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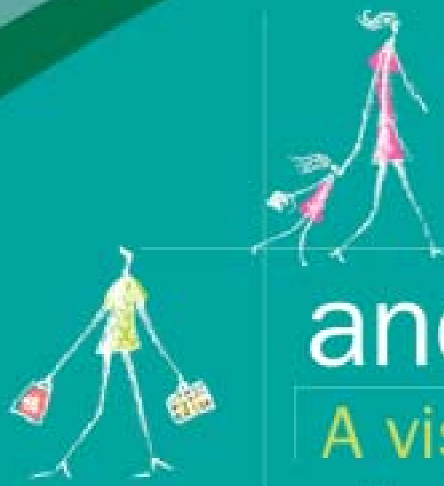

Hydrogen Energy and Fuel Cells

A vision of our future

SPECIAL REPORT

EUR 20719 EN

FINAL REPORT OF THE HIGH LEVEL GROUP

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Hydrogen Energy and Fuel Cells

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2003

Directorate-General for Research
Directorate-General for Energy and Transport

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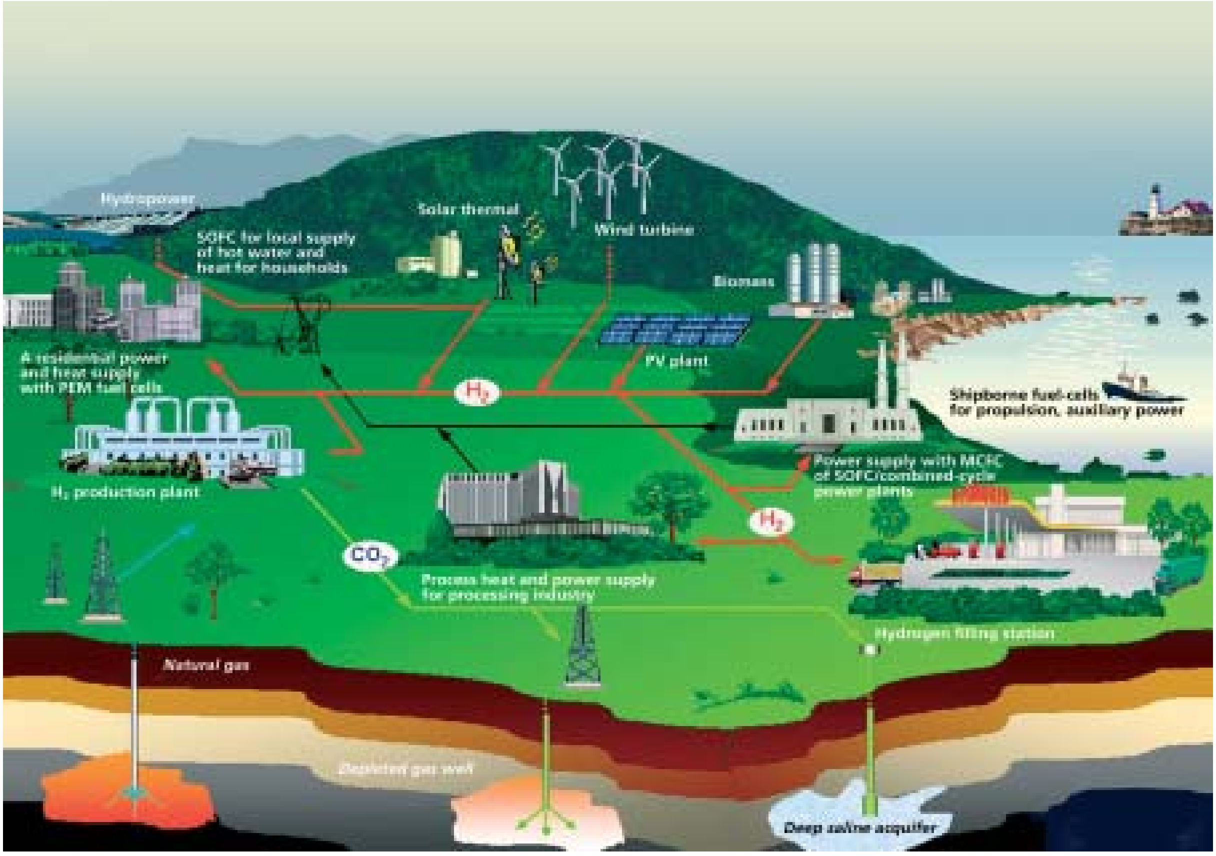

This is how an integrated energy system of the future might look – combining large and small fuel cells for domestic and decentralised heat and electrical power generation. Local hydrogen networks could also be used to fuel conventional or fuel cell vehicles.

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Background to this document

Hydrogen and fuel cells are seen by many as key solutions for the 21st century, enabling clean efficient production of power and heat from a range of primary energy sources. The High Level Group for Hydrogen and Fuel Cells Technologies was initiated in October 2002 by the Vice President of the European Commission, Loyola de Palacio, Commissioner for Energy and Transport, and Mr Philippe Busquin, Commissioner for Research. The group was invited to formulate a collective vision on the contribution that hydrogen and fuel cells could make to the realisation of sustainable energy systems in future.

This final report has been produced as a follow-up to the summary report presented at the conference "The hydrogen economy – A bridge to sustainable energy" held in Brussels on 16-17 June 2003. The terms of reference for the group requested the preparation of a vision report outlining the research, deployment and non-technical actions that would be necessary to move from today's fossil-based energy economy to a future sustainable hydrogen-oriented economy with fuel cell energy converters.

The High Level Group, whose members are listed in Annex I, comprised 19 stakeholders representing the research community, industry, public authorities and end-users. The Group was requested to give a stakeholder, not a company view. The report was compiled with the assistance of the High Level Group Members' 'sherpas' and technical writers who are listed in Annex II.

The report aims to capture a collective vision and agreed recommendations. Whilst members of the group subscribe to the collective view represented in the report, their personal view on detailed aspects of the report may differ.

Foreword

Energy is the very lifeblood of today's society and economy. Our work, leisure, and our economic, social and physical welfare all depend on the sufficient, uninterrupted supply of energy. Yet we take it for granted – and energy demand continues to grow, year after year. Traditional fossil energy sources such as oil are ultimately limited and the growing gap between increasing demand and shrinking supply will, in the not too distant future, have to be met increasingly from alternative primary energy sources. We must strive to make these more sustainable to avoid the negative impacts of global climate change, the growing risk of supply disruptions, price volatility and air pollution that are associated with today's energy systems. The energy policy of the European Commission(1) advocates securing energy supply while at the same time reducing emissions that are associated with climate change. This calls for immediate actions to promote greenhouse gas emissions-free energy sources such as renewable energy sources, alternative fuels for transport and to increase energy efficiency.

On the technology front, hydrogen, a clean energy carrier that can be produced from any primary energy source, and fuel cells which are very efficient energy conversion devices, are attracting the attention of public and private authorities. Hydrogen and fuel cells, by enabling the so-called hydrogen economy, hold great promise for meeting in a quite unique way, our concerns over security of supply and climate change.

With these factors in mind, we established the High Level Group for Hydrogen and Fuel Cell Technologies in October 2002, and asked its members to come forward in six months with a collective vision of how these technologies could help meet Europe's aspirations for sustainable energy systems. This report is the result and, we believe, a first milestone.

The report highlights the need for strategic planning and increased effort on research, development and deployment of hydrogen and fuel cell technologies. It also makes wide-ranging recommendations for a more structured approach to European Energy policy and research, for education and training, and for developing political and public awareness. Foremost amongst its recommendations is the establishment of a European Hydrogen and Fuel Cell Technology Partnership and Advisory Council to guide the process.

(1) Green Paper: "Towards a European Strategy for the Security of Energy Supply" COM (2000) 769

Security of energy supply is of major concern for the European Union. As North Sea production peaks, our dependence on imported oil – vital for today's transport systems – is forecast to grow from around 75% today, to in excess of 85% by 2020, much of it coming from the Middle East. We have also witnessed the disruption and economic loss caused by recent major grid outages in North America and Italy, illustrating the need to reinforce security of supply. In the transatlantic summit held on 25th June 2003 in Washington, President Prodi, Prime Minister Simitis and President Bush stated that the European Union and the United States should co-operate to accelerate the development of the hydrogen economy as a means of addressing energy security and environmental concerns.

Hydrogen based energy systems can build bridges to the future, but planning a cost-effective and efficient transition is hugely complex. The very large capital and human investments implied will require many years before coming to fruition. However, we must begin now to explore this path to a more sustainable future.

The High Level Group's vision was presented at the conference "The hydrogen economy – a bridge to sustainable energy" held in Brussels in June 2003 and presided over by President Prodi. The group's vision and recommendations were strongly supported. We therefore endorse the recommendations of the High level Group and the need for action today. That is why we intend to launch a "European Partnership for the Sustainable Hydrogen Economy" as soon as possible, to mobilize a broad range of stakeholders and structure a coherent effort on advancing sustainable hydrogen and fuel cell technologies in Europe.

Finally, we wish to thank the members of the High Level Group and their "sherpas" for the very considerable time and effort put in to reaching this collective vision, which we believe will prove influential in paving the way to a sustainable hydrogen economy.

Loyola de Palacio

Vice President of
the European Commission,
Commissioner for
Transport and Energy

Philippe Busquin

Commissioner for Research

A sustainable hydrogen economy for transport …

Rain clouds gather

Rain falls

Contents

Reservoir captures rainwater – retained by dam

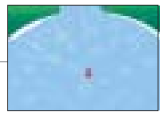
The energy challenge

Worldwide demand for energy is growing at an alarming rate. The European "World Energy Technology and Climate Policy Outlook" (WETO) predicts an average growth rate of 1.8% per annum for the period 2000-2030 for primary energy worldwide. The increased demand is being met largely by reserves of fossil fuel that emit both greenhouse gasses and other pollutants. Those reserves are diminishing and they will become increasingly expensive. Currently, the level of CO_2 emissions per capita for developing nations is 20% of that for the major industrial nations. As developing nations industrialise, this will increase substantially. By 2030, CO_2 emissions from developing nations could account for more than half the world CO_2 emissions. Industrialised countries should lead the development of new energy systems to offset this.

