# HYDROGEN ENERGY AND FUEL CELLS –

# A VISION OF OUR FUTURE

## DOCUMENT STATUS

**This is a preliminary DRAFT document. It contains elements and material that may be used in preparing a vision report representing the collective view of the High Level Group. However this process is ongoing and the group reserves the right to modify the report as a result of further internal discussion, or in response to external inputs and advice. These elements are therefore published in early draft form with the intention of soliciting views and contributions from interested stakeholders who have not had the opportunity to participate to the process.**

## OVERALL CONTEXT

The terms of reference of this group focus on identifying the potential contribution that hydrogen and fuel cells can play in the long term to achieving viable, sustainable energy systems in Europe. The report recommends research structures and actions that are needed to develop them, demonstrate their cost-effectiveness, and foster a suitable environment for their commercialisation - within the context of a broader energy strategy. Hydrogen and fuel cells are one of several energy options and pathways and are expected to play an important role.

## DISCLAIMER

This is a draft document, prepared on behalf of the High Level Group on Hydrogen and Fuel cell Technologies. The information and views contained in this draft are still in the process of verification, and are not necessarily the collective view of the High Level Group, or of the European Commission. Neither the High Level Group, the European Commission, nor any person acting on their behalf, is responsible for the use that might be made of the information contained in this publication.

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## HYDROGEN ENERGY AND FUEL CELLS – A VISION OF OUR FUTURE

**Looking forward to a vision of a clean, secure energy future, adapted to Europe's needs and circumstances….**

*In the coming decades hydrogen will increasingly complement electricity as a key energy carrier, unlocking a diverse range of primary energy sources to help solve Europe's and indeed the world's increasing concerns over energy supply and energy security, air quality, and global warming. Hydrogen will become commonly available on fuel station forecourts, in new housing developments, and in large commercial and industrial facilities. It will fuel conventional combustion systems and fuel cells – new energy converters which are highly efficient, intrinsically clean and quiet. Fuel cell vehicles will circulate freely, with the possibility to be refuelled from home, even offering back-up power for homes or hospitals if required. Hydrogen ferries will transfer tourists to remote islands which are self-sufficient in energy, and where hotels and hire cars run on the same fuel, produced entirely from renewable sources. Intelligent buildings will use fuel cells to maximise efficiency of heat, cold and electrical power. As fuel cells become cheaper and more durable, they will offer beneficial options to conventional combustion systems for stationary, mobile and portable power generation.*

*Europe will be a first class player within the integrated world research network – developing and harnessing hydrogen and electricity as complementary energy carriers for our planet, and exporting technology and know-how to help sustainable development around the world. Integrating hydrogen and electricity as energy carriers will enable the intelligent management and efficient usage of a diverse range of primary energy sources. This flexibility will enable Europe to optimally plan and manage its energy security – with the final goal to become energy independent.*

**…..and looking back from this future to understand the transition from today :**

*The arrival of the hydrogen era – in which hydrogen and electricity, are complementary energy carriers - has been the result of careful strategic planning, fostering consensus amongst the main stakeholders. The transition from an energy economy in the year 2000, in which fossil fuels were a dominant energy source has been managed without disruption. Economic prosperity has been maintained, whilst passing through a transition period when declining reserves of liquid and gaseous fossil primary energy sources have been utilised in cleaner and more efficient ways (e.g. natural gas, hydrogen, methanol, synthetic liquid fuels, coal), complemented increasingly by new primary energy carriers such as bio-mass and other renewable sources. Where necessary and appropriate, traditional sources such as coal and nuclear power have been harnessed to produce hydrogen, but employing technologies that are safe and which allow the capture and retention of damaging emissions – such as greenhouse gases and pollutants.*

**With political will this vision can be realised, but it is recommended to put in place:**

- *A European Hydrogen and Fuel Cell Technology Partnership, steered by an Advisory Council, to provide advice, stimulate initiatives and monitor progress*
- *A Strategic Research Agenda, to define research priorities, planning, technical targets and pathways, for delivering competitive, world-class European hydrogen and fuel cell technologies and socio-economic analysis to back political decisions*

- *A Deployment Strategy to move the technology from the prototype stage, through demonstration to commercialisation, by means of large, prestigious, "lighthouse" demonstration projects, integrating stationary power and transport, and forming the backbone of a trans-European hydrogen network, enabling hydrogen vehicles to travel and refuel from Edinburgh to Athens, and from Lisbon to Helsinki*
- *The Frame Conditions that enable the new technologies to gain market entry, within the broader context of future fuel and energy strategies and policies. This should include identification of suitable policy measures, such as financial incentives, education, fostering public-private partnerships, and business development initiatives*

*SAMPLE ILLUSTRATION*

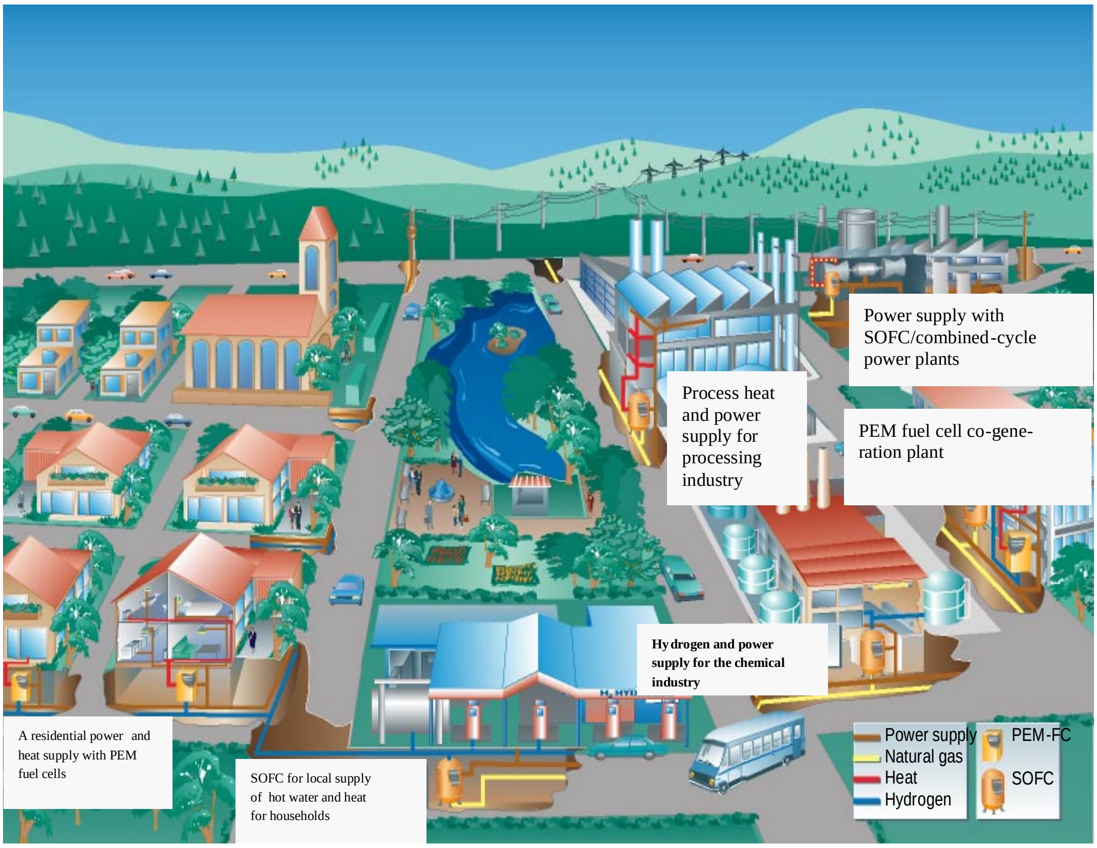


*Figure 1: Schematic representation of future integrated energy system combining small and large fuel cells for domestic and de-centralised power generation with local hydrogen networks which can also be used to fuel conventional or fuel cell vehicles*

# 1. A sustainable energy future

The social and political will to improve our global environment and the need to secure a diverse and sustainable energy supply are the major driving forces behind the vision described in the preface. The technology to achieve such a vision is known - fuel cells powered primarily by hydrogen have the potential to create an integrated energy future in which:

- Hydrogen is a key element in an affordable, equitable, secure and clean European energy system satisfying social, environmental and economic concerns.
- Fuel cells are widely used, providing a more efficient and cleaner alternative to the conventional combustion technologies
- Hydrogen can be produced from a wide variety of locally available resources, opening access to greater use of renewable energy sources, including for transport
- A world class European fuel cell and hydrogen industry leads in the globally emerging markets for hydrogen production, transport, storage and end-use technology.

To achieve this vision within a realistic timeframe, sustained technological innovation would need to be coupled with a continued social, industrial and political commitment. In addition, the necessary framework conditions for the introduction of this new technology should be established while carefully managing the transition period to a de-carbonised energy system.

