction processes	14 %	9 %
Electrolysis	22 %	27 %
Development alternative production routes	20 %	20 %
Basic research and cross-cuttings	16 %	16 %

4.2 Hydrogen storage and distribution

Hydrogen storage is of paramount importance for future usage of hydrogen because the energy density is fairly low for existing storage technologies being 10 to 20% of that of gasoline or diesel. This thus limits the range of operation for transport applications particularly of automobiles. As hydrogen storage is very important a lot more research has already been done on qualifying gaseous and liquid hydrogen as principal candidates for transport applications than for other well-known technologies. Beyond further applied research on these candidates, deployment projects will be appropriate. Basic research, on the other hand, is strongly recommended for novel storage principles promising higher energy densities and emerging material classes like alanates. The following list describes the needs in detail.

Recommended R&D areas

- Long-term behaviour of hydrogen confinement for large-scale underground storage of hydrogen.
- Safety studies and supply chain management for metal hydride storage, including investigation of reuse, recycling and disposal.
- Evaluation of experience with existing refuelling stations, e.g. from CUTE project
- Development of core components for refuelling stations as dispensers, nozzles, hydrogen sensors and mass flow-sensors for refuelling stations
- Optimisation of hydrogen management including components and design for efficient, low-cost and compact hydrogen refuelling stations.
- Increase of hydrogen storage density to at least 1.1 kWh/litre and more than 6 % usable H_2 fraction for either gaseous or liquid storage at a reasonable cost of less than EUR 10/kWh (2010: DOE 4, CONCAWE 18) as well as reasonable operation conditions and longevity for automotive application
- Cost reduction for cryogenic hydrogen storage for automotive applications with a boil-off below 1% per day on board as well as for boil-off management on the way from liquefaction to the filling station.
- Improvement of the energy density of hydrogen storage media for automotive on-board storage with metal hydride or chemical hydrogen storage as well as nanostructured materials.
- Development of hydrogen cartridges for portable applications, based on compressed hydrogen or metal hydrides for reuse and perhaps chemical hydrides for disposal as well as the corresponding filling stations.
- Development of hermetically sealed methanol cartridges for portable DMFC applications.

Recommended basic research areas

- Novel materials, investigation of failure mechanisms and novel sensors for compressed hydrogen storage
- Novel materials for liquid hydrogen storage containers and investigation of processes for fail-safe handling of hydrogen boil-off.
- Systematic investigation of fundamental physical properties of hydrogen storage materials with the aim of increasing storage density and improving degradation caused by cycling.
- Investigation of hydrogen storage mechanisms in solid-state materials and identifying new suitable materials.

- Computational modelling and experimental verification of absorption and desorption in hydrogen storage materials to identify degradation mechanisms in hydrogen storage materials
- Novel analytical and characterisation methods for materials used in hydrogen storage

Recommended cross-cutting areas

Cross-cutting issues exist towards hydrogen production as far as different production methods have an impact on distribution; e.g. centralised vs. decentralised production changes the requirements for distribution and affects costs and energy pathway efficiency. These impacts are to be investigated systematically.

- Safety of gaseous and liquid hydrogen
- Hydrogen sensors
- Computational methods
- Cost analyses are to be done as well-to-wheel/application studies; they are cross-cutting over the whole energy pathways.
- Socio-economic factors, such as public acceptance, legislative instruments, and market entry strategies, are recommended not only to be investigated but an active approach on public outreach should be taken. Public acceptance needs to be built through public confidence in the technology based on true and honest information.
- Effects of hydrogen emissions on the atmosphere

For the research efforts described above budget shares are recommended as follows:

Table 4.2-1: Research budget priorities for hydrogen storage and distribution

	Year 1 – 5	Year 6 – 10
Reversible storage systems for transportation	26 %	23 %
Hydrogen management at transfer, filling (cartridges) and fuelling (vehicles) stations	10 %	11 %
Hydrogen storage at production sites	10 %	10 %
Pipeline infrastructures	9 %	11 %
System analyses and network strategy	5 %	5 %
Reversible and non-reversible storage solutions for portable applications	15 %	15 %
Liquid hydrogen infrastructure components, reduction of boil-off	9 %	9 %
Basic research and cross-cuttings	16 %	16 %

Research in hydrogen distribution needs to be done in a targeted way, but not exclusively. Hence, the envisaged research budget share is proposed to be slightly lower than average despite the paramount importance of the field. Engineering studies have to be done in terms of using existing pipeline systems (hydrogen and natural gas), distributing hydrogen derived from refineries and chemical plants to take maximum advantage of existing lowest cost hydrogen sources up to 2015 and planning pipelines in urban areas after 2030.