Energy security is a major issue. Fossil fuel, particularly crude oil, is confined to a few areas of the world and continuity of supply is governed by political, economic and ecological factors. These factors conspire to force volatile, often high fuel prices while, at the same time, environmental policy is demanding a reduction in greenhouse gases and toxic emissions.

A coherent energy strategy is required, addressing both energy supply and demand, taking account of the whole energy lifecycle including fuel production, transmission and distribution, and energy conversion, and the impact on energy equipment manufacturers and the end-users of energy systems. In the short term, the aim should be to achieve higher energy efficiency and increased supply from European energy sources, in particular renewables. In the long term, a hydrogen-based economy will have an impact on all these sectors. In view of technological developments, vehicle and component manufacturers, transport providers, the energy industry, and even householders are seriously looking at alternative energy sources and fuels and more efficient and cleaner technologies – especially hydrogen and hydrogen-powered fuel cells.

In this document, the High Level Group highlights the potential of hydrogen-based energy systems globally, and for Europe in particular, in the context of a broad energy and environment strategy. It then proposes research structures and actions necessary for their development and market deployment.



Tracking a raindrop from the reservoir

2 Why hydrogen and fuel cells?

A sustainable high quality of life is the basic driver for providing a clean, safe, reliable and secure energy supply in Europe. To ensure a competitive economic environment, energy systems must meet the following societal needs at affordable prices:

– *Mitigate the effects of climate change;*
– *Reduce toxic pollutants; and*
– *Plan for diminishing reserves of oil.*

Failure to meet these needs will have significant negative impacts on:

– *the economy;*
– *the environment; and*
– *public health.*

Measures should therefore be introduced which promote:

– *more efficient use of energy; and*
– *energy supply from a growing proportion of carbon-free sources.*

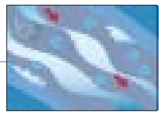
The potential effects of climate change are very serious and most important of all, irreversible. Europe cannot afford to wait before taking remedial action, and it must aim for the ideal – an emissions-free future based on sustainable energy. Electricity and hydrogen together represent one of the most promising ways to achieve this, complemented by fuel cells which provide very efficient energy conversion.

Hydrogen is not a primary energy source like coal and gas. It is an energy carrier. Initially, it will be produced using existing energy systems based on different conventional primary energy carriers and sources. In the longer term, renewable energy sources will become the most important source for the production of hydrogen. Regenerative hydrogen, and hydrogen produced from nuclear sources and fossil-based energy conversion systems with capture, and safe storage (sequestration) of CO_2 emissions, are almost completely carbon-free energy pathways.

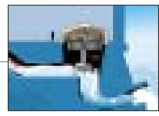
Producing hydrogen in the large quantities necessary for the transport and stationary power markets could become a barrier to progress beyond the initial demonstration phase. If cost and security of supply are dominant considerations, then coal gasification with CO_2 sequestration may be of interest for large parts of Europe. If the political will is to move to renewable energies, then biomass, solar, wind and ocean energy will be more or less viable according to regional geographic and climatic conditions. For example, concentrated solar thermal energy is a potentially affordable and secure option for large-scale hydrogen production, especially for Southern Europe. The wide range of options for sources, converters and applications, shown in Figures 1 and 2, although not exhaustive, illustrates the flexibility of hydrogen and fuel cell energy systems.

Fuel cells will be used in a wide range of products, ranging from very small fuel cells in portable devices such as mobile phones and laptops, through mobile applications like cars, delivery vehicles, buses and ships, to heat and power generators in stationary applications in the domestic and industrial sector. Future energy systems will also include improved conventional energy converters running on hydrogen (e.g. internal combustion engines, Stirling engines, and turbines) as well as other energy carriers (e.g. direct heat and electricity from renewable energy, and bio-fuels for transport).

Rainwater passes into dam



Water drops move through dam



Water passes down dam penstock, enters turbine

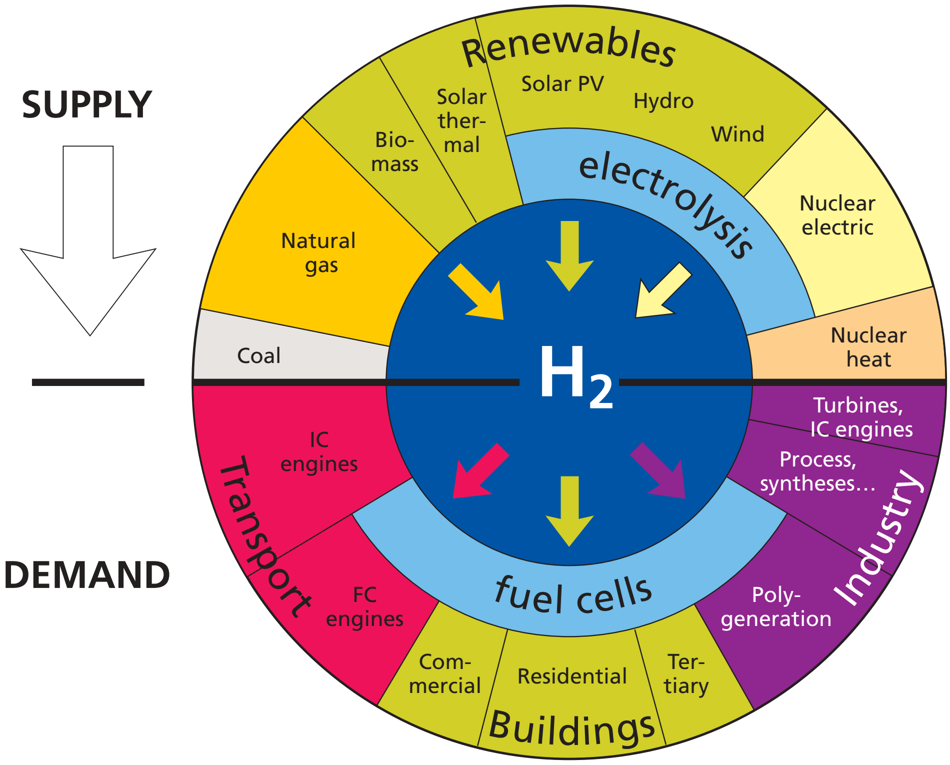


Figure 1: Hydrogen: primary energy sources, energy converters and applications
NB: Size of "sectors" has no connection with current or expected markets.

The benefits of hydrogen and fuel cells are wide ranging, but will not be fully apparent until they are in widespread use. With the use of hydrogen in fuel-cell systems there are very low to zero carbon emissions and no emissions of harmful ambient air substances like nitrogen dioxide, sulphur dioxide or carbon monoxide. Because of their low noise and high power quality, fuel cell systems are ideal for use in hospitals or IT centres, or for mobile applications. They offer high efficiencies which are independent of size. Fuel-cell electric-drive trains can provide a significant reduction in energy consumption and regulated emissions. Fuel cells can also be used as Auxiliary Power Units (APU) in combination with internal combustion engines, or in stationary back-up systems when operated with reformers for on-board conversion of other fuels – saving energy and reducing air pollution, especially in congested urban traffic.

In brief, hydrogen and electricity together represent one of the most promising ways to realise sustainable energy, whilst fuel cells provide the most efficient conversion device for converting hydrogen, and possibly other fuels, into electricity. Hydrogen and fuel cells open the way to integrated "open energy systems" that simultaneously address all of the major energy and environmental challenges, and have the flexibility to adapt to the diverse and intermittent renewable energy sources that will be available in the Europe of 2030.

Dam, turbine, generator and power lines

Force of water turns turbine

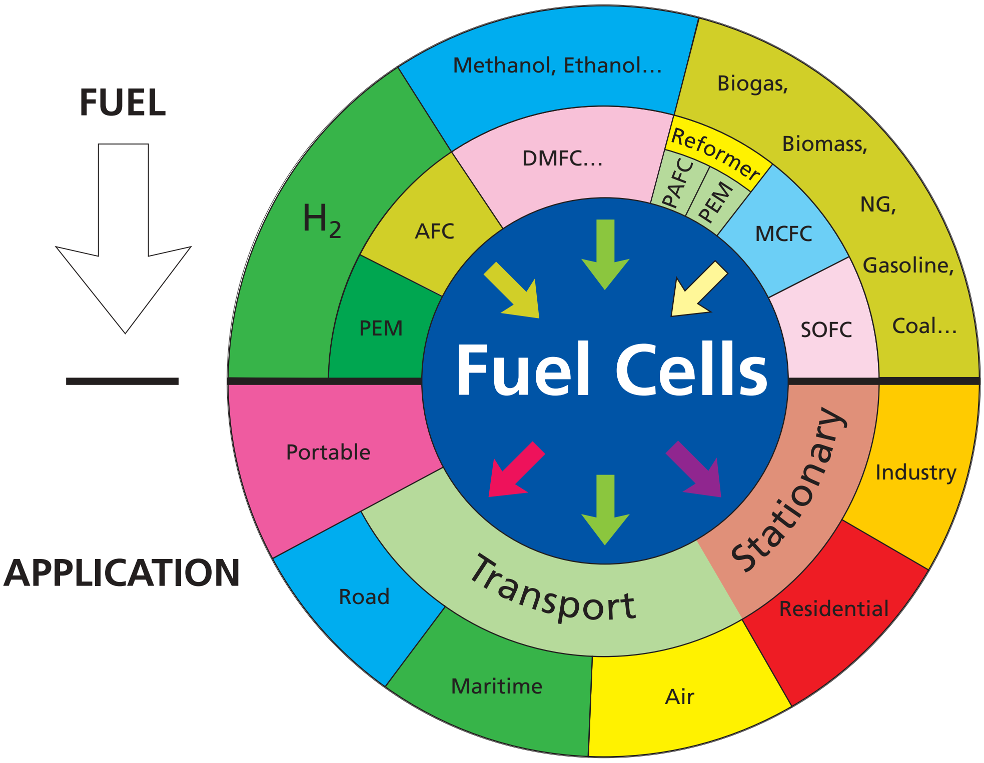


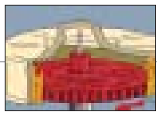
Figure 2: Fuel cell technologies, possible fuels and applications
*NB: Size of "sectors" has no connection with current or expected markets.**
** **PEM** = Proton Exchange Membrane Fuel Cell; **AFC** = Alkaline Fuel Cells;*
***DMFC** = Direct Methanol Fuel Cell; **PAFC** = Phosphoric Acid Fuel Cell;*
***MCFC** = Molten Carbonate Fuel Cell; **SOFC** = Solid Oxide Fuel Cell*

Europe should lead in undertaking rational analysis of alternative energy options and in demonstrating the benefits of a transition to a widespread use of hydrogen and fuel cells. They will have to provide cost-effective solutions to the following key challenges – the main drivers for Europe's future energy systems.

