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# Strengths, Weaknesses, Opportunities and Threats in Energy Research

Directorate-General for Research
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# Foreword

This document is the final report of the "Studies on priority energy technologies (comparison of strengths, weaknesses, achievements/opportunities, performance and threats) – SWOT", carried out for the European Commission, Director-General for Research by JITEX - International Technology and Strategy Experts™.

For Europe, it is vital for energy research and development to provide alternative energy options by making energy services available without excessive costs, reducing dependence on oil and gas, mitigating climate change and developing competitive sustainable energy technologies.

All industrialised countries share these concerns and compete to find the new energy technologies which their market will need, ensuring them with technological advantages and economic benefits.

This report intends therefore to provide for the first time

- A comparative analysis of Europe's present situation with regard to its main competitors (especially Japan and the USA) in key energy technology areas
- An overview of possible developments in science and technology, industry, regulation and relevant market patterns that could affect the European technological situation in a short to medium term, and analyse their possible impact in terms of opportunities to seize or threats to overcome
- The identification of the main gaps existing between Europe and its main competitors.

This work is part of a wider undertaking to build up shared knowledge supporting more strategic and flexible research activities and policies, on the basis of early detection of emerging signals. It has involved the active participation of the industry and research communities who have been invited to contribute and to validate the results in order to increase its relevance for a wider set of potential users in member States and industry.

This study aims at initiating a process of better monitoring of the rapidly changing situations which affect technologies and energy market conditions. It needs to be further carried out and updated in a systematic way in order to identify trends and discontinuities as well as opportunities, possible technology breakthroughs of relevance to European industry and Research, both at EU and Member States levels..

The main messages drawn from the study figure in the Key Findings section, while the bulk of the report provides detailed information on each topic selected for the study, namely photo voltaic, biomass, fuel cells and hydrogen, fossil fuels and carbon dioxide capture and sequestration.

This work will be revisited periodically in order to improve and update regularly the information provided.

# Methodology

A common methodology[1] has been applied to the different key technology areas to be covered by the study, in order to conduct a sound and consistent analysis and to draw up a final report with a coherent structure and content. The work has been divided into four phase as follows:

## Technology screening

In order to focus the analysis on the most promising energy technologies, a first selection of technologies was performed during the initial phase of the study. The selection was undertaken on the basis of a literature review, as well as through an analysis of their relevance with respect to the European Union environment.

A total of 48 technologies were finally selected in agreement with the EC, for power and transport applications, and grouped in 6 technology areas, corresponding to the different parts of the present report.

## Attractiveness and competitiveness assessment

In addition, a survey was conducted, asking more than 500 experts how they evaluate the attractiveness of the technologies listed, and the strengths and weaknesses of the European situation compared to its main competitors (Japan and the USA). Results of this survey are presented in Appendix 1.

## SWOT analysis and key findings

The third phase of the work consisted in a SWOT and trends analysis of the different technology areas, focusing, when possible, on the key priority energy technologies selected in the upper level of the matrix representation.

Experts from different countries, including USA and Japan, were interviewed in order to have a more extensive understanding of their judgments.

For each technology area, results from the literature review and the different expert opinions were combined in order to provide an analysis of the trends, the internal and external environment (SWOT) and identify the most important gaps between Europe, the USA and Japan.

## Panel Discussion and validation

A draft final report, with the full SWOT analysis, was discussed in detail during a panel meeting with stakeholders from research and industry held on December 2004 in Brussels.

To make comparison easier, all amounts in foreign currencies mentioned in the present report have also been systematically converted into euro currency.

The indicative exchange rate applied is the mean value of the past 12 months (November 2003 – October 2004):

1 € = 1.2232 $ 1 € = 133.152 ¥

Unless otherwise marked, all $ currencies are US dollars.

[1] A more complete description of the methodology is provided in Annex 1.

# Key findings

Climate change, the depletion of fossil fuel resources and population growth are driving the search for better, cleaner and more efficient ways to produce, distribute and use energy. That's why the EC conducted a SWOT analysis of the priority energy technologies by comparing its present situation with that of its main competitors, Japan and the USA.

There are 13 findings which are key to strengthening Europe's energy technologies. They take into account possible medium term developments in science, technology, industry, regulation and market patterns. The first nine of the key findings are relevant to all energy technologies while the remaining four refer to specific themes.

## Horizontal issues

### *Targeted priorities and precise goals for RTD programmes*

Europe's competitors have industrial policies which target specific sectors and technologies. They aim to improve and strengthen domestic industries and this strategy is typified by their energy research programmes.

Whenever they use public funds to support R&D programmes precise research and performance goals are set and it is significant that their competitiveness in terms of cost are evaluated. This approach helps to keep efforts focused on technologies which are most likely to become commercially viable.

For example, one method to keep a project on track is the "stage gate process". It's a management tool which keeps the needs of government and industry in line with each other and is particularly useful at the later stages of a project, as it nears commercialisation. Decisions about whether to proceed are taken only after critical elements have been evaluated. These elements include technical feasibility and risks, the legal and regulatory environment, strategic fit and competitive advantage. This tool has been used by the US DOE for its Biomass programme (see page 38) where costs have been shared with industry and the investment risk is high yet the projects have been considered to be essential for the Government's strategy.

Another approach is to set periodic cost targets which must be met at regular, medium-term intervals. This can keep the project focused and is being used effectively by the US DOE's Solid State Energy Conversion Alliance (page 55) where cost targets have been defined for each three year phase.

A different method may be needed when trying to get promising technologies developed for a conservative industry sector which doesn't like taking risks. In these cases it can be appropriate to use public funds for fundamental research into a suite of technologies all of which have the potential for achieving a defined goal. The US DOE is doing this with its FutureGen project to demonstrate the best options for using coal to produce electricity and hydrogen with zero emissions (see page 103).

However, one difficulty when targeting priorities and setting precise goals is making sure the project programme is sufficiently diverse and can be adapted if the world changes. Too narrow a focus could result in projects that are successful in themselves but which don't contribute to global objectives. Experts in Japan say this has happened with some of the country's energy R&D programmes, believing they lack variety and are difficult to change when change is needed (see page 59). It would be beneficial to fund a larger number of unproven technological options, the experts in Japan have said, although they do recognise that it would not be such an efficient strategy.

It is feasible for one or more of these approaches to be adopted more widely in Europe because suitable technological platforms for more efficient, targeted and results-driven projects already exist. They are characterised by the European Research Advisory Board (EURAB) as being "mission-oriented, to tackle a major European need, challenge or problem". These objectives are not as competitive as those stated in the initiatives of Europe's competitors but they are a possible starting point.

### *Funding the development of technologies with industry*

There are significant differences between the ways in which Europe and its competitors fund industrial R&D. The EC is not allowed to finance competitive R&D but there is no such restriction in the USA, where public funds are available to industries for pre-competitive and competitive R&D. This difference puts Europe at a disadvantage.

As an example, the USA dedicates a large part of its R&D funds to the implementation of full-scale demonstration plants because it had identified this stage as a weak link in the transfer technology chain. Also, both Japan and the USA give more support for plants which are the first of their kind, to help companies bridge the gap from science to commercial applications.

This is how USA companies have come to dominate the world gas turbine market. During the '90s there was sustained government support to develop the technology. Today the USA commands more than 80% of the large gas turbines market and is home to the only supplier of 60% efficiency combined cycle systems.

Similarly, the SECA programme in the USA aims to solve issues of solid oxide fuel cell (SOFC) commercialisation, partly by encouraging competition between commercial rivals. The programme shares the costs of the six industry teams which are working on competing designs, although the proportion of funding falls as the research moves closer to commercial development (see page 36). It's worth noting that between 1993 and 2002 the FUEL CELL ENERGY company benefited from awards totalling 134 M$ (110 M€) given by the DOE to develop MCFC technology as part of the SECA programme. It is now a leading manufacturer of MCFC.

The Japanese government also backs industry strongly with targeted funding programmes. In photovoltaic technologies it has been funding industry to develop cheaper manufacturing processes (see page 25) for mass production, manufacturing process improvement and optimisation of BOS so that costs fall. This contrasts with Europe where manufacturing-related issues are poorly addressed in technology development programmes.

To highlight the point, some European companies involved with biomass-related technologies are finding more support in Japan, where they are able to licence their technologies and where the first full-scale demonstration plants are then built. By attracting first-of-a-kind European technologies, some non-European countries are therefore able to gain valuable operational experience and know-how from the demonstration plants they support. The threat is plain - those countries could overtake current European leadership in R&D in a few years.

### *Achieve 'virtuous cycle' development models in Europe*

When a government supports the development of a new technology and, at the same time, encourages demand for it by subsidising market prices, the strategy can lead to a 'virtuous cycle' which becomes self-sustaining. The right technology at the right time may even become an export success.

This has happened in Japan where the government initiated an ambitious project to boost the use of photovoltaic (PV) systems. Through consistent effort Japan has succeeded in creating a world-leading domestic PV market and an industry which can also serve export markets. Thanks to a market-pull strategy and strong partnerships developed with home contractors, the domestic market is now the largest in the world. Moreover, Japanese manufacturers' share of the world PV market is now greater than 40% (see page 26).

The model has taken 15 years to succeed. Japanese manufacturers developed good quality PV systems and consumers were tempted to buy them by heavy government subsidies. The strong market demand enabled PV production to increase rapidly which, in turn, brought economies that helped to bring prices down. Advances in manufacturing technology also contributed to both better quality and lower prices for the modules.

This success from collaboration between academia, industry and government was based on sustained, long-term funding of R&D and is a good example of how to build a virtuous cycle. Japanese stakeholders master these mechanisms well, and, having succeeded with PV, there are policies in place which aim to do the same for the fuel cell market and industry.

So, creating the conditions to achieve a self-sustaining market for a promising industrial technology through a virtuous cycle can have a bigger impact than blind, heavy funding. It will require collaborative efforts among stakeholders to achieve similar successes in Europe.

### *Promote coordination and co-operation between EU administrations*

Working together can accelerate success, as has been shown by efforts such as the reform of the Common Agricultural Policy in 2003, which has implications for biomass energy crops. Yet for some energy areas, Europe is lacking a cooperative approach between the various EU administrations and institutions that should be involved. Meanwhile, Europe's competitors have succeeded in implementing inter-agency initiatives.

For example, federal R&D efforts in the USA have been integrated since the Biomass R&D Act of 2000. Before then, federal agencies had an insular view of biomass but now they recognise that biomass encompasses agriculture, energy, research, environment and commerce. Cooperative DOE and USDA programmes have been set up to take advantage of the expertise of each department and they are working together to establish the critical pathways for meeting the objectives of the initiative (see page 36).

Such cooperation could also be developed within the European Commission, by setting up a matrix-type organisation for projects management, for example. In the biomass area more cooperation between DG AGRI, RTD, TREN, ENV and MARKT should lead to more efficient RTD projects and policies. More should be done to ensure that EU initiatives are mutually supportive.

### *Develop synergies between the Member States' initiatives*

Possible synergies in research efforts and market incentives are often neglected in Europe because of a lack of coordination between Member States. This means that national research initiatives often overlap across Europe while some areas are not studied anywhere. Many European research activities are carried out within national or regional programmes and the European Commission has little knowledge of their content.

Similarly, market incentives can differ between Member States and may even end up retarding the development of energy technologies. For example, Germany gives valuable tax exemptions to subsidise liquid biofuels strongly. In contrast, Italy, France and Spain provide less support and this undermines their own plans because important quantities of raw materials are exported to Germany (see page 43). Also, feed-in tariffs are a dominant instrument in the Member States for both PV and biomass support (see pages 29 and 42) but most countries simply don't offer enough to stimulate their markets.

Europe's competitors stop this happening by making sure that information exchange and the coordination of research efforts and market incentives are practiced. The innovation system for fuel cells in the USA, for example, relies on a network of government agencies, national laboratories, state and local governments, universities and industries, all with dedicated expertise and priorities. Targeted and coordinated efforts by the various players help to improve research efficiency as well as in the diffusion and use of knowledge.

For priority energy technologies to thrive in Europe, networks and technology platforms can build upon the various national experiences and include the different stakeholders to eliminate fragmentation, duplication and omission of R&D.

### *Accelerate the development of codes and standards*

Europe's competitors lead the way in their development of energy codes and standardisation and they continue to be more active.

For example, in 2002, the Japanese government decided to amend 28 items in six laws – including the Traffic Law and the High Pressure Gas Security Law – to ease the introduction of fuel cells and the use of hydrogen (see page 62). In the USA, the National Fire Protection Association (NFPA) has been incorporating hydrogen and fuel cell-related issues in its standards for stationary and transport applications, to assist commercialisation. Moreover, for stationary applications only, the International Code Council (USA) incorporated specific changes directly related to hydrogen in codes for Fire, Fuel Gas, Residential, Building and Mechanical issues in 2003.

In contrast, the regulatory codes and standards landscape for hydrogen and fuel cells is very complex in Europe and involves numerous authorities and stakeholders. Some current national regulations can even impede severely the installation and operation of fuel cell CHP power plants. As part of the European Hydrogen and Fuel Cell Technology Platform (HFP), an Initiative Group on Regulations, Codes and Standards (RCS) is proposed to develop an action plan to accelerate processes for implementation of commercially competitive RCS. Such an initiative will help Europe keep up with its competitors.

### *Getting innovations out of the laboratories by improving collaboration between government, university and industry*

The efficient transfer of basic research to the private sector, to become innovations and commercial products, depends on collaboration between government, university and industry. It can be a key element in an innovation system as long as the right policy support is in place.

In Japan partnership between government, university and industry has been the backbone of the Japanese innovation strategy for many years and it is true for the Japanese energy sector. Private organisations and academia contribute actively to the energy policy by joining METI expert committees. Also, the government contributes to energy R&D with sustained and long-term programmes.

Such collaboration has worked recently for fuel cell technologies following a setback for Japanese SOFC and PAFC developments. A committee drawn from academia, industries and public institutions was created in 1999, to advise the ANRE (Agency of Natural Resources and Energy) part of METI on fuel cell commercialisation strategies. Two years later it suggested that there should be an emphasis on PEMFC development. It drove the creation of the Fuel Cell Commercialisation Conference of Japan (FCCJ), a consortium of 134 firms, to focus on the strategic issues of commercialisation and widespread use of fuel cells, and to influence governmental policies (see page 60).

This kind of networking is expected to help eliminate obstacles which would otherwise hinder the widespread use of fuel cells. It's also worth noting that Japanese industry contributes to scientific knowledge more strongly than in other countries. The industry wrote almost 40% of the Japanese fuel cell-related publications (1990-2000). In the two most active European countries, Germany and the UK, industries contributed less than 20% (see page 62).

In the USA, the DOE has used of public-private partnerships extensively to help identify the need for basic and applied research, and the barriers to commercialisation of PEMFC, especially for automotive applications. Various funding mechanisms help drive this collaborative R&D, including Cooperative Research and Development Agreements (CRADAs) between national laboratories and private partners, These allow industries to protect their intellectual property and ownership rights while tapping into the world-class and multi-disciplinary scientific expertise of the national laboratories. Grants and cooperative agreements are used for university and industry work efforts.

In Europe, however, the level of coordination between governments, universities and industries for energy R&D varies between Member States. Opportunities for applying and disseminating some national level best practices which enhance innovation through Europe-wide public-private partnerships would be beneficial.

### *Implement specific mechanisms for SMEs and early-stage developments*

Small businesses, especially start-ups and spin-offs from private or academic origin, are important to bring the benefits of basic research to the marketplace quickly. They are also key drivers of economic growth for industrialised countries. However, small firms are particularly vulnerable and are more in need of specific support for their early-stage developments.

The USA has implemented some very effective mechanisms to help SMEs develop their products in an entrepreneur-friendly environment. The Small Business Innovation Research and Advanced Technology Program (ATP) programmes are well known to help small businesses bridge the "Valley of Death". Compared to similar national programmes in Europe, such as Enterprise Ireland or ANVAR in France, the American programmes are highly competitive. They attract many applicants and support just a few winners. They have clearer objectives, regular assessments and the public funding is limited in time and amount.

For example, through ATP, the US Department of Commerce shares the cost of high-risk R&D projects with private companies to accelerate the development of innovative technologies. ATP awards are selected through open, peer-reviewed competitions. ATP funded a total of 24 projects in the fuel cell area, among which was the successful PLUGPOWER company. PLUGPOWER was created in 1997 with 22 employees and received a 9.7 M$ (7.9 M€) grant for 3 years to develop membranes to perform better than Nafion of DUPONT (see page 69).

Such programmes are important in the USA to allow small companies to conduct early-stage research and development projects that might not otherwise be funded. EURAB's recommendation for a SBIR-like mechanism within FP6 should be considered further to help establish a similarly effective system in Europe.

*Seek energy markets opportunities in China, India and other South-East Asia countries*

There are huge market opportunities for energy technologies in China and, to a lesser extent, India and other South-East Asia countries in the coming decades, particularly for fossil fuel technologies. Europe might miss a large portion of those Asian opportunities because Japan and the USA are more present in those markets. They benefit from sustained national public R&D programmes on fossil fuels technologies and have already sold several fossil fuel plants in Asia.

Foreign manufacturers need to offer enhanced technologies every couple of years to keep a foot in the Asian market because, after having bought just one foreign plant, the Chinese technological capacity is good enough to be able to build its own. In this context, the strong government support to competitive R&D in Japan and the USA again favours the manufacturers in these countries by helping them develop innovative systems on a regular basis.

China also has the potential of developing a huge fuel cell vehicle market, and, in this respect, the US government is very active in developing relations with China to prepare the market. The American Natural Resources Defense Council (NRDC), supported by the W. Alton Jones Foundation, worked with the Shanghai Economic Commission, Togji University, the Energy Research Institute and the South-North Institute over the last three years to raise awareness in China of the commercialisation of fuel cell vehicles.

Japan, meanwhile, has long experience of economic development in neighbouring Asian countries, through efficient bilateral agreements and support mechanisms. Japanese photovoltaic and fuel cell industries have already benefited from such export opportunities. An important strategic plan has even been launched for biomass, despite the fact that Japan has little domestic biomass potential itself. Nevertheless, the knowledgeable Japanese engineering industry is expected to develop and build plants in biomass producing countries, mainly in South East Asia. It must be pointed out that Japan is already at the forefront of using Kyoto Protocol mechanisms such as Clean Development Mechanisms (CDM) to support renewable energies and energy efficiency projects in South East Asia.

The European Commission is also very pro-active in climate change-related issues so it should support more strongly European industries which are able to propose “clean” innovative technologies through CDM projects in those countries. Fossil-fuel technologies should also be supported for these specific export opportunities.

## Thematic issues

*Sustained R&D on fossil fuels technologies*

Europe’s competitors have very definite short and long-term energy policies and allot public R&D funding accordingly. The European Union, on the other hand, has not established a clear energy research strategy that takes into account the “unavoidable” use of fossil fuels for a few more decades. This does not compare well with its competitors; both the USA and Japan have long-term strategic programmes for clean coal technologies to meet future domestic and export market requirements.

The Vision 21 Technology Roadmap, launched in 2000 by the US DOE is a new initiative for developing the technology necessary for ultra-clean, fossil fuel-based, energy plants. The USA recognises that fossil energy will continue to be a substantial part of the energy mix and the initiative guides the long-term (15-20 years) development efforts in fossil energy technology so as “to meet environmental needs at acceptable cost”. Coal is the main focus of current US DOE fossil energy R&D efforts, for which a commitment of $2 billion over 10 years is made to develop advanced clean coal technologies.

There is evidence that such a sustained R&D effort can succeed. In 1992, the DOE launched the 8-year Advanced Turbine System Program aiming at achieving commercial systems by 2000. The result today is a strong US technology domination of the world markets, winning more than 80% of the large gas turbines market, and being the only supplier of 60% efficiency combined cycle systems.

In Japan also, clean coal technologies have attracted the interest of both the government and industry and government funds for R&D are on a long-term basis. For instance, an 8-year long R&D project on ultra-supercritical coal combustion was successfully completed in 2000, leading to a 44% efficiency plant set up by Toshiba. Today, efforts are concentrated on IGCC systems, mainly through the Clean Coal Power R&D project, which was created by 10 power companies and is funded 30% by METI. Its aim is to achieve pre-commercial application by 2015.

In Europe, up until the EC's Fifth Framework programme (1998-2002), intense advanced research was carried out on fossil energy technologies, e.g. on ultra-supercritical boiler technologies (AD700 project) and IGCC systems. FP5 was followed by FP6 (2002-2006). This was designed to establish a sustainable energy base for Europe. It emphasises the development of renewable energy sources and near-zero emissions fossil fuel-based energy conversion systems founded on the capture and sequestration of $CO_2$. As a result, FP6 excludes conventional fossil fuel technologies. Unless FP7 brings fossil fuels back into the EU research strategy, this lack of support for R&D into fossil fuel-based technologies will have unfortunate consequences. It will affect both the EU security of supply and the competitiveness of the European power generation equipment industry. Fossil fuels will supply 70% of Europe's energy for several decades to come and power plant capacity of 550 GW will have to be built before 2030. It is essential that support for fossil fuel technologies is included in the next Framework programme.

Sustained support for R&D would also strengthen some current actions such as the FENCO coalition, which coordinates the fossil energy programmes of the Member States, and the E-max group of nine major power generators, which partly finances the AD700 project. What's more, it would help Europe to keep its leading position in several clean coal technologies. Currently, European manufacturers already sell high-performance pulverised fuel (PF) combustion and circulating fluidised bed (CFB) combustion systems to the world market. In addition, together with the USA, Europe is a world leader in the demonstration of integrated gasification combined cycles (IGCC).

### *Take advantage of European experience in $CO_2$ storage in offshore aquifers*

Europe has top-level expertise in the storage of $CO_2$ in aquifers, thanks to the world-class Sleipner project in the North Sea. Europe may be able to capitalise on that success by offering process, safety and reliability services to the future operators of $CO_2$ storage plants.

The routes for $CO_2$ storage include deep saline aquifers and deep unmined coal seams as well as depleted oil and gas wells. The latter routes also have the potential for enhanced oil recovery (EOR). The oil industry would be interested in deploying EOR in the North Sea because it is commercially attractive. However, the USA has the best know-how in this technology which it has acquired over 30 years. It has an infrastructure of 3000 km of $CO_2$ pipelines, and, with Canada, it hosts the international Weyburn project which is the first large-scale study of the geological storage of $CO_2$ in a partially depleted oil field. Moreover, the US government's R&D effort for carbon capture and storage is significant. Europe, on the other hand, has no experience in EOR storage and there are other issues, such as logistics, operation and maintenance of the $CO_2$ supply chain, which may impede any such plans for the North Sea.

These issues could make aquifer storage of $CO_2$ an attractive alternative and this is where Europe has the most comprehensive expertise, thanks to the Sleipner project. Europe is gaining valuable hands-on experience from this world-class project, in terms of process development, safety and reliability.

However, major non-technical issues also need to be solved before commercialising $CO_2$ storage technologies. These are mainly regulatory and relate to the Convention for Protection of the Marine Environment of the North-east Atlantic (OSPAR) and London Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter. Moreover, despite the valuable experience gained from the Sleipner project and several other EC supported storage projects, commercial-size integrated demonstrations need to be initiated in Europe. Otherwise Europe, and its industry may not be prepared when commercialisation of the technologies actually starts.

If the regulatory issues are solved and the demonstration projects are successful, Europe could profit from its experience in $CO_2$ storage in the North Sea by providing not only the technology but also the related services which are of higher added value.

### *Stimulate the involvement of European car manufacturers in fuel cell vehicles development*

Some US and Japanese car manufacturers have taken an active part in the development of FCV, and are now leaders in the field.

Although GM, TOYOTA and HONDA invested heavily in FCV development and even developed proprietary stacks, European car manufacturers (except DAIMLERCHRYSLER) seem reluctant to put further efforts into integrated development of FCV. However, some manufacturers, including PEUGEOT and BMW, have chosen to focus on hybrid fuel cell (SOFC) / battery vehicles in which the fuel cell is used as an auxiliary power unit (APU): if they succeed, they will have no competitors in the USA and Japan.

Recent developments in FCV show European car manufacturers (except DAIMLERCHRYSLER) acting more as observers compared to the commitments of their Japanese and American companies. The most active companies are TOYOTA, DAIMLERCHRYSLER, HONDA, FORD, and GM. While European manufacturers support FC module R&D by collaborating with companies such as DELPHI or BALLARD (both from North America), they do not benefit from hands-on experience and perhaps they'll miss the opportunity of fully integrating the FC module in the global design.

Therefore, if FCV are considered a strategic market opportunity for the future, fostering the involvement of European car manufacturers in the whole chain of FCV development and focusing on European suppliers of fuel cells should not be neglected by the EC.

### *Evaluate the potential of developing bio-refineries*

Most US biomass R&D programmes include the possibility of manufacturing materials and chemicals in integrated bio-refineries. Producing high-value, bio-based products for niche markets in those integrated plants can help improve the cost-competitiveness of the mass-market products such as fuels and energy.

Bio-refineries are only at concept level in Europe but are already implemented in the USA where they are supported by strong industrial companies from the chemical, food, textile and agriculture sectors, including ARCHER DANIELS MIDLAND (ADM), CARGILL and DOW CHEMICAL. The ADM complex in Decatur, Illinois, is the prototype of such multiple product plants. It is integrated in an already active corn wet-milling plant. Elsewhere, DUPONT is leading a consortium researching the Integrated Corn-Based Bioproducts Refinery (ICBR) and it was awarded 19 M$ (15.5 M€) from the DOE in 2002 to design and demonstrate its feasibility and practicability. In this respect, the American industries benefit from long-term federal R&D programmes for basic research, an integrated approach with the different sectors and administrations involved, and the competitive development programmes for prototype achievement with 50% matching funds.

Europe lacks such ambitious programmes and industry-oriented mechanisms. It needs a more integrated and coordinated R&D approach with sectors that could use and increase the value of bio-energy by-products. It's also worth questioning whether bio-refineries are appropriate to most European agricultural areas. Perhaps they are most suitable for the USA where transportation costs may be lower and agriculture is more likely to be of a single crop in a concentrated area.

# Introduction

## General context

With the increasing challenges of climate change, depletion of fossil fuel resources and population growth, the search for better, cleaner and more efficient technologies to produce, distribute and use energy is becoming more and more critical. In addition to the growth in global energy use (50% expected by 2020), it is not likely that energy will remain easily affordable to all who need it.

For Europe, it is vital for energy research and development to provide alternative energy options which will mitigate future problems by making energy services available without excessive costs, reducing dependence on oil and gas, lessening climate change and developing competitive sustainable energy technologies.

All industrialised countries share these concerns and are competing to find the new energy technologies which their markets will need, ensuring they have both technological advantages and economic benefits.

In this context, the European Commission wants to obtain a clearer and fairer picture of Europe's comparative strengths and weaknesses in major areas of technology, by:

- anticipating future trends, risks and opportunities in the short, medium and long term;
- establishing a sound dialogue with interested and committed stakeholders in order to establish practical and operational recommendations and implementation strategies;
- identifying appropriate initiatives or remedial actions to be undertaken in Europe aiming at securing and enhancing Europe's position in these major energy technologies and on future related markets.

## Main objectives of the study

Therefore, the general objectives of this study are:

- to produce a comparative analysis of Europe's present situation with regard to its main competitors (Japan and the USA) in some key energy technology areas specified below;
- to take account of possible developments in science and technology, industry, regulation and relevant market patterns that could affect the European technological situation in a short to medium term, and analyse their possible impact in terms of opportunities to seize or threats to overcome;
- to identify the main gaps existing between Europe and its main competitors (Japan and the USA).

The following key energy technology areas have been selected by the European Commission for this study:

- Fuel cells and hydrogen technologies
- Photovoltaic technologies
- Biomass-based technologies (utilisation of biofuels and biomass)
- Use of fossil fuels for heat and power (including technologies for carbon dioxide capture and sequestration).

A SWOT analysis (Strengths, Weaknesses, Opportunities and Threats) and comparison with the situation in the USA and Japan has been conducted with respect to:

- Scientific and technological capabilities
- Industries active in the fields of the chosen energy technology areas or market segments
- Markets (size and responsiveness) for each relevant application
- Legal and regulatory context and measures.

# Photovoltaic technologies

## Technology and market trends

Over the past decade, the global solar electricity market has experienced very high growth rates, with an average of more than 30% in the past 5 years, making further increases in production facilities an attractive investment for industry, with a market possibly expanding from $7 bn (€5.7 bn) in 2004 to $30 bn (€24.5 bn) in 2010 [120].

This growth in photovoltaics (PV) has been generated by well-targeted national market assistance programmes around the world and the development of a more positive legal framework. The EU and Japan have been the main global players in these respects.

In 2003, the photovoltaic industry delivered some 744 MWp in photovoltaic generators and has become a €4.5 bn business.

Considerable advances have been made over the past decade in PV technologies. Improvements through price reductions (roughly by a factor of 5 over the past twenty years), efficiency increases and systems reliability are so significant that some PV solar electricity products are already competitive, and soon they will all be, in their respective segment markets. Off-grid industrial and domestic applications, as well as solar cells used in watches, toys and calculators, or as a power supply for lighting or phone boxes, are economically viable, while on-grid domestic products highly depend on market support programmes. Some communication devices, whose powering scheme efficiency is about 5%, could also benefit from PV incorporation.

Almost half of PV systems are used in applications for which this is the cheapest or the only way of generating electrical power. The other half – grid-connected systems – may demonstrate competitiveness in the medium term in peak power applications within a liberalised utility market.

It must be outlined that the increase by more than 700 MW in solar capacity in 2003 is equal to the output of one natural gas turbine or less than half a typical coal plant. Moreover, an IEA study based on experience methods and learning curves concluded that $50 to $100 bn of learning investments will be necessary to break even with PV with respect to central power plants fuelled by fossil technologies.

By the end of 2003, a cumulative total of more than 1.8 GW of PV capacity had been installed in the IEA PVPS (Photovoltaic Power Systems) countries, with Japan, Germany and the USA accounting for about 85% of this capacity. The proportion of capacity connected to the grid is continuously rising, reaching 78% in 2003. The impact of tariff support or low-interest loans on the installation of new capacity is always visible: when grants stop, markets immediately stagnate. In 2003 R&D spending increased significantly in about one third of IEA countries and market transformation efforts through targeted demonstration and knowledge generation rose slightly, but not enough with respect to needs (see the next figure). Production capacity grew in Europe (mainly in Germany) and in Japan, but dropped in the USA; a consolidation of the industry manufacturing photovoltaic cells is to be expected [190].

*Figure 1 – Public budgets (in M$) for R&D, demonstration/field trials and market stimulation in 2003*

| Country | R&D | Demonstration / field trials | Market stimulation | Total |
|---|---|---|---|---|
| Austria | 1,695 | — | 8,588 | 10,283 |
| Czech Republic | 11,136 | 1,114 | 2,301 | 14,551 |
| Denmark | 3,797 | 759 | — | 4,556 |
| Germany | 33,559 | — | 757,062 | (79,0621) |
| Finland | 531 | — | 5 | 536 |
| France | 5,763 | — | 22,600 | 28,363 |
| United Kingdom | 4,885 | 9,443 | — | 14,328 |
| Italy | 5,424 | 226 | 22,599 | 28,249 |
| Netherlands | 2,373 | 169 | 84,746 | 87,288 |
| Sweden | 2,104 | — | — | 2,104 |
| USA | 65,700 | — | 273,700 | 339,400 |

*Source: IEA, September 2004 [190]*

(It must be noted that German market stimulation efforts are in the form of loans, and so not directly comparable with other figures)

The International Electrotechnical Commission, which establishes international standards for PV materials and systems, actively promotes the use of these standards, designed with a consumer/product-oriented approach. Nevertheless, balance-of-system components and systems tend to lack appropriate standards, which impedes the implementation of grid-connected PV systems. Most countries reported national activities on certification, accreditation, training and quality schemes regarding PV systems and their components [190].

## Technology trends

**Si-crystalline-based cells are a mature technology.** Single and polycrystalline cells represented more than 88% of worldwide cell/module production in 2003. They will remain the backbone of PV applications for the next twenty years with further cost diminution due to manufacturing improvements. However, as worldwide PV power production increases, concern has been expressed regarding a possible shortage of low-cost silicon raw material because of this sustained growth [190].