4.3 Stationary applications

Stationary applications have been rated of average importance. Stationary applications are not dependent on a hydrogen infrastructure in the first place. They can be fed with natural gas for some decades and will nonetheless deliver on the environmental goals. Moreover, high-temperature fuel cells are chiefly required by the stationary sector. This infers a strong focus on high-temperature fuel cells.

Recommended R&D areas

- Industrial production methods and stack design to minimise production costs
- Lower-cost power electronics and sensors
- Tools for in-situ diagnostics and operation control
- More efficient thermal management including reforming and gas treatment
- Standardised as exchangeable fuel-cell stacks and balance of plant (BOP) components, e.g. blowers, valves, sensors and compressors
- Combination of large fuel cell plants with gas turbines or other equipment operating at higher pressure
- Enable large internal combustion engines and gas turbines to operate in more hydrogen-rich fuels
- New approaches in burner design and materials are required to fulfil the demands of failure-free hydrogen combustion
- Peripheral systems and safety features have to be adapted and improved for hydrogen operation

Recommended basic research areas

- Integrated catalyst concepts to meet the demand of an extensive global fuel-cell economy via recycling of stack components
- On-site gas processing requiring desulphurisation of natural and biogas feedstocks, removal of impurities and addition of steam for internal reforming or air for partial oxidation of hydrocarbon fuels such as methane or propane
- Specific stack component development to utilise the specific advantages of the high- and low-temperature technologies
- Modelling of degradation and failure mechanisms for identifying the critical deterioration mechanisms and for reliable lifetime predictions
- Temperature-compatible fuel cleaning, particularly related to biogases from gasification and fermentation
- For thermal technologies such as Stirling engines, internal combustion engines and gas turbines:
  - adaptation of combustion technology to hydrogen-rich fuels
  - higher-temperature, more corrosion-resistant materials
  - reduction of NO_x emissions
  - safety engineering

Recommended cross-cutting areas

- Cross-cutting issues exist with respect to all fuel cell applications attaining commercialisation in spite of small kW size, high allowable cost per kW and short lifetime

- Socio-economic studies should explore the possibilities of subsidies for fuel cells which reflect avoided external costs. Other socio-economic issues should be addressed such as regulatory instruments, public awareness, safety and market development
- PEFC-related research should aimed at cost reduction, degradation mechanisms, high-temperature membranes and MEAs
- Improvement of system components and balance-of-plant considerations with regard to suitability for mass production
- Lifetime prediction and development of accelerated lifetime testing methods, electronics and control for fuel-cell systems and networks
- Reformer technology for hydrogen production
- SOFC and MCFC applications will still require much long-term research to achieve cost reduction, satisfactory reliability and to solve sealing problems. The problem of long cold start-up times and limited number of thermal cycles should be addressed
- Strong synergy between R&D on SOFC and SOFC-based electrolysers

Table 4.3-1: Research budget priorities for stationary applications
HTFC: high-temperature fuel cell
LTFC: low-temperature fuel cell, GT: gas turbine, ICE internal combustion engine

Issue	Year 1 – 5	Year 6 – 10
HTFC stack: materials and design Cells Interconnects Seals Modelling and diagnostics Other stack issues	22 %	20 %
HTFC fuel use	9 %	5 %
HTFC system Design BOP components	11 %	8 %
HTFC demonstration Feasibility studies Verification	4 % -	5 % 8 %
Total high-temperature fuel cells, 37 % SOFC; 10 % MCFC	**46 %**	**46 %**
LTFC stack High-temperature polymer membrane Catalysts Other stack issues (incl. recycling)	13 %	10 %
LTFC system Design BOP components	9 %	8 %
LTFC fuel processing	5 %	5 %
LTFC demonstration Feasibility studies Verification	 1 %	 - 5 %
Total low-temperature fuel cells	**27 %**	**27 %**
Hydrogen turbine systems	**7 %**	**7 %**
Hydrogen combustion engines	**4 %**	**4 %**
Basic research	**16 %**	**16 %**
Total	***100 %***	***100 %***

4.4 Transportation applications

Transportation applications have been the major driver for hydrogen and fuel-cell technology over the past 15 years. As it can substantially deliver on both CO_2 reduction and less dependence on oil it is seen as a principal single technology in the field of hydrogen & fuel cells. The recommendations for further research and development efforts in general comprise cost targets as well as reliable operation, improved efficiency and power density. Also, manufacturability and recycling issues will have to be fulfilled in order to ensure market success of the systems considered. More efficient systems directly reduce variable energy cost and contribute to greenhouse gas emissions reduction. A high power density reduces materials demand and allows for systems of a more compact size, which is desirable in transportation applications in particular.