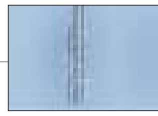
Energy security and supply

Today's society depends crucially on the uninterrupted availability of affordable fossil fuels which, in future, will be increasingly concentrated in a smaller number of countries – creating the potential for geopolitical and price instability. Hydrogen opens access to a broad range of primary energy sources, including fossil fuels, nuclear energy and, increasingly, renewable energy sources (e.g. 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 are best adapted to regional circumstances.

Hydrogen and electricity also allow flexibility in balancing centralised and decentralised power, based on managed, intelligent grids, and power for remote locations (e.g. island, and mountain sites). Decentralised power is attractive both to ensure power quality to meet specific customer needs, as well as reducing



Turbine drives generator



Generator feeds electricity to transformer

exposure to terrorist attack. The ability to store hydrogen more easily than electricity can help with load levelling and in balancing the intermittent nature of renewable energy sources. Hydrogen is also one of the few energy carriers that enables renewable energy sources to be introduced into transport systems.

Economic competitiveness

Since the first oil crisis in the 1970s, economic growth has not been directly linked with growth in energy demand in the industrial sector, whereas in the transport sector increased mobility still leads to a proportionate increase in energy consumption. The amount of energy needed per unit growth must be reduced, while the development of energy carriers and technologies to ensure low-cost energy supply is of great importance. Development and sales of energy systems are also major components of wealth creation, from automobiles to complete power stations, creating substantial employment and export opportunities, especially to the industrialising nations. European leadership in hydrogen and fuel cells will play a key role in creating high-quality employment opportunities, from strategic R&D to production and craftsmen.

In the US and Japan, hydrogen and fuel cells are considered to be core technologies for the 21st century, important for economic prosperity. There is strong investment and industrial activity in the hydrogen and fuel cell arena in these countries, driving the transition to hydrogen – independently of Europe. If Europe wants to compete and become a leading world player, it must intensify its efforts and create a favourable business development environment.

Air quality and health improvements

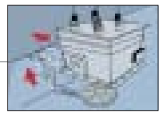
Improved technology and post-combustion treatments for conventional technologies are continuously reducing pollutant emissions. Nevertheless, oxides of nitrogen and particulates remain a problem in certain areas, while the global trend towards urbanisation emphasises the need for clean energy solutions and improved public transport. Vehicles and stationary power generation fuelled by hydrogen are zero emission devices at the point of use, with consequential local air quality benefits.

Greenhouse gas reduction

Hydrogen can be produced from carbon-free or carbon-neutral energy sources or from fossil fuels with CO_2 capture and storage (sequestration). Thus, the use of hydrogen could eventually eliminate greenhouse gas emissions from the energy sector. Fuel cells provide efficient and clean electricity generation from a range of fuels. They can also be sited close to the point of end-use, allowing exploitation of the heat generated in the process.

The table (see next page) illustrates how, in a mature hydrogen oriented economy, the introduction of zero carbon hydrogen-fuelled vehicles could reduce the average greenhouse gas emissions from the European passenger car fleet, compared to the average level of 140g/km CO_2[1] projected for 2008.

(1) The European Automobile Manufacturers' Association (ACEA) has made a voluntary commitment to reduce the average level of CO_2 emissions to 140 g/km for new vehicles sold on the European market in 2008. The average level today is around 165-170 g/km.



Transformer changes voltage for efficient transmission

Rainwater has done its work; it exits dam tail-stock; electricity leaves the power station

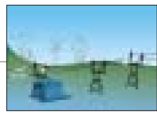
YEAR	% of new cars(1) fuelled by zero-carbon hydrogen	% of fleet fuelled by zero-carbon hydrogen	Average CO_2 reduction (all cars)(2)	CO_2 avoided per year ($MtCO_2$)
2020	5	2	2.8 g/km	15
2030	25	15	21.0 g/km	112
2040	35	32	44.8 g/km	240

(1) Figures based on an assumed European fleet of 175m vehicles. The fleet size will increase significantly by 2040, with correspondingly larger benefits.
(2) Calculation is independent of total number of cars.

The last column shows the corresponding amounts of CO_2 emissions that could be avoided. This may be compared to a projected total level of 750-800 $MtCO_2$ emissions for road transport in 2010. The numbers for H_2-fuelled cars are an assumption based on a survey of experts for conventional and alternative automotive drive trains, but not a prediction of future production or sales.

Greenhouse gas savings of about 140 $MtCO_2$ per year (14% of today's levels of CO_2 emissions from electricity generation) could be achieved if about 17% of the total electricity demand, currently being supplied from centralised power stations, is replaced by more efficient decentralised power stations, incorporating stationary high-temperature fuel-cell systems fuelled by natural gas. Fuel-cell systems will be used as base load in the future decentralised energy systems.

These examples *are not proposed as targets,* but merely to serve as illustrations of the CO_2 savings that could be achieved with quite modest penetrations of hydrogen vehicles and fuel cell-based stationary power generation. Together, 15% regenerative hydrogen vehicles and the above distributed fuel cell/gas turbine hybrid systems could deliver about 250 $MtCO_2$ savings per year. This is approximately 6% of the energy-related CO_2 emissions forecast in 2030, and progress such as this would allow Europe to move beyond the Kyoto Protocol.



Renewable electricity, from solar, wind energy, can also be grid-connected

Electricity is transmitted to cities

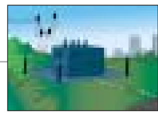
A strong drive in the United States and Japan

A coalition of US fuel cell stakeholders recently called for a ten-year US Federal Government programme to implement and deploy hydrogen and fuel cell technologies. The coalition called for $5.5bn of public funding. The US Administration responded in January 2003 by proposing a total of $1.7 billion (including $720m of new funding) over the next five years to develop hydrogen fuel cells, hydrogen infrastructure and advanced automotive technologies. According to the US Department of Energy, those activities will result in 750 000 new jobs by 2030.

Japan is also aggressively pursuing the research and demonstration of hydrogen and fuel cells with a 2002 budget estimated at around $240m. The Japan Fuel Cell Commercialisation Conference will commission six hydrogen fuelling stations in Tokyo and Yokohama in 2002-3. The Japanese have announced initial commercialisation targets of 50 000 fuel cell vehicles by 2010, and 5m by 2020, and installed stationary fuel cell capacity of 2 100 MW by 2010, with 10 000 MW by 2020.

Europe can only meet this global challenge with similar total levels of investment from individual states and the EU. The proposed US support is around five to six times the level of public support anticipated for hydrogen and fuel cells in the European Sixth Framework Programme for Research. Even with the significant additional support from individual Member State programmes, the level of public support in Europe is still far below that in the United States. A substantial increase is therefore needed for Europe to compete with the US and Japan. To be as effective, research, development and deployment would need to be well co-ordinated to achieve sufficient critical mass and avoid unnecessary duplication.

3



Electricity reaches city, is transformed and distributed underground

What can Europe do?

Europe has the skills, resources and potential to become a leading player in the supply and deployment of hydrogen technologies. Its diversity offers enormous strength if it can be harnessed and strategically guided, but European policy, research and development are presently fragmented both within and across the different countries.

Five actions to a hydrogen energy future:

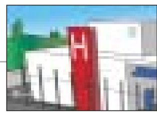
- *A political framework* that enables new technologies to gain market entry within the broader context of future transport and energy strategies and policies.
- *A Strategic Research Agenda*, at European level, guiding community and national programmes in a concerted way.
- *A deployment strategy* to move technology from the prototype stage through demonstration to commercialisation, by means of prestigious 'lighthouse' projects which would integrate stationary power and transport systems and form the backbone of a trans-European hydrogen infrastructure, enabling hydrogen vehicles to travel and refuel between Edinburgh and Athens, Lisbon and Helsinki.
- *A European roadmap for hydrogen and fuel cells* which guides the transition to a hydrogen future, considering options, and setting targets and decision points for research, demonstration, investment and commercialisation.
- *A European Hydrogen and Fuel Cell Technology Partnership,* steered by an *Advisory Council*, to provide advice, stimulate initiatives and monitor progress – as a means of guiding and implementing the above, based on consensus between stakeholders.

The political framework

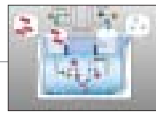
In view of the substantial long-term public and private benefits arising from hydrogen and fuel cells, the European Union and national governments throughout Europe should work towards realising a consistent European policy framework with a sustainable energy policy at its heart. Ideally, any system should include the environmental cost of energy in the decision-making process. Policy developments must be sufficiently long term to provide comfort to industrial organisations and investors so that their investment risk can be managed. Leaders and champions are emerging from the private sector, but no single company, industry, or consortium can make transition happen. This is not only because of the significant investment required in research, development and deployment, and the associated risks. Additional obstacles include the need to reflect public benefit in individual commercial decisions, so that commercial activity can ultimately become the engine of transformation. Without the right pricing signals, the new 'markets' will not develop, given the existence of highly developed, lower-cost (but less clean) alternatives in the existing energy and equipment mix.