**For the long term, in 2030 crystalline silicon, thin film and new concepts could all be equally present on the world market**, with over 110 GW of production for each technology category [54]. As thin-film silicon cells require only few raw materials, they could be a solution in case of silicon scarcity and have good prospects in grid-connected applications. Thin-film Copper-Indium-Diselenide (CIS) cells, already on the market despite low efficiency and high manufacturing costs, involve the use of CdS layers, a polluting material, and raise the issue of indium availability. Compound semiconductors could find niche applications such as PV concentrating systems but are very expensive and could suffer from restricted availability of gallium and indium.

Dye-sensitised cells show instabilities but will be interesting for specific applications (indoor, PV-windows, solar home systems).

Polymer solar cells suffer from poor efficiency and photostability but could be used in buildings.

Technological breakthroughs could accelerate the development of PV electricity: polymer solar cells made of a pigment derived from paraphenylene-vinylene, with a charge carrier material based on a modified fullerene [144]; assembling of nanostructured semiconductor and conducting oxide layers; multiple-threshold or multi-junction devices; quantum multiplication; intermediate bandgap solar cells; hot carrier cells or thermophotovoltaic generation [172]; use of proteins to align quantum dots into arrays which serve as a matrix for conducting electrons and holes [57]; energy coupling in a tunnel-effect, ultrafast diode through an optical antenna [141]; nanocomposite photocells and porous wide bandgap semi-conductors with a light-sensitive dye (Grätzel cells) [32, 236]. **A great amount of fundamental research is nevertheless required,** particularly in material sciences, photoelectronics, quantum physics and optoelectronics.

**As European competitiveness in organic solar cells is widely recognised, priority could be given to research in that domain as well as to the development of more efficient modules and storage devices.**

Numerous scientists think that conversion efficiencies of commercial solar cells could reach 20% to 30% in 2010, while module lifetime could reach thirty years; but no study has as yet shown the industrial and economical feasibility of such solar cells for a reasonable cost [178].

## Market trends

Three GWp of solar power could be installed in Europe by 2010, with a cumulative market share of installed world capacity equal to 26.5%; as a result, 59,000 jobs would be created [12]. PV-generated electricity could benefit thousands of remote, grid-unconnected dwellings in industrialised countries by 2030 and 200,000 to 400,000 jobs could therefore be created in Europe [54]. Solar photovoltaic energy could emerge by 2020 in the ten new Member States and represent 1.1% of total installed capacity in 2030 [33].

EPIA, EREC (European Renewable Energy Council), and the European Commission have drawn up various alternative scenarios which produce contrasting results concerning the share of PV in electricity generation. According to the “reference case”, the **capital costs of photovoltaics could be drastically reduced from €15,000/kW in 1990 and €6,500/kW in 2000, to €4,400/kW in 2010 and €3,200/kW by 2030**, with a halving of overall and maintenance costs between today and 2030. The “renewable case” implies halving reference costs by 2030, but PV-produced electricity would remain uncompetitive except for niche markets, leading to a PV contribution of around 32 TWh by 2030 [4].

EREC has considered global electricity production in 2040 and predicts that PV will account for 15% (reference case) to 31% (renewable case) of the total production of renewable energy. EPIA has estimated a global solar electricity output of 276 TWh in 2020, or 1% of total electricity production, while EREC predicts 42 TWh in 2020, corresponding to total electricity generation of 3,450 TWh of which 1,166 from renewable energy sources.

Some market analysts believe that the solar power industry will soon be profitable, notably in Germany, USA and Japan. Demand for solar power from end-customers in the world’s largest markets is far outstripping capacity and so delivery delays are long; this combination of high demand and tight supply leads to price stability, which, combined with cost reductions, is driving margin expansion [120].

## Main strengths and weaknesses of the USA and Japan

### USA

| | Strengths | Weaknesses |
|---|---|---|
| S&T | • Support from US DOE for PV industry research programmes<br>• Strong position of high-level laboratories in PV academic research | • Too few research credits |
| M&I | • Good market possibilities in states such as California or Arizona | • Lack of infrastructure<br>• No single market<br>• Low cell production capacity<br>• Low profitability of US PV businesses<br>• Public lack of awareness and education |
| P&M | • Combination of federal and state laws to promote the production of PV electricity<br>• Local initiatives to promote PV energy use to the general public | • Absence of market deployment policy at federal level |

*Science and Technology (S&T)*

The US DOE provides support to the PV industry through the "National Photovoltaics Program . $74 M (€60.5 M) were granted to PV research in the framework of the US-DOE Federal Funding Program for fiscal year 2003 [17, 54]. But according to the US PV industry, $250 M p.a. (€204 M) will be needed by 2010 to achieve real American R&D excellence, make solar power broadly cost competitive in the next decade and thus help the US industry regain its market leadership.

US government priorities being hydrogen, nuclear energy and clean coal, **there is a continued decrease in federal investment in R&D for solar energy**. New technologies in particular are not sufficiently funded by the DOE, even though DARPA gave $25 M (€20.5 M) to several firms for the development of nanotechnology-based solar cells [201].

The technological advances of the USA regarding thermal management and interconnecting devices, developed in some military and space programmes, is a competitive advantage in the development of building-integrated PV systems [31].

*Market and Industry (M&I)*

Although PV was developed in the framework of the American Space Program in the 1950s, the United States has lost its dominant market share and is losing its lead in developing and commercialising the technology. While US manufacturers captured more than 40% of the world market in 1997, this market share was down to a mere 14% in 2003, the lowest level ever.

**US PV businesses do not seem profitable enough,** and unable to fund their own research for low-cost PV systems [17, 141]. According to an investment bank analysis, only BP Solar and General Electric are expected to make a small solar operating profit in 2004 [120].

Even though 340 MW of grid-connected and off-grid systems have been installed in the USA in the past decade, **US production of solar panels dropped by 14% in 2003** (with only 104 MW additional capacity produced), for three main reasons: a decrease in BP Solar performances, the bankruptcy of Astropower, the second American manufacturer, and the absence of a strong market development policy. Cell production capacity is not sufficient in the USA to achieve the goal of 400 TWh in 2030 defined in the US PV industry roadmap [167, 201].

There is no single market for PV in the USA but a conglomeration of regional markets and special applications for which PV adoption is relevant in terms of the cost/efficiency ratio [11]. **There is no real market deployment policy at federal level**; each state adopts its own PV promotion policy, mainly based on tax exemptions. Some initiatives are decided only at county level and are often directly aimed at homeowners [54, 139]: the states of New York, Minnesota and Massachusetts encourage the installation of PV systems in "green buildings" through incentives, while public schools in Illinois and Montana are grant-aided in the installation of PV systems, provided they incorporate photovoltaics into their curriculum. At the national level, 69 partnerships involving 1200 local organisations were concluded in 2003 in the framework of the "one million solar roofs" project [3, 53, 133, 139].

*Policies and Measures (P&M)*

Under federal law, utilities must allow independent power producers to be interconnected with the utility grid and must purchase any excess electricity they generate. Many states offer "net-metering" to businesses or home owners equipped with a PV system: when excess electricity is produced, it is fed into the utility grid and sold to the utility at a price inferior to the retail rate in order to cover its costs. Colorado voters endorsed such an initiative in November 2004 [157]. In some states, the RPS (renewable portfolio standards) oblige utilities to produce a minimum quantity of electricity from renewable energy sources; in Arizona, there are several PV plants thanks to this regulation.

## Japan

| | Strengths | Weaknesses |
|---|---|---|
| S&T | • Japanese systems are compact and show good efficiency | • In the future, residential PV may have to fight with CHP |
| M&I | • Japanese industry is world leader in the field and can export its products<br>• High integration level of Japanese PV industry<br>• Important domestic market (¥90 bn in 2002 [€0.67 bn])<br>• Excellent collaboration between manufacturers and home contractors<br>• High cost of electricity in Japan (~¥25 /kWh [€0.19/kWh]) | • High domestic manufacturing costs may impede direct exports<br>• PV business profitability is under pressure due to low margins |
| P&M | • Strong commitment for promotion and incentives by the government<br>• RPS law since 2003 | |

*Science and Technology (S&T)*

In Japan today, photovoltaic technological development has clearly entered a phase of cost reduction, mainly through mass production, manufacturing process improvement, and optimisation of balance of system.

Technology-wise, the trend has shifted from polycrystalline to monocrystalline cells, since the latter need less material, but they still require high-grade Si and complicated processes. For these reasons, Japanese **manufacturers feel compelled to develop and industrialise new, cheaper cells** (thin-film Si, CIS and CIGS, later dye-sensitised), rather than focus on efficiency alone (Sanyo Electric's hybrid solar cell boasts the highest efficiency, but also the highest cost), to market competitive products [221, 87].

The role of NEDO, until 2005, is to back the industry through programme funding in order to help develop cheaper manufacturing processes, optimise balance of system equipments, and conduct basic research on new technologies. However, budgets are expected to be greatly reduced after that date, especially with respect to subsidies. An industrial association (PVTEC) has thus started to think of ways of developing new PV technologies and manufacturing processes "in order to face possible future competition from Europe and the USA" [221], but also **competition with other distributed energy systems**, such as natural gas or fuel-cell CHP, which are both actively promoted by the government.

### *Market and Industry (M&I)*

Today, **Japanese manufacturers[1] own 40% of the world market.** They also benefit from **a large domestic market** and the continued support of the government. Furthermore, they have succeeded in building **compact and efficient PV systems**.

Within domestic production, 60% of systems are intended for residential applications, and 33% are sold abroad. In the future, the share of non-residential systems should steadily grow so that the expected national breakdown of **installed capacity in 2010 is 3.9 GW in 1 million homes, and 0.92 GW on 180,000 non-residential sites** [87, JPEA].

Official forecasts for residential systems costs and total domestic PV market size are as follows [221, 231, 40]:

| (¥100 = €0.75) | Today | 2010 | 2020 | 2030 |
|---|---|---|---|---|
| Module production cost (¥/W) | ~250 | 100 | 75 | 50~60 |
| System price (¥/W) | ~700 | 300 | 250 | — |
| Power price (¥/kWh) | ~40 | 20~25 | 10~15 | — |
| Domestic shipping (MW/year) | ~300 | 1,200 | 4,300 | 10,000 |
| Installed capacity (MW) | ~1,000 | 4,820 | 31,000 | — |

These are ambitious targets, and some experts consider that it will be difficult to attain the ¥300/W [€2.25/W] mark by 2010, especially with the **recent decrease in PV system orders for new houses** (50% PV installation in new houses in 2000, but only 20% today).

Thus far, manufacturers have succeeded in creating sufficient demand, mainly through **partnerships with home contractors,** to confidently upscale their plants. Some property developers have helped reduce the costs of PV by integrating solar power into their original plans and grouping balance of system (BOS), in so-called "solar towns".

### *Policies and Measures (P&M)*

Japan has been **intensively promoting photovoltaic technology development and diffusion** for the past ten years (*New Sunshine Project*, *Residential PV System Dissemination Program*, *Residential PV System Monitoring Program*) in order to build a self-supporting market, and this goal could officially be reached by 2010. Thanks to a **market-pull strategy** and strong partnerships with home contractors, the domestic market has been boosted and is now the largest in the world (637 MW in 2002).



[1] By size of market share: Sharp, Kyocera, Sanyo Electric, Mitsubishi Electric, Kaneka and some others.

This success, resulting from a collaborative effort involving academe, industry and government, is a good example of the creation of a **virtuous cycle for market diffusion, based on sustained, long-term funding of R&D**.

National subsidies are set in accordance with system prices (reduced from ¥90/W [€0.68/W] in 2003, to ¥45/W [€0.34/W] in 2004), which may put the manufacturers under pressure if demand is not sustained. Indeed, **of the Japanese manufacturers, in 2003 only Sharp and Kyocera PV made a profit** [87]. Pressure on profit margin is currently high but decreasing with prospects of mass production and market growth; operating profits are expected to increase considerably to 2 to 10% in 2004 [120].

In parallel, current R&D policies aim to reduce the cost of PV module manufacturing, firstly through the introduction of thin-film silicon and compound cells by 2010-2015, then of new cell types (including dye-sensitised) by 2030 [231].

## SWOT analysis for Europe

| | Strengths | Weaknesses |
|---|---|---|
| S&T | • Very good position in PV academic research<br>• Excellent research and manufacturing capabilities and capacities in industry | • Fragmentation of national R&D programmes<br>• Only $56 M (€46 M) spent in 2003 on R&D programmes, less than Japan and USA<br>• Absence of manufacturing issues in R&D programme |
| M&I | • Close co-operation between industry and research laboratories<br>• High production levels: 193 MW in 2003 (+43%)<br>• Good public acceptance of PV technologies<br>• Strong, world-level silicon wafer industry | • PV cells market excessively linked to national programmes for grid-connected PV systems |
| P&M | • Preparation of European standards and codes for PV systems | • Very limited market deployment programmes from the Member States<br>• Too much public control of R&D policies<br>• Lack of harmonisation of the Member States' policies and regulatory frameworks |
| | **Opportunities** | **Threats** |
| S&T | • Take advantage of strong public support for PV to launch extensive programmes of experimentation, development and implementation of PV plants<br>• Use the good expertise in nanotechnologies in Europe to gain a competitive advantage | • Europe does not take advantage of its current expertise (no world-class and far-reaching programmes, fragmented funding) |
| M&I | • Open new markets by electrifying rural dwellings in developing, Mediterranean countries eager to cooperate with Europe<br>• Develop a specific PV-grade Silicon supply chain | • The strength of Japan's production facilities in PV industries in view of the envisaged capacity in the European countries<br>• Stronger competition from developing Asian countries entering the market |
| P&M | | |

## Strengths and weaknesses of Europe

*Science and Technology (S&T)*

**Europe has achieved a strong position in PV research over the past five years**, covering most technologies. Europe enjoys a solid foundation of R&D institutes and has a "critical mass" for science and technology capacity, particularly in Germany where R&D funding is available and many research institutes work on PV in close co-operation [1, 143, 144]. the existing PV technologies are well accepted in society. This good public support provides a basis for positive legislation on application funding.

**National R&D programmes are too fragmented:** the possible synergies offered by more cooperation are often neglected and too many universities and laboratories are involved in PV research. For instance, some small countries have PV-dedicated laboratories in several universities (e.g. 2 in Denmark and 3 in Austria). This scattering of PV studies and research initiatives puts Europe at a disadvantage compared to large nations such as the USA and Japan, even though there are some international programmes, such as the French CEA-led MOLYCELL. The same can be said about European industry: the British association PV-UK published a roadmap last year without any reference to its European counterparts, neither in terms of collaborative R&D projects nor of industrial partnerships [143]. Furthermore, European and national programmes have different priority areas, approaches and procedures.

**The rapid transfer of technology from research to application is difficult. Manufacturing-related issues are poorly addressed in technology development programmes**. Support from governments for the development of pilot plants for new PV technologies is virtually nonexistent [1, 11, 54].

The eight IEA members of the EU spent about $56 M (€46 M) in 2003 on R&D programmes, significantly less than in Japan or the USA. Germany leads with $33.6 M (€27.5 M), followed by France with $5.8 M (€4.7 M). According to EPIA, R&D budgets for PV need to be tripled: for instance, R&D on dye-sensitised cells and polymer cells is insufficiently funded[190].

### *Market and Industry (M&I)*

**In the EU, the production of photovoltaic panels was up 43% in 2003** with 193 MW produced. Germany reached 400 MW of installed solar electricity capacity; its initial objective was 300 MW. Italy, France and the UK launched PV programmes in 2004 with important support for private investors in solar power. German Q-Cells, for example, announced they would boost their current manufacturing from 170 MW a year to a total of 320 MW expected in 2005, putting them in line to be one of the largest solar photovoltaic producers in the world, and the largest manufacturer in Europe [167, 207].

The **European PV industry, which considered the global market from the very beginning, has followed a dedicated export strategy.** For example, the EREEC (European Renewable Energy Export Council) was funded in 1996 in order to support EU industry. In its roadmap, the EPIA sets a target of 1 GWp and 30 GWp of cumulated PV systems in third-world rural applications in 2010 and 2020 respectively, and firmly believes that the developing countries represent a major market opportunity for the European PV industry [362]. The EPIA will also take into consideration the United Nations Millennium Development goals when endeavouring to contribute to the creation of sustainable development.

At Member State level, in the UK for example, the dedicated PV trade association has been working to enhance the use and development of PV technology, both within the UK as well as for export markets. In January 1999, PV-UK presented a market strategy report outlining its aim to gain 15% global market penetration for the UK PV industry by 2010 [143].

Nevertheless, limited financial budgets prevent European companies from exporting and expanding: the available production capacities for PV cells are still too small to compete with Japan and the industry is too conservative in adopting new or improved processes. Moreover, it is difficult to fund start-up companies for a sufficient period of time. **A long-term, stable environment for big industry investments is lacking.**

The three largest polycrystalline silicon wafer manufacturers are located in the EU, and there are a lot of module, cell and balance-of-system manufacturers, who are competitive at a global level.

The market for PV cells is too closely linked to national programmes for grid-connected PV systems: grid-connected applications and stand-alone proportions dominate the centralised, large on-grid plants producing several MW, which are still marginal [29, 1].

### *Policies and Measures (P&M)*

**European standards and codes** for PV systems and components are being prepared, in accordance with EU directives and in collaboration with international and national committees, in order to support the accelerated market introduction by the harmonisation of standards [190]. However, standards development is a very long process, and Europe is lagging behind Japan in that matter.

**The current regulatory framework for PV in Europe is very heterogeneous** with major differences between Member States, most of which do not show any real commitment to the promotion of PV energy [54]. Apart from Spain, Germany and Belgium, which have implemented incentive feed-in tariffs to encourage the development of PV technology, enabling for instance the German market to expand tenfold in only four years, the remaining Member States have very limited market deployment programmes. The situation is similarly contrasted in the ten new Member States: new feed-in tariff laws, which already exist in the Baltic States, are under discussion in some of the other countries [54].

Administrative barriers, such as bureaucratic delays in Italy, and market unsteadiness are slowing down the introduction of PV technologies. Some of the European countries have opted for a renewable energy portfolio standard, which mainly encourages those renewable energy options with the lowest direct cost, but not photovoltaics. This creates market practices often considered unfair by the PV industry, notably in terms of access to the electrical grid [54].

## Opportunities and threats for Europe

### *Science and Technology (S&T)*

According to US Frost & Sullivan consulting company, **studies on nanomaterials in Europe, such as in the Netherlands, are a key asset** in the development of more efficient solar cells [109]. Generally speaking, nanotechnologies are considered to constitute cutting-edge research that may provide the foundation for a new generation of high-efficiency (more than 60%), low-cost solar cells [31]. Combining European nanosciences and photovoltaic skills could give European PV research a significant advantage.

In 2003, approximately €697 M were allotted to nanoscience research in the USA, €720 M in Japan, and €585 M in western Europe (the EU and Switzerland). Thus, there is a risk of Europe lagging behind.

Moreover, because of the fragmentation of credits, far-reaching world-class research activities are difficult to set up, which may lead to European scientists not being able to fully take advantage of their expertise.

### *Market and Industry (M&I)*

The continued market growth in Europe (35%/yr for several years) and other parts of the world is a sign that **PV could rapidly become a very important and profitable high-tech economical sector**. Continuously rising petroleum prices and electricity needs contribute to the deployment of the PV market, as do, to a lesser extent, ageing electricity production facilities. Prospects for

PV are also good in the USA, where the low reliability of the grid (which costs the US economy €80 bn every year) paves the way for the widespread development of distributed-generation PV sources which could reduce stress on transmission and distribution systems and create new export opportunities for both US and European industry [130].

According to the IEA, **the European PV industry could establish a far greater presence in export markets, particularly for rural installations in developing countries**. The USA and Japan were quick to recognise this opportunity [12]: for US-DOE, solar energy could become a major high-technology growth industry that will contribute significantly to US economic growth while improving the trade balance [31]; Japanese companies are also taking part in numerous collaborative programmes in South-East Asia. The Chinese industry is also increasingly represented at international PV fairs and forums, and India has been successful in promoting a rural PV market while developing its own industry [54]. This new configuration of the world PV landscape could allow profitable partnerships to be established by European industry, in the form of joint ventures or collaborative research and development programmes.

At present in the developing countries, there are numerous isolated dwellings which could take advantage of off-grid PV electricity, but it is very likely that India, China or Indonesia will offer cheaper PV systems in the coming years due to their low labour costs and the proximity of their markets.

**The coming decade will be very important in terms of which countries or regions will dominate the future PV sector.** Europe is relatively well positioned, behind Japan, and can rely on its research capabilities on "advanced concepts" for activity on medium- to long-term markets. However, the future industrial champions need to be in the race for the more short-term opportunities. In that sense, Europe should provide more support to short-term industrial technologies, focusing on manufacturing issues and cost-efficiency improvement, and should develop a coherent and harmonized market development policy.

## References


[3] Greenhouse Gas Control Technologies Vol. I and II - Conference Proceedings. GHGT-6, Kyoto. September 2002.

[4] World energy, technology and climate policy outlook. EC. June 2003.

[11] PV Status Report - Research, Solar cell production and market implementations in Jp, USA and Europe. EC-JRC-IES. September 2003.

[12] Solar electricity in 2010 - building on a decade of industrial and political commitment. EPIA. June 2001.

[17] US Climate Change Technology Program: Technology options for the near and long term. US Department of Energy. November 2003.

[29] Le baromètre européen 2003 des energies renouvelables. Observ'ER. 2002.

[31] Solar Energy Technologies Program: Multi-Year Technical Plan 2003-2007 and Beyond. US Department of Energy, Energy Efficiency and Renewable Energy (EERE). January 2004.

[32] Basic Research Needs to Assure a Secure Energy Future. US Basic Energy Sciences Advisory Committee. February 2003.

[33] European Energy and Transport trends to 2030. EC-DG TREN. January 2003.

[40] Thinking the future of energy. Central Research Institute of Electric Power Industry (CRIEPI), Japan. November 2003.

[53] Trends in photovoltaic applications: survey report of selected IEA countries between 1992 and 2002. International Energy Agency (IEA). December 2003.

[54] A vision for PV technology for 2030 and beyond. European PV-TRAC (the Photovoltaic Technology Research Advisory Council). July 2004.

[57] Photovoltaics Technology Plan. US DOE. September 2003.

[87] The current status and future prospects of photovoltaic market in Japan. Digital Research Institute. December 2003.

[109] Renewable energy gaining market share in Europe. Oil and Gas Journal. September 2004.

[120] Solar power: sector outlook. CLSA Asia-Pacific Markets. July 2004.

[130] Electricity Technology Roadmap: introduction and executive summary. Electric Power Research Institute, USA. 2003.

[133] State incentives for renewable energy: case studies on program effectiveness. North Carolina Solar Center, USA. 2003.

[139] Solar cities: Local government and utility leaders in solar deployment. Segue Energy Consulting. March 2004.

[141] Solar electric power: the US photovoltaic industry roadmap. National Center for Photovoltaics, USA. January 2003.

[143] List of members of the British Photovoltaic Association. National Energy Centre, UK. September 2004.

[144] Photovoltaïque: la course au rendement est lancée. CEA Technologies. September 2004.

[157] PV systems and net metering. US DOE, Energy Efficiency and Renewable Energy (EERE). February 2004.

[167] BP solar annual production boost: 90 to 200 MW. Renewable Energy Access. October 2004.

[172] Status report 2004: energy end-use efficiency and electricity from biomass, wind and photovoltaics in the European Union. EC-DG Research. August 2004.

[178] Energies renouvelables. Académie des technologies, France. September 2003.

[190] Trends in photovoltaic applications: survey report of selected IEA countries between 1992 and 2003. International Energy Agency (IEA). September 2004.

[201] Our solar power future: the US/ Photovoltaics Industry Roadmap Through 2030 and beyond. National Center for Photovoltaics, USA. September 2004.

[207] German Solar PV Firm Increases to 320 MW. Renewable Energy Access. October 2004.

[221] Industrial technology vision of photovoltaic power generation. PVTEC, Japan. June 2003.

[231] Energy Supply and Demand up to 2030. Agency for Natural Resources and Energy (ANRE), Japan. April 2004.

[236] Fuel cell and hydrogen energy society development up to 2030. Agency for Natural Resources and Energy (ANRE), Japan. April 2004.

[362] EPIA roadmap. European Photovoltaic Industry Association. July 2004.

# Biomass technologies

## Technology and market trends

Biomass is defined as "all organic materials, available on a renewable or recurring basis, possessing an intrinsic chemical energy content that allows conversion into bioenergy" [217].

Biomass resources are diverse and widely dispersed. They can be classified according to source (animal or plant), form (solid, liquid or gaseous), and divided into the following principal categories: residues from primary energy production, dedicated plantations (energy crops), by-products and wastes [172]. They are generally low-energy and low-bulk density materials, which are difficult and costly to transport, store and use [243].

Biomass is considered to be "carbon-neutral", in that the amount of carbon it absorbs while growing is the same as the amount it produces when burned. Biomass projects can therefore be included in the CDM and Joint Implementation activities of the Kyoto Protocol.

Different conversion processes and technologies can be used to produce heat, electricity, combined heat and power, chemicals or liquid fuels for transport (ethanol, biodiesel, etc.):

- Thermal conversion: combustion, gasification, pyrolysis, etc
- Biological conversion: fermentation, digestion, etc
- Mechanical conversion: compression and pressing, chipping, etc.

**Biomass potential is very large and widely distributed throughout the world**. The present biomass contribution to total primary energy supply is just under 14% and is essentially based on agro-forestry residues and natural forests. Biomass is the main fuel for 2.4 billion people living in developing countries, and is mostly used - very inefficiently - for heating and cooking needs.

Biomass resources vary greatly across the European countries. While in Finland and Sweden the most significant resource is wood, it is mainly straw in countries like Germany and Poland.

Biomass also has one of the greatest growth potentials of the renewable energies in the EU. The White Paper for renewable energy sources and the RES-E Directive set targets for different renewable energies: biomass electricity production is facing one of the biggest challenges with a tenfold increase planned between 1995 (23 TWh/yr) and 2010 (230 TWh/yr).

In 2001, the largest producers of electricity from biomass of the EU-15 were Finland, Germany, the UK and France, while in the new Member States the largest amount of bioelectricity is generated by the Czech Republic and Poland, though quantities are significantly smaller than in the EU-15 countries [172].

**However, there are barriers to the further development of biomass**, one of which is the high capital and fuel costs compared to fossil fuels, which mean that technology choices more often favour implementing large-scale natural gas systems, for example. Compared to fossil fuel heating technologies, for instance, a biomass plant is more capital-intensive by a factor of 2 or 3 [92]. Furthermore, the production of 1 TWh using biomass demands a ground area of 700 km² (0.1 km² for a thermal fossil or nuclear plant) [178].

Current bioelectricity production costs from dedicated combustion plants range between 60 and €120/MWh depending on the process used and the fuel cost. Power costs from future dedicated plants fuelled with energy crops could be as low as €50/MWh, but would nevertheless be higher than coal and natural gas options. **Bioelectricity could become competitive if the economic benefits of decentralisation and environmental impact are taken into account [42].**

In the IEA countries, biofuel production costs for transport are up to three times the cost of gasoline and diesel fuel. Nevertheless, production of biofuels, especially of ethanol, is growing rapidly around the world, providing important experience and building markets.

New bioenergy conversion technologies may therefore improve potential biomass benefits and plant efficiencies, as well as generating lower costs.

## Technology trends

**Further analysis in the current chapter focuses on the conversion processes, which are either thermochemical (co-combustion, gasification, pyrolysis) or biological, for heat and power or transport applications.**

An American workgroup, the US Biomass R&D Initiative, identified the key milestones for competitive and efficient biomass use [118]:

- Improvement of the technical understanding of plant biochemistry, such as lignin and cellulose metabolic pathways
- Development of chemical/biological pathways necessary to improve the energy density and chemical characteristics of delivered feedstocks
- Optimisation of agronomic practices for sustainable biomass feedstock production
- Optimisation of logistics for collecting, storing and combining multiple feedstocks for biomass use in an environmentally sound manner
- Development of cost-effective, environment-friendly thermochemical conversion technologies to convert biomass feedstocks into useful electric power or biofuels.

Most of the current biomass technologies are commercially available or considered close to maturity. Nevertheless, many efficiency and cost-effectiveness improvements will be needed over the next five to ten years.

During a Supergen Initiative workshop in 2003 (a UK research programme on sustainable power generation), a status report on the various biomass conversion processes as well as the challenges to be addressed by RD&D was presented [243]:

*Figure 2 – Status and challenges of the biomass conversion processes*

| | |
|---|---|
| Fermentation to bio-ethanol | Commercial status but high cost, low efficiency and low yield (~55 GJ/ha with cellulose, 75 GJ/ha with hemicellulose)<br>Challenges are: cost reduction, higher yield, use of hemicellulose, use of lignin |
| Physical processes to bio-diesel | Proven technology with high cost and low yield (~40 GJ/ha)<br>Challenges are: use of by-products, cost reduction and continuous production |
| Anaerobic digestion | Commercial status but digesters have high cost, low efficiency and low yield<br>Challenges are: scale-up, cost reduction and use of mixed wastes |
| Combustion | Commercially available but emission problems and low efficiency at small scale (~170 GJ/ha for heat, ~50 GJ/ha for electricity)<br>Challenges are: emissions, feedstock variability, feedstock contamination and combustion stability |
| Gasification | Technology at demonstration scale, with moderate cost and high efficiency, increased in CHP (~80 GJ/ha for electricity, ~160 GJ/ha for CHP)<br>Challenges are: gas quality, cost reduction, economic down-scaling for liquid fuels and hydrogen |

| | |
|---|---|
| Fast pyrolysis | Technology at development stage for fuel, with moderate cost, moderate efficiency, producing bio-oils that can be stored and transported, used as fuels or chemical raw material<br>Challenges are: product quality and standards, applications development, integration in bio-refinery |

*Source: Supergen Initiative workshop, 2003*

**Fast pyrolysis has received attention in recent years** as it offers a flexible and attractive way of converting solid biomass into an easily-stored and transported liquid, with a much higher density than solid biomass, and which can be successfully used for the production of heat, power and chemicals [172, 208].

There is a tendency to believe that the fuel spectrum for gasification and pyrolysis is large, but when they came close to commercialisation, the industries found that it is not in fact quite so broad due to cleaning and humidity problems. Product quality standards and further application developments are therefore needed. Demonstration of flash pyrolysis on a larger scale will be a crucial step in its development.

**R&D activities regarding bioethanol production are focused on developing processes for using lignocellulosic materials as a feedstock.** Still at the demonstration stage, lignocellulose hydrolysis processes could provide the necessary technological breakthrough for cost-effective production of bioethanol within 15 to 30 years [48, 49, 98]. But the pulp and paper industry has expressed concerns about the availability of raw materials for its own production. Newly developed crops such as marine plants and genetically modified crops may contribute to an increased production of biomass [184].

Biomass gasification is also being studied and synthesis catalysts are being developed. New utilisations for by-products of bioethanol production from sugar crops, such as glycerine, are being reviewed [98].

In the framework of the IEA's bioenergy implementation agreement, the gasification of biomass to obtain transport biofuels such as methanol, ethanol and diethyl ether, is being studied, as are some thermochemical processes such as hydrothermal upgrading (HTU) or fast pyrolysis. Today it is still unclear whether these approaches can achieve sufficient cost reductions to be competitive with other transport fuels over the next 10 to 15 years [95].

## Market trends

**The market potential of biomass for heat and power production is very high**. The global role of biomass resources for energy should be large, yet it will be very much policy dependent.

Electricity from biomass in Europe has grown by about 10% per year over the past 4 years (1999-2003) and is expected to increase by a rate of 6 to 10% per year until 2010. In that case, bioelectricity production will be between 65 and 91 TWh in 2010 without implementation of additional policy measures. However, this is considerably lower than the White Paper targets [172].

A report published by Lund University, in Sweden, showed the difficulty of accurately evaluating bioenergy potential, presenting forecasts with a variation that was at least twofold [89]. In a recent report, WWF International and AEBIOM considered that a 15% contribution of bioelectricity to electricity generation is possible by 2020 [42].

**The potential of biomass for heat and power production is often considered to be much higher than for transport applications.** This is partly due to the biofuel production energy balance and also takes into account environmental and economic concerns. This even applies where the potential of new technologies for bioethanol production from lignocellulose is considered.

The importance of biomass for heat and electricity could technically very much depend on the implementation of energy crops. However, as land availability for energetic farming has not been completely assessed, competition between bioelectricity, biofuels, the pulp and paper industries as well as food production for use of available land could be considerable.