Recommended R&D areas

- performance improvement of PEFC stacks for vehicle propulsion and auxiliary power supply by
  - reducing humidification requirements
  - increasing contaminant tolerance
  - increasing operating temperature for improved thermal management
  - improving stack design and stack components: membrane electrode assemblies, bipolar plates, seals, cooling installations that are suitable for operation at elevated temperature
- performance improvement of SOFC stacks for auxiliary power supply by
  - improving thermal cycling stability, robustness and reliability
  - improving fuel impurity tolerance
  - reducing operating temperature
  - reducing degradation
- performance improvement of hydrogen internal combustion engines for vehicle propulsion
- performance improvement of systems for vehicle propulsion and auxiliary power supply by
  - adjusting systems layout to application-specific ambient conditions, e.g. temperature, pressure, air quality
  - increasing systems efficiency, if necessary by using hybrid configurations
  - improving system dynamics, if necessary by using hybrid configurations
  - decreasing start-up times, if necessary by using hybrid configurations
  - developing air supply systems with low noise, high efficiency, appropriate dynamic performance for operation at moderate pressures
  - simplifying systems
  - assessing passive humidification options, this applies to PEFC technology only
  - developing sensors and controls including operational strategies as well as power electronics devices, in particular DC/AC converters
  - developing electric machinery
- development of new fuel storage systems by
  - developing new composite materials for storage pressures of up to 700 bar
  - developing hydrogen storage alternatives with substantially higher storage density

- development of fuel-gas processing systems for gasoline, diesel and kerosene that are in accordance with fuel quality specifications as well as fuel gas quality requirements of the fuel-cell stack; important areas here are desulphurisation prior to reforming and CO-level reduction of the fuel gas in particular for low-temperature PEFC stacks

Recommended basic research areas

- PEFC stack technology improvement by
  - developing new polymer membranes for operation at elevated temperature and with higher proton conductivity
  - developing new electrocatalysts with higher activity and preferably without platinum group metals also for operation at elevated temperature
  - developing materials for bipolar plates, seals
  - reducing degradation effects through investigation of degradation mechanisms
  - developing methods for accelerated lifetime testing
  - developing reliable lifetime prediction methods
- SOFC stack technology improvement by
  - developing new ion-conducting materials for operation at lower temperatures
  - developing new materials for seals and interconnectors
  - investigating degradation mechanisms
  - developing reliable lifetime prediction methods
- internal combustion technology improvement by
  - improvement of injection technology
  - optimisation of the combustion process
- systems component technology improvement by
  - developing operation strategies for hybrid configurations
  - developing new battery concepts
  - developing supercapacitors
  - developing new stack control procedures
- development of new fuel storage technology by developing reversible storage materials with substantially higher H_2 storage density (cf. Chapter 2.2)
- development of fuel gas processing technology by
  - developing autothermal reformer concepts for gasoline, diesel, kerosene
  - developing desulphurisation concepts
  - developing gas cleaning concepts with shift reaction, preferential oxidation or diffusion membranes

Recommended cross-cutting areas

The SRA sees polymer electrolyte fuel cells and solid oxide fuel cells as the most promising fuel cell types for transportation. Though transportation-specific performance requirements may differ from other areas of fuel cell application some issues can been identified as cross-cutting with portable and stationary applications. Hydrogen converters based on internal combustion technology are not expected to play a role in stationary or portable applications.