Significant public sector involvement is critical to progress. Public sector funding is required to stimulate activity and share risks in research, development, and initial deployment. Public agencies are needed to provide mechanisms for co-ordinating activities efficiently, and to stimulate cross-business and cross-border co-operation. Fiscal and regulatory policies must be formulated which provide the commercial drivers for development, and these policies must be consistent with the stimulation of other parallel developments in clean energy/fuels. Coordination is required in the development of codes and standards, not only within regions but globally, too.

Electricity is also used to produce renewable hydrogen for transport



Electricity is fed to a hydrogen fuel station



Water is split into hydrogen and oxygen by electrolysis

Coordinating policy measures

Ensuring that the take-up of hydrogen and fuel cells is rapid and widespread will mean the coordination of strong policy measures in support of the technology, research and development, taking account of the time required for commercialisation. Such measures should address both supply and demand, taking into account global competitiveness, and reward technologies proportionate to their ability to meet policy objectives. They may include:

- Support (fiscal, financial and regulatory) for demonstration and pilot projects, through direct or indirect actions including fuel duty rebates and enhanced capital allowances;
- Promotion of energy efficiency measures to stimulate demand for clean transport and stationary applications;
- Support for infrastructure design, planning and assessment of viability, at the various stages of market development;
- Review and remove regulatory barriers to commercialisation of hydrogen and fuel cells;
- Review and develop codes and standards to support commercial development;
- Simplification and harmonisation of planning and certification requirements (e.g. fuel and safety standards);
- Assessment of the scope and effectiveness of alternative mixes of policy measures, including market pull/incremental pricing policies and active use of public procurement schemes, including possible defence applications; and
- International coordination of policy development and deployment strategies.

The Strategic Research Agenda

First-class research is critical to the development of competitive, world-class technology. A Strategic Research Agenda should bring together the best research groups in Europe today. It should generate a critical mass in terms of resources, effort and competencies to analyse and address non-technical and socio-economic issues, and solve the remaining technical barriers to the introduction of hydrogen and fuel cells, including:

- Solving the technology challenges of hydrogen production, distribution, storage, infrastructure and safety, and reducing the costs of all of these, as well as the improvement in the materials, components and system design;
- Solving the technology challenges of fuel cell stack performance, durability and costs, as well as of all the peripheral components (reformer, gas cleaning, control valves, sensors, and air and water management systems);
- Executing systems analyses providing scenarios, techno-economic, environmental and socio-economic analyses of different energy carrier/converter configurations and transition pathways, including the range of hydrogen production to end-use routes and the range of fuel cell applications, to assess the viability of different options; and
- Contributing to the definition, ongoing review and refinement of a European hydrogen roadmap with targets, milestones and review criteria based on research results.

The Strategic Research Agenda should identify in detail priorities for focused fundamental research where basic materials research, or in-depth modelling studies, as well as applied research, are required to achieve technical breakthroughs.

Hydrogen is collected and compressed

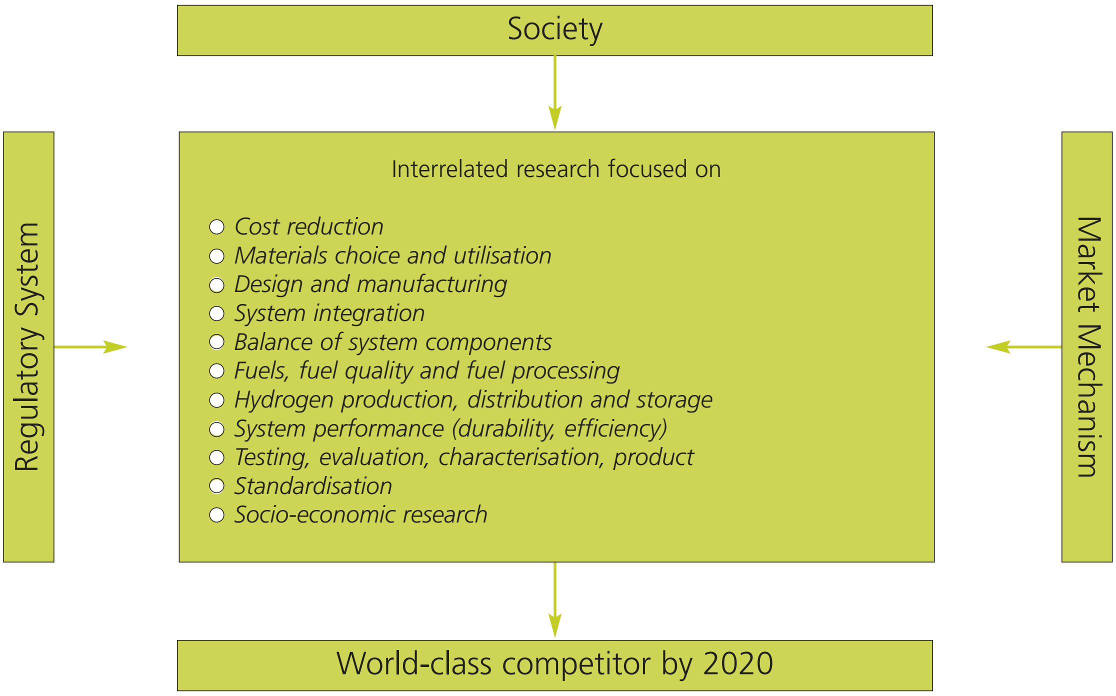


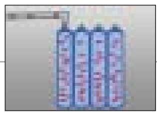
Figure 3: Key elements and drivers of a Strategic Research Agenda

The Strategic Research Agenda should define short-, medium- and long-term actions in a seamless way. Synergies between fuel pathways, infrastructure, and different fuel cell applications should be identified early on. The goal should be modular solutions and systems integration, facilitated by ambitious demonstration projects.

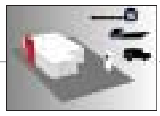
Implementing the research agenda

The Strategic Research Agenda should seek support from various public and private sources, including national and regional research programmes and the European Framework Programme for Research. It should build on ongoing European agreements, initiatives, projects, and thematic networks which have a strategic dimension. Specific implementation measures should include:

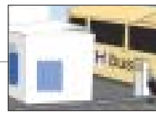
- Designation of a number of strategic European virtual centres of excellence acting as focal points for critical research;
- Establishment of a number of prototype demonstration projects to validate technology;
- Definition of rules on intellectual property leading to co-operative international research;
- Encouragement and facilitation of international co-operation, especially where it can accelerate market development;
- Establishment of stakeholder forums and a Strategic Research Agenda steering committee;
- Investigation of mechanisms for developing joint research



Compressed hydrogen is stored in cylinders



Hydrogen may be liquefied



A fuel cell bus stops at a hydrogen fuel station

programmes between Member States, including the use of article 169;

- Coordination of research and development for defence applications; and
- Reviewing criteria, targets and milestones of the European roadmap for hydrogen and fuel cells.

Setting the Strategic Research Agenda therefore requires co-operation between a broad range of stakeholders including academe, national, defence and contract (private) research centres, industry, end-users, civil society, Small and Medium-sized Enterprises, and public authorities at all levels – local, regional and European. It should also address broader international targets to ensure European technology will be internationally competitive.

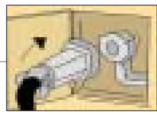
A deployment strategy for hydrogen and fuel cells

At present, hydrogen and fuel cells do not offer sufficient short-term end-user benefits to justify their higher costs compared to conventional technologies. The deployment strategy should therefore aim to identify pathways for increasing infrastructure and production volumes. This approach will reduce costs, create market opportunities, eventually reducing the need for government support. In certain applications, such as portable power, emergency back-up power, and auxiliary power units, fuel cells may offer early customer benefits and attract premium prices. However, for the emerging stationary and transport markets government intervention will be necessary, anticipating public and private benefits in the longer term.

Implementing the transition to hydrogen and fuel cells

Moving from the fossil fuel economy of 2003 to a hydrogen and fuel cell-based economy will not happen immediately. Large physical and economic infrastructures support the status quo. Switching too quickly could cause major economic dislocation. A strategy is required to maximise the benefits of transition technologies such as combustion engines, and to explore on-board reforming options to enable fuel cell vehicles to use existing fuel infrastructures.

Stationary fuel cells are already emerging in specific market niches. Fuel cell vehicle drive trains are still at the pre-commercial development stage. Fuel cells in the stationary market will largely operate on natural gas until hydrogen becomes widely available (it may also be distributed through mixing with natural gas). Fuel cells will also be introduced into portable applications and stand-alone electricity generation, possibly using energy carriers such as bio-fuels or synthetic fuels. Early uses in vehicles may include auxiliary power units for on-board electricity generation, e.g. for refrigerated trucks, air-conditioning units for buses, and luxury cars. Development of fuel cells for defence applications as strategic niche markets could significantly speed development for civilian fuel cells. During the transition phase and even afterwards, conventional technologies will be essential. Hydrogen-fuelled internal combustion engines and turbines can be used for stationary power and transport. Fuel cell vehicles will have to compete with very clean, efficient hybrid combustion engine/electric vehicles, although commercialisation of



A special fuel hose is connected with safety lock

Hydrogen is fed to the bus

hybrid drive trains will reduce the costs of electrical and electronic components shared with fuel cell vehicles.

For transport, a widespread refuelling infrastructure is essential for customer acceptance. Very large capital investments are required for a dedicated hydrogen infrastructure, in the order of some hundreds of billions of euros. This is a major barrier to commercialisation. Hydrogen fuelling stations can be erected, using locally or industrially produced hydrogen.

The existing hydrogen pipeline network in Europe (some 1 100km), which has served industry for many years, could be developed for initial demonstrations. Liquid hydrogen is also routinely distributed by truck, and existing capacity could be readily developed to cope with up to 5% of new vehicles. Hydrogen may be mixed with natural gas and distributed in natural gas pipelines. On-board reforming technologies, which take advantage of current infrastructure, should be investigated in parallel with the development of viable hydrogen storage and refuelling technologies.