Social acceptance could also be an issue for bioenergy market development, "not in my backyard" probably being the major problem.

Three very diverse kinds of markets have to be considered: mostly regional markets for the biomass itself, global trade with biofuels like bioethanol, and an industrial market for the technology, i.e. production plants and components. As biomass is expected to play a major role worldwide, these markets could become voluminous and of interest to Europe, especially that of industrial technologies.

According to the World Biomass Report [164], a total of 12,172 MW is forecast in biomass power plant installations between 2004 and 2013 worldwide. Large thermal biomass plants will make up the largest share of the market, covering 81% of this capacity, with landfill gas coming in second with 15%. Annual installed capacity should more than double for large-scale thermal plants during that period.

**Market potential is especially high in Asia**, for both wood and agricultural materials. Asia and Latin America will see the highest growth as these regions have held massive potential for a long period, which is now beginning to be exploited. Small-scale thermal power is already well established, and the move to large-scale developments is being encouraged. Countries such as China, Indonesia, Thailand and Malaysia show promising biomass potential for power generation, as well as, for some of them, favourable regulatory frameworks and incentives [298].

## Main strengths and weaknesses of the USA and Japan

### USA

| | Strengths | Weaknesses |
|---|---|---|
| S&T | • R&D-driven strategic plan, aiming at creating a domestic bio-based industry and focusing on technology fundamentals<br>• Cooperative programmes from DOE and USDA<br>• Integrated approach for fuels, power, heat, chemicals and materials production<br>• Bio-refineries and biological pathways to use lignocellulosic biomass<br>• Support for genetically engineered crops | • Fewer R&D programmes for demonstrations and commercialisation of near-term technologies in the present plan<br>• Relative lack of support for thermal technologies, such as pyrolysis<br>• Influence of farmers, driving the R&D agenda and focusing on corn |
| M&I | • Favourable conditions for biomass supply: arable land availability, cost advantages for agricultural and forestry resources<br>• Strong ethanol production with cost benefiting from economy of scale<br>• Long-time experience of co-firing in utilities<br>• Powerful industries in agrochemistry<br>• Experimenting with bio-refinery concept on existing plants | • Flexibility of the bio-refinery concept |
| P&M | • Rigorous R&D project management, driven by cost-competitiveness objectives | • Lack of stable energy policy support<br>• Government not environmentally proactive<br>• Not enough support for SMEs, despite SBIR and STTR programmes |

*Science and Technology (S&T)*

Fossil energy being the backbone of the US economy, the US government quickly reacted to the 1973 oil crisis and launched, as a national security issue, different R&D programmes to increase the use of biomass resources for energy and fuel demand.

More than 25 years later, the Biomass R&D Act of 2000 is a key milestone in US involvement in biomass development. Far-reaching goals have been set to increase the role of biomass in the US economy by 2020, and are ultimately aimed at reducing US dependence on foreign sources of oil and **creating a domestic bio-based industry**. The targets are: 10% of transportation fuels, 5% of electricity and heat demand in utilities and industry, and 18% of chemicals and materials produced in the US originating from biomass resources [126].

The 2002 Farm Bill demonstrated the continued legislative support for the development of the bioindustry. For the first time in history, it contains an energy section with five programmes providing mandatory funding for bioenergy activities [232].

Key characteristics of the current US R&D programmes are:

- Integration of the federal efforts under a unique umbrella
- Research focus on technology fundamentals
- Integrated approach for fuels, power and bio-based products
- Defined targets and more rigorous project management.

Traditionally, prior to 2000, the federal agencies had an insular view of biomass. The new strategic plan recognises that the scope of biomass is not limited to specific competencies but encompasses all the fields covered by the USDA (agriculture), DOE (energy), NSF (research), EPA (environment) and DOC (commerce) [233]. **Joint and cooperative DOE and USDA programmes have been set up to take advantage of the expertise of each department**, both of which are working together to establish the critical pathways needed to meet the objectives of the Biomass R&D Initiative [BERA].

Under this integrated effort, the federal agencies have been investing about $250 M (€204 M) per year to fund biomass R&D projects.

The Biomass R&D Act has **redirected the focus from demonstrations of near-term technologies to technology fundamentals**, in order to reduce the inherent cost of bioenergy and bio-based products. The DOE Biomass Program goals are organised around four research areas (feedstock, sugar platform, thermochemical platform and products), focusing heavily on developing the ability to use inexpensive **lignocellulosic biomass**, and establishing **integrated biorefineries** [126].

Most programmes take into consideration the possibility of manufacturing materials and chemicals such as bioplastics, biopolymers and textiles in integrated biorefineries that, in theory, would use multiple forms of biomass to produce a flexible mix of products [232]. Production in such integrated plants of high-value bio-based products for niche markets could help improve the cost-competitiveness of mass-market products such as fuels and energy.

On the other hand, as funding is attributed to precise research goals, some experts regret the current **lack of R&D programmes for demonstration and commercialisation of more near-term technologies,** as was the case under previous administrations. For example, the existing DOE programmes on co-firing ended in 2001, as it was felt that the available techniques had largely been evaluated and demonstrated in utilities [237]. Within the thermochemical conversion processes, the emphasis has now officially shifted to gasification technologies [237], although some experts consider that current R&D priorities may be excessively focused on biological pathways, whereas thermal technologies represent a huge part of the biomass market and have a strong market potential. Pyrolysis, for example, lacks support in the USA, unlike in Canada and Europe.

Some experts also believe that American farmers may have too much influence on the R&D agenda. This means, for example, that particular attention is paid to corn biomass resources, whereas other resources and technologies could also be promoted.

Despite some international controversy, the use of genetically modified seeds continues to expand in the USA, and has been mobilising important R&D efforts. **Genetically engineered crops** could be an important factor in establishing the reliable feedstock supply needed for future bioproducts markets, and have the potential to yield tremendous economic advantages [232].

### *Market and Industry (M&I)*

The USA benefits from a **naturally abundant biomass** [232]. Cheap agricultural and forestry feedstocks coupled with heavily subsidised agriculture provides the USA with a cost advantage for competitiveness of biofuels and bioenergy. The low population density and the excellent availability of arable lands also provide favourable conditions on the biomass supply side.

In addition, as mentioned earlier, the USA has a long history of ethanol production and bioenergy generation, using mature technologies such as co-firing, which has been studied to a great extent by the utilities. **The country is now benefiting from this long-term experience and economy of scale**.

The US ethanol industry is setting new production levels month after month, driving production to nearly 3.5 billion gallons (13.2 billion litres) in 2004, up from 2.81 billion (10.64 billion litres) in 2003. Currently, 79 ethanol plants are operating across the country, and a dozen more are under construction. Production has been increased by 90% in the last 5 years, while cost has been divided by three in ten years [205].

In 2001, the USA produced over 60 TWh of bioelectricity, from 10 GW of electric power capacity (nearly 1% of the total generating capacity in the USA) [233].

In connection with the integrated approach mentioned earlier, some powerful US companies have been investing in the development of the bioenergy and bioproducts market, creating **strategic partnerships between the chemicals industry and the food, textile and agriculture sectors**. A polymer derived from corn, for example, is being produced at a 300 million pound per year plant (136 000 t/year) in Nebraska, from a joint venture between one of the world's largest grain merchants (Cargill) and the largest chemicals producer (Dow Chemical) [232].

Some companies are **already experimenting with the concept of biorefinery.** The Archer Daniels Midland (ADM) complex in Decatur, Illinois, is the prototype of such multiple product plants, integrated in an already active corn wet-milling plant. Dupont is leading a research consortium, known as ICBR (Integrated Corn-Based Bioproducts Refinery), which was granted $19 M (€15.5 M) in matching funds from the DOE in 2002 to design and demonstrate the feasibility and practicality of the biorefinery concept.

Nevertheless, the flexibility of feed-in/input raw materials will be a key factor in maximising the economic viability of the concept, and has not yet been proven.

*Policies and Measures (P&M)*

US DOE, Office of the Biomass Program (OBP), is working in partnership with industry to fund research, development and deployment projects. **R&D programmes are cost-shared with industry**, by up to 50% or more, even for full-scale demonstration projects where the investment is considered high-risk but essential for the government's strategy.

**Different tools have been implemented** at the DOE-OBP **in the last few years to improve the effectiveness** of these **R&D projects**, using stage gate management methods. Industry-led detailed visions and roadmaps are contributing to choosing critical pathways to defined targets. Criteria for evaluating project performances are established at the beginning of the project, and are often driven by cost-competitiveness objectives. Earmarked funding has grown from 18% to over 40% of total R&D funding, providing less flexibility but ensuring that funds are allocated to more precise objectives.

However, the US government is generally considered as **lacking political leadership on energy and greenhouse gas emissions reduction**. The House and the Senate are for example still looking for an agreement on an Energy Bill, after months of trying.

In addition to R&D measures, some experts believe that the USA needs more commercialisation and market incentives for bioenergy and biofuels, as well as more support for SMEs, despite the SBIR and STTR programmes.

Several laws support the development and commercialisation of alternative fuels and alternative fuel vehicles, providing tax incentives for purchasing such cars, promoting the expansion of alternative fuelling infrastructures and requiring the use of alternative fuel vehicles by various public and private entities. Unfortunately, there are few incentives to buy biodiesel, ethanol or methanol for private vehicles [111].

USDA dedicates about $150 M (€122 M) every year to public policy measures to support biomass development. Following the 2002 Farm Bill, for example, USDA launched a programme that introduces a requirement for federal agencies to purchase bio-based products.

## Japan

| | Strengths | Weaknesses |
|---|---|---|
| S&T | • Know-how in fundamental technologies<br>• Japanese manufacturers already own proprietary power generation technologies (furnaces, turbines) | • Experts do not yet agree on the actual potential of biomass energy in Japan |
| M&I | • Biomass energy is potentially cheaper than conventional power<br>• Industrial waste specialist network has good financial power | • All non-recycled biofuels will have to be imported<br>• Difficult to apply PFI to technologies that have not been well-established in Japan<br>• Land area efficiency of biomass power is very low<br>• Difficult to collect directly from sources<br>• Present biomass waste processing may be as low as ¥20,000/t (€150/t) |
| P&M | • Ambitious "Biomass Japan" programme<br>• Coordination between Ministries<br>• Valorisation of biomass helps compliance with various organic waste recycling laws (food, manure, wood, etc.)<br>• RPS law since 2003 | • Biomass potential recognition is very recent (2002)<br>• Wide gap between affordable cost and plant price for small users (farms, sawmills, etc.)<br>• Financing of such projects ("project finance" system) is expensive due to high interest costs |

### *Science and Technology (S&T)*

In terms of power production per land area, biomass power today is a very poor performer (up to 50 times that of photovoltaic), and this is considered a critical issue in Japan [40]. More importantly, **domestic biomass production would not be sufficient to feed a large-scale market,** as Japan is not an agriculture-intensive country.

However, there is a potential for **medium-scale applications focused on organic waste energy recovery**. In this respect, Japan already has sound expertise in municipal waste "energy recycling" (fluidised bed combustion, pyrolysis, co-firing, etc.).

In terms of non-power plant technologies, Japan recognises that today it cannot compete with European (biodiesel and biooil production, biofuel engines) or US (fermentation processes) expertise.

### *Market and Industry (M&I)*

In 2000, biomass power installed capacity was only 80 MW, and the government target for 2010 has been set to 330 MW; this capacity should yield 3.7 TWh of power (~0.4% of total electricity supply) [41].

The Japanese government estimates that the costs of biomass waste processing and power generation could be as low as ¥20,000/t (€150/t) and 7~21 ¥/kWh (0.05~0.16 €/kWh), respectively [231].

These introduction targets represent a 6-fold increase over ten years, which is still a small amount with respect to the potential of biomass power in Japan[1]. Indeed, the government's wish is to **help start the market and validate related technologies by 2010** as a first step [227].

Although Japan has little domestic potential compared to other countries, its industries are knowledgeable in power plant engineering, and advisers to the government recommend that they use this expertise to **develop and build plants in biomass producing countries**.

### *Policies and Measures (P&M)*

In June 2001, biomass heat and power generation was first recognised as a valuable "new energy" source and incorporated into the government's five-year S&T Basic Plan, which led to the drafting of the "Biomass Japan" plan and its approval in December 2002 [35, 218]. Although biomass energy had already been in use, **2002 is considered "Year Zero" of biomass energy in Japan** [219].

Since 2000, several laws have strengthened the regulation on waste disposal, in particular for organic wastes such as food, building materials (wood), animals, winery and distillery. These **waste recycling laws will help the diffusion of biomass power[2].**

The Ministry of the Environment (MoE) has devised a plan to mix 3% of bioethanol with gasoline ("E3" fuel). Starting next year, nationwide distribution is planned for 2012 (supply of 2 bnL EtOH at most). Minimum investment to implement this policy has been estimated at ¥350 bn (€2.63 bn), but the final price of "E3" fuel should eventually be the same as conventional gasoline.

In parallel, the Ministry has been working to promote "E10" fuel (10% EtOH). Conventional cars cannot be fuelled with E10, so distribution will not start before 2015 approximately, and R&D programmes are currently being discussed.

[1] There is a controversy among experts regarding the amount of recoverable biomass reserves in Japan. The government figure for total reserves, excluding black liquor and fuel from wood, is 19.7 MTOE [METI].

[2] For example, under Japan's Food Recycling Law (2001), the food industry is obliged to reduce or recycle food waste at a minimum of 20% by 2006. Power generation through methane fermentation of food waste streams is an approved way to accomplish these goals.

## SWOT analysis for Europe

| | Strengths | Weaknesses |
|---|---|---|
| S&T | • Strong scientific and technological capabilities<br>• Excellent basic and applied research facilities<br>• Good technical networks | • Lack of coordination and exchange of best practices in technical networks<br>• Development of technologies that might be too sophisticated for market needs<br>• Lack of integrated approach for bioenergy by-product valorisation |
| M&I | • Market leader in electricity generation using biomass<br>• Many industrial leaders for biomass technologies and services, with many “success stories” to promote<br>• The world’s largest biofuel CHP plant | • Cooperation between research institutes and industries<br>• Diversity in bioelectricity pricing<br>• High cost and relatively low availability of biomass resources |
| P&M | • Favourable legislation and policy with precise targets at European level<br>• German support scheme | • Support too scattered and dispersed . Lack of integration and coordination of Member State programmes and initiatives.<br>• Little policy coordination with agriculture<br>• Lack of strong market deployment measures, harmonisation, and long-term commitment<br>• Lack of standards for biofuels quality |
| | **Opportunities** | **Threats** |
| S&T | • Research for using cheap lignocellulosic materials as feedstock for biofuels (enzymatic hydrolysis, syngas, Fischer-Tropsch synthesis, etc.)<br>• Multi-products bio-refinery approach for cost-competitiveness | • European position on genetically engineered crops<br>• Foreign countries gaining operational experience, thanks to a better environment for full-scale demonstration plants |
| M&I | • Strong market potential in Asia and non-OECD countries<br>• Biomass resources of East European Countries | • Competition for the use of limited biomass resources |
| P&M | • Larger policy coordination with agriculture<br>• Standardisation efforts for various biofuel products | |

## Strengths and weaknesses of Europe

### *Science and Technology (S&T)*

Europe is considered to be a **leader in scientific and technological capabilities for biomass**. The development of biomass energy technologies is very strong, with several member countries seen as world leaders in their respective fields. There is a high level of know-how, with strong academic and research groups.

The eastern European countries also have very good scientists in this field, with high potential. Support and coordination might be needed to involve them at European level.

**Gasnet and Pyne are regularly quoted as good technical networks existing in Europe**, important for information exchange between researchers and developers of gasification and fast pyrolysis technologies.

However, it is believed that there is still room for improvement. Better coordination at European level is needed, especially between such technology networks and the policy and regulation side, as well as for an **exchange of experience and best practices** among different countries.

Europe has faced some problems in gasification demonstration projects, such as ARBRE in the UK under the THERMIE programme. It is possible that the reasons for these failures have been fully analysed or communicated, and that some decision-makers have lost confidence in these technologies.

As a consequence, some companies have developed equipment that is believed to be too sophisticated and ill-suited to the market needs. **The market, both in Europe and abroad, needs more robust, simple and effective technologies**. As support is mainly awarded to highly innovative technologies, companies may tend to develop complex technologies just to take advantage of subsidies.

Compared to the US and Japanese biomass strategies, **Europe lacks a more integrated and coordinated R&D approach within sectors that could use and increase the value of bioenergy by-products**. Programmes such as AGRICE in France, which was launched 10 years ago, were heading in that direction, providing research funding to develop new markets for agricultural products in energy, chemicals and materials production, but such efforts are too scattered.

### *Market and Industry (M&I)*

Thanks to specific countries such as Finland and Sweden, the **EU is among the market leaders in electricity generation using biomass** in conventional steam cycle power plants [71]. More than 6 GW of bioelectricity capacity is available in the European Union, i.e. 1.4% of total installed capacity, versus about 1% in the USA and less than 0.05% in Japan. 20% of this European capacity is located in Finland (1300 MW) where bioelectricity represents more than 8% of total capacity [42].

At Pietarsaari, in Finland, the world's largest biofuelled power plant (named Alholmens Kraft) was built with one of the largest Circulating Fluidised Bed (CFB) boilers (550 MWth capacity). Since 2001, this CHP plant has been producing steam and district heat and power at competitive prices, using a diverse selection of fuels (peat, bark and wood residues, heavy fuel oil and coal).

The main barrier preventing future market development of bioenergy is the pricing policy for electricity produced from renewable energies. **Bioelectricity prices differ greatly between countries** and tariffs depend on issues such as date of start-up, source of electricity, type of technology or size of facility. Feed-in tariffs are in place as a key instrument in 18 Member States, but the degree of support needs to be higher in order to stimulate bioelectricity production [172] and harmonisation should be pursued.

The market opportunities inside the EU countries are also limited by the **high costs and relatively low availability of biomass**, especially in terms of raw materials for liquid biofuels. There are concerns about the capability of Europe to produce enough biomass feedstock to meet the target demand for biofuels as proposed in the EU Directive of March 2003 [98]. Only few sites in Europe are believed to be capable of producing, sustainably and at close proximity, the 100,000 dry t/year needed to supply a 25 MW electricity generation plant.

Because of their large domestic markets, as well as low-cost biomass resources, strong pulp and paper industries and favourable national policies, the Nordic Member States have also become **main producers and exporters of equipment and services** for bioelectricity generation [172].

Despite the fact that cooperation and information transfer between research institutes and industries could be more efficient [72], many European companies are considered to be global market leaders in their respective fields. Many European "success stories", such as the Alholmens Kraft plant, can be used by those industries to promote their technologies and know-how in promising export markets.

*Policies and Measures (P&M)*

Many different policies and directives currently support biomass energy production and favour more or less directly the technologies considered. **Targets set by the White Paper** for Renewable Energy Sources and the RES-E Directive (Electricity from Renewable Energy Sources) are driving the market for bioenergy use in Europe [172]. As biomass is considered to be $CO_2$-neutral in the European Union Emission Trading Scheme, this should also boost biomass firing and co-firing, notably in larger installations [172].

However, such policies and measures establish general biomass energy objectives for the EU area, but as a rule are not compulsory for the Member States. It is not clear how the general objectives will be achieved and national policies can be very variable. **Incentives are not coordinated between countries,** and experience of advantages or problems related to implemented support schemes is not shared between states [172]. While Germany strongly subsidises liquid biofuels (€0.47/l for biodiesel and €0.65/l for ethanol) with tax exemptions, Italy (0.40 and 0.54 €/l), France (0.33 and 0.38 €/l) and Spain (0.29 and 0.39 €/l) provide less support, so that large quantities of raw materials are for example exported to Germany [163, 205].

Europe also **lacks strong market deployment measures**. European subsidies are low for demonstration plants compared to fundamental research. The efficiency of the various biomass technologies can be improved with innovative approaches, but companies will need more help for first-of-a-kind plants before the system can be cost-competitive.

**Such policies and incentives should also be more stable and reflect a long-term commitment**. Frequent changes in European or national measures, according to the political parties in place, will prevent industries from taking decisions on what can be considered a high-risk investment. Uncertainty on future energy policies or standards for atmospheric emissions is a risk if incentives can change before the investments have paid off. Manufacturers and end-users cannot cover such risks alone when new and innovative technologies are developed.

**Germany is regularly quoted for its excellent example** of strong support for bioelectricity and biofuels. Its very effective scheme allows farmers to earn a good income from farm-generated electricity from biomass. Fairly high feed-in tariffs combined with reasonable investment subsidies and exemption from environmental tax have generated a considerable RES market in this country [172].

The development of the biomass energy sector is also impeded by the **lack of coherence across the policies of the different parties involved**, especially in agriculture. Add to that dependency on other policy frameworks, such as in industry, environment, research, transport or the rural sectors, and the complexity of the bioenergy field is evident [172].

The situation of **energy crops** for example is evolving very slowly. Although the 2003 CAP reform introduced aid of €45/ha for energy crops for the first time, this may not be enough to stimulate farmers' choices [205]. And though the European Commission expects energy crops to expand from 20,000 ha in the late nineties to 6.3 Mha by 2010, a European policy ensuring stable demand for energy crops has yet to be implemented [89].

Finally, **lack of international standards for biofuels quality** is also hampering future market developments [49]. More efforts are needed on the revision of standard EN14214 for biodiesel and an equivalent standard should be pushed through for bio-ethanol.

## Opportunities and threats for Europe

*Science and Technology (S&T)*

**Biofuels made from cellulosic raw materials represent an opportunity to be pursued,** as they could allow the production of a cost-competitive substitute. Low-cost enzymatic hydrolysis processes need to be developed for the chemical conversion of biomass [17], as does Fischer-Tropsch hydrocarbon synthesis from syngas (BTL production).

The US DOE-OBP programme is focusing on the development of a sugar platform with a view to producing inexpensive sugar streams that can be used to make fuels and chemicals that are cost-competitive compared to conventional commodities. The objective is to reduce the cost of sugar feedstock streams suitable for fermentation from $0.14/lb (€0.25/kg) in 2003 to $0.10/lb (€0.18/kg) by 2012. Lower cost sugar sources such as corn stover are being considered for future technology development.

In Europe, Sweden inaugurated a pilot plant this year for the development of ethanol production from wood. The TIME project, conducted under FP5 by a research team from Finland, Denmark, Hungary, Italy, Sweden and the Netherlands, is also working on lignocellulosic conversion.

Long-term strategies should be developed to **encourage the establishment of bio-refineries**. Such multi-product integrated plants could recycle a range of farm by-products in addition to using grains, oilseeds and sugar. These complexes would be capable of producing both energy and materials derived not only from annual crops but also grass, short rotation trees, cereal straws and other by-products [95]. FP6 is calling for proposals on such concepts. Nevertheless, because of the transportation cost issue for biomass, such bio-refineries might not be adapted to all European agricultural areas.

**Controversy surrounding the use of genetically modified crops** in Europe could be a threat to tremendous potential economic advantages such as improved yields, reduced feedstock costs and production of more desirable by-products. This can be accomplished through conventional plant breeding, but would take much longer and be more costly. The USA, along with Canada, Argentina and other countries, is supporting genetically modified crops and could gain a strong competitive edge over Europe thanks to this choice. However, the future for genetically engineered crops is uncertain. Even in the USA, a number of genetically modified crops have been approved but are not being grown because major buyers have rejected them.

As Europe is not providing sufficiently strong financial support to companies trying to bridge the gap from science to commercial applications, some European companies are seeking such aid in other countries (Japan or South-East Asian countries) where they sell their products through licences and where demonstration plants will be built. This is for example the case for the Danish engineering firm Babcock & Wilcox Vølund, which signed an agreement for its gasification technology with JFE Engineering (Japan) in December 2003. And although the European companies try to keep control of these projects by sending people for management and training, the **foreign countries are able to gather instructive operational experience and knowledge from the demonstration plants they support**. European leadership on R&D could therefore be overtaken by those countries in a few years.

*Market and Industry (M&I)*

As mentioned earlier (see the Trends chapter), there is **strong market potential in Asia**, mainly for large-scale thermal plants. Gasification seems to be making good progress in countries such as China and India. Many developing countries are interested in European biomass technologies and need robust systems as well as easy operation and maintenance. European successes in co-firing CHP plants, especially those using coal, are good references for short-term export opportunities.

Some countries are however showing an interest in more sophisticated technologies such as fast pyrolysis, since bio-oil is easier and cheaper to transport than solid biomass. Considering that those countries are willing to develop exportation of their bio-oils to Europe, this should provide an opportunity to develop some trading import/export systems to help Europe export its technology to countries that might export their bio-oils,

As the White Paper and the RES-E Directive targets are pushing for the development of bioelectricity and biofuels production in Europe, some experts have **doubts about the exact biomass resources potential available in Europe.** Agriculture does not seem adapted to provide the necessary biomass surplus yet.

The **biomass potential needs to be more precisely evaluated**, notably in terms of land availability for energetic farming and land use for applications such as biofuels for transport and forest products. Life cycle analyses should also be carried out [112]. Some significant potential does exist, however, in the eastern European countries, where large areas of fallow land are available and forests are over-stocked [112, 173].

*Policies and Measures (P&M)*

The absence of integrated policies to achieve the targets set at EU and Member State level, particularly between the **agriculture and energy sectors**, is hindering the development of biomass as an energy supply source. Efforts have already been made at European level, for example with the CAP reform in 2003, but more must be done in terms of cooperation, following the example of the interagency initiatives implemented in the USA since 2000.

Similarly to what has been initiated for biodiesel with standard EN14214, **other standardisation efforts should be addressed** in order to define various biofuel products and the quality needed for efficient use in processes. Such standards should also ensure that greenhouse gas emissions are reduced and environmental benefits are maximised [95].

## References


[17] US Climate Change Technology Program: Technology options for the near and long term. US Department of Energy. November 2003.

[35] Science and Technology Basic Plan 2001-2005. Council for Science and Technology Policy, Japan. March 2001.

[40] Thinking the future of energy. Central Research Institute of Electric Power Industry (CRIEPI), Japan. November 2003.

[41] Energy in Japan 2003. Agency of Natural Resources and Energy (ANRE), Japan. November 2003.

[42] Bioelectricity Vision: Achieving 15 % of electricity from biomass in OECD countries by 2020. WWF International and AEBIOM. April 2004.

[48] Liquid biofuels and hydrogen from renewable resources in the UK to 2050. E4tech. December 2003.

[49] Liquid biofuels and renewable hydrogen to 2050. UK Department for Transport. July 2004.

[71] Biomass electricity: technical development status. Future RTD needs. EC. 1996.

[72] Technologies for small scale biomass CHP-Plants: an actual survey; Conference Proceedings. Biomasse Info-Zentrum, Risoe. May 2003.

[89] Market development problems for sustainable bio-energy systems in Sweden. Lund University. January 2004.

[92] Biomass as a renewable energy source. Royal Commission on Environmental Pollution. 2004.

[95] Biofuels for transport: an international perspective. International Energy Agency (IEA). 2004.

[98] The introduction of alternative fuels in the European transport sector: technico-economic barriers and perspectives. IPTS / Institute of Energy. 2004.

[111] Alternative transportation fuels and vehicles: energy, environment, and development issues. Congressional Research Service. January 2004.

[112] La part des sources d’énergie renouvelables dans l’UE: évaluation des incidences des instruments législatifs et des autres politiques communautaires. EC. May 2004.

[118] Roadmap for the biomass technologies in the United States. Biomass R&D Initiative. December 2002.

[126] A strong energy portfolio for a strong America. US DOE/EERE, Office of the Biomass Program. 2003.

[163] Le coûteux plan de développement des carburants verts. L’Usine Nouvelle. September 2004.

[164] The world biomass report. Douglas Westwood Ltd. October 2004.

[172] Status report 2004: energy end-use efficiency and electricity from biomass, wind and photovoltaics in the European Union. EC-DG Research. August 2004.

[173] Biomass-energy projects: opportunities in Eastern Europe. GFA Holding, Germany. April 2004.

[178] Energies renouvelables. Académie des technologies, France. September 2003.

[184] Trends in research and development of utilization technology of biomass energy in MAAF, Japan. Japan International Research Center for Agricultural Sciences (JIRCAS). March 2003.

[205] Les débouchés non alimentaires des produits agricoles: un enjeu pour la France et l'Union Européenne. Conseil Economique et Social, France. May 2004.

[208] The future for biomass pyrolysis and gasification: status, opportunities and policies for Europe. Bio-Energy Research Group, Aston University. November 2002.

[217] Renewable for Power Generation: status and prospects. International Energy Agency (IEA). 2003.

[218] "Biomass Japan" general strategy. Japanese Government. December 2002.

[219] Closed loop energy supply with biomass. 15th Fuyo Eco-business Seminar, Japan. March 2003.

[227] Wood biomass utilisation technologies. Digital Research, Japan. December 2003.

[231] Energy Supply and Demand up to 2030. Agency for Natural Resources and Energy (ANRE), Japan. April 2004.

[232] Industrial bioproducts: today and tomorrow. US DOE/EERE, Office of the Biomass Program. July 2003.

[233] Fostering the bioeconomic revolution... in biobased products and bioenergy: an environmental approach. The Biomass Research and Development Board, USA. January 2001.

[237] Biomass cofiring - biomass thermochemical conversion. US DOE: Office of the biomass program. March 2004.

[243] Current and future prospects for biomass and bioenergy. Aston University, Birmingham. November 2003.

[298] Overview of biomass for power generation in Southeast Asia. ASEAN Centre for Energy/ ASEM Green IPP Network. 2003.

# Fuel cells

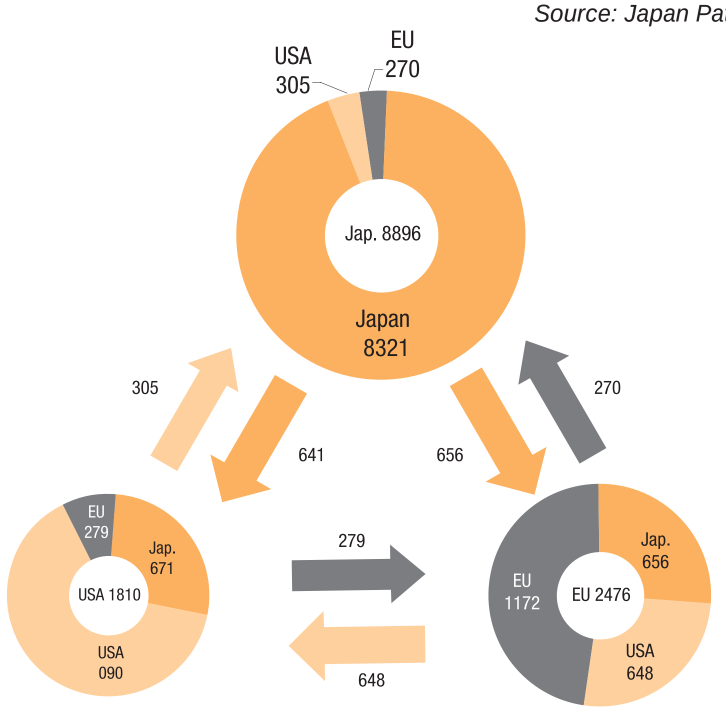
## Technology and market trends

In past years, government programmes have been pivotal in the development of fuel cell systems. For 2003, the total amounts of government funds made available were: $175 M (€143 M) for the EU, $250 M (€204 M) for Japan, almost $50 M (€41 M) for Canada alone and over $300 M (€245 M) for the USA, with a worldwide total of $825 M (€675 M). This support had a clear effect on the number of new fuel cell systems built. In a 3-year time period, the number[1] of complete systems jumped from almost 1000 in 2000 to almost 6,800 in 2003 and sales increased by 41% from $240 M (€196 M) in 2003 to $338 M (€276 M) in 2003 [37, 327].

Japanese and American companies currently have the leading position in fuel cell development, together with Canadian companies. There is still an important gap between those 3 players and the German industry, which is in fourth position [327]. Not only do Japanese and American companies have a strong position, but they are also patenting aggressively. Their patents cover not only Japan, but also the USA and Europe. More than half the patents covering Europe come from Japan and the USA. The situation is very different for biomass for instance where two thirds of patents covering Europe originate in Europe [326].