The transition should be progressive, with cost- and time-effective intermediate steps, which are convergent in the long term. Hydrogen is crucial to this process as, together with electricity, it provides a bridge from today’s largely fossil-based energy sources to tomorrow’s sustainable sources – an “open systems architecture” for energy. It is possible to construct a coherent roadmap for sustainable energy, based on the following stages:

- In the near and medium terms: improve the quality of liquid fuels, and increase the use of natural gas and synthetic liquid fuels based on natural gas, which can be used in conventional combustion systems and fuel cells alike;

- In the medium term: strip out the hydrogen and use it as an energy carrier to effectively de-carbonise these fossil-based energy carriers. The hydrogen thus produced can then be used in suitably modified conventional combustion systems and fuel cells, reducing greenhouse gas and pollutant emissions;

- In the medium and long term : use hydrogen and electricity together as energy carriers to progressively introduce regenerative, or other carbon-free primary sources, such as biological and “new” nuclear energy;

Demand for electricity will continue to grow, and hydrogen will complement it. Electricity consumption is predicted to rise at an annual growth rate of 2.4% over the period to 2030 (World Energy Outlook 2002). Increasingly electricity will be produced from renewable energy sources and, depending on the prevailing socio-economic, regional and climatic circumstances, can be used directly (e.g. in areas with established grids), or used to generate hydrogen by electrolysis. Introducing hydrogen opens interesting possibilities for storing electrical energy both for load levelling and to cope with the intermittent nature of renewable energy systems. It also represents one of the few possibilities for introducing renewable energy sources to the transport chain. These various energy carriers can be used in many different ways, and for different applications. Strategies for commercialisation should be determined by reconciling economic viability (private benefit) with the most cost-effective ways to achieve societal benefits – creating win-win for private and public stakeholders alike.

Fuel cells, which are intrinsically clean and efficient energy converters, are currently the subject of continuing technological development and optimisation. They can be gradually introduced alongside conventional combustion technologies for producing heat and electrical power for stationary and transport applications, bringing significant benefits, as for example :

- if gasoline vehicles were gradually replaced by fuel cell vehicles fuelled by renewable hydrogen, then, for every 10% of the European fleet thus substituted, annual savings of nearly 40 million metric tonnes of $CO_2$ ($MtCO_2$)emissions could be achieved (or $11MtCO_2$, if fuelled by hydrogen from natural gas) ; a *regenerative* hydrogen fuel cell vehicle achieves a 100% reduction in $CO_{2;}$

- stationary power generation by future solid oxide fuel cell systems combined with a micro gas turbine powered by natural gas at 1 MW scale can reach electrical efficiencies of about 60 %, compared to 47 % for today's comparably sized combined cycle plant running on natural gas; annual savings of 50%, or approximately 2500 metric of carbon dioxide emissions, are possible for combined heat and power;

- fuel cells for both stationary and transport emit zero regulated emissions when fuelled by regenerative hydrogen and negligible emissions for methanol, ethanol, natural gas or synthetic diesel;

These examples illustrate the very substantial societal benefits that can be won, provided that the remaining technological barriers are solved by research and development and that an effective deployment strategy is implemented to overcome the non-technical barriers to market entry. The next chapters of this report outline the energy challenge Europe faces, the possible solutions that hydrogen and fuel cells offer, and the necessary steps that need to be taken at European level for introducing and commercialising them.

This vision of using hydrogen and fuel cells can bring substantial societal benefits in the future and can certainly come true – but to achieve it in a realistic timeframe requires political strength, industrial and social commitment and innovative technical solutions..

# 2. The Energy Challenge

Worldwide, increased quality of life is the basic driver for improving energy supply. Increased quality of life is correlated with widespread access to the goods and services that energy enables. A key ambition for Europe is to realise secure, clean, safe, reliable and affordable future energy systems, accessible to all. Hydrogen and fuel cells, integrated with conventional energy systems, can make a substantial long term contribution to this goal.

## The Energy Situation

While economically recoverable supplies of fossil energy will diminish, total energy demand in Europe for all energy end-use sectors is predicted to continue rising, as illustrated by the graph, Figure 2,.

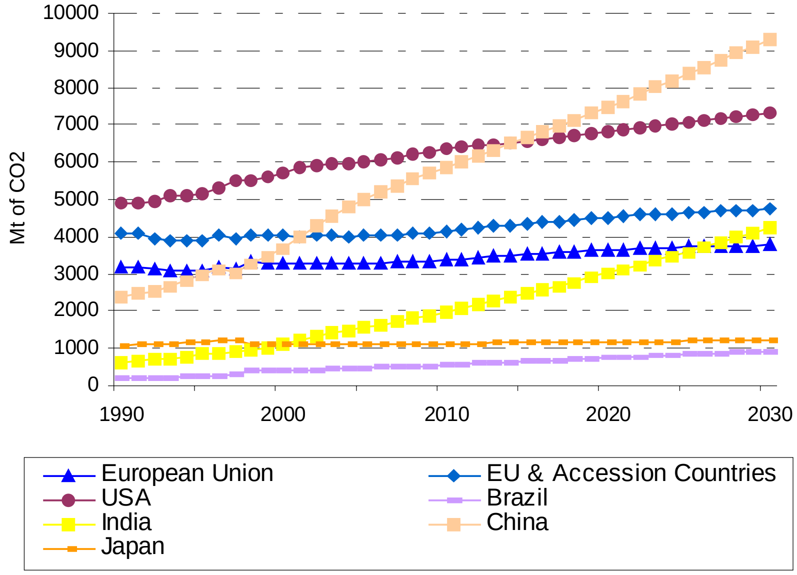


*Figure 2: Forecast World Energy-related $CO_2$ emissions (European Commission, DG Research, "World Energy Technology and Climate Policy Outlook - 2030", OPOCE, Luxembourg, 2003.*

More people will drive and fly further, and both increased access to energy and EU expansion will create new demand for stationary power. An increase in energy related $CO_2$ emissions of 20% is predicted for the period 2000 to 2030, for the EU alone, as well as for the EU plus new Accession States (NAS). These forecasts correspond to the “business as usual” scenario, where no particularly strong policy measures are implemented to combat growth.. The forecast growth in CO2 emissions for the developing industrial nations such as China and India is especially significant.

In Europe, most electrical energy is produced in large centralised power plants, fired by coal, gas or uranium and distributed via the grid. Around 13% of electricity is produced in a distributed manner from renewable sources like hydropower, solar power and wind energy. The European Union has committed to increase this share to 22% by 2010, although progress in this direction needs to be accelerated. Currently, central power plants provide the base load back-up to ensure a reliable and stable energy grid.

Energy for heating comes mainly from burning oil or gas, whereas energy supply for transport is almost exclusively from oil, with around 35% originating from the Middle East. Conventional oil is expected to reach its production maximum in the coming decades, and alternatives may come at much higher prices than today..

The majority of the population in prosperous, modern industrial societies takes for granted the apparently unlimited and virtually uninterrupted supply of cheap energy to their homes, vehicles and workplace. Yet, during the last thirty years, there have been several significant interruptions to energy supply that have demonstrated the potential to profoundly disrupt our comfortable, daily lives. Fortunately these disruptions have been relatively short-lived, and there was a speedy return to "business as usual".

The fact remains that in the next decades, both developed and developing nations, will compete for diminishing finite resources of fossil energy, which to date have provided the bulk of Europe's energy needs, firstly in the form of coal, then oil and natural gas. Inevitably, prices will rise, heralding the end of cheap energy as we know it. Although expert opinion varies on when and how rapidly this will happen, it is surely time now to start long and detailed planning for this future, avoiding false starts and economic disruption, by gradually introducing new sources of affordable clean energy, along with more efficient energy converters. As European economies grow with enlargement, centralised and de-centralised systems will have to be integrated into a single, liberalised energy market with integrated energy networks. Flexible, open system architectures will be required.

Europe has access to vast renewable energy resources that could be harnessed to provide heat and power and fuel for transportation, using hydrogen and electricity as complementary energy carriers. Hydrogen can be used both directly or to buffer store intermittent renewable electricity to balance supply and demand. Hydrogen, because it opens access to new and renewable energy sources, and fuel cells, because they are intrinsically cleaner and more efficient than conventional energy converters, offer great promise to meet the challenge of supplying affordable sustainable energy in the enlarged market.

Energy consumption in Europe is growing. The projected increase in demand, especially in developing industrial coutnries, coupled with the risk of energy supply instabilities worldwide and the environmental necessity of both greenhouse gas and local emissions reductions, increase the urgency of making structural changes in the energy supply and conversion systems in Europe.

Apart from introducing measures to promote more efficient use of energy, energy conversion systems must be improved, and the energy used should contain a growing fraction of carbon–free energy sources and carriers: hydrogen and electricity.

Europe cannot afford to wait until this transition is forced upon it.

## **Fulfilling the needs of society**

Europe requires an energy system that meets the needs of the population across all sectors, ensuring economic competitiveness, yet with as few negative consequences as possible. There is uncertainty as regards the severity of the consequences on the economy, the environment and public health of global warming, harmful pollutants, finite oil supply and other factors. It is therefore unclear what will be "good enough". The very fact that the predicted effects of climate change are potentially extremely serious and moreover irreversible, means that Europe cannot afford to wait for them to happen before implementing remedial action. It must aim for the ideal – an emissions-free, sustainable energy future built on electricity and hydrogen produced from de-carbonised, or preferably carbon-free sources which addresses the key challenges symbolised in the sustainability triangle in Figure 3.