The introduction of hydrogen vehicles is expected to start with centrally operated fleets of buses and city goods delivery vehicles in densely settled mega-cities, followed by private cars. Urban buses are attractive due to the centralised refuelling facilities, the availability of skilled personnel, the engineering tradition of public transport companies, the intensive service schedule under arduous, congested conditions, and for the promotion of public awareness. A trans-European hydrogen energy network can then be progressively grown from these strategically sited nuclei.

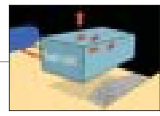
Maritime applications from canal barges to ocean-going vessels will provide opportunities for hydrogen and fuel cells. The successful introduction of fuel cells – and hydrogen – into transport, will involve considerable initial support from governments and industry. The development of improved codes and standards and the establishment of ‘best practice’ for fuel station layouts, preferably coordinated internationally, should lead to significant reductions in licensing times and costs. And, of course, initial demonstration projects should promote public acceptance, and demonstrate that hydrogen is safe.

Stationary hydrogen combustion and fuel cell systems should be demonstrated in application areas where they offer early benefits such as remote areas, island communities with renewable resources, and micro-grids with combined heat and power. Actually linking together stationary and transport demonstrations will help to get the most from the technology and improve understanding of the probable synergies. Support should be given not only to large companies but also to small entrepreneurial companies seeking to establish niches. Extensive demonstrations and field trials are critical to commercialisation. They are necessary to demonstrate the benefits, reliability and durability to potential users and governments.

Funding the transition

The investment required for building a hydrogen and fuel cell energy economy is estimated at some hundreds of billions of euros, which can only be realised over decades as existing capital investments are depreciated. For example, installing hydrogen at 30% of Europe’s fuel stations (penetration needed for

Roof tanks are filled



Hydrogen is fed from roof tanks to fuel cell

customer comfort) could cost in the order of 100-200 billion euros. Public funding is very important, symbolising government commitment to the technology and generating leverage for private finance, the main engine of change. The Framework Programme and national programmes will remain the main public-funding instruments for research, development and demonstration, while regional aid projects could provide opportunities for larger deployment initiatives. For ambitious projects, co-financing from several sources should be explored.

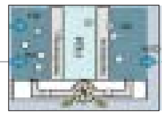
A European roadmap for hydrogen and fuel cells

Moving Europe away from its 20th century dependency on fossil fuels to an era powered by the complementary energy carriers, electricity and hydrogen, will require careful strategic planning. Hydrogen is not likely to be the only fuel for transport in future. Moreover, maintaining economic prosperity during the transition period will involve maximising the efficient use of various forms of fossil-based energy carriers and fuels such as natural gas, methanol, coal, and synthetic liquid fuels derived from natural gas. During that time it will also be important to introduce renewable energy sources such as biomass, organic material – mainly produced by the agriculture and forestry sectors – that can be used to generate heat, electricity, and a range of fuels such as synthetic liquid fuels and hydrogen. Where appropriate, traditional forms of electricity generation can be harnessed to produce hydrogen through the electrolysis of water, while employing new, safe technologies and renewable sources to minimise harmful emissions of greenhouse gasses and pollutants. Throughout the period, electricity from renewable energy sources can be increasingly used to generate hydrogen. The ability to store hydrogen more easily than electricity opens up interesting possibilities for storing energy, helping to level the peaks and troughs experienced in the electricity generating industry. Hydrogen fuelling stations can be erected, using locally or industrially produced hydrogen. Given the complex range of options, a framework for the introduction of hydrogen and fuel cells needs to be established. This transition should be executed progressively along the following broad lines:

In the short and medium term (to 2010):

- Intensify the use of renewable energy sources for electricity which can be used to produce hydrogen by electrolysis or fed directly into electricity supply grids;
- Improve the efficiency of fossil-based technologies and the quality of fossil-based liquid fuels;
- Increase the use of synthetic liquid fuels produced from natural gas and biomass, which can be used in both conventional combustion systems and fuel-cell systems;
- Introduce early applications for hydrogen and fuel cells in premium niche markets, stimulating the market, public acceptance and experience through demonstration, and taking advantage of existing hydrogen pipeline systems; and
- Develop hydrogen-fuelled IC engines for stationary and transport applications, supporting the early deployment of a hydrogen infrastructure, providing they do not increase the overall CO_2 burden.

Considerable fundamental research is needed throughout this period, on key technology bottlenecks, e.g. hydrogen production, storage and safety, and fuel cell performance costs and durability.



Fuel cell generates electricity by combining the hydrogen with oxygen from air

In the medium term (to 2020):

- Continue increasing the use of liquid fuels from biomass;
- Continue using fossil-based liquid and gaseous fuels in fuel cells directly, and reforming fossil fuels (including coal) to extract hydrogen. This enables transition to a hydrogen economy, capturing and sequestering the CO_2. The hydrogen thus produced can then be used in suitably modified conventional combustion systems, hydrogen turbines and fuel-cell systems, reducing greenhouse gas and pollutant emissions; and
- Develop and implement systems for hydrogen production from renewable electricity, and biomass; continue research and development of other carbon-free sources, such as solar thermal and advanced nuclear.

In the medium to long term (beyond 2020):

- Demand for electricity will continue to grow, and hydrogen will complement it. Use both electricity and hydrogen together as energy carriers to replace the carbon-based energy carriers progressively by the introduction of renewable energy sources and improved nuclear energy. Expand hydrogen distribution networks. Maintain other environmentally benign options for fuels.

A very preliminary, skeleton proposal for the main elements and time lines of a European roadmap for the production and distribution of hydrogen, as well as fuel cells and hydrogen systems, is presented in Figure 4 (see next page) as a basis for wider consultation and discussion.

The European Hydrogen and Fuel Cell Technology Partnership

It is recommended that, to stimulate and manage the above initiatives, a European Hydrogen and Fuel Cell Technology Partnership should be formed without delay. This partnership should include the most important and innovative companies working on hydrogen and fuel cells in Europe and also represent a balance of expert knowledge and stakeholder interests. It should be steered and monitored by an Advisory Council which should provide guidance on how to initiate and push forward the individual elements above, building on existing European initiatives, networks and structures.

The High Level Group is ready and willing to offer advice on the implementation of the partnership and assist with the next steps. Specific ‘initiative groups’ should be created including, for example: strategic technical and socio-economic research; hydrogen policy; business development; demonstration; education and training; safety and standards, etc. A business framework should be developed as soon as possible to support the development of a component supply chain and stimulate innovation. The partnership should:

- Set clear objectives and commercialisation targets, foster strategic planning and deployment in response to policy priorities and monitor progress;
- Launch a business development initiative to foster investment in innovation, involving venture capital companies, institutional investors, regional development initiatives, and the European Investment Bank;

Fuel cell emits only water vapour

Fuel cell electricity is fed to electric motor

Electric motor propels bus

- Promote an education and training programme, through the development of a master plan for education and information, to stimulate learning at all levels;
- Introduce a strategy for building international co-operation with both developed and developing countries with a view to co-operating on technology bottlenecks, codes and standards, and technology transfer; and
- Establish a centre for consolidating and disseminating information that could significantly aid coordination of a shift towards hydrogen and fuel cells.

A challenging European hydrogen vision

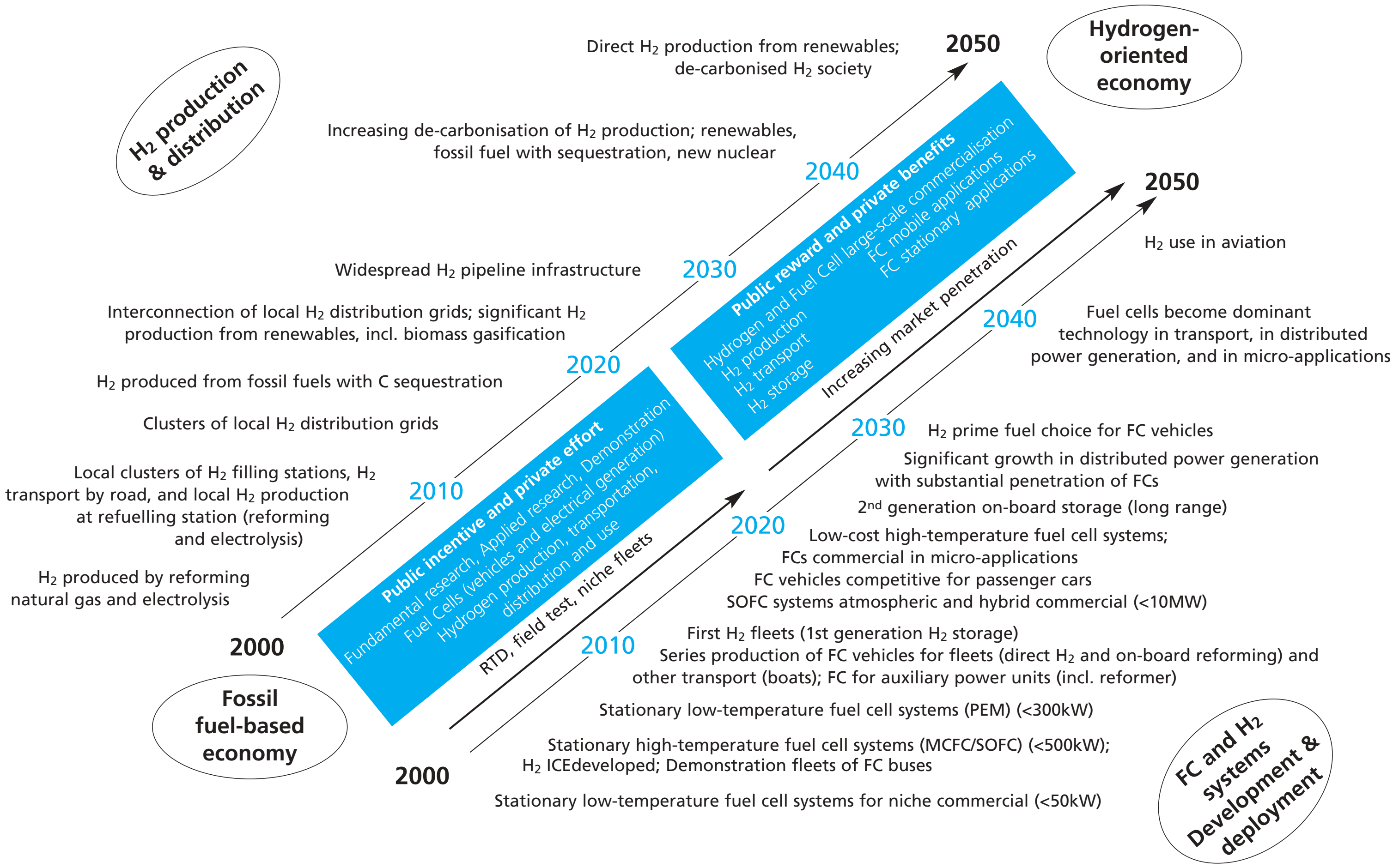
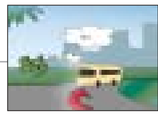