- Areas within PEFC stack technology that are seen as cross-cutting with decentralised power generation and portable power generators:
  - development of high-temperature membranes with high proton conductivity

– development of new electrocatalysts with higher activity
– development of new catalysts with non-noble metals
– development of materials for bipolar plates, seals
– investigation of degradation mechanisms
– development of methods for accelerated lifetime testing
– development of lifetime prediction methods

- Areas within SOFC stack technology that can be seen as cross-cutting with decentralised power generation:
  – development of new ion-conducting materials for operation at lower temperatures
  – development of new materials for seals and interconnectors
  – investigation of degradation mechanisms for reliable lifetime prediction
- Areas within fuel-gas processing technology that can be seen as cross-cutting with portable power generators:
  – developing autothermal reformer concepts for gasoline, diesel, kerosene
  – developing desulphurisation concepts
  – developing gas cleaning concepts with shift reaction, preferential-oxidation or diffusion membranes

Table 4.4-1: Research budget priorities for transportation applications

	Year 1 – 5	Year 6 – 10
PEM stack Membrane Catalyst Other stack issues	40 %	18 %
SOFC for transportation	4 %	5 %
Reformer systems	7 %	6 %
PEM system components Air supply E-drive	12 %	8 %
System integration Verification	16 %	14 % 8 %
Verification programme	-	20 %
Internal combustion engines	5 %	5 %
Basic research and cross-cuttings	16 %	16 %

4.5 Portable applications

Portable applications are seen as important and it is strongly advised that they should be part of future EU research programmes. They will help proliferate fuel cells by early market entry and create an early industry which will probably have a high share of small and medium-sized enterprises. As they have only a minor, though growing, impact on the energy sector as such and on CO_2 savings the effort is suggested to be clearly below average. A budget share of 10% is recommended.

Recommended R&D areas

- PEFC stack performance improvement by
  - improving fuel cell-stack efficiency and power density
  - improving CO and S tolerance
  - reducing PGM loading
  - developing stack components: bipolar plates, seals, end plates, cooling installations
- DMFC stack performance improvement by
  - improving efficiency and power density
  - decreasing methanol crossover
  - developing stack components: bipolar plates, seals, end plates, cooling installations
- SOFC stack performance improvement by
  - increasing fuel-cell stack efficiency and power density
  - improving thermal cycling stability, robustness and reliability
  - reducing corrosion and degradation
  - improving fuel impurity tolerance
  - reduction of operating temperature
- systems performance improvement by
  - increasing systems efficiency, if necessary by using hybrid system configurations
  - improving system dynamics, if necessary by using hybrid system configurations
  - improving start-up time, if necessary by using hybrid system configurations
  - miniaturising systems
  - simplifying systems
  - developing fluid handling components
  - developing air supply systems
  - assessing water recovery options
  - assessing passive systems operation options
  - improving thermal integration (with metal hydride storage containers)
  - developing power electronics devices, sensors, controls including operational strategies
  - ensuring reliable operation
- development of new fuel storage systems by
  - developing methanol cartridges
  - developing hydrogen storage alternatives
- development of fuel gas processing systems that are in accordance with fuel quality specifications as well as fuel gas quality requirements of the fuel cell stack

Recommended basic research areas

- PEFC stack technology improvement by
  - developing high-temperature membranes
  - developing CO- and S-tolerant catalysts
  - developing new MEAs: improving catalyst utilisation, improving flow-field design and gas diffusion layers
  - developing materials for seals, bipolar plates
- SOFC stack technology improvement by
  - developing new ion-conducting materials for operation at lower temperatures
  - developing new materials for seals and interconnectors
  - investigating degradation mechanisms for reliable lifetime prediction
- DMFC stack technology improvement by
  - developing new methanol oxidation catalysts
  - developing methanol-resistant cathode catalysts
  - developing composite membranes
- system component technology improvement by
  - developing alternative options for humidification
  - selecting appropriate materials for methanol storage
  - developing new battery concepts
  - developing supercapacitors
  - developing stack control procedures (concentration, humidification, mass flow, voltage temperature)
- development of new fuel storage technology by developing storage materials with substantially higher H_2 storage density (cf. *Hydrogen storage and distribution*)
- development of fuel gas processing technology by
  - developing autothermal reformer concepts for LPG and hydrocarbon fuels
  - developing desulphurisation concepts
  - developing gas cleaning concepts with shift reaction, preferential-oxidation or diffusion membranes

Recommended cross-cutting areas

Within the area of portable applications of hydrogen and fuel cells development efforts targeting miniaturisation and technological development of direct methanol fuel cell do not apply for transportation and stationary applications. Thus, cross-cutting areas of research and development may be seen in the field of portable power generators. Here polymer electrolyte and solid oxide fuel cells and also internal combustion engines will be used.