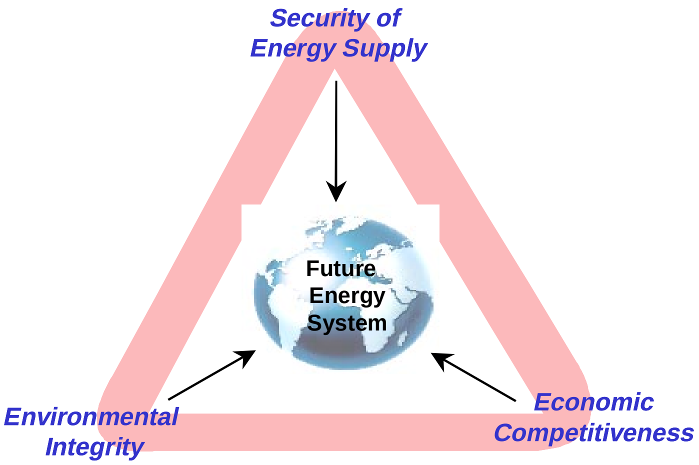


*Figure 3: The sustainability triangle*

Hydrogen and fuel cells will become a key part of the future energy system, at the centre of the sustainability triangle, because they can address the key challenges:-

- **Energy Security:** A high quality of life is increasingly considered to depend on unrestricted mobility, and unlimited availability of heat, refrigeration, and electrical power. In turn, these increasingly depend on the uninterrupted availability of fossil fuels. The fact that hydrogen can be produced from a diverse range of different resources means its availability and price should be more stable than any single energy source.
- **Environmental Integrity: CO2 Reduction:** Hydrogen can be produced from carbon-free energy sources (including nuclear), or from fossil fuels with $CO_2$ capture and sequestration, and converted in efficient fuel cells to reduce and eventually eliminate greenhouse gas emissions, from the energy sector; **Air quality and health improvements:** Hydrogen offers the potential for zero emissions transport and stationary power generation. The global trend of urbanisation only emphasises the need for clean solutions to urban problems, to improve the quality of life in cities. Whilst zero-emission and greenhouse gas free power generation is also possible from electricity produced directly from nuclear and renewable sources, hydrogen and electricity together allow possibilities for load levelling and buffering intermittent supply.
- **Economic Competitiveness:** Energy is linked inextricably to economic growth, though the amount of energy needed per unit growth must be reduced. Development and sales of energy systems are also a major component of wealth creation, from cars to power stations. Developing, producing and selling new hydrogen and fuel cell energy technologies to meet the first three requirements can also enhance economic growth as well as avoid their importation from competitors in future. There is strong international competition, as evidence by the US Freedom Fuel and Freedom Car programmes, and the Japanese fuel cell commercialisation programme.

What is of particular interest regarding hydrogen is that it can address each of the concerns raised above without compromising the others - unlike many alternative solutions. Whilst there have been several attempts in the past to introduce hydrogen as an energy vector, there has never been the same confluence of political and technical drivers all occurring at the same time.

Hydrogen energy, produced from non-fossil sources, can help to simultaneously address concerns on climate change, air quality and energy security, without the need for compromise.

# 3. Technologies for Meeting the Energy Challenge

## Hydrogen and Electricity Pathways: complementary and clean energy carriers that access both conventional and renewable primary energy sources

Hydrogen is an energy carrier, or vector and not a primary energy source. This means it can be made from a wide range of (locally-available) resources, including renewable, fossil and nuclear. It is always found only in compound form – in water, oil, natural gas and biomass, for example. Electricity – another energy carrier - can be used to electrolyse water to produce hydrogen. Hydrogen offers great flexibility, since a mix of primary energy sources and carriers can be used to produce it. However, it will always be more expensive per energy unit than the energy source used to produce it. Hydrogen can be used both very efficiently and very cleanly for example in fuel fuel cells. The end service it provides can be cheaper or better than the alternative sources used directly.

Hydrogen is also a very light gas, so storing and transporting it can be wasteful – using energy and adding cost. Until a widespread infrastructure is established, hydrogen may not be transported long distances, but must be produced and used in *distributed* energy and fuelling systems, close to the point of demand. Some of the many possible sources of hydrogen are shown below in figure 4.

Technologies for hydrogen production, storage, transportation and use are widely available – mainly in the context of chemical process and petro-chemical industries. They are not focused on meeting the requirements of hydrogen as an energy vector.

DIAGRAM UNDER PREPARATION

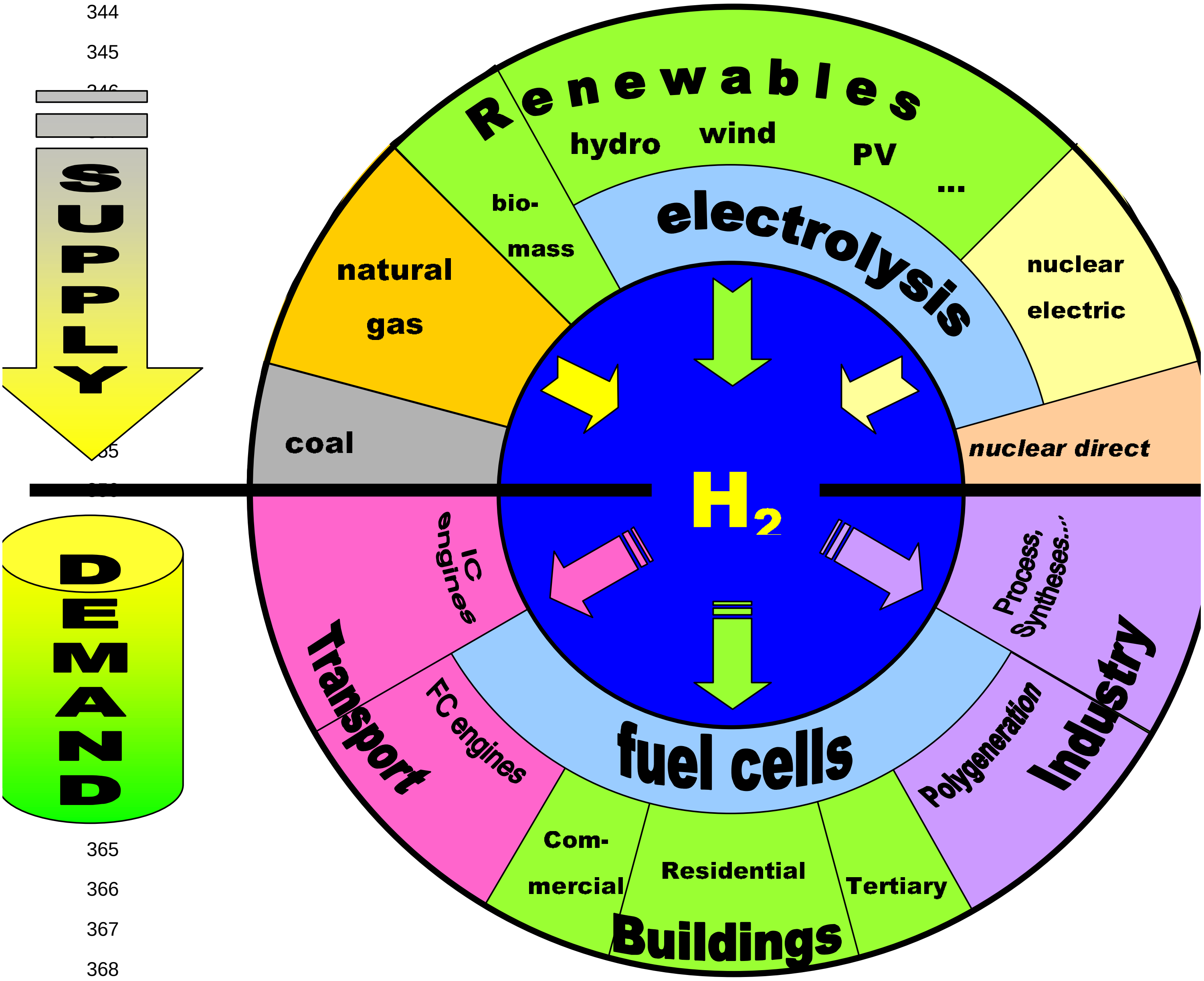


*Figure 4: Hydrogen: primary energy sources, energy converters and applications*

*Note - Sizes of “sectors” have no connection to their real or expected market sizes.*

**Hydrogen production**

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

Important technologies for hydrogen production are mostly at large scales. Before a hydrogen energy system is fully proven and fully introduced, many demonstration and pilot projects will be focused on a small geographical area. Instead of large-scale industrial equipment, small-scale production technologies, including steam reformers and electrolysis units, will be needed. Many organisations are developing technologies specifically applicable to this scale. The table below compares some hydrogen production routes.

| 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 H2 from renewable electricity, compensates for intermittent nature of some renewables | Electricty prices strongly impact the cost of the hydrogen produced;<br>efficiency of whole chain;<br>competition with direct use of renewable electricity ; |
| *Steam reforming*: splitting hydrocarbon gases with heat and steam | Well-understood at large scale; widespread; low-cost hydrogen; CO2 sequestration at large scale | Small-scale units not commercial; hydrogen contains some impurities; CO2 emissions; primary fuel may be used directly |
| *Gasification*: splitting heavy hydrocarbons and biomass into hydrogen and gases for reforming | Well-understood at large scale; can be used for solids and liquids | Small units very rare; hydrogen usually requires extensive cleaning before use; biomass gasification still under research; in competion with synthetic fuels from biomass; |
| *Themochemical Cycles* using cheap high temperature heat from nuclear or concentrated solar energy | Potentially massive production at low cost and without GHG emission for big heavy industry or transportation<br>High efficiency process(near 50% from total primary heat)<br>International collaboration (USA, Europe and Japan on research, development and deployment. | Not commercial, research and development needed over 10 years on the process: materials, chemistry technology;<br>High Temperature nuclear reactor (HTR) deployment needed.<br>Hydrogen infrastructure needed for transportation application. |
| *Biological production*: algae and bacteria produce hydrogen directly in some conditions | Potentially large resource; no feedstock required. | Slow hydrogen production rates; large area needed; most appropriate organisms not yet found; still under research; |