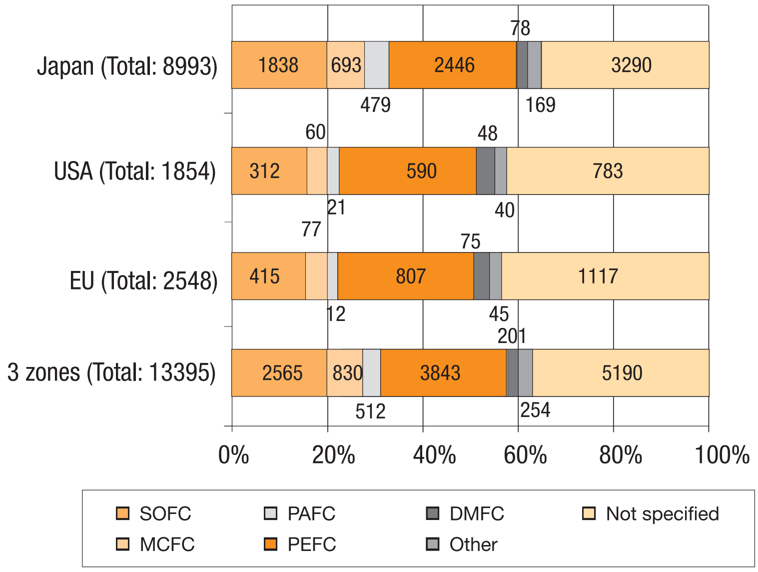
*Figure 3 – Fuel cell-related patent applications in Europe, Japan and the USA between 1991 and 2000 (number of patent families and transfers between zones)*

*Source: Japan Patent Office, 2003 [326]*




[1] Except small systems used for educational purposes and metal air fuel cells [37].

*Figure 4 – Fuel cell-related patent applications in Europe, Japan and the USA between 1991 and 2000 (number of patent families by technology)*




*Source: Japan Patent Office, 2003 [326]*

Looking at the number of units built up to 2004, the most dominant fuel cell type is the Proton Exchange Membrane Fuel Cell (**PEMFC**), **which accounts for 65%**, far ahead of the PAFC (6%), SOFC (4%) and MCFC (3%). The **PEMFC also accounts for more than 50% of the new units built in 2004**, DMFC[2] more than 40%, SOFC around 1.7% and MCFC around 0.2% [328].

However the development of the various technologies **depends very much on the field of application**. **For transport applications**, the tendency over recent years has been that nearly all efforts focus on the **PEMFC**. In contrast, more than 25% of the companies developing **small stationary** units have chosen SOFC technology. For large stationary systems (scaled 10 kW or more), a fairly broad range of technologies is used, and the **Phosphoric Acid Fuel Cell** (PAFC), **Molten Carbonate Fuel Cell** (MCFC) and **Solid Oxide Fuel Cell** (SOFC) represent important competitors for PEMFC [37, 328].

## Technology trends

The PAFC is considered to be a “first generation” fuel cell (now in its third improved version) and has already proven its reliability [99]. There are already 350 PAFC units installed worldwide (around 70% of which were sold [3] by the American company ONSI), with only 15 units installed in Europe, whereas the Japanese have already installed more than 200 units [213]. However, many experts perceive this technology as **declining** [37, 216], which can be explained by the limited prospects for cost reductions, the higher efficiency (+10%) of the next generation of SOFC and MCFC [216] and its decreasing market share [244]. **In view of these aspects, the analysis below disregards PAFC technology, since Europe has no real interest in investing in that technology.**

The **PEMFC** corresponds to the new generation of fuel cells and a pre-commercial version has just been released thanks to a pivotal commitment of governments through large deployment of demonstration programmes. The PEMFC is the most versatile fuel cell, and can power anything from small electronic devices to buses and submarines as well as some stationary applications

[2] Portable applications were not considered in this study, therefore DMFC type fuel cells are not mentioned.

[3] Sold at a price of 3,000-4,000 $/kW (2,400-3,300 €/kW) [61, 213].

(depending on the power range, less than 1 watt to 300 kW). But although the PEMFC appears to have the largest potential markets, many technical barriers remain and **a technical breakthrough is needed to obtain a reliable cost-competitive product.** The main technical challenges for the PEMFC are: the membrane (sensitivity to water, to CO, operating temperature[4]), the electrode costs (platinum cost), the stability of the stack and the fuel flexibility (need for high purity hydrogen) [6, 101, 330]. In the short term, the PEMFC will be introduced where pure hydrogen is already available or will be associated with an external reforming device [330]. However, in a long-term perspective, for which mass production of fuel cell vehicles is considered, the mass production of the PEMFC will depend on the early **development of a hydrogen infrastructure,** since external reforming for hydrogen production reduces the performance of the system and should only be a transitional stage.

For the **SOFC,** the technical challenges are: **stack reliability, and in particular thermal cycling resistance** [101, 331]. This implies looking into reducing the operating temperature (from 1,000 to 750°C), the resistance of the stack materials and the use of new materials. Reducing the manufacturing costs of the SOFC is also of great importance. The SOFC is not expected to develop much for transport applications but it is being considered for very special niches like APU trucks [37, 43, 61]. The SOFC (like the MCFC) is particularly useful for high power ranges (over several MW) where it could achieve even greater efficiency with a gas turbine in a combined cycle [332].

The **MCFC** is more advanced than the SOFC for large-scale applications and this technology has shown a good rate of progress over the last two years, in particular thanks to the solutions offered by FuelCell Energy (USA) and MTU CFC (Germany), who put units out into the field for real-world testing [61, 214]. Commercialisation is expected in the short to medium term [61, 214]. For the MCFC, unlike the other technologies, the major problem is not cost (much lower than for PAFCs) but **the very limited duration of the materials of the cell itself** and in general the technical difficulties linked to the use of a **corrosive electrolyte**. On the other hand, the MCFC is currently (of all the types of FCs) the best-suited for biogas utilisation because the internal chemical reaction in the MCFC takes advantage of the presence of $CO_2$. Biogas contains 40% of $CO_{2,}$ which is normally a major barrier to utilisation in FCs [214]. MCFC field trials fuelled with biogas are underway, such as the 300 kW biogas fuelled system built by the Japanese company Ishikawajima Harima Heavy Industries (IHI).

In addition to the technical challenges of stacks, a special effort is needed for optimisation of the Balance of Plantt (**BOP**) or Balance of System (**BOS**). In fact the fuel cell stack represents only one third of the cost of a fuel cell plant, the remaining two thirds coming from the balance of plant. The cost of the BOP (blowers, valves, sensors, compressor, intelligent communication equipment, robust grid connectors and inverters) must be lowered [330].

## Market trends

Fuel cell markets worldwide are in an embryonic stage in both stationary (small- or large-scale) and transport applications, as no fuel cell systems are **cost-competitive** yet (except in some niches [238]). Moreover **reliability** is still unproven for most systems. On the other hand, the utilities will only start investing in fuel cell systems for centralised power generation (where the investment costs are even higher) once the reliability and the possibility of cost reductions have been proven on small-scale applications.

[4] At a higher temperature, the system is less sensitive to impurities, which simplifies its design. On the other hand, the development of systems that are reliable at very low temperatures is needed.

For most fuel cells, **investment costs** still exceed €10,000/kW. This is an improvement compared to the situation some years ago (€50,000/kW) but is far from the competitive **cost targets of the market**[5]: €700-1,500/kW for large stationary applications, €3,000-4,000/kW for small stationary applications, €150-300/kW for city transportation and €50-60/kW for private cars[6] [166, http://www.reseaupaco.org/, 330]. Some American experts estimate that the fuel cell system, including on-board storage of hydrogen, will have to decrease to a cost less than $100/kW (~ €80/kW) before fuel cell vehicles (FCVs) become a plausible commercial option [333].

Regarding **reliability**, the targets are a proven lifetime (with only minor degradation) of 40,000 h (around 4.5 years) for stationary and 5,000 h for transport applications [266].

### *Stationary applications*

For stationary applications, fuel cell systems will compete with different technologies depending on the range of power considered and the application [6, 332,330]:

- domestic/small commercial CHP (0.5 -10 kW): Stirling engines, conventional boilers
- small Genset and remote power (1-25 kW): diesel engine generators, batteries
- distributed power/industrial CHP (100 kW- 1 MW): micro-turbines in small CHP systems (bellow 500kW), diesel and natural gas engines, gas turbines
- above 10 MW, severe competition of combined cycle gas turbines

Since the first field trials in the 1970s, a cumulative total of 650 large **stationary units**[7] was tested worldwide up to 2003, among which a total of 65 new systems were installed in 2003 (with a total capacity of 15 MW).

**Up to 2002, the technology installed was predominantly PAFC** (with a first version introduced in 1990), **but today MCFC systems account for 40%** of all production. Interestingly, almost 50% of the large stationary fuel cell makers are developing SOFC systems and the share of SOFC is also growing [37, 244].

Production of **small fuel cells** for the residential sector[8] has increased sharply in recent years, with 1,400 new systems built in the last two years (2003-2004). PEMFC remains the technology of choice, although the **number of companies** that are releasing **SOFC units** is increasing, representing nearly a third of the total in 2004 (compared to 20% in 2003). However, the market share of SOFC units did decreased slightly from 2003 to 2004, while the number of large demonstration projects has been pushing the number of PEM units on the market upwards [244].

For the short term, mass production of fuel cell systems is not expected but some early commercialisation could become a reality in special niches: **municipal buildings (less cost-sensitive than private buildings and industry), remote places[9], environmentally sensitive areas, and critical power** [6]. **Plugpower** announced that its product is already **cost-competitive for the special niche of backup power** [238].

[5] As explained in the next chapter, the timescale of these cost targets differs from one country to the other.

[6] Internal Combustion Engines (ICE) have a cost of $25/kW (~€20/kW) [116].

[7] From 10 kW to several tens of MW, although the average is in fact near 200 kW.

[8] Below 10 kW, but usually scaled to either 1~2 kW or 3~5 kW.

[9] Remote power applications have a range of requirements and cost is often not the main consideration. Connection to the grid network may have a much higher cost.

In the medium term, on the distributed power and/or large CHP market, fuel cells face tough challenges due to the need to be cost-competitive and thoroughly proven (with respect to their competitors micro-turbines and ICE) [6]. The dropping prices and increasing efficiency of gas/steam turbine combined cycles have placed challenging goals on the cost targets of fuel cell systems [61]. **For domestic and small commercial CHP**, there is good medium-term potential for fuel cells, but **Stirling engines might enter this market earlier and at a lower cost** [6].

Although some experts expect the development of **hybrid systems** with a turbine for high temperature FC after 2012 [6, 84], the mass production of this technology is considered only in a long-term perspective since **hybrid systems are dedicated to large plants.**

For the long term (2050), fuel cells in stationary applications are not expected to replace the current large electricity generation stations. They will more likely be used in a network combining a broad spectrum of power generation technologies (advanced nuclear power, coal gasification with gas turbines, wind power, solar energies, fuel cells, etc.) in architecture with centralised stations and decentralised nodes. These distributed nodes may consist of renewable and/or fuel cell systems [330, 333].

*Transport applications*

In 2003, it was estimated that around **300 light-duty Fuel Cell Vehicles** (FCV) had been built and operated worldwide. The major Japanese, American and European car manufacturers are involved in this development [248]. Boosted by several large demonstration programmes, the number of buses operating has doubled in one year, reaching **65 buses** in 2003. Like the FCVs, most of the buses in demonstration use PEMFC technology and are fuelled with compressed hydrogen [241, 247].

To enter the **vehicle market**, the PEMFC (the best technology for this application) will have to overcome other specific challenges than those mentioned above. A **widespread refuelling infrastructure** is essential for customer acceptance. Major investments are required for a dedicated hydrogen infrastructure. Installing hydrogen at 30% of Europe's fuel stations (penetration needed for customer comfort) could cost in the range of €100-200 bn [27]. In addition to the cost of this infrastructure, the deployment of a real market of fuel cell vehicles will depend on the progress made in **mass production of hydrogen** and the development of compact **hydrogen storage** [99]. For these reasons, some experts who are sceptical about the "hydrogen economy" are advising a focus on other alternatives such as electric battery-powered drive, new energy carriers, or other fuel cells like the SOFC or DMFC which do not require the production of hydrogen fuel [277, 278].

Fuel cell vehicles will compete with a number of technologies (and societal behaviour changes) that could satisfy the short- and medium-term requirements for very low $CO_2$ and pollutant emissions [6]. Among these competitors, hybrid vehicles are already very successful on the American market and Japanese manufacturers have clearly shown their commitment to the field. Some experts see the development of fuel cell hybrid vehicles (combining a fuel cell and a battery) as very promising for the medium-term transition phase [251]. Although fewer in number, **buses are potentially an easier market to break into** than light-duty vehicles for the short- and the medium-term. Fuel choice, for example, is less of an issue as bus fleets tend to be refuelled in-house at depots. Furthermore, bus markets have already been a successful testing ground for other alternative fuels such as compressed natural gas (CNG), which should also facilitate the switch to hydrogen.

This general context explains why none of the technologies considered (except the PAFC – see below) are expected to be ready for marketing before 2008 and 2015 for stationary and transport applications, respectively. Individual fuel cell cars have good prospects in the long term (after 2020) and the date of introduction will depend on the commitment of the governments and industries into the "hydrogen economy".

**In the 5-10 year perspective, production of the PEMFC, SOFC and MCFC is expected to further develop thanks to demonstration programmes and less cost-sensitive niche markets, such as stationary applications –** back-up power, UPS, remote places and hospital – **and transport –** buses and fleet. **The success of fuel cells in those areas will be a milestone to mass markets such as small CHP or fuel cell vehicles.**

## Main strengths and weaknesses of the USA and Japan

### USA

| | Strengths | Weaknesses |
|---|---|---|
| S&T | • Long experience in the field of fuel cell research with large portfolio of PEMFC and SOFC projects<br>• Massive support from the DOE, states and some cities for RTD<br>• Clear targets for accelerating commercialisation, such as in the SECA program (for SOFC)<br>• Major demonstration programmes with a special focus on niche markets<br>• Hydrogen and FC Roadmaps | • Fundamental research or technical cooperation is not always compatible with commercial approach |
| M&I | • Leading companies for stack, membrane, PEMFC and PAFCs, as well as SOFCs and MCFCs on the American, European and Japanese markets<br>• Commitment of car manufacturers<br>• GM has proprietary FC stacks<br>• US Fuel Cell Council: trade association | • The pre-commercialisation of American products is still far short of the market targets<br>• Development of fuel cell vehicles slower than initially expected |
| P&M | • Industry Recruitment Incentive and Corporate Tax credits<br>• Small Business Innovation Research (SBIR)<br>• Advanced Technology Programme (ATP)<br>• ZEV Californian legislation for transport<br>• Government has active relations with China<br>• Early involvement in definition of codes and standards | • ZEV legislation targets have been reduced<br>• Lack of consistency of the succeeding governments' policy (previous administration was very keen on hybrid drive)<br>• Non-alignment with Kyoto<br>• The US government may reduce the fiscal year budget to allocate the money to issues that are currently more important |

#### *Science and Technology (S&T)*

**US fuel cell activities started in the 1960s** with NASA projects to implement fuel cells in Gemini Space stations. Since then, the USA has been involved in the development of the different fuel cells. Since putting PAFCs on the market, the USA has focused its research on the MCFC, DMFC, PEMFC and SOFC. The latter two have been attracting even more attention in recent years [61].

In the field of fuel cells and hydrogen, US RTD benefits from a general commitment to the field of $H_2$ and fuel cells. Well-established plans are supported by substantial public funds and a €190 M request is contained in the 2005 federal budget (cf. **Policies and Measures (P&M)**) [329]: $6 M (€4.9 M) for the systems, $17 M (€13.9 M) for fuel processing, and $14 M (€11.4 M) for the stack subsystem [272]. The national programme "**PEMFC for transport applications**" received support in the 2000 fiscal year. This **massive support** comes not only **from the relevant government entities but also from states (like California) and even cities** [27, 329].

**In addition to the level of funding and the long experience in the field of fuel cell research, US research programmes benefit from clear targets for product commercialisation**. An example is the structure of the SECA programme (**Solid State Energy Conversion Alliance**), which focuses on solving the remaining issues of SOFC commercialisation (with a target of $400/kW [€330/kW] by 2012). The various projects underway include private-sector cost sharing of more than 20% (and 50% as the research moves closer to commercial development). Six industry teams[10] are working on competing designs for distributed generation and auxiliary power applications. The SECA industry teams receive core technology support from leading researchers in small businesses, universities and national laboratories[11]. **This type of structure is seen as a very efficient way to bring innovative ideas onto the market. Some experts, however, point out that an individual company's own interest may be an obstacle in some innovative research areas.**

In addition to the funding attributed to research, the US DOE and some regional governments support **many demonstration programmes, which will indirectly accelerate the development of fuel cells.** Some of those programmes are: **US Freedom Car Partnership plan** [6, 84], **The California Fuel Cell Partnership**[12], **PFCA (Public Fuel Cell Alliance**) [135], **Residential PEM Demonstration Projects**[13] run by the US Department of Defence (31 PEM fuel cells demonstrated at 20 different military sites in 2003) and the world's largest SOFC operating power plant at the University of Toronto[14].

**Another strength of the USA is that its government has drawn up a detailed fuel cell commercialisation roadmap**. The US roadmap defines not only the final performance and cost targets but also determines on which particular technical issues the RTD programme has to focus [84, 279].

### *Market and Industry (M&I)*

The market growth forecasts by Frost & Sullivan for North America are summarised in the table below.

| | By 2005 | 2006-2009 | Beyond 2010 |
|---|---|---|---|
| SOFC<br>Marketable price<br>Output (MW) | $10,000/kW<br>(€8,175/kW)<br>few MW (2005) | $3,000-5,000/kW<br>(€2,450-4,090/kW)<br>about 50 MW (2007) | Less than $1,000/kW<br>(< €820/kW)<br>about 200 MW (2009) |
| PEMFC<br>Marketable price<br>Output (MW) | $3,000/kW<br>(€2,450/kW)<br>almost 50 MW (2005) | $1,500/kW<br>(€1,225/kW)<br>almost 200 MW (2007) | $500/kW<br>(€410/kW)<br>more than 500 MW (2009) |
| MCFC<br>Marketable price<br>Output (MW) | $3,000-3,500/kW<br>(€2,450-2,860/kW)<br>almost 20 MW (2005) | $2,000-3,000/kW<br>(€1,635-2,455/kW)<br>almost 60 MW (2007) | Less than $1,500/kW<br>(< €1,225/kW)<br>more than 130 MW (2009) |

[10] DELPHI, GE, CUMMINS, SOFCO, ACUMETRICS, FCE.

[11] http://www.seca.doe.gov/

[12] http://www.fuelcellpartnership.org/

[13] http://www.dodfuelcell.com

[14] An agreement was signed by Ontario Power Generation, Natural Resources Canada, Siemens Westinghouse Power Corporation and the US DOE to design, assemble, commission and operate a 250 kW solid oxide fuel cell (SOFC) combined heat and power demonstration plant. All signing organisations contributed to the funding of this project.

However, the current US administration has set much lower targets in terms of cost [84]:

- **For stationary applications:** 2-25 MW installed by 2008 and 500 MW installed by 2010 with an objective of $400/kW (€327/kW).
- **For transportation applications:** hydrogen vehicles are to achieve 2000 h durability at $125/kW (~€100/kW) by 2009, and 5000 h durability and a cost of $30/kW (~€25/kW) by 2015.

The US Freedom Car programme aims to commercialise 100,000 vehicles in 2012 [6] while the Japanese government has a target of 50,000 vehicles in 2010 and close to 5 million vehicles in 2020 [231]. The 2003 DOE programme assumes initial penetration in 2018, increasing to 27% in 2020 and to 78% in 2030. However the committee of the National Academy of Sciences predicts much slower market penetration based on the experience of the hybrid vehicle (1% in 2015, growing to 12% of new light-duty vehicles sold in 2020 and 40% in 2030). This major discrepancy between the forecasts for fuel cell vehicle market penetration also appears in other studies [333].

**For all the types of fuel cells considered, the USA has a large number of companies which are in leading positions and are patenting intensively, be it in stack systems or fuel cell and vehicle manufacturing.**

UTC Fuel cell[15] is one of the most active patentees in the field of fuel cells in the USA, with records similar to those of Ballard[16] [260]. Its joint venture with Toshiba, ONSI, is the international market leader for PAFCs, with 70% of the current market share. Plugpower is also very active and is competing with Ballard in the area of flow field plate designs [261]. Plugpower has strengthened its position in Europe and Japan through its cooperation with Vaillant GmbH and Honda respectively. IdaTech's portfolio of fuel cell solutions is based on its proprietary multi-fuel fuel processing technology, its own fuel cell stack and power module, and fuel cell system integration. Idatech is strengthening its position in Europe with various partners like the German and French utilities RWE and EdF, the Italian energy engineering firm RENCO S.p.A and Volkswagen. IdaTech, the fuel cell subsidiary of IDACORP, Inc. (NYSE:IDA), has been awarded a $9.6 million development program by the US Department of Energy (DOE) for the development of a 50 kW proton exchange membrane (PEM) fuel cell system suitable for providing grid-independent energy sources for large facilities.

In SOFC technology, Ballard's counterpart is Siemens Westinghouse, which not only dominates the number of patents (close to the number of patents from the Japanese firm Murata manufacturing) [261], but has also already participated in demonstration programmes worldwide (USA, Canada, Europe particularly in Germany and Norway) [101, 248]. One of these is the world's largest operating SOFC power plant at the University of Toronto at Mississauga [263]. Moreover, Siemens Westinghouse is concluding a project for strategic collaboration with Fuel Cell Technologies Ltd, and is establishing strategic regional marketing relationships that will ultimately cover all parts of the globe [271]. FuelCell Energy is leading the way in MCFC development and has entered into various cooperation projects with Caterpillar, PPL (for the US markets), MTU CFC Solutions (for the European market) and Marubeni and Mitsubishi heavy industries (for Australasia and Japan).

The American firm Dupont, which benefited from a virtual monopoly on PEMFC membranes with its *Nafion©* membrane, is now facing competition from other North American manufacturers like Hoku (USA, Hawaii), Dow Chemicals (USA, Michigan) or Polyfuel (Canada), which recently announced their progress in developing a membrane at a reduced cost [150].

[15] Formerly also known as International Fuel Cells (IFC).

[16] Canadian company which holds the leading position worldwide and takes great advantage of international demonstration programmes on fuel cell vehicles, in particular through its cooperation with Daimlerchrysler [101].

The large number of US companies involved in the field of fuel cells is not necessarily an absolute factor of leadership. In the USA, it is possible to create a company quickly, which explains the large number of companies working with fuel cells. However, as these companies approach the commercialisation phase, larger well-established companies often acquire them. Avista Labs and Hpower are two examples of this. It should also be added that up to now none of the **American PEMFC and SOFC products have made a technical breakthrough and that the American manufacturers still have many technical barriers to overcome.**

**In the automotive industry, in addition to DaimlerChrysler, General Motors (GM) and Ford have already built several prototypes.** Ballard Power Systems, DaimlerChrysler and Ford entered into a comprehensive non-binding Memorandum Of Understanding (MOU) outlining a series of aims, including further definition of the roles and responsibilities of their Alliance and further establishing programme funding requirements to ensure that the Alliance continues to build on its leadership. Under the terms of the MOU, DaimlerChrysler and Ford will provide up to $58 M in funding for the next two generations of vehicular fuel cells and the next generation electric drive system. General Motors has several vehicles running outside the USA, in China and in Japan [248] and has recently greatly improved the performance of its FCVs. In May/June 2004, during a unique long-distance drive through 14 European countries, GM/Opel's *HydroGen3* covered 9,696 km in five and a half weeks. Another key point is that GM has developed its own stack[17] and therefore does not depend on the progress made by Ballard, as is the case for DaimlerChrysler and Ford (they have a fixed supply contract with this company) [336]. However, concerning the **timetable for commercialisation, GM has been less optimistic** than the DOE (cf. 2.1.1) or DaimlerChrysler, and plans to build one million cars by 2020 [267].

Like the Fuel Cell Commercialisation Conference of Japan, fuel cell industrials have established a trade association called «*the US Fuel Cell Council (USFCC)*», comprising more than 115 companies, research institutes and others dedicated to fuel cell commercialisation in the USA. The USFCC is an important contact point for the US government and protects the interests of fuel cell companies. Recently the US Fuel Cell Council urged the Congress to "keep its course on fuel cell funding" [341].

### *Policies and Measures (P&M)*

**One important asset of the USA is that in addition to the support given to RTD programmes (by the DOE or by the states) and SECA, there are also some federal state incentives for fuel cell manufacturers and special programmes that help innovative small companies.**

Five states - California, Hawaii, Michigan, Montana and Ohio - offer generous corporate tax credits or exemptions in an effort to recruit fuel cell manufacturers [135]. Pittsburgh attracted Siemens Westinghouse with $8.2 M (€6.7 M) in incentives and nearly $4 M (€3.3 M) in low-interest loans [6].

The US Department of Commerce shares the cost of high-risk R&D projects with private companies through the ATP (**Advanced Technology Program**) in order to accelerate the development of innovative technologies. ATP awards are selected through open, peer-reviewed competitions. The ATP has funded a total of 24 projects in the fuel cell area (among which Plug Power, Avista labs, and H-Power-Nuvera). The **ATP is an important tool that allows companies to conduct early-stage research development projects, which might not otherwise be funded** [274]. However in

[17] Close cooperation with TOYOTA but each company has its own stack development.

November 2004, the United States Congress passed the Consolidated Appropriations Act, 2005, which includes funding for NIST[18]. As part of the NIST appropriation, the ATP received $142.3 M (€116.3 M) to fund mortgages of prior awards and administration of the programme; however, it did not receive any funds for new awards. Consequently, the **ATP will not hold a competition for funding high-risk R&D in fiscal year 2005.**[19]

Another way to influence fuel cell introduction is by implementing **strict car emission legislation**. California has already introduced legislation on ZEV (Zero-Emission Vehicles) and LEV (Low Emission Vehicle) , which requires a certain percentage of passenger cars produced and offered for sale in California to be ZEV. Initially, the target was 10% in 2003. **However, the rules have been revised, reducing the requirement for 2006 but setting a new target of 16% for 2016** [101, 240].

With respect to the fuel cell vehicle, China has the potential to develop a huge market and it should be noted that the **US government is active in developing relations with China**. The US American Natural Resources Defense Council (NRDC), with the support of the W. Alton Jones Foundation, has worked over the last three years with the Shanghai Economic Commission, Togji University, the Energy Research Institute and the South-North Institute to raise awareness in China regarding the commercialisation of fuel cell vehicles.

Issues related to codes and standards are discussed in the chapter "hydrogen technologies".

[18] NIST: National Institute for Standards and Technology, http://www.atp.nist.gov/. Like the SBIR Program, ATP is part of the Economic Assessment Office within NIST's Technology Services [http://www.atp.nist.gov/eao/eao_pubs.htm].



[19] http://www.atp.nist.gov/atp/05comp.htm

## Japan

| | Strengths | Weaknesses |
|---|---|---|
| S&T | • Massive funding<br>• Strong in development of BOS<br>• Good experience in PAFC development and operation<br>• Strong emphasis on demonstration programmes (stationary applications and FCVs)<br>• Japan has been fostering an ambitious development and diffusion programme centred on the PEMFC | • Weak in basic science |
| M&I | • Joint ventures with North American fuel cell stack manufacturers<br>• Fuel Cell Commercialisation Conference was set up<br>• FCV already in pre-commercialisation phase for the Japanese and American markets<br>• Toyota and Honda have developed proprietary FC stacks and developed good experience of complex BOS with hybrid cars<br>• Large domestic market potential for residential CHP systems<br>• High cost of electricity in Japan (~¥25/kWh) | • Low price of gasoline compared to Europe<br>• Japan does not have a meshed network of gas pipelines on its territory to carry hydrogen |
| P&M | • Consistent effort put into drafting roadmaps<br>• Public-private partnership led to identification of 28 regulatory barriers to be lifted in 2005 | • Manufacturers hope for more government support for basic research<br>• Targets are often set without considering the R&D path in detail |

### *Science and Technology (S&T)*

With public R&D spending for fuel cells and hydrogen of about $250 M (€204 M) in 2003 – at the level of the USA – **Japan has been massively investing in fuel cell and hydrogen technologies** for several years now, and will carry on with €260 M for the 2005 budget [37, 329].

However, experts have realised that, in the haste to ship fuel cell products to the market, the **government neglected to encourage alternative scientific options** (on electrolyte, anode reaction, etc.). Although good progress has been made to optimise current technologies, a breakthrough is now needed; consequently, these experts have recommended that NEDO should play a greater role in sponsoring research in the academic sector [265].

For the PEMFC in particular, manufacturers have gathered good expertise **in system integration,** but have been lacking in PEMFC stack R&D ability. For this reason, Japanese experts currently consider that North American researchers are leading the field. Fuel cell R&D projects currently aim at lowering costs, while increasing reliability, durability and efficiency. NEDO also places **considerable emphasis on the demonstration and validation** of systems.

• **PEMFC**

NEDO sponsoring of PEMFC R&D in Japan started in 1992 and the **PEMFC is now at the forefront of its New Energy R&D Programme**. Considering R&D on PEMFC systems alone, ¥5.1 and 4.2 bn (€38.3 and 31.5 M) were awarded in 2003 and 2004, respectively.

Performance targets for FCV and residential systems aim to increase efficiency from, respectively, 50% and 32% today, to 60% and 40% by 2015 [236].

In automotive applications, Toyota was first to succeed in developing a proprietary stack – now exclusively powering its line of FCV – and Honda's own prototype (currently using Ballard's modules) demonstrated excellent performances, but is still lacking in durability.

- **SOFC**

NEDO has been subsidising SOFC basic research and development for over 20 years now, and the programme will enter the system (100 kWe class) development stage starting in 2005, for both its tubular and planar SOFC. This year, the last of the five-year long Phase 3, NEDO funding totalled ¥2.5 bn (€19 M).

In Japan, **SOFC are not considered for transportation applications**.

- **MCFC**

The MCFC development programme at NEDO also dates back to the early 80s, and is steadily pursuing introduction of this technology over the medium term (~2015). **Starting in 2005, a 6~7 MW class MCFC pilot plant will be built** (8×750 kW modules with reformer, 1.2 MPa, coupled with a gas turbine) and operated until 2010 [NEDO].

- **PAFC**

PAFC R&D is no longer on the agenda, but the major efforts conceded helped the Japanese industry gather a large body of knowledge on distributed cogeneration systems, fuel reforming, and all aspects of fuel cell efficiency and durability improvement. **Japanese expertise in PAFC should be very helpful for the development of next generation fuel cell systems.**

### *Market and Industry (M&I)*

*The Fuel Cell Commercialization Conference of Japan* was established in March 2001 to create a forum in which the relevant members of Japan's private PEMFC sector could examine and discuss pertinent subjects, and offers policy recommendations to the relevant ministries and agencies. Composed of 134 corporate and individual members, the FCCJ covers nearly all domestic companies associated with fuel cell technology. The consortium is chaired by the Chairman of Toshiba Corporation with the assistance of four vice-chairs who are leaders in the sectors of oil supply (Nippon Oil), gas (Tokyo gas), automobile manufacturing (Toyota) and consumer electronics (Matsushita Electric Industrial) [349].

The Japanese government has set the following introduction targets

- for stationary (small and large) fuel cell systems:

| | 2010 | 2020 | 2030 |
|---|---|---|---|
| Total installed Capacity (MW) | 2,200 | 10,000 | 12,500 |
| Technologies and Applications | PEMFC (1~10kW), SOFC (10~300kW), MCFC (6~7MW) | | |

- for Fuel Cell Vehicles (FCV) and transportation-related infrastructure:

| | 2010 | 2020 | 2030 |
|---|---|---|---|
| FCV (#) | 50,000 | 5,000,000 | 15,000,000 |
| $H_2$ demand (t) | 40,000 | 580,000 | 1,510,000 |
| $H_2$ stations (#) | 500 | 3,500 | 8,500 |

However, the above figures should not be taken literally, as it is common practice for the government to set very ambitious targets.

While the Japanese government apparently has no major plans in the 3-10 kW segment for the stationary fuel cell system, it has focused its efforts on two main categories [329, 35]:

- 1 kW for domestic applications
- 200 kW for commercial applications (hotel, office, etc.) and buildings.

However, some manufacturers, such as MHI (in partnership with Nippon Oil) or IHI (in partnership with Idemitsu), have developed some 5 or 10 kW PEMFC systems for fast food, refuelling stations and back-up systems [35].