- PEFC stack technology improvement by
  - developing CO- and S-tolerant catalysts
  - developing new MEAs: improving catalyst utilisation, improving flow-field design and GDL
  - developing high-temperature membranes
  - developing materials for seals, bipolar plates
- SOFC stack technology improvement by
  - developing new ion-conducting materials for operation at lower temperatures
  - developing new materials for seals and interconnectors

  - investigating degradation mechanisms for reliable lifetime prediction
- system component technology improvement by
  - developing alternative options for humidification
  - selecting appropriate materials for methanol storage
  - developing new battery concepts
  - developing supercapacitors
  - developing stack control procedures (concentration, humidification, mass flow, voltage temperature)
- development of new fuel storage technology by developing storage materials with substantially higher H_2 storage density (cf. *Hydrogen storage and distribution*)
- development of fuel-gas processing technology by
  - developing autothermal reformer concepts for LPG and hydrocarbon fuels
  - developing desulphurisation concepts
  - developing gas cleaning concepts with shift reaction, preferential-oxidation or diffusion membranes

Table 5.1-1: Research budget priorities for portable applications

	Year 1 – 5	Year 6 – 10
PEFC, DMFC stack Membranes New catalysts Membrane electrode assemblies	30 %	30 %
Simplified water management in low-temperature systems	4 %	6 %
PEFC system components Sensors, pumps Fuel storage systems	13 %	9 %
Microreformers	13 %	11 %
System integration and miniaturisation Verification	16 %	12 % 8 %
Verification programme	8 %	8 %
Basic research and cross-cutting issues	16 %	16 %

4.6 Socio-economic issues

The proposed budget share of socio-economics of 3% reflects the great importance of this sector, bearing in mind that no cost-intensive experiments, verification or demonstration is necessary. Thus, the involvement might be comparable to that of the portables for the lower budget assigned.

Recommended cross-cutting areas:

- identification of policy evaluation for market development and assessment of social, economic and environmental impacts of hydrogen and fuel cells in terms of employment effects.
- pathway and life cycle assessment of hydrogen systems, including well-to-wheel and well-to-tank analysis
- fostering of education and public acceptance are pivotal topics to be addressed in order to achieve a spread of hydrogen applications to the broader public.
- starting energy systems analyses in order to derive benchmarks and evaluation criteria for research management and technology assessment.
- identifying suitable niche markets that allow an early demonstration and commercialisation of hydrogen and fuel-cell applications. (short to medium term)
- socio-economic research delivers important insights on innovation penetration and diffusion, both with regard to markets and policies.

Recommended Research Strategy 2005-2015

Strategic assessment of technologies and pathways: What are robust hydrogen technology options and long-term development trajectories towards a sustainable hydrogen economy?

- development and/or refinement of research tools
- provision of input data for strategic decision-making in science, industry and policy
- development of tools for qualitative and quantitative strategic energy systems analyses as a vital part of the short- and medium-term research agenda in terms of environment, material and primary energy demand as well as life cycle costs.
- strategic assessment of technologies and pathways: What are robust hydrogen technology options and long-term development trajectories towards a sustainable hydrogen-oriented economy?
- definition, analysis and review of boundary conditions to specify the added value of the transition to hydrogen.
- evaluating the plausible hydrogen and fuel cell transition scenarios on the basis of current technological status, market trends and policies

Market development: What parameters and mechanisms determine the penetration and broad diffusion of hydrogen and fuel-cell applications in the economy and society – what are the possibilities and limitations for enhancing market transformation and co-evolution of the socio-economic context?

- providing methodologies and basic knowledge needed for designing effective and efficient market introduction policies, covering for example the whole range of parameters triggering public acceptance, the crucial area of codes and standards as well as public technology procurement schemes, innovative financing mechanisms and others.
- fostering strategic niche management and wider market management

- transferring approaches from innovation and diffusion research to the topic of hydrogen and fuel cells in order to gain knowledge about important issues such as the role of (regional or topical) networks, the co-evolution of institutions and others
- breaking down sociocultural barriers by identifying mechanisms of opinion forming and decision making

Socio-economic impact assessment: What are the effects of a transition to a hydrogen economy with regard to the EU's social targets, employment and economic growth and competitiveness?

- evaluation and monitoring of the transformation of energy chains with regard to different socio-economic criteria not covered by the aforementioned research areas such as employment, job creation and job migration, changing industrial structures, international trade, regional development and quality of life
- investigating opportunities and means of securing strategic partnerships and potential markets; this includes both the assessment of specific market requirements in these regions as benchmarks for technology and product development as well as cooperative approaches for capacity and institution building
- accompanying socio-economic research as a mandatory element of technical R&D and especially of deployment activities, in this case more specifically designed but still reflecting the overarching structure of the research area

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