## Hydrogen storage

Hydrogen storage is commonplace in industry, where it works safely and provides the service required. However, to achieve a comparable driving range compared to modern diesel vehicles, a breakthrough in on-board vehicle hydrogen storage technology is still required. Innovative vehicle designs could help overcome current drawbacks. Significant research and development is underway, 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 metal hydrides, chemical hydrides and carbon systems require further development and evaluation.

| Hydrogen storage technology | Benefits | Barriers |
|---|---|---|
| *Compressed cylinders*: hydrogen is stored at high pressure in a metal or composite tank | Well-understood at low and medium pressure; generally available; can be low cost | Small amount of hydrogen stored at low pressures; high pressure still in development; heavy; energy stored still not comparable to liquid fossil fuels |
| *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 stored still not comparable to liquid fossil fuels |
| *Metal hydrides*: | Some technology available; solid state storage; can be made into different shapes | Heavy, low energy storage density; can degrade with time; currently expensive |
| *Carbon structures*: | May allow high storage density; light; may be cheap | Not fully understood or developed; early promise remains unfulfilled; |

## **Hydrogen end-use**

Hydrogen can be burned in conventional systems to provide heat, or to drive turbines, or in internal combustion engines for motive and electrical power. Many of these technologies are quite mature, though improvements in materials will help them work better and last longer. Hydrogen internal combustion engines in vehicles may also provide an important route to enable hydrogen introduction as other technologies develop.

## **Hydrogen Infrastructure**

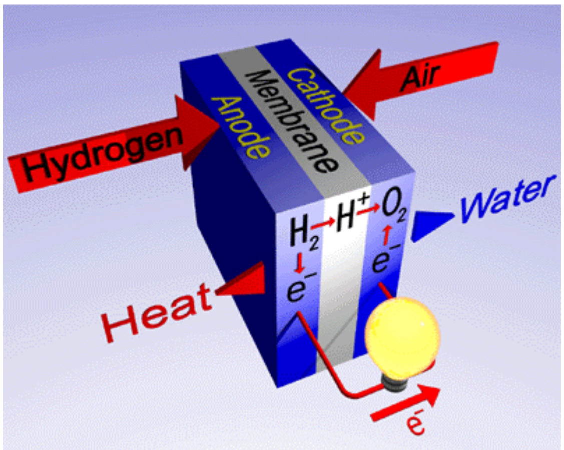
Infrastructure is required for hydrogen production, storage, and distribution, and in the case of transport, special facilities will be required for vehicle refuelling. This has implications for land-use planning, and safe production, operation and maintenance of hydrogen facilities.

The use of hydrogen in any transport mode will depend on the successful development of an affordable and widespread fuelling infrastructure. Currently, only a few hydrogen refuelling stations exist worldwide. 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 transport could also come early in the development of an infrastructure.

Other issues must also be addressed. Trained maintenance personnel, educated 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.

## Fuel Cell Systems

Fuel cells convert fuel and air directly to electricity, heat and water in an electrochemical process, as shown in the schematic 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 to fail. The schematic shows how a simple fuel cell works.



Their advantages are:

- high efficiency, and hence low greenhouse gas emissions
- zero emissions when using hydrogen, and very low emissions when using other fuels
- mechanical simplicity, low vibration and noise, low maintenance requirements
- a high ratio of electricity to heat compared with conventional combined heat and power plants

Different fuel cell systems operate at different temperature levels, from room temperature up to 1000°C, and some can use fuels other than hydrogen directly – for example, natural gas, or methanol. Their modular nature allows 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 importantly, 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.

## Hydrogen and Fuel Cells for Transport

Hydrogen can be envisaged as the dominant fuel for fuel cell-powered electric vehicles like passenger cars, light duty vehicles and buses, making clean and quieter transport possible. Hydrogen could be stored onboard the vehicles either in a liquid or compressed state.

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 fuel cell vehicle using hydrogen offers the greatest advantages, compared either with the internal combustion engine of the future or with fuel cells using other fuels. Furthermore, fuel cells can also serve as an on-board electrical power source – an auxiliary power unit (APU) for conventionally powered cars and trucks, enabling significantly cleaner and more efficient use of the combustion engine for propulsion, especially in congested traffic.

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

Liquid hydrogen could even be an important fuel for aircraft. Ongoing European research has proved its potential, though putting it into practice will take considerable time and investment.

**Benefits of transport fuel cells:**

- Efficiency: fuel cell cars have demonstrated very high efficiencies when operated with hydrogen;
- CO2 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
- Regulated emissions: fuel cell cars have very low, even zero emissions, when fuelled by hydrogen
- Power: Fuel cell cars can provide on-board electricity with high efficiency
- Performance: Fuel cell electric drivetrains have high acceleration
- Congestion: Silent vehicles could deliver at night, taking traffic off daytime roads
- Comfort: Fuel cell vehicles will have a very smooth, refined ride and very low noise
- Convenience: Hydrogen cars could be refuelled on hydrogen produced at home
- Power: Fuel cell cars could produce power for homes, offices, or remote locations

## Fuel Cells for Stationary Power

Stationary fuel cells permit high efficiency, low emissions energy generation over a wide range of sizes. Several different types of stationary fuel cells exist, using different materials and running at temperatures from 60°C to 1000°C. They can be used in decentralised systems to supply electricity, hot water and heat – even in very small units for individual households.

For stationary applications, natural gas can be used immediately as a fuel, with biogas and hydrogen in the long run. For stationary use, gasified biomass (via fermentation or gasification) seem to be the more likely fuels as high temperature fuel cells can convert methane and carbon monoxide either directly of via internal reforming. For low temperature fuel cells onsite reforming might be the preferable solution.

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 Sates, fuel cells are being used to power military bases.

As with transport, challenges still lie ahead for stationary fuel cells. 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. The fuel cells used in transport can be used also in some stationary systems. This should allow synergies in research and development. All types of fuel cell are expected to have roles in a future hydrogen economy.

**Benefits of stationary fuel cells:**

- Efficiency: Fuel cells operate with high efficiency, independently of size
- Emissions: Low noise and polluting emissions means fuel cells can be sited in sensitive areas
- Convenience: Fuel cells can provide both heat and power from a range of fuels

## Portable

Although their contribution to greenhouse gas emissions reduction and air quality is not direct, fuel cells in portable applications could provide electric power with a much longer operation time than batteries. The increasing electrification of personal equipment (mobile phones, radios, lap- and palmtop computers, power tools, etc.) could open up a wide range of very different applications. Portable fuel cells will probably be fuelled by hydrogen or methanol, or ethanol which is abundant in Europe. Importantly, portable systems with long operation time are strongly in demand and compete with high cost batteries, so this market could help bring fuel cells into widespread acceptance. Clearly, for these low energy consumption applications, the potential for greenhouse gas reduction is low, compared to stationary and transport applications. However, there is great scope for innovation in this area, such as direct ethanol fuel cells and micro-fuel cells.

### 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 proving. 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 for fuel cells:

- Cost: All fuel cells are currently much 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 to compete
- Fundamentals: In some areas, scientific breakthroughs would be most beneficial in 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

## Understanding the benefits

The benefits of hydrogen and fuel cell energy systems will be felt most once widespread introduction has occurred, which will take time. The International Energy Agency has suggested that supportive policies could enable fuel cells using natural gas to produce 6% of OECD power by 2030. Greenhouse gas reductions compared with conventional technologies could lie between 40MtC and 200MtC. Other studies suggest that if hydrogen technologies are supported by strong policies, by society and by technical development, in 2020 Europe could have 10 million vehicles powered by hydrogen. Although that number corresponds only to 5% of the overall vehicles in Europe it equals 12% of new vehicle sales. This could reduce $CO_2$ emissions by up to 20MtC.

## Defining Europe’s ambitions

Europe has the skills, resources and potential to lead the world in supplying and in deploying hydrogen technologies. Its diversity offers enormous strength if it can be harnessed and strategically guided. Of course, other areas of the world have similar ambitions, and international co-operation will be essential to maximise benefits from a future hydrogen society. Europe must work together with both developed and developing countries, to produce options for energy and transport that can be truly sustainable, and perhaps enable a ‘leapfrogging’ in developing countries that bypasses current conventional technology.

In the long term, fuel cells and other hydrogen technologies have huge market potential, and competition to introduce them is strong. Many emerging economies are trying to gain market share by focusing on new technologies rather than on trying to catch up on old ones. As new members join the European Union, more diversity in skills, resources and production cost bases could assist in developing the hydrogen technology market.

## Challenges lie ahead

In harnessing European potential to develop and implement a hydrogen economy, substantial challenges must be addressed. These encompass the technical issues described above, the strategic research and development requirements in chapter 3, and the policy environment and deployment strategy outlined in chapter 4. 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. Of course, many of the companies that will take forward hydrogen energy are multinational, and can develop and implement solutions globally, but Europe will nevertheless require strong leadership and a policy environment in which these industries can thrive.

# 3. What can Europe do?

Europe has the resources, the skills and the potential to move towards a hydrogen era. However, the current policy framework, research and development are fragmented both within and across the different countries. It will take time, investment, leadership and a coherent strategy to achieve the three strands of Europe's vision:

- Leading from a technical and industrial perspective
- Leading from a sustainable energy and environmental perspective
- Leading from a political perspective

The strategy itself must contain three key elements, closely interlinked:

- Research and development
- Demonstration and deployment
- Policy support and the enabling environment

Ensuring a sound research base is a key priority, both to support European industry in developing technologies, and to support uptake of those technologies. A cross-cutting strategic research agenda must meet the technical, economic and social challenges facing the new technologies, while continuing to move towards the final goals of social benefit and economic prosperity.