- **PEMFC**

  The government and manufacturers are currently aiming at the following price targets for PEMFC systems, to be attained between 2010 and 2015: ¥5,000/kW (€37.6/kW) for an automotive stack, and ¥300,000/system (€2,253) for residential applications [36]. For the latter, a figure of ¥500,000 (€3,755) by 2015~20 is believed by experts to be more realistic.

  On the manufacturing side, residential systems production capacity could reach 100,000 units/year, representing a market of ¥50 bn (€376 M) by 2020 [235].

Regarding the market development of FCVs, independent analysts forecast a possible domestic production capacity increase (Toyota, Honda, Nissan) to 300,000 FCV/year in 2020, with the market entry of FCV starting in 15 years' time [235]. The official scenario states that introduction of FCV will first start with buses, then small trucks, and finally private cars (with a price tag of ~¥3 M [€22,500] by 2020) [231]. **Japanese automakers have good knowledge of electric, hybrid and CNG vehicles**, all useful in FCV design.

Toyota, Honda and Nissan are the most active of the Japanese car manufacturers, and announced in July 2002 that they had started limited sales of FCVs in line with their goal of developing practical FCVs by around 2004. Those 3 companies are participating in the *California Fuel Cell Partnership,* developing strategies in tune with the American market [349]. Toyota started research and development of fuel cell vehicles in 1992, as a result of hybrid technology advancement[20]. It is developing the world's leading fuel cell hybrid vehicle (FCHV) based on its own proprietary technology [267]. In July 2002 the Honda FCX was certified by the United States Environmental Protection Agency (EPA) and the California Air Resources Board (CARB) as the first fuel cell vehicle that could be sold in the USA. Honda delivered one FCX to the Japanese government and one FCX to Los Angeles City on December 2, 2002. It was planning to sell a total of about 30 FCXs in Japan and the USA by 2005. Since December 2002, Honda has delivered a total of five FCX vehicles in the metropolitan Tokyo area to organisations including the Japanese Cabinet Office, the Ministry of the Environment, the Ministry of Economy, Trade and Industry, Iwatani International Corporation, and Idemitsu Kosan Co., Ltd.

- **SOFC**

  **SOFC are not considered suitable for individual home** applications in Japan, rather are targeting current PAFC niche markets with a more advanced cogeneration solution. In the future, SOFC may also be applied to medium-scale power plants [NEDO].

  Today, SOFC technology is still in the development phase, and experts do not foresee commercial products before 2015 [235, 88].

Several Japanese companies are active in the development of SOFC. J-power, for example, is trying to develop the world's first Integrated Coal Gasification Fuel Cell, and Mitsubishi Materials

[20] TOYOTA sold more than 100,00 units of its hybrid Prius in 2003.

intends to commercialise several 10 kW systems by the end of fiscal year 2006. Mitsubishi heavy Industries is developing a 50 kW co-generator with Chubu Electric Power with the aim of developing a marketable product for the 2007 fiscal year. They also intend to commercialise 20-50 MW systems combined with high-efficiency gas turbines in 2010.

- **MCFC**

  MCFC field trials refuelled with biogas are underway, such as the 300 kW biogas fuelled systems built by Japan's Ishikawajima Harima Heavy Industries (IHI). IHI is participating in a national project to create a 1 MW pilot plant and is developing a highly efficient MCFC/gas turbine CHP system.

- **PAFC**

  The PAFC became available in Japan in the late 1990s, and this country still represents the largest market in the world: 200 systems have been installed since 1990, and about 50 systems (mostly 200 kWe class) are currently in operation. However, this market is not expected to develop further due to **competition from both next-generation fuel cells (SOFC and MCFC) and other cogeneration systems**.

  Toshiba International Fuel Cells and Fuji Electric remain the only two manufacturers of PAFC in Japan, but they have now shifted their interest to PEMFC.

  In the framework of its co-operation activities, NEDO has already sponsored the installation of PAFC systems in east Asia. Although the potential for price reduction is low, private and public observers consider that **a demand for PAFC systems may appear in developing countries**.

Finally, one specificity of Japan is that **Japanese industry contributes more strongly to scientific** knowledge than in other countries. Industry wrote almost 40% of Japanese fuel cell-related publications in 1990-2000, whereas in Germany and the UK (the two most active European countries), industry contributed less than 20% [336].

### *Policies and Measures (P&M)*

The government wants fuel cells and hydrogen to play a major role in the future. In coordination with academics and industry, it has been **consistently endeavouring to draft technological and market roadmaps**. However, advisers often argue that targets are sometimes set without considering the R&D path in detail.

In 2002, **the Japanese government decided to amend 28 items in 6 laws** – such as the Traffic Law, the High Pressure Gas Security Law, etc. – in order to eliminate obstacles to the introduction of fuel cells and the use of hydrogen. Application of these amendments will be decided in 2005.

In terms of diffusion, fuel cell systems today already benefit from the same incentives as natural gas cogeneration systems: local governments or non-profit organisations can receive **subsidies of up to 50% of the system price**. Finally, the need for international standardisation efforts is often cited by experts, especially in the automotive field [265].

## SWOT analysis for Europe

| | Strengths | Weaknesses |
|---|---|---|
| S&T | • Good basic research capacity especially in the fields of chemistry, material sciences and energy systems<br>• Recent focus on the most promising technologies (PEMFC and SOFC)<br>• Strong support for stationary demonstration programmes in Germany for niche markets<br>• Several programmes of FCV demonstration and the world's largest bus demonstration programme CUTE<br>• New instruments within FP6 (and future FP7) to improve the coherence of RTD efforts | • Lack of knowledge transfer between industries and universities<br>• Lack of coordination between European and national or regional programmes |
| M&I | • European utilities (EDF, RWE, etc.) are active in the development of systems<br>• Leading MCFC-type fuel cell companies and good involvement in the SOFC area<br>• Commitment of Mercedes-Benz<br>• Strong know-how in electric drive systems | • Only European companies specialised in MCFC and SOFC have reached a high industrial level compared with the USA<br>• The very few leading industries developing PEMFC stacks or membranes are in competition with the USA and Japan<br>• Since the end of the FEVER programme, the European fuel cell manufacturers have not seemed well-positioned to get into the automotive market |
| P&M | • Strong support of the German government<br>• FCV tax exemption legislation in Norway<br>• The German "CHP law" will support the FC/CHP market for decentralised power generation | |
| | **Opportunities** | **Threats** |
| S&T | • Develop new membranes or electrodes for PEMFC<br>• Make a breakthrough in SOFC (thermal cycling resistance)<br>• Make a breakthrough in MCFC (taking advantage of Europe's good position in biomass use and strong industrial players)<br>• Optimise the balance of plant or systems | • The USA attracts innovative European ideas<br>• The European FP structure is not adapted to respond to changing R&D needs |
| M&I | • Strategic technical alliance with North America or Japan, especially for PEMFC<br>• Entering the niche markets<br>• Develop know-how of the BOS for energy and vehicle markets<br>• Develop cooperation for the very large Chinese market | • Difficulties in introducing fuel cell cars on the market<br>• Fuel cell cost and reliability<br>• Aggressive patenting of Japanese and American companies<br>• North American/Japanese Joint-Venture<br>• USA and Japan developing knowledge of operating large stationary systems<br>• Large North American companies buy Europe's small innovative companies |
| P&M | • Take advantage of national commitments on fuel cells such as in Germany, UK, France, Norway, Italy, Finland | • USA could be more attractive than Europe for getting innovative ideas into products |

## Strengths and weaknesses of Europe

*Science and Technology (S&T)*

Europe has very **highly educated researchers**, especially in the fields of chemistry, material science and energy systems, which is a great strength in the face of the remaining challenges for fuel cells. The work achieved by the CEA in France, which succeeded in developing a membrane with better performance than the well-known *Nafion®*, is an example of this capacity. In Germany, the Juelich research centre (Forchungszentrum Juelich GMBH) has almost as many German patents on fuel cells as ballard power systems AG and is thus the third leading organisation in terms of German patents on fuel cells [336].

**Europe** has contributed greatly to S&T activities on fuel cells through a large number of publications which, in 2000, represented 40% of all publications from OECD countries (with Japan and the USA both covering around 20%) [334][21]. A recent OECD study shows that between 1990 and 2000 **Europe acquired a scientific specialisation[22] in DMFC and MCFC** where the USA specialised in DMFC and PEMFC, and Japan in MCFC, PAFC and SOFC [334]. Recently however, the focus of FP5 and FP6 was transferred to PEMFC and SOFC [43], fields in which Germany (for PEMFC) and the UK, Denmark, Switzerland and Norway (for SOFC) were already active before 2000 (in terms of publications) [334].

In 2003, Europe lagged behind its competitors Japan and the United States in public expenditure for fuel cell research and particularly demonstration. In comparison to the €240 to 280 M Japan and the USA each spent, Fuel Cell Europe estimated that European expenditure including European Union and national funding was only €60 M per year [337].

In November 2003 however, the European Commission launched the "*European Initiative for growth*" which includes the hydrogen quick start projects. These are two 10-year projects[23] (2005-2015) for hydrogen-related research, production and use [99, 338]:

- Hypogen: large-scale test facility for production of hydrogen and electricity from fossil fuels with sequestration of $CO_2$ (estimated budget €1.3 bn)
- Hycom: establishment of a limited number of «hydrogen communities» around the Union, using hydrogen as source of energy for heat and electricity and fuel for vehicles (estimated budget: €1.5 bn). This project will make an important contribution to Europe's fuel cell demonstration capability.

**In addition to the European Commission programme, several of the Member States, such as Germany, the UK, Italy, France and the Netherlands and to an extent the Nordic countries and Spain, are active in fuel cell development** [334, 336, 349, 350, 340, 349].

At both national and regional level, Germany is one of the most active countries thanks to its support for fuel cell research and installation of fuel cell systems (¾ of all stationary fuel cells installed in Europe) [280]. Between 1990 and 2003, the German government allotted €120 M for distributed power applications (MCFC/SOFC), providing major support to MTU demonstration projects. Furthermore, €105 M were allocated to automotive applications, from which DaimlerChrysler benefited with the early launch of prototype buses on the road.

[21] However, as already mentioned, in terms of patents, the USA and Japan are ahead of Europe [336].

[22] Analysis based on publications and triadic patents.

[23] Phasing: 2005- 2007 (500 M€), 2007- 2012 (1.5 bn€), 2013- 2015 (800 M€).

In France, for fiscal year 2002, a total amount of €40 M of public funding was dedicated to **hydrogen and fuel cell** research (approximately €4.5 M were subsidies from FP5). France has strengthened its position with the creation of the PACO network which enabled the launch of scientific and industrial activity in France, and through which two companies have made an entry into the fuel cell market (Axane, Heloin) and start-ups (CETH, N-GHY) have also emerged specialising in the development of compact fuel processors for fuel cell systems.

Several European demonstration projects, funded by the EU or by national governments, have focused their attention on the **niche markets**, as identified on page 52:

- MTU CFC implemented an MCFC in a hospital (Rhön Klinikum AG) and in tire production (Michelin Karlsruhe) where **steam production** is needed (50% funded by the German government) [256]
- Norsk Hydro is demonstrating a hydrogen system to supply **remote locations** (10 households in the small Norwegian Island of Utsira will no longer be dependent on the mainland for electricity) [255]. In the EU area alone, there are around 20 million people living on islands who may in the future be guaranteed an independent energy supply
- Edf/Idatech: the systems will be used for integration with solar photovoltaic (PV) technology in a hybrid power system for **remote locations**
- RWE/Nuvera: is developing a 5kW PEMFC system to supply primary or auxiliary **back-up power** to residential homes
- CUTE (Clear Urban Transport for Europe): a demonstration programme of 33 fuel cell buses started in 2003, with more than 10 refuelling stations and a total budget of €18 M [6, 122].

In the framework of past programmes, it was noticed **that Europe has the skill and the potential to become a key player in the development of fuel cell and hydrogen technologies** but that the research and development programmes are **fragmented within and across the different countries** [27].

**To compensate for this lack of consistency across RTD efforts, new instruments have been implemented in FP6 (or will be in FP7) [122]:**

- European Networks of excellence through collaboration between laboratories
- European Hydrogen and Fuel Cell Technology Platform, (FP6 HyCell-TPS)
- European Hydrogen Energy Roadmap (FP6 HyWays)
- **SOFCNET** (47 member organisations), created to virtually link all types of stakeholders involved in SOFC development in the EU
- Networking of national or regional programmes (ERA-NET, FP6).

The *European Hydrogen and Fuel Cell Technology Platform (HFP)* ensures balanced and active participation of all major stakeholders in Europe. Organisations active in HFP include industry (from SMEs to multinational companies), the scientific community, public authorities, users and civil society. All stakeholders working in hydrogen and fuel cells are invited to contribute actively to the work of the HFP.

### *Market and Industry (M&I)*

The *European fuel cell and Hydrogen platform* gives an indication as to the targeted deployment status by 2020, summarised in the following table [329].

| | Portable Generators and Early Markets | Stationary FCs CHP | Road Transport |
|---|---|---|---|
| EU $H_2$/FC units sold per year Projection 2020 | ~ 100,000 per year<br><br>(~ 1 GW) | 100,000 to 200,000 per year<br><br>(2-4 GW) | 0.4 –1.8 million per year |
| EU cumulative sales projections until 2020 | ~ 600,000<br>(~ 6 GW) | 400,000 to 800,000<br>(8-16 GW) | n.a. |
| EU expected market status 2020 | Established | Growth | Mass market roll-out |
| Average power FC system | 10 kW | 3 kW (micro CHP)<br>350 kW (industrial CHP) | |
| FC system cost target | €500/kW | €2,000/kW (micro CHP)<br>€1,000-1,500/kW (industrial CHP) | < €100/kW<br>(150,000 units per year) |

The projections of Frost & Sullivan are quite in accordance with the figures above, predicting an annual European market size of 2000 MW, worth €3.6 bn by 2011 for the stationary fuel cell sector. Frost & Sullivan identify the largest single potential area of growth as CHP applications in the residential sector (micro CHP) [344].

For stationary fuel cells systems, two main applications have been identified which are expected to have larger penetration rates by 2020 [329, 347]:

- Residential and small commercial segment: promising market for fuel-cell-based CHP (1-5 kW)
- CHP (200-500 kW) for industrial and commercial use.

Siemens is a major actor in the European fuel cell industry, having ranked first in the number of German patents granted for example [336]. As a leader in SOFC technology through its US subsidiary Siemens Westinghouse (which has worldwide responsibility for Siemens' SOFC activities), this company is also active in the development of PEMFC. It has successfully launched the first three fuel cell submarines in the world and has been working with Howaldtswerke-Deutsche Werft AG (HDW) to develop fuel cell systems for ships.

**DaimlerChrysler, working through the undertakings of Mercedes-Benz, is a key actor in fuel cell development in transport.** Of the many vehicle manufacturers, **Mercedes-Benz** has been a pioneer in the development of fuel cell vehicles and in 1994 presented the world's first vehicle functioning fully with fuel cell technology at its research centre in Ulm (Germany). **Mercedes-Benz** recently confirmed its commitment in this area, particularly through its participation in demonstration programmes worldwide (in the USA, Europe, Iceland, Australia, but also in Asian countries such as Japan, Singapore and China). At the end of 2004, there were already 100 Mercedes-Benz vehicles powered by fuel cells, some of them operating in the most severe climatic conditions. Several customers are taking part in a project due to last until 2007 to test **Mercedes-Benz**'s 60 FC class A worldwide. They will cover 16,000 km a year. In addition, DaimlerChrysler and Ballard have already sold three of the 100 fuel cell buses planned for the 2008 Olympic Games in China.

With the large-scale CUTE project, almost all European bus suppliers (Evobus, Irisbus, Man, Neoplan, Van Hool and Volvo Bus) have launched a fuel cell prototype to run tests. On the other hand, the car manufacturers (except **Mercedes-Benz**) seem hesitant to put further efforts into fuel cell vehicles [246]. However, the involvement of actors such as Michelin in the field of hybrid cars has boosted the development of the electric drive of fuel cells [252]. Some manufacturers like Peugeot are going in the direction of a hybrid fuel cell/battery vehicle using the fuel cell as an APU [251]. To date none of the European car manufacturers has its own proprietary stack system.

**European PEMFC fuel cell manufacturers do not seem well positioned** to get into the **automotive market**. DaimlerChrysler chose a fixed supply contract with Ballard together with Ford (which now owns Volvo and Jaguar). Ballard has already delivered individual stacks to Renault, Volkswagen, Volvo, Mitsubishi, Nissan and Honda [336]. General Motors has developed its own stack in cooperation with Toyota. Renault now has in-house fuel cell resources together with Nissan. Siemens and De Nora still have much to achieve if they want to remain in this market. Moreover Ballard has been aggressively patenting in Europe as well and is the second leading German actor in fuel cell research in terms of number of patents [336].

Europe is home to several companies which have developed their own stationary fuel cell systems. Rolls-Royce benefited from extensive support under FP5 and may become an important actor in the development of SOFC, as may Sulzer Hexis which recently launched one of the largest residential fuel cell demonstration projects [280, 342]. Ansaldo is also a major stakeholder in MCFC systems development. However, **most of the systems installed in European demonstration programmes include Canadian or American products** [329]. Some European companies **have in fact made strategic alliances with North American companies.** This is the case for example for MTU/Fuel Cell Energy (their common product, *HotModule* Ottobrunn, set a new world record for high-temperature fuel cells by logging up over 21,000 operating hours) [256]. A new joint venture, called MTU CFC, will attempt to launch MTU's fuel cell product onto the market using RWE's customer base and marketing capabilities. Since July 2003, RWE Fuel Cells GmbH, Essen, has held a 25.1% share in MTU CFC Solutions.

More recently, Alstom reached an agreement with Ballard for the development of stationary applications for PEMFC in Europe, with a manufacturing site in Dresden (Germany). Vaillant GmbH and PlugPower have jointly developed the PEM fuel cell units installed for the "*Virtual Power plant projects*" (connecting 31 decentralised residential fuel cell systems in Germany, Holland, Spain and Portugal) [343].

**Another of Europe's strengths is the involvement of utilities like Electricité de France and RWE** in the deployment of fuel cells [101]. However even though the system integrator or distributor in current demonstration programmes is often European , most of the fuel cell system OEMs are Canadian or American companies [344].

### *Policies and Measures (P&M)*

In addition to the "*Quick Start Programme*" of the European Commission, the Member States have initiated several projects aimed at promoting the commercialisation of fuel cells.

In France, the PACo Network was created in June 1999 to encourage a combination of public research and industrial research in the fuel cell area. It supports funding of selected R&D projects. More than sixty teams are involved in this network. The public funding for PACO is about €10 M/year. In December 2003, 52 projects had been labelled and financed (ratio of public funding close to 45%). Allotted funding was: 16% for the CNRS and universities, 22% for the CEA, 25% for small and medium-sized companies, and 32% for large companies (5% others).

**Concerning car $CO_2$ emissions, the current target set by car manufacturers (140 g/km in 2008) is not considered a sufficient incentive for the introduction of fuel cell vehicles** since other low-emission vehicles such as ICE/hybrid drive are already able to meet this target. However, **Norway** is on the way to implementing **tax incentives for hydrogen fuel cell vehicles** and to passing legislation that exempts hydrogen cars from vehicle taxes (including registration fees and annual taxes) and VAT. FCV comparable to the Opal Zaire HyGen3 will benefit from a tax exemption of approximately €10,500 and the FCHV-4 from Toyota, which is a larger vehicle, will get a tax exemption of €23,000, according to the figures provided by the Bellona Environmental Foundation [335].

**In Germany, the CHP law is a driver for the development of residential CHP applications.** In 2002, the German federal government enacted the "CHP law" which subsidises electricity production from CHP stations of up to 2MW with €4.4 bn until 2010. As part of this law, the government supports electricity generated from fuel cell stationary power plants of up to 50 kW with €0.051/kWh provided the installation is built before the end of 2005.

## Opportunities and threats for Europe

### *Science and Technology (S&T)*

Europe has **very good potential in Science and Technology** and there are **some niche markets** in which the Europeans are already active through demonstration programmes, which are essential for the further development of fuel cells. However, it should be noted that for stationary applications, most of the funding comes from the German government. To make a technical breakthrough in this area, national and EU efforts should be consistent and cumulative.

In addition, the European Framework Programme structure is not well adapted for responding to changing RTD needs: for FP7, scientific teams have to define now their needs and priorities for the period 2006-2010.

The **USA** would appear to be more aggressive, has set better-defined targets, and is also **more attractive for researchers**. The case of Siemens Westinghouse is a good example of this trend. Although European firm Siemens bought Westinghouse, all the scientific knowledge of Siemens in the field of SOFC has been transferred to the USA, where Siemens Westinghouse is now in charge of technology development.

### *Market and Industry (M&I)*

**Stationary applications** may appear on the market earlier (micro CHP and industrial CHP), and some products could soon be available in niches. Europe is already believed to have a leading position in industrial and large commercial CHP [329], and the local European context (demand and regulation) is recognised as being favourable to the development of CHP units. European companies are active in the development of SOFC and MCFC.

However, the US SECA programme has clearer short-term targets and strict peer controls, and could be more effective in making the breakthroughs needed in cost reduction and reliability of fuel cell systems. It could be underlined that FuelCell Energy, which is now a leading MCFC manufacturer, benefited from a $134 M (€110 M) DOE grant between 1993 and 2002 for the development of its MCFC technology in the framework of the SECA programme. In addition, Japanese and American companies are ahead of Europe in operating **large stationary systems**, with most of the current operating systems being built in North America (mainly the USA) and Japan [328].

In terms of industry, it seems clear that even if Europe is not in a leading position in the manufacture of **PEMFC** (where the USA and Canada are the definite leaders), Europe could have an important role **to play in developing the balance of system (BOS).** This is an opportunity to develop good know-how in integrating systems (like MTU with its *hot module*), taking advantage of the commitments of large European utilities (EdF, GDF, RWE, Norsk Hydro, ETC...). In low-temperature fuel cell systems in particular, the OEMs are mostly well-established Canadian and American companies. By entering into strategic cooperation with North American companies – like MTU did with FuelCell Energy – Europe might succeed in becoming a strong player in the fuel cell and hydrogen economy.

While most European companies **co-operate** with North American companies, Japanese companies tend to create **joint ventures** with them. In 2001, UTC Fuel Cells and Toshiba Corporation formed a joint venture, Toshiba International Fuel Cells Company (TIFC), to develop and market UTC's stationary fuel cell technology in Japan. Recently Acumentrics and Sumitomo formed a joint venture to market Acumentrics proprietary tubular solid oxide fuel cell power systems in Japan. Marubeni and FuelCell Energy expect to form a joint venture for the purpose of assembling modules in Asia from components produced by FuelCell Energy at its manufacturing facility in Torrington (Canada). Ebara Ballard is jointly owned by Ballard Generation Systems (BGS) and Ebara Corp. of Japan, a world-leading manufacturer and distributor of fluid machinery and environmental engineering systems.

Fuel cell vehicles face important challenges and their commercialisation is expected in the long term. The European car manufacturers (except Mercedes Benz/DaimlerChrysler) are not as advanced as their Japanese competitors, which already have pre-commercial versions of FCVs adapted not only to the Japanese, but also to the American market.

For cost reduction purposes, China offers the perspective of a huge market. However, the US government is already developing relations with China, and so is Japan. Europe could encourage its leading companies in their efforts to enter this market.

### *Policies and Measures (P&M)*

Compared to Europe, **Japan and the USA are much more active and ahead in energy codes and standardisation**. As mentioned in the Steering Panel Deployment Strategy Report released by the *European Hydrogen and Fuel Cell Technology Platform*, the regulatory codes and standards landscape for hydrogen and fuel cells is very complex in Europe and involves numerous authorities and stakeholders. Some current national regulations can severely impede the installation and operation of fuel cell CHP power plants. The creation of an Initiative Group on Regulations, Codes and Standards (RCS) has been proposed with a view to developing an action plan to accelerate processes for implementation of commercially competitive RCS. Such an initiative is really needed to enable Europe to catch up with the USA and Japan.

North America seems to have **better instruments for bringing innovative ideas out of its laboratories** and onto the market. The study "*The evolution of the PEM stationary Fuel Cell in the US Innovation system*" [274] clearly showed that in the context of the technical challenges surrounding fuel cells, **support given to small companies can be a very important driver of innovation**. One example is the success of PLUGPOWER, which was created in 1997 with 22 employees, and received a \$9.7 M (€7.9 M) award for 3 years to tackle the problem of carbon monoxide contamination, to develop high-temperature operating stacks and to obtain better results than with *Nafion* of Dupont.

## References


[6] Review of FC commercial potential for DTI and the Carbon Trust. UK Department of Trade and Industry. February 2003.

[27] Hydrogen Energy and Fuel Cells. EC-DG Research. 2003.

[35] Science and Technology Basic Plan 2001-2005. Japan Council for Science and Technology Policy. March 2001.

[36] Promotion Strategy by Sector. Council for Science and Technology Policy, Japan. September 2001.

[37] Fuel Cell Systems: A survey of worldwide activity. Fuel Cell Today. November 2003.

[43] European Fuel Cell and Hydrogen Projects 1999-2002. EC-DG Research. 2003.

[61] Fuel cells for a sustainable future? Tyndall Centre for Climate Change Research. March 2004.

[84] Leading our nation towards energy independence. Stanford University Global Climate and Energy Program. April 2003.

[88] Fuel Cell Japan. Digital Research Institute. September 2004.

[99] Potential of hydrogen as a fuel for transport in the long term (2020-2030). IPTS / EC-JRC. March 2004.

[101] Impact and consequences of fuel cells technology on sustainable development. IPTS / EC-JRC. March 2003.

[122] European hydrogen and fuel cell projects. EC-DG Research. 2004.

[135] Financial Incentives for stationary fuel cells: a report of state-level policy in the US. North Carolina Solar Center, USA. April 2004.

[150] Prospective sur l'énergie au 21ème siècle. Académie des technologies, France. February 2004.

[213] PAFC system survey. Fuel Cell Today. October 2001.

[214] Biogas in Brennstoffzellen in fünf Jahre Serienreif (Biogas in fuel cells ready for mass commercialisation in five years' time). Erneuerbare Energien, Germany. June 2004.

[216] Fuel cell market overview. www.fuelcellsohio.org. May 2004.

[231] Energy Supply and Demand up to 2030. Agency for Natural Resources and Energy (ANRE), Japan. April 2004.

[235] Future development of fuel cell market. Fuji Keizai, Japan. November 2004.

[236] Fuel cell and hydrogen energy society development up to 2030. Agency for Natural Resources and Energy (ANRE), Japan. April 2004.

[238] Fuel cells cost analysis for backup power. Plug Power. March 2004.

[240] Automotive legislation in California. Platinum Matthey. 2001.

[241] Fuel cell market survey: niche transport. Fuel Cell Today. June 2004.

[244] Fuel cell market survey: Large stationary applications. Fuel Cell Today. October 2004.

[246] Fuel cell market survey: light duty vehicles. Fuel Cell Today. April 2004.

[247] Fuel cells in transit buses. US DOE, Energy Efficiency and Renewable Energy (EERE). May 2004.

[248] Major Government-Supported Fuel Cell Vehicle Projects. US DOE, Energy Efficiency and Renewable Energy (EERE). May 2004.

[251] Peugeot dares. Moteur nature. 2004.

[252] Michelin Hy-light. Moteur nature. 2004.

[255] Utsira project. Hydro. 2004.

[256] World record: Rhön Klinikum's hot module already over 21000 hours in operation. Fuel Cell World. 2004.

[260] Technical intelligence profile: fuel cells. www.fuelcelltoday.com. May 2002.

[261] Fuel cell market survey: patents, a rich vein of knowledge. www.fuelcelltoday.com. February 2004.

[263] Siemens Westinghouse, OPG Choose Toronto for World's Largest SOFC Demonstration Plant. US DOE - EERE - SECA. September 2004.

[265] Committee on fuel cell and hydrogen technology. New Energy and Industrial Technology Development Organization (NEDO), Japan. 2004.

[266] IPHE Country Paper: Germany. International Partnership for the Hydrogen Economy (IPHE). February 2004.

[267] The fuel cell vehicle survey 2003. Breakthrough Technologies Institute, for US DOE - EERE. February 2004.

[271] Fuel Cell Technologies and Siemens Westinghouse Power Sign Memorandum of Understanding. Fuel Cell Today. November 2004.

[272] Proton Exchange Membrane (PEM) fuel cells for transportation. US DOE - EERE - SECA. June 2000.

[274] The evolution of the PEM stationary fuel cell in the US innovation system. OECD. 2003.

[277] Ten steps to a sustainable energy future. Rudolf Rechsteiner, Swiss Parliament. July 2004.

[278] Efficiency of hydrogen fuel cell, diesel SOFC hybrid and battery electric vehicles. European Fuel Cell Forum. October 2003.

[279] Roadmaps for the fuel cell industry. Fuel Cell Today. June 2003.

[280] Fuel cells in Germany: a survey of current developments. Fuel Cell Today. June 2003.

[326] Survey on technological trends of patent applications related to low environmental impact energy technologies. Japan Patent Office. April 2003.

[327] Worldwide fuel cell Industry survey. Pricewaterhouse Coopers. 2004

[328] Fuel cell Systems: a survey of worldwide activity. Fuel Cell Today. September 2003

[329] Deployment Strategy Panel Foundation Report. European Hydrogen and Fuel Cell Technology Platform. December 2004.

[330] Strategic Research Agenda Foundation Report. European Hydrogen and Fuel Cell Technology Platform. December 2004.

[331] Operation of CFCL's all-ceramic stack technology, Ceramic fuel Cells limited. 6th European SOFC Forum. June 2004.

[332] Fuel cells in the power market: separating the hope from the hype, IFEU, Institut für Energie and Umweltforschung Heidelberg. September 2003.

[333] The hydrogen economy: opportunities, costs, barriers and R&D needs. National research council and national academy of engineering. 2004.

[334] Mapping the knowledge Base for Fuel Cells: a bibliometric Approach. OECD. September 2003.

[335] Norway implements tax incentives for hydrogen-fuel cell vehicles. Bellona, December 2004.

[336] Fuel cell Innovation in Germany. OECD Fraunhofer ISI. September 2003.

[337] Regulatory obstacles are inhibiting fuel cell deployment. Fuel cell Europe. March 2003

[338] European Commission statement. IPHE Steering Committee. Beijing, 27th May 2004.

[339] The UK fuel Cell Industry: a Capabilities Guide. DTI/Fuel Cells UK. 2003

[340] Innovation in fuel cells and related hydrogen technology in Norway. University of Oslo. 2002-2003.

[341] Industry urges Congress to «stay the course» on fuel cell funding. US Fuel Cell Council. March 2004.

[342] The world-leading features of the Rolls-Royce Solid-Oxide fuel Cell system. Rolls-Royce. 2003

[343] Best Practice Description Germany 1: «Virtual Power Plant». OPET CHP/DH Cluster. 2002

[344] European stationary market seeking a breakthrough. The business of Fuel Cells. February 2002

[345] Fuel cell market survey: large stationary applications. Fuel Cell Today. 2003.

[346] Brief summary of France’s priorities. IPHE. February 2004.

[347] Virtuelle Kraftwerke mit Brennstoffzellen zur Hausenergieversorgung. Forschungstelle für Energiewirtschaft e.V. München. April 2003.

[348] Innovation in fuel cell technologies in Japan: development and commercialization of PEMFC. OECD. November 2003.

[349] Innovation case study ion fuel cell technology: Italy. IEA/OECD. September 2003.

# Hydrogen technologies

## Technology and market trends

Many policy-makers, energy analysts, environmental organisations and industry leaders have asserted that hydrogen is the fuel of the future. Different reasons are given:

- **hydrogen is clean** (its use in fuel cells produces only water), an important factor in the context of urban **air quality** and **global warming (reduction of greenhouse gases, especially $CO_2$)**
- its production does not necessarily have to be taken from fossil sources. Thus for the long term, it will be an **alternative to fossil fuel feedstock** which could be scarce in approximately fifty years [307], and for the medium term will reduce dependence on the Middle East and will improve the **security of fuel supply**
- hydrogen is a **good energy carrier** and represents a means of storing the excess energy produced by green electricity and helping solve the problem of intermittent supply of some renewable energies like wind and solar power [303].

However, a variety of critical issues remain to be resolved before hydrogen can take its place on the market for energy carriers and vehicle fuel. These include developing **clean production technologies,** reducing hydrogen **production costs,** building and financing a global safe **hydrogen infrastructure** system (including transport, **storage** and final distribution), developing reliable and cost-competitive fuel cells (cf. chapter on fuel cells), and establishing safety standards for hydrogen use.