Figure 4: Skeleton proposal for European hydrogen and fuel cell roadmap



Fuel cell exhausts water vapour to atmosphere

Vapour joins clouds; hydrogen cycle restarts

4 Summary, conclusions and recommendations

To maintain economic prosperity and quality of life, Europe requires a sustainable energy system that meets the conflicting demands for increased supply and increased energy security, whilst maintaining cost–competitiveness, reducing climate change, and improving air quality.

Hydrogen and fuel cells are firmly established as strategic technologies to meet these objectives. They can create win-win situations for public and private stakeholders alike. The benefits will only start to really flow after public incentives and private effort is applied to stimulate and develop the main markets – stationary power and transport. This should be done in a balanced way that reflects the most cost-effective use of the various alternative primary energy sources and energy carriers.

Competition from North America and Pacific Rim countries is especially strong, and Europe must substantially increase its efforts and budgets to build and deploy a competitive hydrogen technology and fuel cell industry. This should not be left to develop in an uncoordinated fashion, at the level of individual Member States. Gaining global leadership will require a coherent European-level strategy, encompassing research and development, demonstration, and market entry similar to the development of the European aircraft industry.

The High Level Group therefore recommends the formation of a **Hydrogen and Fuel Cell Technology Partnership**, steered by a **European Hydrogen and Fuel Cell Advisory Council,** to provide advice, stimulate initiatives and monitor progress. The Advisory Council will provide governance and input from the different stakeholders in the hydrogen energy arena, and oversee the establishment of specific 'initiative' groups to take forward the development of a broad and far-reaching hydrogen and fuel cell programme, comprising:

- Creation of **a policy framework that is coherent across transport, energy, and environment** to reward technologies that meet policy objectives;
- A **substantially increased technical research and development budget** in hydrogen and fuel cell technologies, from fundamental science to validation programmes;
- A **demonstration and pilot programme** to extend the technology validation exercises into the market development arena, through a number of 'lighthouse' demonstration projects;
- An **integrated socio-economic research programme** to complement and steer the technical support;
- A **business development initiative**, bringing together the different financing organisations to provide leadership for technology exploitation
- A **Europe-wide education and training programme**, spanning primary schooling to world-class research;
- **Enhanced international co-operation**, working in partnership with North America and the Pacific Rim, as well as the developing world, to speed up the introduction of sustainable energy technologies; and
- **A communication and dissemination centre** for all these initiatives.

Detailed planning and actions for implementing these recommendations needs to start now, with a twenty to thirty year perspective.

TECHNICAL ANNEX

Hydrogen and fuel cell technologies and related challenges

Hydrogen production

Hydrogen can be produced in many different ways, using a wide range of technologies. Some of these involve established industrial processes while others are still at the laboratory stage. Some can be introduced immediately to help develop a hydrogen energy supply system; while others need considerable research and development.

Current hydrogen production is mostly at a large scale. Before a hydrogen energy system is fully proven and fully introduced, many regional demonstration and pilot projects will be required. Aside from large-scale industrial equipment, small-scale production technologies, including electrolysers and stationary and on-board reformers, which extract hydrogen from gaseous and liquid fuels like natural gas, gasoline and methanol, will be needed. Many organisations are developing technologies specifically for this scale of operation. Safety will be a paramount issue. The table 1 below compares the principal hydrogen production routes.

Hydrogen storage

Hydrogen storage is common practice in industry, where it works safely and provides the service required. Also, hydrogen can easily be stored at large scale in vessels or in underground caverns. However, for mobile applications, to achieve a driving range comparable to modern diesel or gasoline vehicles, a

Table 1: Summary of hydrogen production technologies

Hydrogen production technology	Benefits	Barriers
Electrolysis: splitting water using electricity	Commercially available with proven technology; Well-understood industrial process; modular; high purity hydrogen, convenient for producing H_2 from renewable electricity, compensates for intermittent nature of some renewables	Competition with direct use of renewable electricity
Reforming (stationary and vehicle applications): splitting hydrocarbon fuel with heat and steam	Well-understood at large scale; widespread; low-cost hydrogen from natural gas; opportunity to combine with large scale CO_2 sequestration ('carbon storage')	Small-scale units not commercial; hydrogen contains some impurities - gas cleaning may be required for some applications; CO_2 emissions; CO_2 sequestration adds costs; primary fuel may be used directly
Gasification: splitting heavy hydrocarbons and biomass into hydrogen and gases for reforming	Well-understood for heavy hydro-carbons at large scale; can be used for solid and liquid fuels; possible synergies with synthetic fuels from bio-mass- biomass gasification being demonstrated	Small units very rare; hydrogen usually requires extensive cleaning before use; biomass gasification still under research; biomass has land-use implications; competition with synthetic fuels from biomass
Thermochemical cycles using cheap high temperature heat from nuclear or concentrated solar energy	Potentially large scale production at low cost and without greenhouse gas emission for heavy industry or transportation; International collaboration (USA, Europe and Japan) on research, development and deployment	Complex, not yet commercial, research and development needed over 10 years on the process: materials, chemistry technology; High Temperature nuclear reactor (HTR) deployment needed, or solar thermal concentrators
Biological production: algae and bacteria produce hydrogen directly in some conditions	Potentially large resource	Slow hydrogen production rates; large area needed; most appropriate organisms not yet found; still under research

breakthrough in on-board vehicle hydrogen storage technology is still required. Innovative vehicle designs could help overcome current drawbacks. Significant research and development is under way, with new systems in demonstration.

Conventional storage, such as compressed gas cylinders and liquid tanks, can be made stronger, lighter and cheaper. Novel methods, including hydrogen absorption using metal hydrides, chemical hydrides and carbon systems, require further development and evaluation.

Hydrogen end-use

Hydrogen can be burned either to provide heat, or to drive turbines, or in internal combustion engines for motive and electrical power. Many of these technologies are quite mature, although improvements in materials and processes will help them work better and last longer. Fuel cells are in the early stages of commercialisation and offer a more efficient hydrogen use. Hydrogen internal combustion engines in vehicles may provide an important route to enable hydrogen introduction while other technologies, such as fuel cell electric drive trains develop.

Hydrogen infrastructure

Infrastructure is required for hydrogen production, storage, and distribution and, in the case of transport, special facilities will be required for vehicle refuelling. This has implications for land-use planning as well as for the safe operation and maintenance of hydrogen equipment.

Other issues must also be addressed. Trained maintenance personnel, specifically trained researchers; accepted codes and standards all form part of a successful support infrastructure for any product or service, and will be vital for the successful introduction of hydrogen and fuel cells.

The use of hydrogen-fuelled transport will depend on the successful development of an affordable and widespread refuelling infrastructure. Currently, only a few expensive hydrogen refuelling stations exist worldwide, and refuelling station costs need to be reduced to make them commercially viable. The greatest challenge will be to support millions of private cars but, before that, fleet vehicle fuelling stations will be introduced. Providing hydrogen fuel for ferries and other local water-based vehicles could also come early in the development of an infrastructure, particularly in environmentally sensitive areas.

Table 2: Summary of hydrogen storage technologies

Hydrogen storage technology	Benefits	Barriers
Compressed gas cylinders:	Well understood up to pressures of 200bar; generally available; can be low cost	Only relatively small amounts of H_2 are stored at 200bar; fuel and storage energy densities at high pressure (700bar) are comparable to liquid hydrogen, but still lower than for gasoline and diesel; high pressure storage still under development
Liquid tanks:	Well-understood technology; good storage density possible	Very low temperatures require super insulation; cost can be high; some hydrogen is lost through evaporation; energy intensity of liquid hydrogen production; energy stored still not comparable to liquid fossil fuels
Metal hydrides:	Some technology available; solid-state storage; can be made into different shapes; thermal effects can be used in subsystems; very safe	Heavy; can degrade with time; currently expensive; filling requires cooling-circuit
Chemical hydrides:	Well-known reversible hydride formation reactions e.g. NaBH; compact	Challenges in the logistics of handling of waste products and in infrastructure requirements
Carbon structures:	May allow high storage density; light; may be cheap	Not fully understood or developed; early promise remains unfulfilled

Relative greenhouse gas emissions and costs of hydrogen fuelling pathways

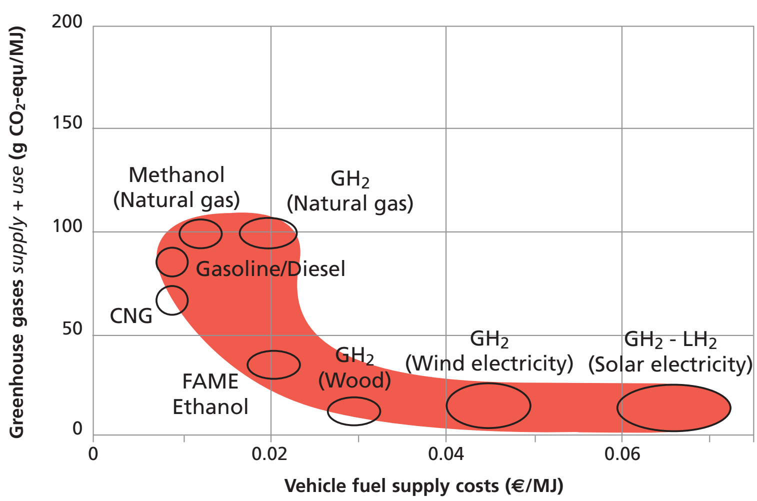
The total electricity generating capacity in the 15 European Union member states (EU15) is currently around 573GW$_{el}$. Forecasts for 2020 to 2030 predict electricity generating capacities from fuel cells will be in the range 30 to 60 GW$_{el}$. Assuming fuel cell generating capacity of 60 GW$_{el}$ by 2020-2030 (at the upper end of the forecast range), would result in CO_2 savings of around 140Mt per annum. This would correspond to around 10% of forecast CO_2 emissions in 2030 from electricity generation in the EU15. These figures assume base load operation of future natural gas fuelled fuel cell power stations having an efficiency of 60% and operating 7500hours per year, with no CO_2 capture.