## Elaborate a Strategic Research Agenda for hydrogen and fuel cell technologies

Today's technologies show great promise, but are not yet adapted to mass production, and so are neither cheap enough nor sufficiently durable to be competitive with conventional technologies which have benefited from decades of development and optimisation. There is strong international competition. A Strategic Research Agenda is required to achieve and maintain leadership, drawing together the best available resources and research groups in Europe today. Research in basic science needs to be mobilised to provide in-depth understanding of phenomena that inhibit performance.

Increased research effort is needed across the spectrum of product and process development, from focused fundamental research, through process and component-level development, to complete systems integration, aiming to promote synergies between applications and infrastructure. This should be linked with a comprehensive programme of socio-economic research, directed at providing policy-makers with cost-benefit analyses and modelling tools to support rational decision making – e.g. to provide the basis for graded incentive schemes to classify and promote promising technologies. The research agenda should also define a framework for economic and environmental impact assessment, validated where necessary by scientific measurement (e.g. performance benchmarking). The elements and drivers of the strategic research agenda area illustrated schematically in Figure 5, with the aspiration to deliver world-class technology.

DIAGRAM UNDER PREPARATION

*Figure 5: Key elements and drivers of a Strategic Research Agenda*

*Closing the research /demonstration/exploitation loop*

Links also need to be made between technical research and demonstration. Research results need to be fed forward to ongoing demonstrations so that they may be validated in rigorous field tests. Conversely, the results of demonstrations need to be fed back to re-focus research where it is most needed – thus creating a closed cycle of innovation, demonstration and validation, with opportunities for exit routes for exploiting mature technologies.

*The stakeholders*

Setting the Strategic Research Agenda therefore requires co-operation between a broad range of stakeholders including academe, national and contract (private) research centres, industry, end-users, civil society, and public authorities at all levels – local, regional and European. There must be interest to participate in the creation of public/private partnerships, as this will drive the way forward to creating a favourable business environment to attract private investment and commercialisation. There should also be opportunities for SMEs, which often have favourable dynamics and lean structures for driving innovation.

Implementing a European Strategic Research Agenda will bring substantial benefits that can be addressed only, or most cost-effectively, at European level. The Strategic Research Agenda should be developed to include:

*Actions which are necessary because of the diversity of Europe's economic and political circumstances*

- Clearly define overall objectives for the Strategic Research Agenda, in terms of European economic, environmental, mobility and industrial policy goals;
- Set ambitious targets that reflect the best available technologies and ensure strong competition;
- Bring in the diversity of geographic, climatic, energy supply, economic and market conditions that need to be addressed in the product development cycle;
- Analyse the options and recommend fuel pathways for hydrogen production and fuel cell fuels that reflect regional variations and availability of primary energy sources in Europe today and over the next decades

- Harmonise benchmarking and test procedures, enabling transparent comparative assessment of competing technologies;

*Actions to promote European excellence in the fields of hydrogen and fuel cell research*

- Provide a prestigious forum for drawing together the best research groups and facilities;
- Create critical mass that matches the strongest international competitors;
- Rationalise effort so that wasteful duplication is avoided;
- Identify Europe's research strengths and weaknesses by means of technology mapping and analysis,
- If necessary, propose remedial action at European level to achieve world-class status – perhaps including the establishment of specific centres of excellence in key fields;
- Analyse opportunities and formal or informal ways to link national programmes or sub-programmes, and the European Commission Framework Programme
- Assess the benefit and interest in establishing a coalition between national programmes under Article 169 of the Sixth Framework Programme, or using other programmes such as Eureka;
- Create opportunities for training first class researchers, including international exchanges;

*Research to stimulate a favourable environment for innovation and business development*

- Analyse synergies between different applications and infrastructure so as to create long term opportunities for modular solutions addressing more than one market, e.g. development of low cost automotive products, could be used to advantage in stationary applications, leading to reduced development effort and maximising scarce resources.
- Undertake socio-economic impact assessment to guide industrial development strategies and development of human resource
- Investigate the requirements for fostering a European component supply chain (largely non-existent today) for fuel cell systems and recommend actions to develop it;
- Analyse the role of small and medium enterprises (SMEs) in driving forward innovation and create a favourable research environment for them to develop
- Pre-normative research in support of harmonised standards, regulations and test procedures

*Research on defence applications for fuel cells and hydrogen*

Fuel cells being very efficient, multi-fuel, and near silent energy converters are a dual use technology for defence and civilian applications. Defence applications, whilst less cost-sensitive are often very demanding in terms of performance specifications – e.g., robustness and operation in harsh environments. In the early stages of commercialisation, with sub-critical markets, the opportunities for synergistic civilian and defence applications should be investigated, both to stimulate high product performance and increase market. These include stationary and small portable (including miniature) power generation, land vehicle, maritime and submarine propulsion. A specific area of interest for defence applications will be multi-fuel processors capable of reforming logistics fuels to hydrogen.

*The Strategic Research Agenda : programme content and projected deliverables*

Results and deliverables should reflect specific European characteristics (e.g. current and future projected energy mix in Europe), as well as broader international targets, to ensure European technology will be internationally competitive.

Socio-economic research will also have a profound bearing on the successful introduction of hydrogen and fuel cell technologies. A range of socio-economic factors, including education and public acceptance, affect the success of any new technology. Research in this area, coupled with a long-term education programme will be required to support the introduction of hydrogen and fuel cells

Different alternatives exist for the development of a delivery infrastructure for hydrogen as an energy carrier. The existing power and natural gas grids may form part of the solution, or more innovative and dedicated technologies may emerge. Solutions will depend upon local conditions and competing alternatives. The policies, economics and technologies affecting different solutions must be evaluated within a coherent framework.

*The Strategic Research Agenda should develop a programme capable of delivering :*

Target setting, technical benchmarking, economic appraisal and socio-economic impact assessment

- Ambitious but realistic cost and technical performance targets to drive technology development on a technology-neutral basis (e.g. not specifying specific energy converter technologies);
- Results of prototype validation and technical benchmarking;
- Results of scenario analysis and econometric modelling, indicating the cost-benefits and most cost-effective combinations and routes to commercialising fuel cells and hydrogen, including use of conventional fuels and energy converters and investigation of alternative scenarios for transition strategies;
- Environmental and energetic impact assessments of alternative pathways for producing hydrogen for decentralised generation, domestic and transport applications, including hydrogen production from fossil (with $CO_2$ capture and sequestration), nuclear, renewable and novel, non-conventional sources;
- Techno-economic and investment appraisal of options for developing a hydrogen fuelling infrastructure for stationary and transport applications including for example, distribution by tanker, pipeline and stand-alone remote “hydrogen villages” with local hydrogen networks;

*Principal results :*

*Agreed technical performance and cost targets to stimulate and monitor technical research;*

*Short list of most cost-effective options for pathways (including transition) for producing hydrogen*

Focused fundamental and applied technical research

Successful R&D is based on knowledge and insight, and systematic analysis and synthesis of underlying physical and chemical principles. Trial and error approaches very rarely achieve the substantial improvements needed. The strategic research agenda should identify in detail priorities for focused fundamental research where basic materials research, or in-depth modelling studies are required to achieve technical breakthroughs to overcome technology bottlenecks. Successful innovation in these key areas could avoid importing technology in future, create opportunities for wealth creation in Europe, and accelerate penetration of hydrogen technologies. Of course, real inventions cannot be guaranteed, but a favourable environment and conditions for inventions can be created. Our most promising junior scientists should be encouraged to focus on these problems. Key areas for research can be identified:

*Focused fundamental research*

- Analytical modelling tools validated with experimental analysis to foster a deep understanding of fundamental physical, chemical and electro-chemical principles, governing performance and durability of fuel cell and hydrogen technologies;
- Fuel cell reliability, longevity, operating temperature and costs are fundamentally linked to the basic materials of fuel cells, the core technologies being the electrolytes and catalysts. Innovations in these fields could solve most current technical problems, reduce costs and gain European leadership.
- New, carbon-free low cost methods for small and large-scale hydrogen production are required. Candidate processes include biological processes, thermo-chemical cycles, water splitting
- Improved on-board vehicle hydrogen storage technology able to store similar amounts of energy by mass and by volume to gasoline would immediately solve two problems: the currently limited range of hydrogen vehicles and the cost-effective transport and distribution of hydrogen. Cost–effective and efficient large scale hydrogen storage is also required for stationary applications to buffer intermittent renewable energy supply.

*Applied research*

- Process development designed for low cost, reliable and consistent series production of key technologies, e.g. for hydrogen storage, fuelling infrastructure, control systems, and fuel cell components such as membranes, bi-polar plates
- Component and system design of hydrogen and fuel cell systems. Within systems, the operation of new technologies coupled with old must be tested in integrated systems. Successfully linking wind power, electrolysers, hydrogen storage and fuel cells, for example, will require not only the successful functioning of each component, but also a detailed understanding of control systems, power electronics, and other characteristics of the system.
- Development and optimisation of hydrogen combustion engines, aiming at improving efficiency and power density and reducing emissions;
- Hydrogen safety must be ensured, and codes and standards put in place to enable simple and well-structured procedures for demonstration and deployment of hydrogen technologies. Hydrogen can be considered as safe in many ways as other fuels used today. However it has different characteristics and requires different safety measures. Research and development is will identify and classify risks and ways to manage them, so that hydrogen can be widely introduced.