## Technology trends

### *Production technologies*

Today, the two available production routes are: **conversion of hydrocarbon** (with various processes to convert oil, natural gas, biomass or coal), and **electrolysis of water** by electricity (electricity produced by a variety of inputs including fossil, nuclear or renewable energy). Nowadays, natural gas steam reforming is the principal route to hydrogen production.

Other routes are considered **for the future**, such as **thermochemical water splitting**[1] which could be obtained with the association of sunlight concentrators or nuclear reactors. Concentrated solar energy can be used to generate temperatures of several hundred to over 2,000 degrees Celsius at which **thermochemical reaction cycles** can be used to produce hydrogen from water. These multi-step thermochemical cycles offer potentially attractive paths for generating hydrogen. The same thermochemical cycles could also be induced by the direct use of heat from nuclear energy, using Very High Temperature Reactors (VHTR) [122]. This is seen as one of the most promising future technologies by the US government [323, 324]. **Chemical conversion of natural gas**[2] **or biomass using high temperature heat** from Generation IV nuclear reactors or solar-thermal concentrators are further possible future pathways for hydrogen production [330].

**Photolytic production** (photobiological and photoelectrochemical[3] hydrogen production) is another path being considered for future hydrogen production. In addition to biophotolysis, which involves the use of photosynthetic micro-organisms like bacteria or algae, several fermentation technologies are under study: **photo-fermentation** by anaerobic photosynthetic bacteria or "**dark fermentation**". In those processes, hydrogen can be derived from organic residues [352].

[1] Water splitting through thermochemical cycles.

[2] Like steam reforming.

[3] Also referred to as photo-electrolysis or photocatalytic water splitting.

The production of hydrogen, currently generated at 98% from hydrocarbons, yields considerable $CO_2$. A number of **alternative** routes have been proposed to **eliminate the $CO_2$**, such as:

- using intrinsically non-emitting processes (electrolysis with electricity from nuclear power or renewable energies, thermochemical water splitting, biophotolysis),
- associating $CO_2$ capture and sequestration technologies with emitting processes[4] (coal gasification, fossil fuel reforming or electrolysis from electricity derived from fossil fuels).

**Regarding the security of fuel supply**, hydrogen will contribute in a different way depending on how primary energy sources (oil, natural gas, coal, biomass, uranium) are involved in the global process (including the production of electricity in the case of electrolysis) and how sizeable the domestic resources are.

As we will see in the following chapters, **the ways in which countries will be able to produce hydrogen in the future will depend greatly on their general energy policy,** their position on nuclear power generation, their commitment to the use of renewable energies and, for instance, on their adhesion to the Kyoto Protocol.

The **nature of the distribution network** (decentralised, centralised) is another important issue for the hydrogen infrastructure since the **technical and economic challenges** faced are very different. For example conventional reforming, biomass or coal gasification and nuclear-based hydrogen production are not adapted to small on-site production (or liquid hydrogen production) [60, 99, 351].

The various technologies described above have very different challenges and benefits [27, 60, 99, 330, 351], as reported in the tables below[5], and they cannot all be considered for small-scale on-site production[6].

Although some industrial processes are already being commercialised, hydrogen production is facing major challenges with respect to **cost, the low GHG emission rate, and the scale of the plant. Low costs are often associated with low environmental performances** and **centralised production**. Moreover, $CO_2$ capture and sequestration will not be attractive for decentralised production since efficient separation only works in large-scale centralised units.

**In the next 5 years**, further developments are expected in **small-scale reforming** (for efficiency and cost) and on-site **electrolysis** (for reliability and efficiency) in association with demonstration programmes for fuel cell technologies. Although electrolysis has already been proven to be suited for decentralised hydrogen production, the role of on-site reforming is still uncertain for the medium term and will depend on future research results [330].

Thanks to short-term demonstration programmes, experience will also be gained from the association of hydrogen technologies with renewable energies (especially wind and hydropower). Demonstrations of biomass gasification are also expected to take place in 2-3 years' time.

[4] Biomass conversion is considered $CO_2$-free over its life cycle even if $CO_2$ is released during chemical conversion [330].

[5] The most important categories are presented.

[6] Small scale: ~1,000 $Nm^3/h$; large scale: ~150,000 $Nm^3/h$.

*Figure 5 – State of development, drivers and barriers of the major hydrogen production routes – part 1*

| | Steam reforming from natural gas | Gasification of Coal |
|---|---|---|
| Trends | • Large scale: commercially available<br>• Small scale: conventional "refinery type" commercially available (efficiency 50-60%), new design (efficiency 70-80%) at R&D and pilot stage | • Commercialisation of Integrated Gasification Combined Cycle (IGCC)<br>• Dedicated to large scale |
| Drivers | • Relatively low cost but not yet competitive (€10 - 26/GJ) (large scale: €0.85 -1/kg, small scale: €2.4 - 4.3/kg)<br>• Large scale: high overall energy efficiency in comparison with electrolysis (70 to 80%)<br>• High potential for further improvements, moderate effort on concept process units<br>• By-product steam (primarily for large-scale plants)<br>• Efficient $CO_2$ capture (~71%)<br>• Possible use of biogas (with raw biogas upgrading) | • Relatively low cost: €10-13/GJ,<br>• Overall efficiency 49 to 53% (LHV)<br>• Efficient $CO_2$ capture (~92%)<br>• High improvement potential<br>• By-product electricity |
| Challenges Barriers | • High emission: well to tank GHG (90 –150 g/MJ)<br>• $CO_2$ intensity: 9.5 kg $CO_2$/ kg $H_2$<br>• R&D for small scale: improved efficiency (currently 50-60%), reduction of cost (research to incorporate an adsorbent in the reformer to remove $CO_2$, 25-30% reduction in cost) | • High well to tank GHG of 252 g/MJ, need to develop $CO_2$ storage<br>• These processes cannot be downscaled efficiently for distributed onsite use<br>• Lower efficiency compared to steam reforming<br>• Higher effort on process units (such as reforming) |
| | **Gasification of biomass** | **By-product hydrogen** |
| Trends | • Several prototypes and system components commercially available | Already available |
| Drivers | • Low emission: well to tank GHG (7-25 (1) g/MJ)<br>• Direct use of renewable energy<br>• Very high improvement potential | • In a short-term perspective, potentially large resource at relatively cheap cost |
| Challenges Barriers | • Need to demonstrate satisfactory production over longer periods<br>• Lower efficiency than natural gas steam reforming (60 to 65%)<br>• Influence of fertilizer input over $N_2O$ emission<br>• Installation should not be too small (reduced efficiency at small scale)<br>• Transport distances of biomass should not be too large<br>• Gas purification (3) needed when disposal of organic waste is used<br>• Competition with synthetic fuels from biomass | • Limited in quantity in a long-term perspective<br>• Should be used close to the chemical plant |

*Figure 6 – State of development, drivers and barriers of the major hydrogen production routes – part 2*

| | Electrolysis | Thermochemical water splitting (solar or Nuclear) |
|---|---|---|
| Trends | • Conventional electrolysis has been proven for both large and small scale, commercially available<br>• High-pressure and high-temperature electrolysis and photo-electrolysis are under development. Reversible Fuel Cells/Electrolysers under development | • Research and development |
| Drivers | • Possibility of very low GHG emission<br>• Possible integration of intermittent renewable resources (PV and wind) with electrolysers for producing hydrogen to be used as a fuel or for energy storage | • Potentially large-scale production at low cost and without greenhouse gas emission<br>• High energy efficiency (practical direct, high-temperature water-splitting processes) |
| Challenges Barriers | • Higher cost than reforming - at least twice as high (€20/Gj) or more [(2)], large scale: €2.9-4.8/kg, small scale: €4-25 /kg)<br>• No environmental benefit when electricity produced from coal or natural gas (well to tank GHG 0-242 [(1)] g/MJ, 0-27 kg $CO_2$/kg$H_2$)<br>• Hydrogen production cost has a high dependency on the electricity price (reduction of renewable energy price)<br>• Large scale: compete with direct use of renewable electricity<br>• Not yet adapted for intermittent supply<br>• Need to improve reliability in fluctuating operating conditions (newly-developed diaphragms and membranes)<br>• Development of reversible fuel cells/electrolysers | • Over 10 years R&D needed for the process<br>• Understanding the kinetics and mechanisms of high-temperature chemical reactions<br>• Development of solar thermal concentrator or new nuclear reactor (VHTR)<br>• Nuclear: low social acceptance of nuclear energy in some countries<br>• Nuclear: plants are located as far as possible from urban zone (connection with long-distance transport of hydrogen will be needed) |
| | **Biological production (biophotolysis and fermentation)** | **Comments** |
| Trends | • Under research, demonstration of technical feasibility within the next 2 years, in 5-8 years a market-ready concept | [(1)] depending on the biomass treatments and origin<br>[(2)] depending heavily on the source of electricity used<br>[(3)] sensitivity toward CO and S content of PEMFC<br>[(4)] natural gas, heavy fuel oil, biomass |
| Drivers | • Potentially large resource at relatively cheap cost | |
| Challenges Barriers | • Slow hydrogen production rates<br>• Large area needed<br>• Most appropriate organisms not yet found | |

Based on industrial past experiences, experts have shown that hydrogen can be manufactured and used by trained professionals in centralised production. Thus safety issues are most likely to arise when hydrogen is used by consumers or refuelling staff with no special training. Moreover the use of hydrogen as a fuel for transport throws up new safety challenges (in fuelling processes, garage storage, tunnels, during collisions, accidental fires and explosions). Public acceptance is also a major issue in relation to safety standards [330, 333].

*Storage technologies*

**Hydrogen storage is the key to the dissemination** of fuel cell power systems and the advent of the hydrogen economy. We must however distinguish between stationary transportation and applications.

Hydrogen storage is a common practice in industry and is governed by well-defined safety standards. Hydrogen can easily be stored in large amounts in vessels or in underground caverns. However, for mobile applications, to achieve a driving range comparable to modern diesel or gasoline vehicles, **a breakthrough in on-board vehicle hydrogen storage technology is still required** [27, 99, 317]. The overarching technical challenge for hydrogen storage is how to store the amount of hydrogen required for a conventional driving range within the vehicular constraints of weight, volume, efficiency, safety and cost.

**Low-cost, energy-efficient off-board storage of hydrogen will also be needed throughout the hydrogen delivery system infrastructure**, at hydrogen production sites, hydrogen refuelling stations, and stationary power sites. These are less restrictive in terms of weight and volume, but “footprint” and filling/unfilling time limitations may arise. The available technological options include the following: **compressed hydrogen, liquid hydrogen, storage by adsorption** (in metal hydrides or carbon nanotubes) and **chemical storage** (especially in chemical hydrides).

Compressed gas cylinders are the most common technology used in the **demonstration of fuel cell vehicles** [101]. **Compressed gas cylinder** technologies are well understood up to pressures of 200 bar, but at this level only a small amount of hydrogen can be stored. A pressure of 350 bar is considered sufficient for most city buses and urban utility vehicles, whereas a minimum of 700 bar is necessary for passenger cars (due to their requirements in operating range and consumer space). The recent development of high-pressure tanks (700 bar) allows fuel and storage energy densities comparable to liquid hydrogen, but which are still lower than for gasoline and diesel. Further research on **high-pressure storage (including safety issues)** and **materials** (focusing on reducing the cost) are needed. The biggest challenge is in fact cost, which needs to be reduced by a factor of 20 [359]. In view of these challenges, compressed gas technology is often thought of as a transitional technology which will allow the demonstration of fuel cell technology but will be replaced by more efficient devices such as metal hydrides or carbon nanotubes in the long term.

**As a liquid, hydrogen energy density is substantially improved**, but thermal insulation and boil-off losses are a concern and could be prohibitive for private cars. This is why many experts do not expect this technology to be widely introduced on the transport market. Moreover the cost reduction achieved by economies of scale is one reason why this technology is more adapted to centralised production.

**Hydrogen storage in metal hydrides is considered to be the most promising technology in the field of transport.** Some technologies are already available and offer many advantages over liquid or compressed gas storage (high volumetric density, no losses, no safety risk). However, the available products are **still heavy** and suffer from **degradation over time**. Furthermore, these products are still **very expensive** and thus extensive research has to be undertaken in order to reduce their cost.

**Complex hydrides** and **carbon nanotubes** are in the early stages of research. Although complex hydrides can be very interesting, fundamental understanding of hydrogen physisorption and chemisorption processes is lacking. Improved understanding and optimisation of absorption/

desorption kinetics is needed to optimise hydrogen uptake and release and to provide sufficient flow rates of hydrogen for vehicle use.

### *Hydrogen end-use technologies*

Although the hydrogen economy is often associated with fuel cell development for stationary and transport applications, fuel cells are not the only technology considered for hydrogen use. Over the last three decades several companies and research institutes have dedicated significant efforts to developing internal combustion engines (ICE) for hydrogen use in vehicles. An interesting possibility for future hydrogen use lies in aviation, using gas turbines, although hydrogen gas turbines are more commonly studied in the context of stationary applications.

Among the technologies producing energy from hydrogen, fuel cells are often considered as the most promising, mainly because of their better environmental performances ($CO_2$ and NOx emissions) and their high efficiency [101].

Turbines and ICE engines, however, are almost mature technologies and are expected to come onto the market **slightly earlier than fuel cells** in the fields of large stationary and transport applications respectively (cf. fuel cells chapter). The technical challenges facing these technologies are: the adaptation of combustion technology to hydrogen-rich fuels, more corrosion-resistant materials at higher temperatures, minimisation of NOx production and safety engineering. Hydrogen-fuelled ICE could be used to promote the use of hydrogen for local emission reductions [330].

## Market trends

Hydrogen is a clean energy vector that could be used in both stationary and transport applications. As already mentioned, the main drivers behind the current interest in the hydrogen economy are: depletion of oil and gas resources, global warming, urban air quality (especially for transport systems), security of energy supply (particularly for transport systems), lack of suitable large-scale electricity storage media (especially for stationary applications).

As will be developed in the following chapters, there are several specific barriers to the introduction of hydrogen in stationary and transport applications. However, for both areas, the **lack of efficient (cheap and clean) hydrogen production routes is one of the main issues which is impeding any large-scale shift to a hydrogen economy**. Hydrogen production is already an industrial reality, and has been used extensively in the gas, chemical, metallurgy, and food sectors among others. The largest part of the 500 billion $Nm^3$ of $H_2$ produced world-wide today is generated from fossil sources: 48% of hydrogen is produced from natural gas, 30% from oil (mostly consumed in refineries), 18% from coal, and the remaining 4% via water electrolysis. However, even if today's hydrocarbon-based technologies can produce enough hydrogen from natural gas to meet the demand of the industrial sector (400 bn $Nm^3$ per year), these technologies cannot be relied on to supply the much larger volumes needed for a hydrogen-based economy, because the **processes presently available add to the build-up of $CO_2$ in the atmosphere.**

However, in the **short term**, hydrocarbon-based hydrogen production (especially from natural gas reforming) is still expected to dominate despite its relatively high level of greenhouse gases [330, 333]. In the **medium term**, competitive pricing of hydrogen in the initial phase of the hydrogen economy would require fuel de-taxation to kick-start broad market introduction and rapidly reach a state of economic self-subsistence [320].

For the long term, in the context of oil and gas depletion, there is discordance between experts regarding the best option to follow: some argue for processes using **nuclear power (high-efficiency electrolysis or thermochemical water splitting in association with VHTR)**, whereas others focus on **renewable-energy-driven technologies (biomass, photoelectrolysis, fermentation, thermochemical water splitting driven by solar energy** or electrolysis associated with hydro or wind power).

*Stationary applications*

The World Energy Outlook (2002) foresees that by 2020, although electricity will still be the vector of choice, the importance of $H_2$ will increase, arising from **niche areas** where **grid connection remains difficult or where surplus off-peak electricity is produced.**

Several studies show that the economics of renewable-powered electrolysis could be improved by the use of off-peak electricity where wind/solar energy is available, and the sale of electricity from wind/solar energy during peak tariff times. These combinations could improve economics by a factor of 2 (dependent on the wind/solar regime, electricity tariffs, feed-in contracts, etc.) [60].

**Hydrogen used as an energy storage means in various renewable energy systems** is one of the key areas of interest identified in the recent hydrogen roadmap drawn up in Denmark [316]. In this sense, the Danish Energy Agency not only recommends investigation of the development of **reversible fuel cells/electrolysers** but also **hydrogen storage in aquifers** [316]. Reversible fuel cells/electrolysers, although attractive in principle, are so far limited in practice due to the fact that electrode design is different for the electrolysis and fuel cell energy flows [60].

**Using hydrogen as an energy storage vector** will overcome the barrier of possible **competition with renewable energies** often mentioned in studies that are sceptical about the hydrogen economy. It is argued in fact that renewable energies could be used directly to produce green electricity instead of being used to produce hydrogen through electrolysis [127].

*Transport applications*

The transport sector is clearly that in which sustainable energy sources are the most difficult to implement, but also where they are the most needed (in view of city air pollution and fossil fuel dependency). For the past three decades, hopes have been pinned on **battery-based electric vehicles**, but the performance goals of the **battery have not yet been reached** and battery-driven cars suffer from low acceptance by the public (especially in the US where long distance autonomy is needed). For **hydrogen cars, on the other hand, the lack of compact, light, efficient and safe storage devices** is an important barrier against their introduction on the market.

The **hydrogen infrastructure** is rather like a "chicken and egg" problem. On the one hand energy companies will not want to invest large sums of money developing a complex hydrogen infrastructure until they are sure that demand will exist, which means, for most of them, only once fuel cell vehicles have overcome the inherent problems of cost and reliability (cf. fuel cell chapter). On the other hand, the car manufacturers could hesitate to invest in technologies like the fuel cell if the future implementation of a hydrogen infrastructure is unclear.

One possible means to overcome this dilemma would be the use of **small-scale on-site production of hydrogen from natural gas** (which today is the cheapest way of producing hydrogen). In the context of the Kyoto Protocol and global GHG reduction, this solution should only be used in a transitional phase since this production route emits $CO_2$ and the capture and sequestration technologies are not yet adapted to small-scale plants. Moreover, the use of natural gas will prolong dependency on carbon-based fuels.

A hydrogen economy based on electrolysis with insufficient renewables (or nuclear) penetration is likely to result in more fossil fuels being burned to supply electricity demand. **A move towards a hydrogen economy should therefore be accompanied by the installation of suitable low-carbon production technologies**. According to the IEA, replacing all the transportation fuels used in France with hydrogen would require around four times the present electricity consumption (i.e. around 700 TWh in additional consumption). Producing this electricity would require 60 new nuclear plants of 1,500 MW, or approximately 350,000 wind turbines covering 6% of French territory, or PV cells covering 1% of the land (at an even higher cost) [283].

When comparing the **cost of hydrogen production** with gasoline production, **none of the technologies available today (though already commercially available in the case of electrolysis and reforming) are competitive** [283]. The IPHE (International Partnership for the Hydrogen Economy) reports that the production of hydrogen is currently twice to four times more expensive than gasoline production [283]. Furthermore, the additional expense of $CO_2$ capture and sequestration would further increase this cost [283, 284].

It should be underlined that if $CO_2$-free production routes are considered, the production of hydrogen using renewable energy remains the most expensive [60, 283, 308]. Some studies show, however, that the cost of hydrogen from renewable-electrolysis systems could fall considerably ($11-25/GJ [€9-20/GJ]) by 2010, due to cost improvements for large wind systems [60]. **Reducing renewable electricity prices** will be an important driver in this sense. In the case of hydrogen production from off-shore wind power with assumed electricity costs of €0.0685/kWh, **83% of the pure hydrogen generation costs** would be **electricity costs** [99]. It is suggested that an exemption from **fossil fuel tax** for hydrogen might help wind-based electrolysis become competitive [60, 99].

## Main strengths and weaknesses of the USA and Japan

### USA

| | Strengths | Weaknesses |
|---|---|---|
| S&T | • Massive support from DOE (focus on production, storage, fuel cells and regulation)<br>• R&D-driven strategic plan with clear technical targets (2010-2015) and annual merit and peer review<br>• Economic/institutional barriers also addressed<br>• Synergy of parallel projects from the production of hydrogen to the end use (FutureGen)<br>• Leader of international partnership programmes (IPHE, PATH, GIF) | • Need to incorporate “go/no go” decisions in the roadmap to a greater extent<br>• Need to map transition phase<br>• Wind energy hydrogen production is not an important element of DOE’s programme |
| M&I | • Coal massive resource<br>• California hydrogen highways<br>• Leading companies in each link in the chain of the hydrogen economy<br>• Decentralised hydrogen production: companies developing small reformer and high-pressure electrolysis<br>• US fuel cell industry base covers all technologies<br>• Leadership in gas turbine technology (highest efficiency) | • Low price of gasoline compared with Europe and Japan<br>• Huge amount of carbon could need to be captured and stored<br>• Small renewable portfolio<br>• Energy industry not involved enough in hydrogen programmes |
| P&M | • $H_2$ roadmap<br>• Clear commitment to hydrogen economy<br>• Government has active relations with China<br>• Development of standards | • No alignment to Kyoto Protocol<br>• Lack of coordinated strategy to adopt or develop regional hydrogen plan<br>• Competition among states |

*Science and Technology (S&T)*

As mentioned in the fuel cells chapter, **US RTD benefits** from a general commitment to the field of $H_2$ and fuel cells, this **massive support** coming not only **from government entities like the Department of Energy (DOE), but also from states (such as California) and even cities** [27].

The *Energy and Water appropriations* of the US Senate for hydrogen technologies (fiscal years 2003 and 2004) are summarised in the table below. In 2004, a special focus was placed on critical path technologies (**production, storage**) and **codes and standards [353].**

| Key activity | FY 03<br>M$ (M€) | FY 04<br>M$ (M€) |
|---|---|---|
| Hydrogen production and delivery | 11.8 (9.6) | 23.0 (18.8) |
| Hydrogen storage | 11.3 (9.2) | 30.0 (24.5) |
| Infrastructure validation | 10.1 (8.3) | 13.16 (10.8) |
| Safety, codes and standards, utilisation | 4.8 (3.9) | 16 (13.1) |
| Education and cross-cutting analyses | 2 (1.6) | 5.82 (4.8) |
| TOTAL | 40.0 (32.7) | 87.98 (71.9)[7] |

President Bush demonstrated **the greatest financial support worldwide** (together with the Japanese), by assigning a total of $1.7 bn (€1.4 bn) over 5 years to the “*Hydrogen fuel initiative*”, of which $1.2 bn (€1 bn) has been earmarked for hydrogen and fuel cells. The strength of the

[7] $37 M have been earmarked for activities that will not particularly advance the hydrogen initiative [333].

American system is not only that it gives **substantial support** to $H_2$ research but also that it defines **clear technical targets for the short and medium terms (2005, 2008-2010, 2015)** [84, 304, 355] (cf. "Market trends" above). The DOE has developed a detailed plan for conducting R&D and demonstrations: "*Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan*" [307] in which **the critical path technology barriers are clearly identified**:

- Hydrogen storage (for transport, range of over 300 miles [483 km])
- Hydrogen production cost ($1.5 - 2.00/GJ [€1.2 - 1.6/GJ])
- Fuel cell stack cost (< $50/kW [€41/kW]).

**Economic and institutional barriers** are also addressed, such as codes and standards (safety, global competitiveness), hydrogen delivery (investment for new distribution infrastructure) and education.

As for the fuel cell programme, the hydrogen programme is submitted to **merit review and peer evaluation annually.** The maximum, minimum and average project scores for the overall hydrogen programme were 3.92, 1.55 and 2.92 respectively in 2004 (the lowest and best possible scores are 0 and 5) [354].

In addition to the *Fuel cell and hydrogen initiative*, the DOE Office of Nuclear Energy, Science and Technology (NE) is contemplating a major project which would demonstrate the commercial potential of hydrogen production from nuclear energy at a 50 MW scale by 2016 and should provide a basis for industry investment decisions. The Next Generation Nuclear Plan (NGNP) project would develop and demonstrate VHTR with the hydrogen production processes developed by the *Nuclear Hydrogen Initiative* [323].

The *Hydrogen fuel initiative* benefits from good synergy with **parallel track projects** such as the Office of Fossil Energy's (FE) *Hydrogen from Coal* programme, which was initiated in fiscal year 2004 [355, 356], and the *FutureGen* project (cf. chapter on fossil fuel) focusing on coal-based hydrogen production, development of $CO_2$ sequestration, development of turbines and development of fuel cells [321]. In contrast, wind power for hydrogen production does not appear, at the present time, to be an important element in the DOE's plan [333]. In addition to national programmes, the endeavours of the state of California should be singled out: the *California Hydrogen highways* is one of the most ambitious efforts currently underway towards creating a hydrogen infrastructure. The number of fuelling stations (currently 15) is expected to increase to 200 in 2010.

The Americans are also leaders in **international collaboration and partnership programmes such as the IPHE** (International Partnership for the Hydrogen Economy) or **PATH** (Partnership for Advancing the Transition to Hydrogen), which help accelerate technical breakthroughs. Here again technical targets are formalised to provide clearly quantifiable measures which can be used to **track progress.**

The PATH was established in 2002 as a collaboration between the governments and national hydrogen associations of Canada, Japan and the United States. Its mission is to spread a consensus vision of the hydrogen economy globally and strives to implement a hydrogen energy future by providing a forum for sharing information. The USA also initiated the **GIF Generation IV International Forum** which aims to develop advanced nuclear reactors for hydrogen production.

However the *National committee on alternatives and strategies for future hydrogen production and use* underlined that the US hydrogen programmes are "an attempt to meet **many extreme challenges**, set in too many areas, creating a very diverse and somewhat **unfocused programme"**. Therefore the DOE was advised to map out and **evaluate a transitional plan**. The DOE's plan needs to incorporate to a greater extent sets of milestones and **"go/no go" decision points** in the various development lines. For this task, the DOE will need a **viable hydrogen systems analysis programme** to understand the full costs and define the options.

### *Market and Industry (M&I)*

The *National committee on alternatives and strategies for future hydrogen production*'s upper-bound market penetration case for fuel cell vehicles, premised on hybrid vehicle experience, assumes that fuel cell vehicles will enter the US light-duty vehicle market in 2015, in competition with conventional and hybrid electric vehicles, reaching 25% of light-duty vehicle sales in the USA around 2027. The demand for hydrogen, in about 20 years, could thus be approximately equal to the current production of **9 million tonnes per year**. That will be only a small fraction of the 100 million tonnes required for the full replacement of gasoline light-duty vehicles with hydrogen vehicles, supposed to take place in 2050.

For the **production of hydrogen**, the USA intends to promote the **use of natural gas for the short and medium terms** and **coal, nuclear power and renewable energies** for the long term [284]. During the transition time, as natural gas reforming (without sequestration) has substantial GHG emissions and $CO_2$ sequestration will not be available, the USA will draw considerable advantages from **its non-alignment with the Kyoto Protocol.**

**Coal is a massive resource in the USA:** it has enough coal to make all the hydrogen that the hydrogen economy would need for the next 200 years. A substantial coal infrastructure already exists, and commercial technologies for converting coal to hydrogen are already available from several licensors.

However the *National committee on alternatives and strategies for future hydrogen production* estimates that the most important stake of the **hydrogen programme is the successful launch of carbon capture and storage activity.** Without carbon capture and sequestration (CCS), the annual carbon emissions from natural gas production would be 255 Mt-C and 518 Mt-C from coal plants in 2020. Considering the efficiency of capture technologies, 200 to 400 Mt-C/year would have to be captured and stored in 2050, if hydrogen production from nuclear and renewable energies is insignificant. In order to store this carbon, thousands of projects equivalent to the *Sleipner* demonstration programme (0.3Mt-C/year) would be required.

In the USA, the strategy is to develop **in parallel** all the necessary elements for the **hydrogen economy**, meaning that US companies are not only active in the field of **fuel cells** (cf. fuel cells chapter) but also in the key areas **of hydrogen production and fuelling stations, $CO_2$ sequestration, storage for mobile applications and turbines. However, the National committee on alternatives and strategies for future hydrogen production has underlined the poor commitment of the energy sector to the development of the hydrogen economy [333].**

**Several companies lead the field for decentralised production** of hydrogen (which is the short-term goal of the DOE): for example ONSI has proposed the first commercial version of a **small-scale reformer** with its PAFC, and recently PlugPower released its *Gensite* product, which is a small-scale autothermal reforming system. Stuart Energy is a leading electrolyser manufacturer across the globe and has installed approximately 1,100 hydrogen generation products in more than 100 countries around the world (more than 60% of all hydrogen vehicle fuelling projects in North America). Av_lence LLC has been awarded a DOE grant to conduct a comprehensive assessment of its proprietary process for the direct electrolytic production of **ultra-high-pressure hydrogen gas**. Air Products and Chemicals and Praxair, which both have industrial hydrogen pipelines in use in the USA, are involved in numerous demonstration projects in the USA but also in Europe and Asia [357, 360].

In the USA, the price of gasoline at the station is very low in comparison with Japan or some of the European Member States (about €0.35/l vs. €0.72 in Japan and more than €1/l in most European countries). That means that the challenge of obtaining a hydrogen fuel at a comparable price to gasoline will be even greater in the USA.

**In the field of storage in metal hydrides**, North America is reaping the rewards of **recent joint ventures** which should concentrate the available knowledge within a few leading actors, such as the Canadian HERA Hydrogen Storage Systems or the American Texaco Ovonic Hydrogen Systems (TOHS). TOHS engineers identified the Hybrid Prius as a logical platform for demonstrating solid hydrogen storage. Dynetek has developed and manufactures lightweight composite cylinders and its compressed hydrogen fuel storage systems have been incorporated in many fuel cell vehicles and buses (including DaimlerChrysler, Ford and Nissan).

In the field of $H_2$ turbines, the USA benefits from its know-how and leadership in the gas turbine sector.

### *Policies and Measures (P&M)*

As mentioned above, one of the USA's strengths is the commitment of its government to finding a path towards the hydrogen economy and establishing a hydrogen roadmap. However, a study by the DOE recently pointed out the **lack of a coordinated strategy** for adapting and developing **local hydrogen plans.** The DOE has therefore initiated six "hydrogen 101 workshops" for state and local government officials, intended to explain the hydrogen vision and technologies.

The US government rejected the Kyoto protocol and has opted to set voluntary emission limits for US companies. Thus the general issue of developing a "cheap and clean process for hydrogen production" might have different "boundary conditions" than in Europe.

As already mentioned in the fuel cell chapter, the USA has developed several mechanisms for helping innovative ideas become products, such as very strong public-private partnerships and tax incentives. But **competition does arise between states** vying to attract innovative companies.

**The National Hydrogen Association (NHA) is working in close collaboration with the DOE to coordinate codes and standards efforts in the USA** so as to develop a hydrogen infrastructure that has the public's confidence in matters of safety. Consequently, they have set up **expert working groups to develop industry consensus on safety, standards and product certification.** However, the NHA does not intervene in fields where specialised institutions are already working on the topic of hydrogen safety.

For instance, the National Fire Protection Association (NFPA) has incorporated hydrogen and fuel-cell-related issues into its standards, both for stationary and transport applications, to overcome commercialisation barriers. Moreover, for stationary applications only, the International Code Council[8] incorporated specific changes directly related to hydrogen into five codes (on Fire, Fuel Gas, Residential, Building and Mechanical issues) in 2003.



[6] A US organisation whose goal is to define safety standards mainly in the building sector.

## Japan

| | Strengths | Weaknesses |
|---|---|---|
| S&T | • JHFC demonstration programme for hydrogen stations underway<br>• Good expertise in carbon nanostructures with hydrogen storage potential<br>• Japan hydrogen and fuel cell demonstration project<br>• EAGLE project on hydrogen production through coal gasification | • Up to now, too much emphasis on compressed $H_2$ storage, and low expertise in $H_2$ liquefaction<br>• Too much emphasis on demonstration and utilisation, neglecting basic research |
| M&I | • Huge amount of by-product hydrogen available<br>• Automobile makers have a good experience of CNG cars and buses<br>• Japanese companies leading in materials used in compressed hydrogen tanks<br>• Japanese companies have a very good position in metal hydride<br>• FCV already in pre-commercialisation phase<br>• High cost of electricity and gas in Japan | • Low price of gasoline compared to Europe<br>• Japan does not have a meshed network of gas pipelines on its territory to carry hydrogen<br>• No domestic natural resources (natural gas, coal, uranium) to produce hydrogen |
| P&M | • Plans to build new nuclear power plants<br>• Strong drive towards diversification of energy sources<br>• Consistent effort in drafting roadmaps<br>• Public-private partnership led to identification of 28 regulatory barriers to be lifted in 2005<br>• Negotiation with USA on common goals (R&D, standards, etc.) | • Growing unpopularity of nuclear energy |

### *Science and Technology (S&T)*

**Hydrogen energy utilisation technology R&D was started at NEDO in 1993** with the "World Energy Network" (WE-NET) Programme, a part of the wider "New Sunshine Project" (1993-2001) on new and renewable energy. Originated in Japan, it also involved 36 participating organisations from 12 countries.