The current relative costs of hydrogen as a transport fuel are indicated in Figure 1. This figure provides an indication of the relative costs and levels of greenhouse gas emissions per unit of energy delivered by various fuels, including compressed and liquid hydrogen, produced by different routes. The levels of greenhouse gases include those released in the production of the fuel, and during its complete combustion under ideal conditions. They do not include variations in its end use due to differences in converter technology and duty cycle.

It can be seen that hydrogen costs delivered to the end user will generally be significantly higher than the costs of current fossil fuel options when fuel excise duty (e.g. energy tax, value-added tax) is excluded. However, hydrogen in some cases (e.g. gaseous hydrogen produced by large scale reforming of natural gas) could be delivered today at a cost excluding fuel duty that would be comparable to, or cheaper than, liquid fossil fuel costs including fuel duty, allowing scope for introducing fiscal incentives.

Gaseous hydrogen similarly produced could also be delivered at a cost (excluding fuel duty) competitive with other alternative fuels, notably bio-fuels. However, if the fossil based hydrogen production were combined with CO_2-capture and seqestration

Figure 1: Specific greenhouse gas emissions supply and use – as a function of vehicle fuel supply costs



Notes:
1. *FAME - Fatty Acid Methyl Ester (biodiesel).*
2. *Non zero emissions from direct renewable electricity routes result from building and erecting the RES equipment, for which the European mix includes a proportion of fossil fuels and therefore GHG emissions.*
3. *End-use efficiencies will affect end cost of transport for the consumer. More efficient technologies like fuel cells could allow competitive transport costs with higher fuel costs.*
4. *Above calculations do not include CO_2 savings and related costs that could result from CO_2 sequestration.*
5. *Gasoline and diesel prices are based on a crude oil price of approximately $25 per barrel.*
6. *Costs of hydrogen from renewable sources will reduce as technology develops.*
7. *Specific greenhouse gas emissions correspond to emissions from **complete combustion under ideal conditions** of 1MJ of the delivered fuel and from any processes used to produce it. This removes variations resulting from final energy conversion in different types of combustion engine. In this sense it is a comparison on a "well to complete combustion" basis.*

in order to reduce greenhouse gas emissions, this would add to the cost of the hydrogen. On the other hand, the cost of hydrogen produced from renewable energy sources will go down as the technology is further developed. In addition, prudent introduction of hydrogen would result in reduced external costs associated with energy conversion in power generation and transport because of reduced air pollution and associated health impacts, and mitigation of extreme weather events caused by climate change.

Greenhouse gas emissions associated with hydrogen produced from renewable primary sources are generally very low, but not necessarily zero. They include elements of greenhouse gas emissions associated with energy consumption from conventional sources for example in hydrogen compression, liquefaction, distribution or storage.

The high conversion efficiency of fuel cells could further reduce the gap between conventional fossil fuels and hydrogen. Furthermore, the environmental benefits of hydrogen could be significant in economic terms, especially considering the potential of zero emissions from renewable sources. The potential for hydrogen production from renewable energy sources is believed to be large, but remains a subject of debate.

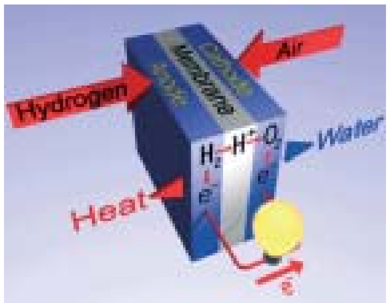
Fuel cell systems

Different fuel cell systems operate at different temperature levels, from room temperature up to 1 000°C, and some can use fuels other than hydrogen – such as natural gas or methanol. Their modular nature means fuel cells can be used over a broad range of applications, from small portable electronic devices to large stationary applications, as well as for transport.

Perhaps most important of all, fuel cells are viewed as a 'disruptive technology' which could dramatically accelerate the transition from our established world to a new, cleaner and more efficient one running on hydrogen. Fuel cells offer considerable scope for innovation and could enable technologies or services not presently foreseen.

However, fuels cells are not yet fully commercial. Considerable investment is still needed in research, development and manufacturing to reduce current high costs and improve functional performance and long-term reliability.

Fuel cells convert fuel and air directly to electricity, heat and water in an electrochemical process, as shown in the diagram below. Unlike conventional engines, they do not burn the fuel and run pistons or shafts, and so have fewer efficiency losses, low emissions and no moving parts. The diagram shows how a single fuel cell works.



Their advantages are:

- high efficiency;
- zero emissions when using hydrogen, and very low emissions when using other fuels (e.g. NOx, CO…);
- mechanical simplicity, low vibration and noise, low maintenance requirements; and
- a high ratio of electricity to heat compared with conventional combined heat and power plants.

Hydrogen and fuel cells for transport

Hydrogen is generally considered the most likely fuel for fuel cell-powered electric vehicles such as passenger cars, light-duty

vehicles, and buses. Hydrogen can be stored on-board a vehicle either in a liquid or compressed state or in metal or chemical hydrides. Fuel cell vehicles could have very low fuel consumption without compromising driveability or comfort. Reduced emissions would improve local air quality and the global environment. Many of the world's major car manufacturers have presented fuel cell vehicles as demonstrations, and are even beginning to lease small numbers of vehicles to the first selected customers.
Fuel cell vehicles have a greater range than battery vehicles, though prototypes cannot yet match conventional vehicles running on petrol or diesel. However, a hydrogen fuel cell vehicle offers advantages over hydrogen-fuelled internal combustion engines or fuel cells powered by other fuels.

Furthermore, fuel cells can also serve as an on-board electrical power source. Fuel cell-based auxiliary power units (APU) installed in conventionally powered cars and trucks, reduce emissions by driving air-conditioning, refrigeration or electrical equipment – especially when the vehicle is stationary.

Fuel cells and hydrogen are equally applicable in water-based transport, where problems of emissions and noise are also significant. Hydrogen fuel cells already provide on-board, silent power – with no heat signature – for submarines. They could provide on-board electrical power and even propulsion for ships, especially in environmentally sensitive areas where only very low, or even no emissions are allowed from boats.

Liquid hydrogen could even have potential for aircraft, as European research has shown, although putting it into practice will take considerable time and investment.

Fuel cells for stationary power

Stationary fuel cells come in a wide range of sizes and types, are constructed using different materials, and operate at temperatures from 60°C to 1 000°C. They can be used in decentralised systems to supply electricity and heat for a range of end-uses – even in domestic units providing power for individual households. They can run directly on natural gas, as well as biogas and hydrogen. Gasified biomass (via fermentation or gasification) seems a likely choice of fuel, as high-temperature fuel cells can convert methane and carbon monoxide either directly or via internal reforming. For low-temperature fuel cells, on-site reforming might be a preferable solution.

Benefits of transport fuel cells:

- Efficiency: Fuel cell cars have demonstrated very high efficiencies when operated with hydrogen, compared both to internal combustion engines and fuel cells coupled with on-board reforming of methanol or gasoline;
- CO_2 emissions and energy security: Fuel cell vehicles using hydrogen offer the greatest benefits over internal combustion engines of the future and over fuel cell vehicles using other fuels, especially when viewed in the context of a longer term transition to renewable hydrogen;
- Regulated emissions: Fuel cell cars have very low emissions, and even zero emissions at the point of use when fuelled by hydrogen;
- Power: Fuel cells can provide on-board electricity with high efficiency. Fuel cell cars could produce (back-up) power for homes, offices, or remote locations;
- Performance and convenience: Hydrogen and fuel cell vehicles could provide similar or improved qualities in terms of performance and convenience;
- Congestion: Silent vehicles could deliver goods at night, taking traffic off roads during the day;
- Comfort: Fuel cell vehicles have a very smooth, refined ride and emit low noise.

Large numbers of stationary fuel cells are being tested in field trials and demonstrations – in single houses as well as in larger applications such as hospitals. In the United States, fuel cells are being used to power military bases.

In common with transport, challenges still lie ahead for stationary fuel cell applications. Research, development and demonstration, combined with the improvement of manufacturing processes, are still required to improve the lifetime, reliability and cost of the systems. In the early stages of commercialisation, fuel cells will penetrate markets where they have unique advantages. Fuel cells used in transport can also be used in some stationary systems. This should allow synergies in research and development. All types of fuel cells are expected to have roles in a future energy economy, especially a hydrogen economy. But for the moment the costs are too high to be competitive with conventional systems in most applications.

Benefits of stationary fuel cells:

- Efficiency: Fuel cells are highly efficient, whatever the size, and have high power quality.
- Emissions: Very low to zero carbon emissions and no emissions of harmful ambient air pollutants such as nitrogen dioxide, sulphur dioxide or carbon monoxide.
- Environment: Low levels of noise and emissions mean fuel cells can be sited in sensitive areas.
- Convenience: Fuel cells can provide both heat and power from a range of fuels; compared to conventional Combined Heat and Power (CHP) systems they operate at a higher power to heat ratio.