*Principal results :*

*Fuel cell system technologies that meet competitive cost, performance and durability targets for stationary and transport applications;*

*Hydrogen production, storage and distribution systems meeting environmental, efficiency, and cost targets over the whole pathway from primary source to end-use;*

Recommendations for implementing the Strategic Research Agenda

The implementation of the Strategic Research Agenda should draw on various instruments for supporting research, such as public-funded national and regional research programmes, and the European Framework Programme for Research. It should, where possible and appropriate, build on ongoing European agreements, initiatives, projects, and thematic networks which have a strategic dimension. The timelines and expected deliverables from these initiatives (see box insert) should be determined and taken into consideration in developing the Strategic Research Agenda.

**Strategic Research Agenda should draw together results and recommendations from already established initiatives and projects, including :**

1. Alternative Fuels Contact Group – group established by DG Transport and Energy to analyse prospects and strategies for introducing alternative motor fuels, including bio-fuels, natural gas and hydrogen
2. International Energy Agency – implementing arrangements for hydrogen and fuel cells
3. HYNET – thematic network for hydrogen
4. EIHP II – project concerned with harmonising regulations and standards for hydrogen fuelled vehicles, infrastructure and refuelling connectors;
5. SOFCNET – thematic network to advance Solid Oxide Fuel Cell Technology
6. FCTESTNET – thematic network for developing common approaches for bench and field testing of fuel cells for stationary and transport applications
7. CUTE and ECTOS – demonstration project of 30 compressed hydrogen fuel cell buses in 10 European cities, evaluating different pathways to hydrogen production
8. FUERO/FUEVA – automotive industry led cluster project developing fuel cell components and systems, drivetrain simulation tools, and test procedures for fuel cell cars and buses;
9. NFCCPP – component industry led project for developing modular software for simulating individual fuel cell components and systems;
10. National project…….

In drawing up the Strategic Research Agenda, specific implementation measures should be considered:-

- Designate a number of strategic European real or virtual centres of excellence acting as focal points for critical research, including for example, safety and standards research, high temperature membrane development, catalysis, fuel processing, hydrogen storage and novel methods for hydrogen production.
- Validation projects will ensure that research is both fundamental and applied and that key issues are addressed as priorities. Prototype validation is necessary to develop technologies to a stage where they can enter into demonstration and pilot projects as part of the deployment phase.
- Rules on intellectual property provisions, consistent with public interest, should be reviewed and modified to address industry needs concerning co-operative international research. This should boost co-operation programmes.
- International co-operation should be encouraged and facilitated, especially where it can accelerate market development (e.g. globally harmonised test procedures, standards and regulations).

*Defining the timeframe*

The Strategic Research Agenda should be developed to include short, medium and long-term actions. There should be sufficient flexibility to re-orient goals and priorities according to changing circumstances and progress against specified milestones and decision criteria

It is envisaged that research and development on hydrogen, the different fuel cell technologies, and applications will initially follow parallel streams. These will reflect the specific technical challenges and near term bottlenecks in each field, identified above. However, synergies between fuel pathways, infrastructure, and different fuel cell applications should be identified early on and the development paths should come together in the medium to long term, as illustrated in Figure 6 below. The goal should be to move towards modular solutions and systems integration, facilitated by ambitious demonstration projects.

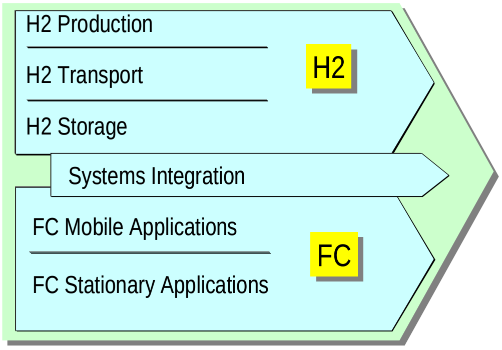


*Figure 6: R&D paths, initially focusing on bottlenecks, start to converge in large scale integrated systems*

Nevertheless, priorities should be set for research, development and demonstration, and some fundamental ones are given below in the research timeline:

DIAGRAM UNDER PREPARATION

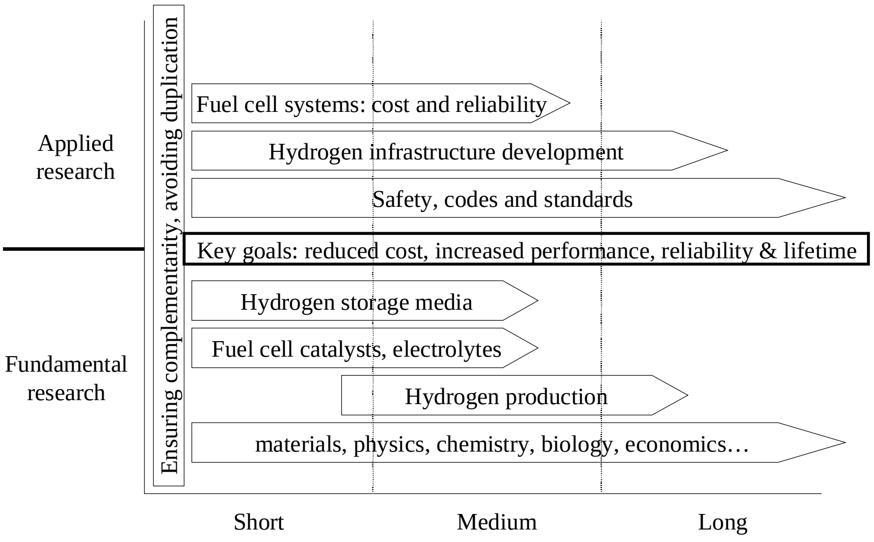


*Figure 7: A research timeline*

A substantial increase in research and development effort will be central to realising the vision of the hydrogen era. This should be co-ordinated at European level, bringing together key stakeholders to define common research goals and set priorities and timelines for implementing a focused research programme with clearly specified technical performance targets, decision points, and pathways to development, technology transfer and exploitation.

## Elaborate a Strategic Deployment Plan to steer the transition to commercialisation

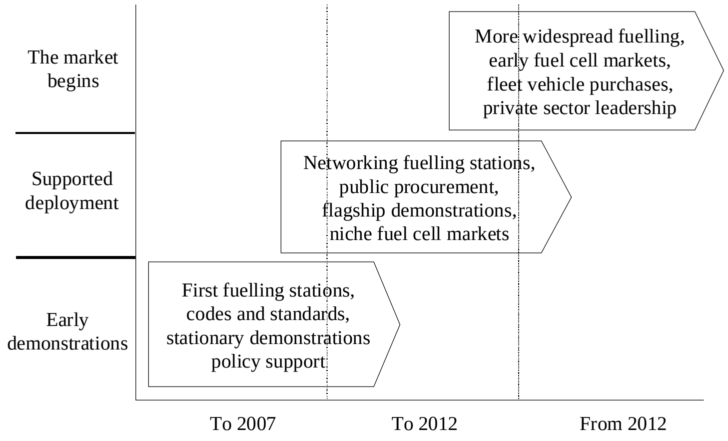
The initial benefits arising from the commercialisation of hydrogen and fuel cells will mainly be on the "public reward" side (e.g. the societal benefits of energy security and environmental benefits) and, to a lesser extent, on the "private benefit" side (i.e. the direct functional benefit to the customer). The "public rewards" of hydrogen and fuel cells will of course feed through to "private benefit", especially in the medium-long term, creating a win-win situation for both public and private stakeholders. Hydrogen and fuel cells offer the prospect of substantially reducing the negative external costs associated with today's technology, for example climate change, air quality, noise, and health. Sensible quantification of these benefits is however the subject of socio-economic research, as noted above, considering the many options and scenarios for deployment and different pathways for producing hydrogen and deploying fuel cells or conventional converters running on hydrogen.

The challenge that hydrogen and fuel cells face is that, at least for stationary and transport applications, they do not offer sufficient additional functional benefits to the customer in the immediate short term, to justify their much higher price. The high price is in part due to low production volumes, creating a "chicken and egg" problem. Today's combustion technologies fully meet customer expectations at very reasonable, even low cost. However, there are specific segments, such as small portable power, (e.g. power for mobile phones), or emergency back-up power, where direct customer benefits will drive the emergence of premium price markets. This is unlikely to happen in the main stationary and transport markets. Therefore government intervention will certainly be necessary to stimulate and provide temporary support for the emergence of the main stationary and transport markets, so that the substantial long term public and private benefits can be realised.

A strategic deployment plan is needed, focused on delivering mutual benefits for public and private stakeholders alike, and linked directly with the research and development agenda. The deployment programme should aim to identify pathways and opportunities for progressively increasing infrastructure and production volumes. This is necessary for reducing costs, creating market opportunities and eventually reducing the need for government support.

The timeline below shows the steps in a stairway leading to market entry for fuel cell and hydrogen technologies. Deployment must be supported both by active industrial development and by financing.

DIAGRAM UNDER PREPARATION – SEE ANNEX 1



The European Union and national governments throughout Europe should work towards realising a consistent European policy framework with a sustainable energy policy at the heart of this framework. A coherent energy policy sets the scene, but it must face squarely up to its environmental consequences. Ideally, this would result in a system in which the environmental cost of energy was fully included in the decision-making process.