WE-NET was originally divided into three stages. The first stage (1993~1998) was dedicated to research, mainly analysing the possibilities for production, storage and usage of hydrogen. The second stage (1999~2005) addressed the construction of demonstration facilities, and ended ahead of schedule in 2002.

The main areas of investigation during the first two stages included:

- polymer electrolyte membrane electrolysis
- large-scale hydrogen liquefaction plant
- large tanker for transporting liquid hydrogen
- hydrogen storage in metal alloys
- behaviour of structures at low temperatures
- hydrogen-burning turbine, and the associated materials and combustion cycles

Stage three, the longest of the stages, was scheduled to run from 2006 to 2020, when the technologies would actually be put to use. However, it was replaced by the current **programme on R&D for safe utilisation of hydrogen and related infrastructures** (mainly storage and hydrogen stations). The budget for 2004 was ¥6.35 bn (€47.69 M), up 40% from 2003 (€34.17 M).

The original project on hydrogen-burning turbine (Toshiba) was shifted to an internal reforming methane-burning turbine during Phase II, and has not been continued onto Phase III.

Public R&D spending has thus been restricted to fuel cell (mainly PEMFC) applications, but automotive makers (Mazda, Hino) have been conducting R&D on **hydrogen-fuelled internal combustion engines** for transport. Car makers, however, fully recognise that these applications will not be primary drivers towards a hydrogen society.

With respect to storage materials for transport applications, the **focus has shifted from metal hydrides towards storage within carbon nanostructures**, a low-energy, lightweight option with higher storage potential, and with which domestic researchers and industries already have good working expertise. For stationary applications however, liquid or compressed hydrogen remain the preferred options to date.

Outside Phase III of WE-NET, NEDO has been sponsoring useful elemental technologies, such as the development of a nanoporous, high-temperature and high-efficiency ceramic membrane for hydrogen separation (2002-2006, ¥20 M [€150 k]) [38].

Concerning infrastructures, **particular efforts were made with respect to building and operating hydrogen stations** through the “Japan Hydrogen and Fuel Cell Demonstration Project” (JHFC), which aimed to test a host of technological options[9]. Ten hydrogen stations and 1 large liquid hydrogen production plant are currently operating in the Tokyo area [236, JHFC].

This project centres on infrastructures for FCV, and this vision of the hydrogen economy is sometimes thought to be too narrow – or pragmatic – neglecting to also look into building infrastructures catering to other applications (residential CHP, portable devices, etc.) [265].

Finally, concerning hydrogen production, we can single out the EAGLE project, which has been dedicated to developing high-performance coal gasification technologies on an IGCC power plant. A 250 MW pilot plant is under construction. (See chapter on fossil fuels for more details on this project.)

The Japan Atomic Energy Research Institute (JAERI) is also in charge of the development of nuclear-driven thermochemical water splitting processes. It recently succeeded in producing hydrogen automatically with an experimental reactor HTTR (High temperature engineering reactor) (30 L/h hydrogen).

### *Market and Industry (M&I)*

The current amount of recoverable by-product hydrogen from industry (hydrogen from gas purification of coke ovens, from salt electrolysis and from the oil industry) has been estimated at 824,000 t/year[236]. Therefore, as large amounts of (by-product) $H_2$ are already available, **the biggest issues for the government are building the necessary infrastructure (including storage) and ensuring safety**, rather than production or utilisation technologies.



[6] Reforming of LPG, methanol, gasoline, natural gas, naphtha, paraffin oil, etc.; recuperation of by-product hydrogen from different industries; storage of liquid or compressed hydrogen; water electrolysis; etc.

Government targets for hydrogen introduction are as follows [236]:

| | 2010 | 2020 | 2030 |
|---|---|---|---|
| Hydrogen demand for transportation (t/year) | 40,000 | 580,000 | 1,510,000 |
| Hydrogen price | — | ¥450/kg (¥40/Nm$^3$)<br>€3.38/kg (€0.30/Nm$^3$) | — |
| Hydrogen stations (#) | 500 | 3,500 | 8,500 |
| FCV tank capacity (kg-$H_2$) | 4.5 | 5.0 | 7.0 |
| Pressure of compressed $H_2$ tank (atm) | 700 | 700 | — |
| Capacity of $H_2$ storage materials (wt%) | 4 | 6 | 6 |
| Hydrogen supply sources | ~2005: By-product recuperation, Fossil fuel reforming, Electrolysis<br>~2015-2020: Biomass fermentation, thermochemical water splitting, Nuclear, (other) | | |

The NEDO objective for hydrogen supply infrastructure is to reach an overall efficiency of over 70% by 2007, while reducing the size of systems by 50 to 65%.

On the industry side, several companies are working on the development of hydrogen production technologies, some of which are close to commercialisation. For instance Shinko Pantec has presented the HHOG (High-purity Hydrogen and Oxygen Generator), based on proton exchange membrane technology, and Mitsubishi Corporation has the world's first high-pressure hydrogen gas production system without a compressor, through its prototype electrolyser HHEG (High-pressure Hydrogen Energy Generator).

*Policies and Measures (P&M)*

In 2001, the Council for Science and Technology Policy, the highest advisory body in Japan, proposed a general framework to build a "Hydrogen Society" [36]. Consequently, in its "Energy Basic Plan" (October 2003), the government drafted the necessary policies for promoting hydrogen and other gas energy carriers [287].

**A hydrogen economy is being supported for energy security** – through diversification of energy sources – **rather than energy independence issues**. Indeed, Japan does not own sufficient domestic hydrogen resources (biomass, nuclear or renewables) to supply its own market. Thus, the **government policy is to develop hydrogen production technologies from various sources**.

Since Japan wants fuel cells and hydrogen to play a major role in the future, it has been putting **consistent efforts into drafting technological and market roadmaps**, in coordination with academics and the industry.

For instance, in 2005, **the Japanese government will amend 28 items in 6 laws** – such as the Traffic Law, the High Pressure Gas Security Law, etc. – in order to eliminate obstacles to the introduction of fuel cells and the use of hydrogen.

Promotion of awareness of hydrogen and fuel cells has been undertaken in recent years amongst the general public in the light of the Kyoto Protocol. In particular, their role in the energy-intensive transportation sector has been stressed, especially in view of the strict and growing social demand for air quality.

Finally, the need for **international standardisation efforts for verification and safety** is often cited by experts, especially in the automotive field (cf. ISO/TC197) [265].

## SWOT analysis for Europe

| | Strengths | Weaknesses |
|---|---|---|
| S&T | • Good fundamental research capacity<br>• All $H_2$ technologies (from production to end use) are addressed with a recent focus on the bottleneck technologies and non-technological barriers (Hysociety)<br>• Several key demonstration, lighthouse programmes (CUTE, HYCOM, HYPOGEN, ECTOS, etc.) | • Knowledge transfer between industries and universities needs to be further supported |
| M&I | • Experience in large-scale hydrogen generation, distribution and applications including know-how in safety and handling<br>• Wide variety of national resources for hydrogen production ("cheap" renewable [wind, geothermal, coal, hydro], uranium, biomass)<br>• European companies active in the combination of green energy/electrolysis<br>• Commitment of DaimlerChrysler to fuel cell technology, of BMW to $H_2$-ICE<br>• Energy companies are active | • Compressed hydrogen storage: weak EU supplier position<br>• European fuel cell manufacturers not well positioned to enter the automotive market<br>• Metal hydrides know-how transferred to North America |
| P&M | • EU and some Member States have roadmaps underway *(Fuel cell and hydrogen platform efforts)* | • No sufficient EU-wide regulations, codes and standards<br>• No EU-wide fiscal incentives for hydrogen, FC |
| | **Opportunities** | **Threats** |
| S&T | • Need for chemical and materials competence for technical breakthrough | • USA could get better results thanks to its short/ medium-term technical targets |
| M&I | For the short/medium term:<br>• Develop small-scale appliances operating reliably and safely in a typical fuelling station (untrained staff)<br>• Cleaner chemical conversion, cheaper electrolysis, improvement of storage of compressed or liquefied gas<br>• Map the transition to the hydrogen economy<br>For the medium/long term:<br>• Development of hydrogen as a means to store the energy of green electricity<br>• Develop various clean and cheap processes for the production of hydrogen, a reliable mobile compact storage device, as well as reliable and cost-competitive fuel cell systems | • Use of biomass for other purposes<br>• Poor acceptance of nuclear power in some countries<br>• The USA and Japan impose their "hydrogen economy vision" as well as their standards<br>For the short/medium term:<br>• Cars using alternative fuels<br>• Chicken/egg between $H_2$ infrastructure and FC vehicles<br>• The European demonstration will profit more the American and Canadian FC OEM<br>For the medium/long term:<br>• Legal issues and public acceptance of $CO_2$ storage<br>• Japanese or North American companies make a breakthrough in mobile hydrogen storage earlier |
| P&M | • Take advantage of national commitments to the hydrogen economy and defined national roadmaps | • The current legislation for car emissions is not a sufficient driver<br>• North America is attractive for Europe's innovative ideas |

## Strengths and weaknesses of Europe

*Science and Technology (S&T)*

As mentioned in the fuel cell chapter, Europe **has a good fundamental research capacity, especially in the field of chemistry, material sciences and energy systems**. The first 700 bar composite hydrogen storage tank developed by the CEA with the French company Composites Aquitaine in the frame of a European programme is a good example of this [346]. This research capacity is important because many hydrogen issues need fundamental research in these fields. In FP6, the focus has been placed onto the bottlenecks in all $H_2$ technologies from production to end use (i.e. fuel cells, ICE, turbine, $H_2$ production, mobile storage) [122].

In November 2003, The European Commission presented a «Quick Start Programme» with a list of public-private investment projects for developing European infrastructures, networks and knowledge. The aim is to encourage the creation of **public-private partnerships** (HYPOGEN, HYCOM) in co-operation with industry, the research community, and other partners, including notably the European Investment Bank to leverage finance.

In FP6 and the "quick start programme", a significant focus has been put on finding pathways to a hydrogen economy, and on the preparation of standards, in coordination with key demonstration programmes and **large-scale lighthouse projects** integrating all of the core elements of a hydrogen economy in a limited number of selected regions (CUTE, HYCOM, HYPOGEN, ECTOS, ZERO REGIO). These programmes will enhance European knowledge in stationary and transport applications as well as production and distribution.

HySociety is an important project undertaken by a consortium of 20 organisations from 14 countries in Europe (including Iceland and Norway), which aims to address **non-technical barriers** to the deployment of hydrogen energy systems. HySociety will deliver lines of action on codes and standards, measures for addressing infrastructure build-ups and dissemination to different sectors of society such as the general public, decision-makers and business leaders. The social, economic and environmental impacts of hydrogen technologies are reviewed in an effort to highlight the opportunities for establishing a clean, safe, efficient hydrogen energy system in Europe.

There are also some important national demonstration programmes like:

- *Utsira Island project* (wind hydrogen production on remote island)
- *HyNor* (580 km hydrogen road to demonstrate real-life implementation of hydrogen energy construction during the years 2005 to 2008)
- *The Berlin Clean energy partnership*, similar in concept to the *California fuel cell partnership*, is an alliance between the German federal government and nine companies (2003-2007).

As we mentioned in the fuel cell chapter, several efforts have also been undertaken to **coordinate the technical know-how and the research initiatives** of the different European countries. Among them, the *Fuel cell and hydrogen platform* provides important input for the European position in the hydrogen economy. In December 2004[10], the platform delivered a draft of two documents: the "*Strategic research agenda*" and the "*Deployment strategy*" [329, 330]. The *Fuel cell and hydrogen platform* recommends, for hydrogen production, a **special focus on technologies with short- and medium-term availability**. Half of the research budget dedicated to hydrogen production should be spent **on chemical conversion processes** (with a special focus on gas separation technologies) and one third on **electrolysis.** For storage and distribution, **a focus on storage** devices is recommended as is a clear emphasis on basic research. With respect

[3] 2 years after the DOE.

to end-use technologies, the platform indicates a **clear choice for fuel cell technologies** (57% recommended for high-temperature fuel cells and 30% for low-temperature fuel cells). However it is recommended that 10 % of the budget (5% for each technology) should be attributed to hydrogen **ICE and turbine.**

### *Market and Industry (M&I)*

By 2050, fossil fuels are still expected to provide more than half of EU primary energy consumption (the windmill capacity of Europe will increase to 180 GW by 2020[11]).

A study conducted by the European *alternative fuel contact groups* shows that alternative motor fuels have the potential to gain significant market share within the coming decades. Market share estimates for the main alternative fuels in 2020 are: 15% for biomass-derived fuels, 10% for natural gas, 5% for LPG, and a few per cent for hydrogen [320].

The EU intends to have hydrogen cars ready for the customer in 2020, which will require both availability of hydrogen fuel cell vehicles and a hydrogen-filling infrastructure. With scenarios assuming a market share of between 1 and 5% for hydrogen car population in 2020, between 360,000 and 1,825,000 hydrogen-fuelled cars could be sold in Europe in 2020. It is considered that a fleet of at least several hundred thousand hydrogen cars is needed to ensure that a few thousand hydrogen filling stations are built as a basic infrastructure in large clusters around the biggest European cities [330, 358].

For the short term, where important demonstration programmes are deployed Europe will take advantage of the by-product hydrogen production already available. In addition to that, large-scale hydrogen production, liquefaction and subsequent trucking of liquefied hydrogen will be implemented. With the same intensity, and in parallel, onsite pathways will be deployed.

For the long term, a target for the delivered cost of hydrogen for transport applications in 2030 could be €1.5/kg at an oil price basis of $30 (€24.5) per barrel (corresponding to a 50% surplus compared with untaxed gasoline at €0.27/$l_{gasoline}$).

Europe is a leader in the fields of catalysis and process development relevant for **hydrogen production** via chemical conversion, as well as in the **field of electrolysis**, the other major route to hydrogen. In electrolysis, Norsk Hydro Electrolysers AS is a well-established manufacturer of conventional electrolysers and is involved in a project aiming to combine hydro-electricity with electrolysis. Statoil and Norsk Hydro are those two Norwegian assignees with the most patents granted in the USA in that domain. However, with regard to fuel cells and hydrogen technologies, all the references contained in Norsk hydro patents are from US companies such as General Electrics, TexACO Inc. and Jacobs Engineering limited [340]. Ahlström, Gotaverken, HTW and Lurgi GmbH are developing processes in biomass gasification.

In the field of industrial hydrogen production, conditioning and distribution, Europe plays a leading role in liquefied hydrogen, with key players the likes of Linde and Air Liquide. By contrast, Europe appears to be a poor supplier in compressed gas [330]. For mobile hydrogen storage, GfE Gesellschaft für Elektrometallurgie GmbH, one of the world's leading companies in the development and production of high-performance specialty materials, has already developed a light metal hydride. However, the know-how has been transferred to the Canadian joint venture HERA.



[11] Based on the EU target to double electricity production by renewables from 6% to 12% by 2010 [330].

*Policies and Measures (P&M)*

Recently, the EU invested a large budget in defining its hydrogen roadmap and transitional strategy. Some of the EU Member States have already released their roadmaps, such as Denmark, which is proposing a very different vision to that of the USA and Japan, placing the emphasis on wind-energy-driven electrolysis and hydrogen as an energy carrier. Moreover, different roadmaps are being proposed based on the possible (or not) breakthrough of fuel cells.

In the EU, several EN standards can be applied to hydrogen and fuel-cell-related issues, but harmonisation is considered necessary to ensure transparent application of codes. The main needs are thought to be co-operation and co-ordination rather than technical issues.

Therefore, the Institute of Energy's "Fuel Cell TEsting and STandardisation thematic NETwork" (FCTESTNET) has been gathering opinions within and outside Europe, and the "Fuel Cell TEsting, Safety and Quality Assurance" ($FCTES^{QA}$) project was started during FP6, in collaboration with the International Partnership for the Hydrogen Economy (IPHE).

## Opportunities and threats for Europe

*Science and Technology (S&T)*

The need for breakthroughs in several $H_2$ technologies involving chemical processes or materials development is a great opportunity for research teams in Europe where there are several leading research centres. Through the efforts of the *European fuel cell and hydrogen platform* and especially through the "*Business development and financing*" interest group, Europe wants to avoid investing in research projects that will lead to technologies that will never come onto the market. This approach is important in view of competition with the USA and Japan, which have defined technical bottlenecks and their own vision of final market targets.

For the short and medium term, Europe is the market leader in those fields of catalysis and process development that are relevant for **hydrogen production** via chemical conversion, as well as in the **field of electrolysis**, the other major route to hydrogen. Support for basic and applied research in these areas will further reinforce this strategic lead [330].

For the long term, a breakthrough in compact storage devices is important for the future of hydrogen-fuelled cars. The concentration of metal hydride knowledge in a few big North American companies might be a threat for small innovative European companies.

*Market and Industry (M&I)*

Despite the good position held by European industries ion the high-temperature fuel cell and liquid hydrogen markets, the situation is different for low-temperature fuel cells and compressed gas. Thus in those fields, the demonstration programme might bring greater benefit to American and Canadian companies, than the few small European companies.

The USA and Japan have set many ambitious short- and medium-term challenges in order to develop the hydrogen economy and push up their industry. They are also very active in international cooperation. Thus Europe will have to make greater efforts (initiated by the Fuel cell and hydrogen platform) to remain in the running.

There are several opportunities to solve the "chicken and egg" problem of fuel cell vehicles and $H_2$ infrastructure. Europe could develop a decentralised infrastructure (on-site production/compressed gas) combined with trucking liquefied hydrogen produced in large-scale plant, thereby benefiting from Europe's good position in those technology fields.

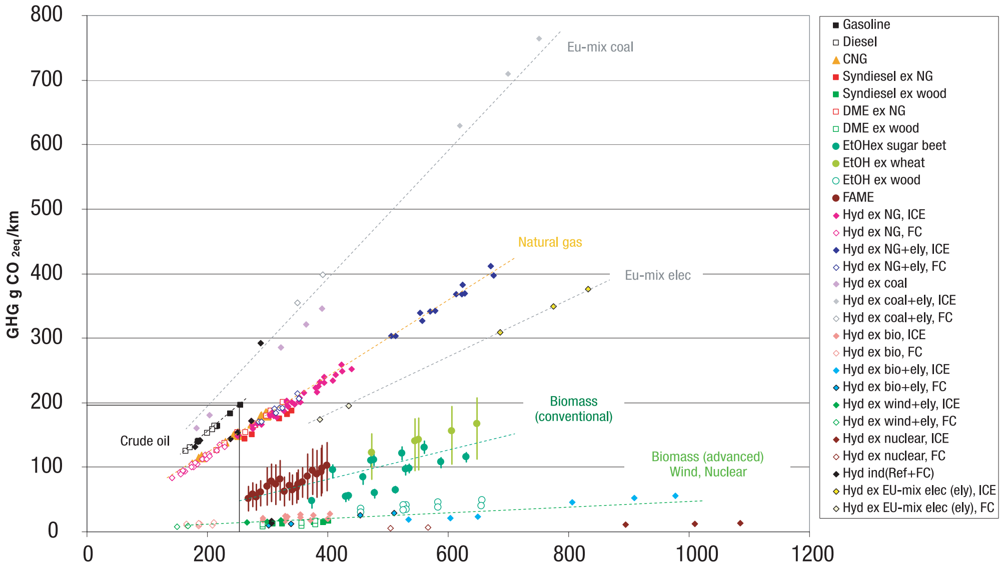
One threat concerning hydrogen production is that there is no clean and cheap efficient way to produce hydrogen for the medium term. Electrolysis has a low energy efficiency and provides environmental advantages only when combined with green electricity.

For the long term, in addition to the strong capacities of some of the Member States in nuclear power, Europe could benefit from its knowledge in systems combining wind energy and hydrogen as a vector to store energy. Europe would thus take advantage of the commitment of several of the Member States to developing "cheap renewable energies" like wind or hydro power. The storage of energy could help solve the peak demand issue as well as the problem of intermittence of some renewable energies.

### *Policies and Measures (P&M)*

The current regulations on $CO_2$ emissions do not offer any advantage for fuel cells using hydrogen produced by low-$CO_2$ processes. However, the figure on the next page clearly shows that a regulation favouring processes with a "well to wheel GHG" value lower that 100g $CO_2$ equivalent/km could boost the production of hydrogen from biomass or from wind energy [361].

*Figure 7 – Well-to-well greenhouse gas emissions and energy efficiencies for various primary energy sources with different vehicle technologies*




*Source: European Commission, alternative fuel group, 2003 [361]*

Compared to Europe, Japan and the USA are much more active and advanced in terms of energy codes and standardisation. A European Initiative Group on Regulations, Codes and Standards (RCS) has been proposed with a view to developing an action plan to accelerate processes for implementation of commercially competitive RCS. An initiative of this kind is definitely needed to bring Europe up to speed with Japan and the USA.

As mentioned in the fuel cell chapter, the USA has implemented several incentives to attract hydrogen businesses. In Europe, although Norway has implemented fuel cell de-taxation, there is still a lack of EU-wide incentives [329].

## References

[27] Hydrogen Energy and Fuel Cells. EC-DG Research. 2003.

[36] Promotion Strategy by Sector. Council for Science and Technology Policy, Japan. September 2001.

[38] Outline of NEDO. New Energy and Industrial Technology Development Organization (NEDO), Japan. June 2003.

[60] Hydrogen Energy Technology. Tyndall Centre for Climate Change Research. April 2002.

[64] The role of hydrogen in powering road transport. Tyndall Centre for Climate Change Research. April 2002.

[84] Leading our nation towards energy independence. Stanford University Global Climate and Energy Program. April 2003.

[99] Potential of hydrogen as a fuel for transport in the long term (2020-2030). IPTS / EC-JRC. March 2004.

[101] Impact and consequences of fuel cell technology on sustainable development. IPTS / EC-JRC. March 2003.

[122] European hydrogen and fuel cell projects. EC-DG Research. 2004.

[127] The future of the hydrogen economy: bright or bleak?. European Fuel Cell Forum. April 2003.

[236] Fuel cell and hydrogen energy society development up to 2030. Agency for Natural Resources and Energy (ANRE), Japan. April 2004.

[265] Committee on fuel cell and hydrogen technology. New Energy and Industrial Technology Development Organization (NEDO), Japan. 2004.

[283] Moving to a hydrogen economy: dreams and realities. International Energy Agency (IEA). January 2003.

[284] Hydrogen production scoping paper: R&D for alternative production processes. International Partnership for the Hydrogen Economy (IPHE). September 2004.

[287] Energy Basic Plan. Agency for Natural Resources and Energy (ANRE), Japan. October 2003.

[303] Hydrogen in the energy sector. L-B-Systemtechnik GmbH, Germany. July 1996.

[304] Leading our nation towards energy and environmental security through hydrogen. US DOE. September 2004.

[307] Hydrogen, fuel cells, and infrastructure technologies program: multi-year research, development and demonstration plan. US DOE, EERE. June 2003.

[308] IEA hydrogen and fuel cell activities. International Energy Agency (IEA). May 2004.

[316] A strategy for development of hydrogen technologies in Denmark. Danish Energy Agency. November 2004.

[317] Hydrogen storage scoping paper. International Partnership for the Hydrogen Economy (IPHE). September 2004.

[320] Market development of alternative fuels. European Commission, Report of alternative fuels contact group. December 2003.

[321] DOE’s Fossil Energy Turbine Program, Second international conference on industrial gas turbine technologies. US DOE. April 2004.

[323] Hydrogen R&D Plan. DOE Nuclear Energy Research Initiatives. 2003.

[324] Options for the near and long term: hydrogen production from nuclear fission and fusion. US climate change technology Program. November 2003.

[325] Hydrogen economy. The World Nuclear Association. October 2004.

[351] Assessment of the Pathways for the production of Hydrogen in Europe at the 2020 Horizon and Beyond. Institut für Energetik und Umwelt GmbH, DG JRC. December 2004.

[352] Hydrogen by microorganism. BioCycle. January 2004.

[353] DOE hydrogen and fuel cells coordination meeting. US DOE. June 2003.

[354] Summary of Annual Merit review, hydrogen production and delivery sub-program. US DOE. 2004.

[355] Hydrogen from coal program. Research, development and demonstration plan for the period 2004 through 2015. DOE Office of Fossil Energy. June 2004.

[356] Hydrogen from coal. DOE workshop on hydrogen separation and purification technologies. September 2004.

[357] Hydrogen infrastructure delivery reliability R&D needs. SAIC for DOE/NETL. August 2004.

[358] Considering a basic area-wide hydrogen fuelling station network in Europe. Hynet. August 2004.

[359] Hydrogen Composite Tank project. DOE. Fiscal Year 2003 Progress Report.

[360] Worldwide hydrogen fuelling stations. FuelCells.org. 2000.

[361] Market development of alternative fuels. European Commission's alternative fuels contact group. December 2003.

# Fossil fuel technologies

## Technology and market trends

Energy (electric and thermal) is for a large part produced from the three forms of fossil fuels: coal, petroleum, and natural gas.

Coal is the most abundant fossil fuel and is the least expensive energy source for generating electricity. Many environmental problems are however associated with the burning of coal: $NO_x$ and $SO_x$ are released, as are particulate matter and $CO_2$.

Some of the advantages of petroleum are the ease with which it can be handled, stored and transported. Although petroleum burns more cleanly than coal, the same pollutants are produced.

Natural gas is the least available fossil fuel and it is difficult and costly to transport. It burns more cleanly than the other fossil fuels. Less $NO_x$, $SO_x$ and particulate matter are produced, but $CO_2$ is still produced.

**71% of worldwide electricity production is of fossil fuel origin** (62% coal, 26% natural gas and 12% oil) [IEA], and **this share is predicted to remain at a constant level at least until 2025** (with a slight decrease in oil compensated by an increase in natural gas).

In 2002, installed electric production capacity across the globe was about 3,800 GW, broken down as 31% in Europe, 30% in North America and 9% in China. In terms of technology, 50% of total capacity is covered by conventional steam turbines, 20% by hydropower, 17% gas turbines, and 10% nuclear.

In Europe, the installed capacity amounts to 1,188 GW, with about one third (385 GW) provided by plants that are over 30 years old. These old plants are mainly conventional steam plants (61%) and hydropower plants (35%) [293].

Of the 124 GW capacity ordered in 2002 worldwide, 82% was fossil–fuel-based (35% of which was produced by gas turbines and combined cycles).

Fossil fuels can be used in various types of technologies that produce either heat or electricity or both (in cogeneration - also called CHP - applications).

The liberalisation of the energy market in Europe initiated a complex reorganisation of the electric power industry. Previously based on **centralised power production** and delivery, a novel concept is emerging moving towards **distributed generation**. The technologies behind distributed generation are numerous, ranging from renewable technologies (solar, wind, hydro, etc.) to CHP plants and other small- and medium-scale plants.

The major advanced technologies based on fossil fuels and applicable for centralised and distributed generation are given below. Those in bold characters were the focus of this study.

The fossil fuel technologies for distributed generation looked at in this study are those supplying power in a range of 1 kW to 10 MW.

| Centralised production | Distributed production (including CHP) |
|---|---|
| **Gas turbine**<br>**• Simple cycle**<br>**• Natural-gas-fired combined cycles (NGCC)**<br>**• Integrated gasification combined cycles (IGCC)**<br><br>**Steam turbine**<br>**• Pulverised fuel supercritical steam cycle (PF)**<br>• Circulating fluidised bed combustion (CFBC) | **Gas turbine**<br>**• Simple and combined cycles**<br>**• Microturbine**<br><br>**Steam turbine**<br>**Steam engine**<br>**Stirling engine**<br>**Reciprocating engine**<br>**Organic Rankine Cycle** |

## Technology trends

*Centralised power production technologies*

Gas turbines cover a wide range of applications and sizes. For large gas turbines, cost of electricity is the main driving force that determines technical needs. Efficiency, reliability, availability and initial cost all contribute to the cost of electricity. With smaller turbines, fuel flexibility and maintenance costs can be more important parameters than in large machines.

Significant progress has been made on **gas turbine technology over the last decade and today this technology is considered to be mature.** Although NGCC is a widespread technology, technical barriers still remain, particularly in terms of the limitations imposed by materials and design on efficiency and operating temperatures. The target efficiency levels are 45-50% for simple cycles and 70% for NGCC. Such improvements may require totally new concepts and cycles.

Clean Coal Technologies are those which facilitate the use of coal in an environmentally satisfactory and economically viable way.

Various methods for coal-fired power generation are well established and widely used: pulverised fuel combustion (PF) with subcritical steam driving a steam turbine, cyclone-fired wet bottom boilers with subcritical steam driving a steam turbine, and stoker boilers for small applications with subcritical steam.

In addition, various advanced technologies are undergoing development in order to come up with an environmentally satisfactory method of using coal as a basic fuel for power production in new plants. Some are now commercially available, backed by large-scale operating experience in a number of countries. Others are still at the demonstration stage. These technologies include:

- **pulverised fuel combustion** with supercritical steam driving a steam turbine
- **atmospheric pressure fluidised bed combustion (FBC)** in both bubbling (BFBC) and circulating (CFBC) beds, mainly with subcritical steam turbines
- **pressurized fluidised bed combustion (PFBC)**, which currently uses bubbling bed boilers, in combined cycles with both a gas and steam turbine
- **integrated gasification combined cycle (IGCC)**, using different types of gasifier, and in combined cycles with both a gas and steam turbine. The syngas stream undergoes combustion and expansion of the combustion products through the turbine. The **IGCC process is still at the demonstration stage** and is facing several types of barriers, including numerous technical issues and the need to increase efficiency and decrease operating cost.

**Coal-fuelled power plants are expected to reach a capacity of 1200 MW by 2020**, enabling significant economies of scale and localised $CO_2$ production.

The most commonly used advanced coal-based technology worldwide is pulverised fuel (PF) supercritical steam cycle plants, with the best efficiency available currently being 45%. Due to the increasingly stringent emissions regulations, further developments are essential in order to maintain and improve the prospects of coal use in pulverised coal-based generating plants. Moreover, advanced materials for boilers, turbines and other components are needed to develop ultra-supercritical steam plants and thereby increase the overall efficiency of the coal combustion system. While PF plants operate at a steam temperature of 600°, the ultra-supercritical plants still under development are expected to operate at 700°C and very high pressures, thus leading to improved efficiencies.

The development of IGCC technology started in the early 90s, and **several demonstration plants with 250 to 300 MW capacity are currently in operation, including two in Europe** (Puertollano in Spain since 1998 and Buggenum in the Netherlands since 1994), and two in the USA.

**Third generation IGCC development is currently underway worldwide,** with projects concerning non-capture IGCC (which aim to increase efficiency and availability and decrease capital expenditure), improvement of refinery IGCC and demonstration of capture coal IGCC. The main ongoing projects, all involving IGCC but with various long-term commitments and integration approaches, are: **FutureGen in the USA, EAGLE (demonstration plant) in Japan**, $CO_2$CRC, an Australian demonstration project, the Canadian Clean Power Coalition project for two demonstration plants, the **EU projects Hypogen and ENCAP**, and the **German project COORETEC** [74]. The reliability of IGCC technology is still an issue and the cost of electricity it generates is too high.

Today, in terms of efficiency, IGCC is not necessarily the best pathway, since it has 43% efficiency (against 45% for PF supercritical steam cycle systems), its capital expense is 20% higher and plant availability is only 70% (90% for PF supercritical steam cycles). The progress targeted for 2015 should lead to ultra supercritical (USC) combustion systems with 50% efficiency but an increase in capital expense equal to that of IGCC plants, whereas IGCC plants will have improved efficiency (52%) and improved availability (85-90%) without extra cost [74]. Both technologies are expected to be mature in the medium term.