Fuel cells for portable power

Fuel cells have the potential to deliver electrical power for much longer periods than batteries in portable applications. The increased use of portable electronic and electrical equipment (mobile phones, radios, laptop computers, PDAs and power tools) could open up a wide range of different applications. Portable fuel cells may be fuelled by hydrogen, methanol, or ethanol. Importantly, increasing the operating time of portable equipment is high on the consumer agenda at the moment and the ability to outperform batteries in this respect could help bring about widespread acceptance of fuel cells. Clearly, for such low energy consumption applications, the potential for greenhouse gas reduction is low in comparison with stationary power generation and transport applications. However, there remains great scope for innovation in this area.

Defence and aerospace applications:

Fuel cells have large potential in defence applications, providing silent power in place of diesel generators, as auxiliary power units for tanks, or producing high levels of power for advanced soldier uniforms. Defence markets are less cost-sensitive than private markets, and can provide an excellent opportunity for technology development and verification. Likewise, aerospace offers the potential for fuel cells in spaceships, where they are already used, and in aircraft for fly-by-wire or auxiliary power requirements.

Challenges lie ahead

The hydrogen energy ‘industry’ is only now beginning to evolve, and both North America and the Pacific Rim countries are in positions of strength in research, development and deployment.

Many of the companies that will take forward hydrogen energy are multinational, and able to develop and implement solutions globally, but Europe will nevertheless require strong leadership and a policy environment in which these industries can thrive.

Challenges for fuel cells:

- Cost: Except in premium applications such as back-up power generation for major financial institutions, fuel cells are generally today too expensive for commercial introduction.
- Lifetime: Some fuel cell systems have been demonstrated for thousands of hours, but the majority must still be proven.
- Reliability: Not only fuel cells, but also supporting equipment such as fuel processors, must be proven.
- Novelty: In most conservative markets, any new technology requires significant support and public understanding in order to compete.
- Technological breakthroughs are needed for simultaneously improving fuel cell performance, reliability and cost.
- Infrastructure: Refuelling, large-scale manufacturing processes and support infrastructures, such as trained personnel, are not yet available for fuel cell systems.

ANNEX I

High Level Group on Hydrogen and Fuel Cells Technologies

Company/Organisation	Person	Position
Air Liquide	Michel Mouliney, then Daniel Deloche	General Manager, Advanced Technologies and Aerospace Division Vice-president Space and Advance Technical Division
Ballard Power Systems	Andreas Truckenbrodt, then André Martin	Vice President and General Manager, Transport Division Managing Director Europe and Transportation Programs Chairman
CEA	Pascal Colombani, then Alain Bugat	Chairman and Chief Executive Officer, President, French Association for the Advancement of Science Chairman, and Chief Executive Officer
CIEMAT	César Dopazo	General Director
DaimlerChrysler	Herbert Kohler	Vice-president for Research Body and Powertrain, Chief Environmental Officer
ENEA	Carlo Rubbia	President
FZ Julich	Gerd Eisenbeiß	Member of the Board of Directors
Iceland	Hjalmar Arnason	Member of Parliament for Iceland
Johnson Matthey	Neil Carson	Executive Director
Norsk Hydro	Tore Torvund	Executive Vice-president of Norsk Hydro and CEO of Norsk Hydro Oil and Energy
Nuvera	Roberto Cordaro	President and Chief Executive Officer
Renault	Pierre Beuzit	Vice-president of Research, Renault SA
Rolls-Royce	Charles Coltman	Chairman and CEO Rolls-Royce Fuel Cell Systems Ltd
Shell	Don Huberts, then Jeremy Bentham	Chief Executive Officer of Shell Hydrogen Chief Executive Officer of Shell Hydrogen
Siemens-Westinghouse	Thomas Voigt	President Stationary Fuel Cell Division
Solvay	Leopold Demiddeleer	Solvay Corporate R&D Director
Sydkraft	Lars Sjunnesson	Director of Corporate R&D and Environment
UITP	Wolfgang Meyer	President
Vandenborre Technologies	Hugo Vandenborre	President and Chief Executive Officer

ANNEX II

High Level Group on Hydrogen and Fuel Cells Technologies: Sherpas

Company/Organisation	Person	Position
Air Liquide	Philippe Paulmier	Marketing Manager
Ballard Power Systems	Arnold van Zyl	Research Delegate
CEA	Paul Lucchese	Hydrogen & Fuel Cells Project Manager
CIEMAT	Pedro Garcia Ybarra	Sub-director General
DaimlerChrysler	Andreas Docter Jörg Wind	Project Manager Fuel Cells Senior manager, Alternative energy and drive systems
ENEA	Raffaele Vellone	Head of Project
FZ Julich	Bernd Hoehlein	Deputy Head of Institute for Materials and Processes in Energy Systems
Icelandic New Energy	Jon Bjorn Skulason	General Manager
Johnson Matthey	Ian Stephenson	Executive Director Environment
Norsk Hydro	Ivar Hexeberg	Vice-president and leader of the Hydrogen Business Unit in Hydro Energy
Nuvera	Alessandro Delfrate	Sales Manager
Renault	Christophe Garnier	Head of Department Energy Systems
Rolls-Royce	Olivier Tarnowski	Principal Technologist
Shell	Chris de Koning	External Affairs & Communication Manager
Siemens-Westinghouse	Klaus Willnow	Key Account Manager, Energy Policy
Solvay	Guy Laurent	Programme Manager
Sydkraft	Bengt Ridell	Consultant
UITP	Laurent Dauby Arno Kerkhof	Manager Programmes and Studies Manager Bus / Industry Division
Vandenborre Technologies	Christian Machens	Co-ordinator European Programme

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European Commission

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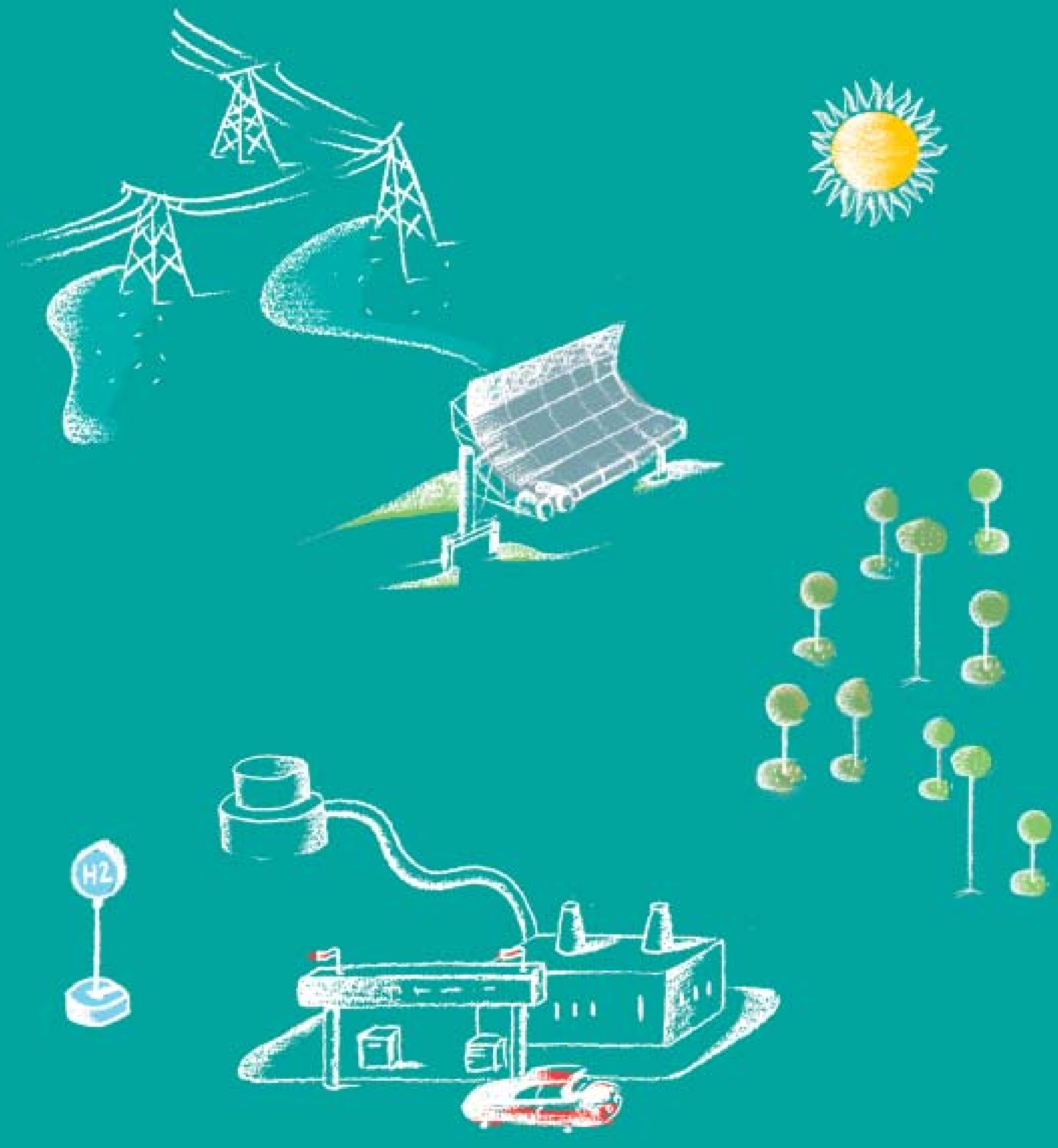
This report of the High Level Group for Hydrogen and Fuel Cell Technologies sets out a vision for these technologies in future sustainable energy systems - improving energy security of supply and air quality, whilst mitigating climate change. The report recommends actions for developing world-class European hydrogen technologies and fostering their commercial exploitation. The High Level Group comprised key stakeholders from industry, the research community and public authorities. It was initiated by Vice President Loyola de Palacio and Commissioner Philippe Busquin, in association with President Romano Prodi.



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