In the second chapter, a confluence of economic, environmental, technological and other drivers was presented. While the underlying drivers *are* moving in the same direction, only a coherent policy dimension – encompassing energy, transport, waste, environment, industrial and financial policies – can ensure that market signals are also in confluence.

Initially three axes of policy development should be explored: stimulation of demand; development of infrastructure for production and distribution (de-carbonised Energy trans-European Network); and global competitiveness.

## Managing the transition

Moving from the entrenched fossil fuel economy of 2003 to a hydrogen and fuel cell-based economy cannot happen fast. Large physical and economic infrastructures support the status quo, and energy demand is intrinsically linked to this infrastructure and vice versa, therefore 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 take advantage of existing expertise.

### *Getting the hydrogen*

Most hydrogen produced in 2003 is made at large scale by reforming natural gas and then distributed either by pipe or by truck. Hydrogen also comes as a by-product from oil refining, or from electrolysis. Large quantities are produced and handled daily in industry, but *not as an energy carrier*.

Hydrogen energy for vehicles and stationary power systems may require different production methods and different delivery infrastructures. Smaller scale production technologies will be an important transition link between the small demand centres initially building up around niche markets, and the eventually larger demand evolving through mass penetration of hydrogen technologies.

In the far future, hydrogen may be produced from a wide range of locally appropriate resources, at locally appropriate scales, and transmitted through pipeline networks to end-users. Early on, these resources will probably be fossil fuels, with their widespread availability and low prices. Successful carbon sequestration techniques would allow fossil hydrogen to be used on a large scale with limited greenhouse gas emissions. As renewable energy technologies mature and their costs continue to drop, more hydrogen will come from renewable sources. In the longer term, nuclear energy could provide large amounts of cheap hydrogen, complementing the renewable energy sources

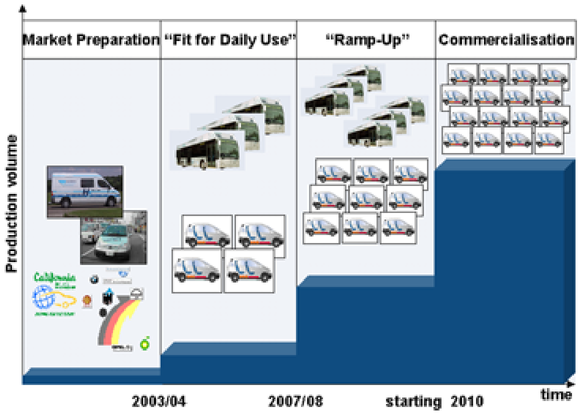
*Fuel cell niche markets and transition technologies*

Stationary fuel cell power production for specific market niches is emerging nowadays while vehicle fuel cell drive systems 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. Fuel cells will also be introduced into portable applications, and stand-alone electricity generation. Early uses in vehicles may be as auxiliary power units for on-board electricity generation, e.g. for refrigerated trucks, or luxury cars.

The use of fuel cells for defence applications has already been mentioned as early niche markets. Strategic development of fuel cells for defence applications could significantly speed development for civilian fuel cells and should be strongly considered.

During the transition phase and even afterwards, conventional technologies will be essential. Internal combustion engines can be used for stationary power and transport as fuel cells are refined and cost is reduced. Hydrogen fuelling stations can be erected, using locally or industrial produced hydrogen. 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, as indicated below.

DIAGRAM UNDER PREPARATION



For transport, a widespread refuelling infrastructure is essential for customer acceptance. However, fuelling stations will not be economically justifiable in the introduction phase. For any successful introduction of fuel cells – and hydrogen – into road transport, considerable support and financial risk sharing from governments and industry will be required. The USA and Japan have already begun to commit high levels of resources to this support.

The development of improved codes and standards and the establishment of common station lay-outs, preferably co-ordinated internationally, should lead to significant reductions in licensing times and costs. And of course, initial demonstration projects should be used for technical and non-technical learning like public acceptance, and to demonstrate that hydrogen is a safe and realistic option for the future.

*Benefiting from transitions*

The transition phase to widespread use of hydrogen and fuel cells will also have benefits for society:

- Learn from the process and redefine it based on experience;
- Local environments will be improved by a reduction of harmful emissions
- Emissions of $CO_2$ and other greenhouse gases will be reduced
- Reliance on single energy sources will gradually diminish
- New industries will emerge

**Managing risk**

Any policy developments must be long-term enough to provide comfort to industrial organisations and investors that their investment risk can be managed. Support for commercialisation is just as important as that for research, and the rewards for Europe could be very large. Successful technology development and early market entrance would ultimately represent a global market of hundreds of billions of Euros.

*Technologies of transition*

Hydrogen buses, using fuel cells or internal combustion engines, are already being introduced into major cities around the world. Supported by the European Union, 30 fuel cell buses are being put into cities around Europe from 2003, fuelled by compressed hydrogen from different primary resources. Once these buses are fully proven, wider sales can begin. Other fleet vehicles should also be incorporated into the process, to optimise the use of fuelling stations and encourage the development of infrastructure.

At the same time, stationary hydrogen combustion and fuel cell systems should be demonstrated in areas where they offer early benefits: remote areas; island communities with renewable resources; micro-grids with combined heat and power. Operating these stationary systems will add to the learning in the transport systems, as the way these similar technologies are used will be very different. Actually linking together stationary and transport demonstrations will help in getting the most from the technology, and in understanding the synergies that may exist. In the same way, maritime applications from canal barges to ocean-going vessels will provide opportunities for hydrogen and fuel cells to make a positive impact. And linking demonstrations with both renewable and conventional energy sources will help to develop the appropriate way to exploit each while moving towards a sustainable energy supply.

During the demonstration and pilot phases, research and development must continue, guided by this experience. Support should be given not only to large, established companies but also to small and medium enterprises, and to entrepreneurial companies seeking to establish niches. Specifically, support networks giving clarity to funding sources and regulations, and to skills and companies working in the area, will be essential.

Ensuring that the take-up is rapid and widespread will mean co-ordination of strong policy measures in support of the technology. Such measures should address both supply and demand and taking into account global competitiveness. 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 through excellence in applications, services and integration of technologies
- Infrastructure design, planning and assessment of viability, at various stages of market development
- Simplification and harmonisation of planning and certification requirements; consider EU directives on common standards, where currently appropriate (e.g. fuel and safety standards)

- Active use of public procurement schemes and programmes, which might include defence applications;
- Active encouragement for and promotion of $CO_2$-free hydrogen production;
- Promotion of emission free zones in cities or regions to stimulate demand for transport and stationary applications
- Market pull/incremental pricing policies
- Education and training programmes.
- International co-ordination of policy development and deployment strategies

The transitional steps towards a European hydrogen economy are not simple. The multifaceted interlinking between different energy sources and carriers; stationary, transport and portable power; energy, transport and economic policies is coupled with the diversity of the economic, political and social situations in the existing and prospective Member States. A pathway to this hydrogen economy will be globally coherent but locally diverse. A comprehensive road-mapping exercise taking into account stakeholder views and aspirations, technical progress and socio-economic factors will be required to enable targeted policy.

### European Level Actions

To maximise the potential for success in moving towards the hydrogen and fuel cell era, a coherent programme, spanning research, demonstration, education and supportive policy should be developed:

- A **political framework** must be created, setting clear policy objectives, that guides research, fosters strategic planning and deployment in response to policy priorities, technical progress, and economic planning for the phase in of new technology. This will build on existing policies, such as achieving clean air for Europe, the introduction of alternative fuels, increasing the share of renewable energy sources, and the realisation of trans-European networks for transport and energy. The framework should assess the scope and effectiveness of alternative mixes of policy measures, including direct support, research and demonstration, public procurement schemes, fiscal and other measures such as graded incentive schemes, tax credits, and preferential treatment and access in environmentally sensitive areas. These overarching policy objectives should be clarified within the period to 2005, creating a favourable and more certain climate for investment.
- A well-structured, well-funded and strong European **technical research and development programme** is required, spanning fundamental materials research, through product and process development, to demonstration and validation. Complementary **socio-economic research** must be conducted integrally to technical research and development projects, designed to deliver clear recommendations on the costs and benefits of various scenarios and time-scales for deployment – including social and external costs;A five-fold funding increase over current spending is needed to meaningfully compete with the USA and Japan;
- A structured set of prestigious "**lighthouse" demonstration** initiatives in both transport and stationary power is needed, large enough to provide real learning, and building on demonstrations that have gone before, such as the CUTE and ECTOS fuel cell bus and hydrogen infrastructure projects. These will typically involve public/private partnerships. Research and development for defence applications should also be co-ordinated;
- A **business development initiative** should be designed to foster investment in innovation, bringing together public private partnerships, venture capital companies and

institutional investors, regional development initiatives, and the European Investment Bank;

- An **education and training programme** is required to stimulate learning at all levels in the basic and applied sciences relevant to hydrogen and fuel cells, with pan-European training opportunities;
- A strategy for building **international co-operation** with both developed and developing countries is essential, with a view to co-operating on technology bottlenecks, developing international codes and standards, enabling global market opportunities, and negotiating technology transfer to reduce negative impacts of global industrialisation.
- A **centre for consolidating and disseminating information** on each of the above recommendations would significantly aid co-ordination of a shift towards hydrogen and fuel cells.

To achieve all of the above, a **European Hydrogen and Fuel Cell Technology Partnership** should be formed, with representation from a broad range of stakeholder groups, steered and monitored by an **Advisory Council**. The Council would give guidance on how to initiate and push forward the individual elements above, building on existing European initiatives, groups and structures.

The Council should decide on the best way to achieve the objectives above, but one suggestion is that specific ‘initiative groups’ may be created. Where possible and appropriate, these should build on existing groups, networks, and projects, as described under the Strategic Research Agenda and be responsible for specific areas of the strategy, reporting to the Council. Possible initiative groups could include for example: strategic technical and socio-economic research; hydrogen policy; business development; demonstration; education and training; safety and standards, etc..

## Financing the Partnership

The investment required for building a hydrogen and fuel cell energy economy is very large, but no more than is spent on existing energy infrastructures. It will only be realised over decades, as existing capital investments are depreciated. The investment will also generate new businesses and industries, and allow Europe to compete with other regions already committing funds to this area.

Public funding has an important and symbolic value, generating the confidence and leverage required for private finance, which will be the main engine of change. The Framework Programme and national programmes will remain the main public-funding instruments for research and development, while regional aid projects could provide opportunities for demonstration.

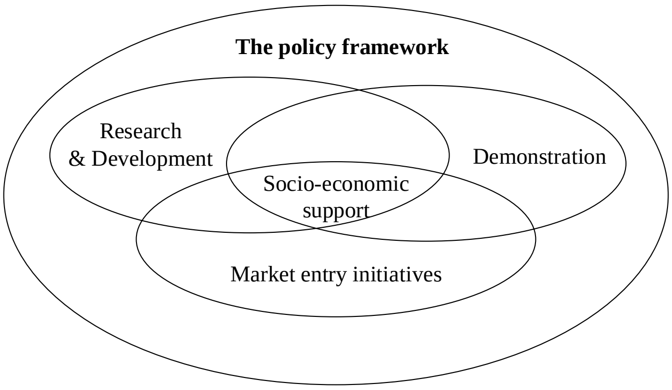
A coalition of US fuel cell stakeholders recently called for a 10-year US Federal Government Programme to implement and deploy hydrogen and fuel cell technologies. The coalition called for $5.5bn public funding – the estimated critical mass required to kick start market driven penetration. The US administration has since announced a strategic $1.2bn hydrogen energy programme to complement the $500m Freedom Car Programme. Europe can only meet this global challenge with similar total levels of investment from individual states and the EU.

Failure to respond could result in Europe failing to capitalise on the enormous economic opportunity and public reward that would flow from a shift in energy technologies to hydrogen and fuel cells.

# 5. 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, increased energy security, whilst maintaining cost–competitiveness, reducing global warming and improving air quality. Hydrogen and fuel cells are firmly established as strategic technologies to meet these objectives, and industrialised countries are increasingly committing to accelerate the mastery of these technologies. They can create win-win for public and private stakeholders alike, but private wealth creation and societal 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 vectors.

Competition from North America and Pacific Rim countries is especially strong, and Europe must substantially increase its efforts to build and deploy a competitive hydrogen 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. The policy framework shown below encompasses all of these areas, while socio-economic initiatives link all aspects of the programme.



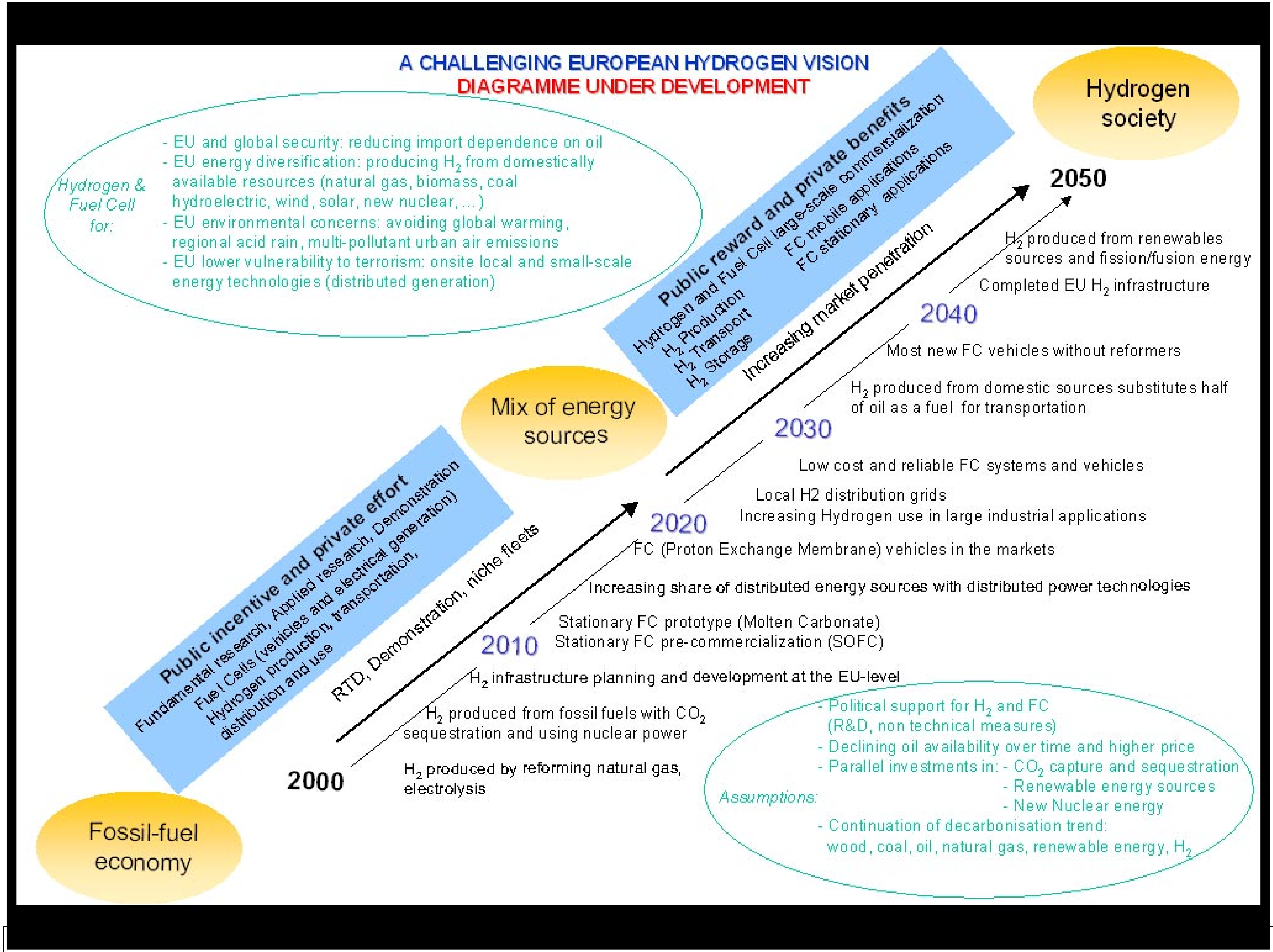
The High Level Group therefore recommends the formation of **a Hydrogen and Fuel Cell Technology Partnership**, steered by a **European Hydrogen Advisory Council** to provide advice, stimulate initiatives and monitor progress**.**

The Advisory Council will provide governance and input from the different stakeholders in the hydrogen energy arena, and oversee a Technology Partnership consisting 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 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 the technical support

- A **business development initiative**, bringing together 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 the introduction of sustainable energy technologies

Detailed analysis and planning needs to start now, with a twenty to thirty year perspective, to avoid the economic disruption that could follow in the event that global circumstances forced a more rapid and de-stabilising structural change.



A CHALLENGING EUROPEAN HYDROGEN VISION

DIAGRAMME UNDER DEVELOPMENT

*Hydrogen & Fuel Cell for:*

- EU and global security: reducing import dependence on oil
- EU energy diversification: producing $H_2$ from domestically available resources (natural gas, biomass, coal hydroelectric, wind, solar, new nuclear, …)
- EU environmental concerns: avoiding global warming, regional acid rain, multi-pollutant urban air emissions
- EU lower vulnerability to terrorism: onsite local and small-scale energy technologies (distributed generation)

Fossil-fuel economy

Mix of energy sources

Hydrogen society

**Public incentive and private effort**

Fundamental research, Applied research, Demonstration

Fuel Cells (vehicles and electrical generation)

Hydrogen production, transportation, distribution and use

**Public reward and private benefits**

Hydrogen and Fuel Cell large-scale commercialization

$H_2$ Production FC mobile applications

$H_2$ Transport FC stationary applications

$H_2$ Storage

RTD, Demonstration, niche fleets

Increasing market penetration

2000

$H_2$ produced by reforming natural gas, electrolysis

$H_2$ produced from fossil fuels with $CO_2$ sequestration and using nuclear power

$H_2$ infrastructure planning and development at the EU-level

2010

Stationary FC prototype (Molten Carbonate)

Stationary FC pre-commercialization (SOFC)

Increasing share of distributed energy sources with distributed power technologies

FC (Proton Exchange Membrane) vehicles in the markets

2020

Local H2 distribution grids

Increasing Hydrogen use in large industrial applications

Low cost and reliable FC systems and vehicles

2030

$H_2$ produced from domestic sources substitutes half of oil as a fuel for transportation

Most new FC vehicles without reformers

2040

Completed EU $H_2$ infrastructure

$H_2$ produced from renewables sources and fission/fusion energy

2050

*Assumptions:*

- Political support for $H_2$ and FC (R&D, non technical measures)
- Declining oil availability over time and higher price
- Parallel investments in: - $CO_2$ capture and sequestration
  - Renewable energy sources
  - New Nuclear energy
- Continuation of decarbonisation trend: wood, coal, oil, natural gas, renewable energy, $H_2$