In addition to improving the efficiency and emission levels of the conversion technologies, there is currently a trend towards developing (near-) Zero-Emission Technologies, which combine advanced power production systems with $CO_2$ capture processes so as to reduce the overall $CO_2$ emission level by around 90%. Three types of processes can be used to capture $CO_2$ at the main industrial emission sources:

- **Post-combustion capture**, where $CO_2$ is extracted from flue gas, and which is highly suitable for retrofitting
- **Pre-combustion capture**, which leads to a high $CO_2$ concentration stream, enabling simple separation techniques to be applied, and which can also be used to produce hydrogen
- **Oxy-fuel technologies**, which use combustion in almost pure oxygen, leading to a high $CO_2$ concentration in the flue gas

These zero $CO_2$ emission solutions **suffer from considerable efficiency losses**. For instance, for both coal-fired steam power plant and IGCC power plant in a post-combustion configuration, the efficiency loss is 11-15% (8-12% due to capture and 3% due to liquefaction). To offset these efficiency losses, a significant increase in combined cycle and steam power plants is required [311].

*Distributed power production technologies*

The advantages of microturbines are: simplicity, compactness, fuel flexibility and low $NO_x$ emissions, as well as potentially low investment and maintenance costs [118]. The current efficiency levels are 30% (electric) and around 80% (heat and power).

**Microturbine technology has been identified by the US DOE as one of the 27 critical technologies of today.**

Industrial gas turbines are also used for DG with units of a capacity of up to several tens of MW. They are particularly suitable for large cogeneration applications where high-temperature steam is needed. They have emissions lower than reciprocating engines and they require less maintenance. On the other hand, for units under 2 MW, their electrical efficiency is lower than for reciprocating engines.

Today, **only a few small gas turbines (<2 MW) for power generation are available on the market** (5 MW power is the smallest gas turbine offered by both Siemens and General Electric). In Europe, only OPRA Gas Turbines in the Netherlands offers a 1.5 MW gas turbine, and in the USA only Solar Turbines – Caterpillar does this. Such small power gas turbines could find niche markets in DG applications, but further developments are needed to enhance their performance. Research efforts should focus on the development of advanced materials (composite ceramics, thermal barrier coatings), and of a combustion system leading to lower $NO_x$ and $CO_2$ emissions. From the resulting advanced gas turbines, a whole new range of DG applications could be addressed. The US DOE has an Advanced Industrial Gas Turbine Program which is working to enhance the performance of 1-20 MW gas turbines, and the Japanese are also working on such equipment.

## Market trends

*Centralised power production technologies*

In Europe, demand for new electricity production capacity will be driven by the necessary replacement of ageing fossil power plants, the replacement of nuclear plants and growth in demand. For example, some **550 GW in power plant capacity** (i.e. 90% of current capacity) **will have to be built by 2030 within the EU-15 alone** to satisfy new demand and the essential replacement of aging plants.

To reduce consumption of gas and coal for power generation, solar and wind energy are being introduced. However, these renewable energies can only compensate to a certain extent and some experts consider that nuclear energy will be inevitable as a major energy source in the future.

Most experts and studies agree that **fossil-fuel-based power production will continue to represent a large share of the energy mix for at least 50 years**. Therefore, technological development of advanced generation plants, particularly gas turbines and coal gasification systems, needs to be continued in order to achieve improved efficiency and environmental performance at an acceptable cost.

Although Europe, the USA and Japan are conducting ambitious long-term projects to develop so-called “zero-emission” power plants, such technologies will probably be costly for a long time because of the large technology gap they involve. Therefore, **in the meantime, it is essential to continue to develop technologies that enable electricity production to be “de-carbonised”**, for example by switching to natural gas systems or by using cleaner coal combustion systems. A similar goal is being pursued through the current emphasis put on improving the efficiency of existing systems.

In Europe, 10% of coal plants are old plants (over 35 years old) operating at an efficiency rate of less than 30%. Replacing those 10% of old plants with NGCC plants would be sufficient to fulfil the Kyoto Protocol commitments in Europe.

**A significant part of the coal-combustion-based capacity is expected to use supercritical steam cycles by 2020. Moreover, a trend toward biomass/coal co-combustion is being confirmed.**

Large- and medium-scale fossil-fired heat and power-generating technologies are almost exclusively supplied by large multinational companies, whether in the European Union (Siemens, Alstom Power, etc.), the USA (General Electric, Foster Wheeler, etc.) or Japan (Mitsubishi Heavy Industries, etc.).

**The number of NGCC plants is expected to increase significantly**, mainly thanks to the high levels of efficiency they present (close to 60%), their low capital costs, and the low emission levels. The worldwide market potential will however depend on the availability and price of gas, and also on possible competition arising from the success of the emerging “clean-coal” technologies.

Whereas NGCC is a well-established technique, **the technology associated with IGCC power generation is still at the demonstration stage,** with several pilot plants installed in Europe, the USA, and Japan.

In the new Member States, energy sources and technologies are variable from country to country. Looking at the Baltic countries alone, Estonia’s electricity is 95% based on oil shale, Lithuania mostly uses nuclear energy (one nuclear plant has to be closed soon and will be replaced by a fossil-fuel-based plant), and Latvia is mostly hydropower-based.

A number of the new Member States, primarily **Poland, the Czech Republic and Hungary, produce and consume considerable amounts of coal and lignite** and their incorporation into the EU has had a significant impact on overall EU coal reserves, production and consumption. These new Member States have boosted EU coal reserves from 72 Gt to over 100 Gt, an increase of over 40%. Annual consumption of coal in the enlarged EU has also increased significantly, by about 50% (~510 Mt before May 2004, and ~750 Mt after) [IEA]. **These figures help confirm that coal is continuing, and will continue, to play a major role in European power generation**.

In China, coal represents close to 70% of total primary energy consumption. The rate of energy growth is such that the Chinese government recently estimated that by 2020 total coal consumption will increase by 40% (1,700 Mt in 2003, of which 850 Mt used for power production). The new plant capacity figures in China speak for themselves: 45 GW of coal-based power capacity was built in 2003 alone. It is therefore important that environmental issues related to coal use are tackled in China, as well as in all other developing economies [82]. **While China recognises the need to import foreign technology, it also wants to localise as much of this technology as possible. Even so, the market for foreign power technologies is huge.**

The major impact of climate change policies will be the increased prices faced by users of fossil fuels, particularly coal. The direct cost impact of a simple carbon tax of \$10/t$CO_2$ (€8.2/t$CO_2$) on different fuels varies from country to country. That fuel most affected by such a tax would be coal, with a coal price increase ranging from 16% (Germany) to 82% (Canada), with 37% for the UK and 64% for the USA. Coal would nonetheless remain the most competitively priced industrial fuel in Canada, the USA, the UK, Japan and Australia, whereas in Germany the coal price would exceed that of gas by 15%. The gas price increase would be less: between 4% for Japan and 21% for Australia.

The impact of a $10/t$CO_2$ (€8.2/t$CO_2$) tax on the cost of electricity would be an increase of 7% for Japan, between 18% and 22% for Australia, Germany, the UK and the USA, and 31% for Canada. Other indirect costs will impact on the operations of coal users and producers. For example, increased shipping and road/rail transport costs would contribute to increased costs, and potentially impact on the technology chosen for electricity generation [155].

An IEA report concluded that coal-fired power plants could keep their competitive advantage in the EU if the price of $CO_2$ remained "relatively low", i.e. below €9/t$CO_2$. The report also concluded that it would not be economically viable for a company to replace its existing coal-fired capacity with modern NGCC plant until the $CO_2$ price reached €23/t$CO_2$. Moreover, $CO_2$ prices would have to be in the range €30-200/t$CO_2$ for renewable technologies to be competitive [310]. **Therefore, some experts wonder what the true effect of $CO_2$ permits will be, whether they will actually reduce emissions or just increase the price of electricity.**

In view of these price impacts, some coal users (e.g. Germany) are likely to investigate a full or partial switch to lower carbon fuels such as natural gas or "no carbon" fuels (biomass). Major barriers to fuel switching will be the availability of a low-cost alternative fuel and the capital cost of converting existing equipment or installing new technology.

In the long term, **fuel switching may have a significant impact on the supply of all fuels**. For example, Russia could decide to build more coal-fired power capacity to free up more natural gas for sale to Europe.

*Distributed power production technologies*

**Most experts are not convinced that a widespread distributed generation system will actually appear**. Economic considerations suggest that such a system would only make sense in specific situations:

- The distributed generation system delivers electricity only: in this case it would of course have to compete with the grid and if the grid is reliable and cheap this would be difficult. However, if the grid is not available or otherwise unreliable, then it may be cost effective
- The distributed generation system delivers, apart from electricity, also heat: in this case the system rapidly be competitive (payback time is/can often be lower than 5 years). These systems are also effective if a grid is in place (in fact most of these systems are connected to the grid)
- The distributed generation system supports businesses with high revenue per minute (e.g. credit card buildings), thus requiring reliability of energy.

The 1997 Community Strategy to Promote CHP set a target of doubling the share of CHP from 9% to 18% of the total gross electricity generation of the Community produced by CHP by the year 2010. However, large discrepancies are to be noted amongst the Member States, with variations in these shares of between 2% and 60% of electricity production.

In terms of installed capacity, the share of electricity produced by cogeneration processes rose to 10% in the EU in 2001.

Provided it were possible to deliver 5 to 12 million micro-CHP systems in Europe in the medium term, the UK, Germany and the Netherlands being the initial markets, a maximum $CO_2$ reduction of 7.5 Mt $CO_2$/year could then be achieved [197, 199].

On a worldwide level, **global DG capacity may experience significant growth but retain only a small share of installed capacity by 2020** [292]:

- DG installed capacity (<10 MW) is expected to grow 185 GW by 2020
- DG (<10 MW) should represent 3% of new installed capacity in 2005 and 6% in 2020
- over half of this growth should take place in developing countries and transition economies
- Asia appears as the largest potential market.

Some technologies used for large-scale power production are also well suited for distributed production applications: these are gas turbines and steam turbines.

However, many other fossil-fuel-based technologies are better suited for distributed power production. Some of these are:

- **Reciprocating engines**: the technology is mature and they represent the most common current form of distributed power production. MAN, Deutz, and MTU are just some of the many manufacturers in Europe, who provide a very wide range of output, from 1 kW units to 10 MW plants, usually fuelled by natural gas or diesel. Improvements focus on lowering emissions and increasing efficiency (currently 25-40%). The investment cost ranges from 400 to €820/kW, and the cost of electricity produced from €0.04 to 0.08/kWh [292]
- **Microturbines**: they operate on the same principles as conventional gas turbines, but at a significantly higher rotational speed (around 70,000 rpm). Several companies have developed products that are beginning to be commercialised: Capstone and Ingersoll Rand (USA), Turbec (Sweden) and Bowman (UK). Microturbines, available in the 20-200 kW range, are well adapted for CHP applications. This technology is still in the early stage of commercialisation. Compared to reciprocating engines, the investment cost is about 50% higher for microturbines while the cost of the electricity produced is equivalent. They are currently the most cost-effective alternative to reciprocating engines for small-scale cogeneration, and in the long term, as their cost decreases, they should become more attractive than engines
- **Stirling engines** are in a pre-commercial phase, and the costs related to investment and electricity production are similar to those for microturbines.

By way of a comparison, fuel cells and solar cells have much higher investment costs (€2500-3000/kW and €2500-4000/kW respectively) and power costs (€0.1-0.15/kWh and €0.2-0.4/kWh respectively).

Microturbines are commercially available today, and are expected to be cost-competitive in the short term. For the moment though, the number of installed units is increasing very slowly (about 3000 units worldwide). The **US maker Capstone is the current world leader, holding 85% of the market share worldwide**. In Europe however, this US company's share is only 13%, while the Swedish company Turbec holds 49% and the British company Bowman holds 38%. Prior to 2003, the microturbine market in Europe did not live up to the high expectations placed on it, as only 300 units were sold – against several thousand more in the USA. Indeed, in 2003 Turbec decided to stop the production of microturbines due to low sales figures. At the end of 2003, the Italian firm API acquired Turbec and seems to be keen to continue activities in the field of microturbines. The situation of Bowman is quite similar, since the company went bankrupt at the beginning of 2004, but eventually managed to gather some funds and has recently started operation again.

## Main strengths and weaknesses of the USA and Japan

## USA

| | Strengths | Weaknesses |
|---|---|---|
| S&T | • Major focus on clean coal R&D, with high investments and good organisation<br>• Two coal gasification plants already in operation<br>• Integrated modular approach with FutureGen: co-production of electricity and $H_2$ from coal, and $CO_2$ sequestration<br>• Leadership in gas turbine technology (highest efficiency)<br>• R&D on advanced turbines continues | • Microturbines still need reliability improvements for stand-alone applications |
| M&I | • Large indigenous coal reserves<br>• Early entrance into the Chinese coal market<br>• US companies dominate the world gas turbine market (more than 80%)<br>• Distributed generation systems (micro-turbines, reciprocating engines) can be cost-competitive in some states | • Social acceptance issue with coal<br>• No regulation forcing low-efficiency coal power plants to be changed (grandfathering)<br>• US gas turbine market is saturated, demand has been weak since 2002 |
| P&M | • Efficient funding system, with major public funds for industries for pre-competitive and competitive R&D<br>• Very determined view on coal, supported by a commitment at Presidential level<br>• Industries benefit from DOD funds then transpose to non-military energy systems<br>• Funding attributions and roadmaps are driven by technical staff and industries<br>• Some state laws allow residential power systems to be connected to the grid and sell excess electricity | • $CO_2$ mitigation strategy mainly relies on capture and sequestration<br>• No federal incentive for distributed generation; most incentives for DG are decided at municipality level<br>• Grid exit fees and stand-by charges, imposed by some utilities, can make DG uneconomical<br>• Complex regulatory framework for DG interconnection |

In 2000, the US DOE launched the **Vision 21 Technology Roadmap**, a new initiative for developing the technology necessary for ultra-clean fossil-fuel-based energy plants. Through this initiative, the USA recognises that fossil energy will continue to be a substantial part of the energy mix, and guides long-term (15-20 years) development efforts in fossil energy technology so as "to meet environmental needs at an acceptable cost".

### *Science and Technology (S&T)*

**Coal is the main focus of current US DOE fossil energy R&D efforts** and is supported by the US Administration, which pledged during its first campaign to commit $2 bn (€1.64 bn) over 10 years to advance clean coal technologies. The USA, Japan and Australia seem to be those countries that are most heavily involved in coal R&D and from which future innovative technologies may come. For example, Japan is working intensively on supercritical coal combustion, whereas this option is not being pursued in the USA.

The US fossil energy R&D budget was $673 M (€550 M) in 2004, while an allocation of $636 M (€520 M) has been requested for 2005. An important part of this budget ($447 M [€365 M] or 70%) is expected to go to the various coal research initiatives. That will represent an 18% increase on the 2004 budget, while this **coal commitment has more than doubled on historical amounts** prior to the Bush administration [290].

**A key component of the coal R&D efforts is the Clean Coal Power Initiative (CCPI), the demonstration portion of the programme,** which is providing government co-financing for new coal technologies that can help the utilities meet the Clear Skies Initiative to cut sulphur, nitrogen and mercury pollutants from power plants by nearly 70% by the year 2018. Almost 2/3 of the coal R&D budget ($287 M [€235 M]) may be allocated to this CCPI programme, where 70 to 80% of the overall project costs are provided by the private sector. Generally speaking, the US government has identified the demonstration phase as the weak link in the technology transfer chain, and has therefore dedicated a large share of its R&D funds to the implementation of full-scale demonstration plants.

At a more fundamental research level, the US DOE is working on an **integrated modular approach**, based on a “polygeneration” concept: poly primary source (e.g. coal and biomass), and poly energy production (electricity, transportation fuels, chemicals, synthetic gas and hydrogen). This concept is at the root of the Vision 21 technology roadmap [21], according to which future energy plants will be groups of plants using advanced technologies and with different configurations tailored to meet specific market needs. The aim is to develop a suite of technology modules that can be interconnected to produce a number of commodities at efficiencies of greater than 60% for coal-based systems and 75% for natural-gas-based systems, with near zero emissions.

**A first concrete example of this integrated approach is FutureGen**, a 10-year DOE research project with an overall cost of $1 bn (€817 M). The goal of this project is to design, build and operate a 275 MW plant that will showcase the **best technology options for using coal to produce electricity and hydrogen with zero emissions**. This large-scale prototype plant will provide a platform for testing new clean power, carbon capture and coal-to-hydrogen technologies: coal gasification, syngas production, advanced technologies to react the syngas with steam to produce hydrogen, novel membranes, fuel cells, etc.

The project was started in 2004 and the prototype plant construction should begin at the end of 2008, followed by operation and monitoring in 2011 and beyond. One million tons of $CO_2$ are to be stored on site per year in a geologic formation. The economic objectives are to produce electricity with less than a 10% increase in cost compared to a non-sequestered system, and produce hydrogen at $4 (€3.3) per million Btu (wholesale), equivalent to $0.48 per gallon (€0.10/litre) of gasoline, which is $0.22 per gallon (€0.05/litre) less than today’s wholesale prices.

In the light of the very challenging goals of FutureGen, the US DOE has officially stated that **public investment is required to offset the high risk** associated with this project, in a sector where coal and utility industries are generally conservative and risk-adverse [289]. In order to fully seize the benefits and opportunities of domestic coal resources, the DOE will provide $500 M (€408 M) in direct funding and an additional $120 M (€98 M) from the DOE sequestration programme. Private industry investment should be limited to about 25% of the overall project cost, while international partners are expected to provide some $80 M (€65 M), mainly through membership of the Government Steering Committee. The White House has requested a total of $237 M for FutureGen in fiscal year 2005, with $18 M to be spent in 2005 and the additional funding for later years of the programme. However, by late 2004, the US Congress had only approved the amount of $18 M, for the expenses planned in 2005, implying that the continuation of the funding for this project will be have to submitted to Congress again. One of the reasons why the global request was rejected is that it would provide $237 M for the FutureGen programme at the expense of most of the ongoing fossil energy research programmes.

The US DOE expects to include a broad spectrum of the leading companies involved in the coal and power industry, and that the Consortium will select the system designers, equipment vendors and research organisations needed. Widespread replication of the technologies developed by the private sector will be sought.

At present, there are no off-the-shelf commercial technologies available to help reach FutureGen's goals. **Technological breakthroughs in gasification, oxygen production, hydrogen production, gas cleanup, hydrogen turbines, fuel cells (1 MW fuel cells required) and carbon sequestration will be necessary**, and will require coordination with other programmes such as SECA for fuel cells (see the fuel cells chapter) and the Carbon Sequestration Leadership Forum (CSLF).

**Advanced coal gasification research** will benefit from the experience gathered from the two first American plants using commercial-scale applications, i.e. the Tampa Electric IGCC Project and Wabash River Coal Gasification Repowering Project.

To reach their full market potential, future gasification concepts will however need significant improvements in efficiency, fuel flexibility and economics. The US DOE is working with private partners to develop, at the Power Systems Development Facility (PSDF) in Alabama, a new, potentially low-cost configuration for a future gasifier. Called the "transport reactor", it is an advanced circulating fluidised bed reactor, with a chemical sorbent that can be added to capture sulphur impurities.

Lower cost alternatives are also being explored for oxygen production, to be used in the gasification process. Ceramic membranes and advanced Ion Transport Membranes (ITM) are being developed and are to be tested at the PSDF.

Advanced coal combustion technologies are also still being pursued. The DOE programme is focusing its efforts on **new types of hybrid technologies, typically coal-based systems that combine coal combustion and coal gasification**. The coal would be partially gasified, to produce a fuel gas that can be combusted in a gas turbine. Left in the gasifier would be a combustible char that could be burned in a fluidised bed combustor or advanced high-temperature furnace to produce steam to drive a steam-turbine power cycle and to heat combustion air for the gas turbine. This type of integrated system could result in a high overall fuel-to-electricity efficiency, exceeding 55%, whereas the average efficiency of today's coal burning power plants is around 33-35%.

DOE funds for natural gas technologies have been steadily decreasing in the past few years, to the profit of coal research. The budget requested for 2005 is $26 M (€21.3 M), instead of the $43 M (€35.1 M) in funding allocated in 2004. The priorities chosen are exploration and production technologies, as well as gas hydrates.

**R&D efforts on gas turbines are now part of Vision 21 and FutureGen. The aim is to provide advanced turbines for syngas and hydrogen fuels in coal gasification applications on a short-term basis**, and turbines for fuel cell turbine hybrid systems in the medium term [291]. The challenge for developing a gas turbine that burns fuels derived from coal is that syngas has a far lower energy content than natural gas, can vary more in composition, and also contains more impurities that can affect combustion stability and damage turbine blades. High concentrations of hydrogen can create higher $NO_x$ emissions but offer the prospect of operating with zero emissions of pollutants. Limited short-term testing has indicated that nearly 100% of hydrogen fuel could be fired in F-class turbines, but major technical issues still need to be addressed [289].

Current projects on gas turbines are following a much more intensive effort that began in 1992 under a US DOE programme to break through technical barriers that had essentially targeted gas turbine efficiencies. Within eight years, this programme produced turbine systems that could operate at temperatures in excess of 1400 °C (150 °C hotter than conventional turbines) and achieve efficiencies above 60%. The USA has accumulated some highly significant experience from this programme and can now be considered as a world leader in gas turbine technology research, even if funding is now far from the levels of 10 years ago.

The Distributed Energy (DE) Program within the US DOE was established in 2001. It conducts R&D activities in partnership with equipment manufacturers, utilities and laboratories on industrial gas turbines, microturbines, reciprocating engines, and “technology base” areas such as advanced materials, sensors, and communication and control systems. Funding for the DE programme is expected to decline in 2005 from $61 M (€50 M) to $53 M (€43 M). This is because increasingly, the objectives are within the reach of industry.

Although microturbines, small gas turbines and reciprocating engines are already commercialised products, they all need greater efficiency, higher reliability, lower emissions and cost-competitive prices to improve their market position. For example, the DE microturbines targets are to obtain 40% efficiency (instead of 17 to 30% now) and single digit ppm $NO_x$ by 2007. Reciprocating engines are also set to be cost-competitive on the market by 2007, with 50% efficiency and less than 0.15 grams/kWh of $NO_x$. These objectives are being pursued through the DOE ARES (Advanced Reciprocating Engine Systems) programme, in which major manufacturers (such as Caterpillar and Cummins) and National Laboratories (such as Argonne, Oak Ridge, Sandia, etc.) are involved. An equivalent Californian programme, ARICE, coordinated with ARES, is pursuing the same performance targets.

### *Market and Industry (M&I)*

The USA relies on fossil fuels for about 85% of its energy consumption, and this figure could exceed 87% by 2025. Using domestic coal efficiently and cleanly is considered in the USA to be the key to reducing dependency on foreign energy imports, not only for electricity, but as a source for transportation fuels as well.

More than half of the electricity generated in the USA today comes from coal. This country has important domestic reserves. In addition to decreasing energy dependence, the use of **indigenous coal** – instead of imported oil and gas – will have beneficial effects on the balance of trade. In the current situation, i.e. with a significant trade deficit, the impact on the balance of trade may constitute a policy-relevant issue [211]. Coal is therefore likely to remain one of this country’s lowest-cost electric power sources for several decades.

However, **social acceptance of new coal power plants has not yet been guaranteed**. The traditional US coal-powered plants emit 2.3 billion tons of carbon dioxide into the air each year – twice the amount cars produce. Moreover, thanks to a “grandfathering” loophole included in the Clean Air Act, **old coal power plants are exempt from meeting the modern pollution control standards that new facilities have to adopt**. Environment groups regularly file suits against these traditional plants and are urging the US government to place greater efforts into renewable energies instead of coal.

In order to maximise public acceptance for the FutureGen programme, using coal and sequestrating carbon, the environmental community, state agencies and research organisations are to be closely involved in the project from the outset. Representatives from these groups will be included in the management Consortium as advisors or consultants, while technical experts will be involved in the design of the project.

Apart from the US market, **American industries involved in coal-based technologies are also well positioned in the world's current most promising market: China**. This country is both the largest consumer and producer of coal in the world. China's coal consumption in 2002 was 1.3 billion tons, or 27% of the world total. The available resources could be exploited for more than a hundred years at a rate of 1.9 billion tons per year. China has expressed a strong interest in foreign investments in new coal technologies such as coalbed methane production, coal gasification or coal liquefaction, and US companies have been the first to enter the market. At the end of 2002 for example, ShenHua Group signed a liquefying coal project joint management contract with the US-based company ABB Lummus Global. "Coal-into-oil" is entering a full-scale implementation phase in China, with the government expecting to maintain the future price at around $20 (€16.3) per barrel.

**Sustained government support for gas turbine development in the 90s has resulted in strong US domination of this technology on the world's markets**. The US has shares of more than 80% of the large gas turbines market, more than 70% of the small turbine market, and is the only supplier of 60% efficiency class NGCC systems [293].

Market deregulation and increased technology maturity resulted in strong demand for gas turbines in the USA in the late 90s as they give the lowest cost of electricity. However, over-ordering of new generating capacity quickly produced a margin of capacity over demand of more than 20%, such that excess orders were cancelled, and the market collapsed in 2002 with recently built NGCC plants closing down. **The US market is still saturated for the moment** and international competition is fierce. Even though the use of natural gas will most probably not grow as quickly as was expected one or two years ago, it is still predicted to show a 50% increase by 2020 [70]. High efficiency, availability, and fuel flexibility could be the drivers behind GT market development over the next 30 years [293].

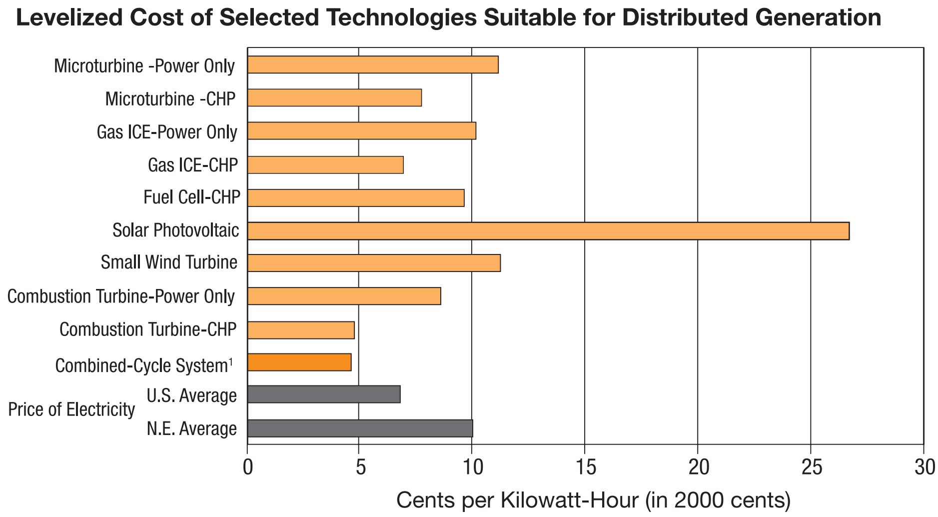
Given that the electricity transmission grid in the USA is in a critical state of disrepair, and recent power failures have had an economic cost of several billions of dollars, independent analyses predict that within ten years, the US market for distributed generation could reach 24 GW, with reciprocating engines and CHP plants dominating [296]. The initial prospective market players in the purchase of DG units include businesses that need exceptional power reliability, such as credit card companies, brokerage operations or computer chip manufacturers.

**Distributed generation systems such as microturbines and reciprocating engines are already cost-competitive in the USA**. Several specific reasons linked to the American energy context can explain this situation:

- grid electricity is very expensive in some states, more than $0.10/kWh on average, and close to $0.60/kWh on spot prices
- the grid electric efficiency is very low (~30%)
- since the recent blackouts, both the public and some US industries are keen to have more reliable sources of energy.

Figure 8 shows an estimate of the current cost per kilowatt-hour for various DG technologies, assuming that the capital costs are spread over the life of the project. These US electricity averages do not include transmission and distribution costs, which were estimated at approximately 0.024 $/kWh [295].

*Figure 8 – Cost per kilowatt-hour of various DG technologies in the USA*




Notes: CHP = combined heat anp power (also known as cogeneration); ICE = internal combustion engine: N.E = New England

The levelized cost is the average cost of electricity (cents per kilowatt-hour) over the operating life of the generation equipment. Future costs and output flows are based on data in Table 2 and are discounted at 7 percent from their present values. The cost estimates assume that the systems powered by fossil fuels will be operated 90 percent of the time and that the wind and solar photovoltaic systems will run 40 percent and 27 percents of the time, respectively Levelized cost comparisons do not include the effects of tax credits or other direct subsidies for specific technologies.

*Source: US Congressional Budget Office*

While the European microturbine manufacturers are having difficulty breaking into the market, the US makers, mainly Capstone, have already sold over 2,500 units. As its microturbines were first used in the oil sector using flare gas, Capstone gained valuable experience that helped it launch onto the market a unit that is quite versatile in terms of suitable gas types, and is acceptable in price. Better reliability is however still needed for stand-alone applications, and production volumes of 100 000 units per year might be required to bring the unit cost down to $400/kW (€327/kW) for a 30 kW microturbine [296]. A hostile regulatory environment is also preventing further market developments.

### *Policies and Measures (P&M)*

In some places, the utilities have succeeded in being allowed to bill stand-by charges to distributed generators that want to retain the grid as a backup, or in imposing grid exit fees for stand-alone generators. Other utilities are imposing expensive protective equipment before allowing synchronisation of CHP plants to the grid. Such charges can kill the economic benefits of DG projects.

Some states, such as California, are more favourable towards distributed generation. Fuel cells, designated as “ultra-clean” technologies, are exempted from stand-by charges and grid exit fees, and end-users are allowed to sell back unused power to publicly owned utilities at established rates.

Some tremendous incentives for DG can be found in the USA, but only at state or municipality level. They are very local in nature and can vary from town to town in the same state. Current federal incentive programmes only address fuel cells. The Energy Policy Act of 2003 (HR 6) contained new incentives for fuel cells and CHP power plants, including turbines and hybrid power systems. Although HR 6 was not enacted in 2003, experts do believe that those incentives are likely to be adopted relatively soon [297].

The regulatory framework for DG interconnection to the grid is for the moment rather complex. Some of the FERC rules and procedures applicable to small generator interconnection agreements are ambiguous, while strict application of the Public Utility Holding Company Act (PUHCA) can qualify distributed generators as a utility, which means they can therefore be regulated as such by the federal government. Once again, if HR 6 is enacted soon, it could greatly simplify this regulatory framework, so that more players will be able to enter the market without fear of unintended adverse regulatory consequences [297].

## Japan

| | Strengths | Weaknesses |
|---|---|---|
| S&T | • Industrial expertise in extreme condition materials (supercritical)<br>• Leader in supercritical coal combustion | • Behind US technology for gas turbine<br>• R&D investments in FBC are not paying out |
| M&I | • Actively trying to compete (with USA) on the Chinese market<br>• Partnerships between public and private organisations | • Efficiency of fossil fuel power plants already high<br>• Japan has almost no fossil fuels on its territory |
| P&M | • Strong will to diversify the energy mix<br>• Important subsidies for installation of distributed natural gas cogeneration systems | |

Japan owns almost no natural resources, and therefore its energy security policy aims at **securing energy independence through diversification of energy sources and of their provenance**.

Coal and LNG, but also methane hydrates and synthetic energy carriers (DME, $H_2$, etc.) have attracted interest from both the government and industry. In particular, “clean coal” technologies have been at the heart of fossil fuel R&D, with IGCC the prevalent option for the medium term.

### *Science and Technology (S&T)*

**The efficiency of fossil fuel power plants in Japan is already high** (40.6% on average, on par with Germany) compared to other industrialised countries (France: 37,6%; UK: 38.2%; USA: 36.4%; Canada: 33.5%); more specifically, it is 43% and 53% respectively for coal and natural gas power plants [40]. Therefore, any new technologies will need to demonstrate much higher efficiencies in order to be adopted.

Forecast of technology R&D trends for new power production systems using fossil fuels in Japan [294]:

| | Present | ~2010 | ~2015 | ~2015 |
|---|---|---|---|---|
| Coal | USC (630 °C)<br>PFBC | | IGCC | USC (700 °C)<br>IGFC |
| LNG | | | MGC-GT | AHAT<br>GT (1700 °C) |
| Distributed power | | MGT<br>MGE | Ceramic GT | |

*USC: Ultra Supercritical power*
*PFBC: Pressurised Fluidised Bed Combustion*
*MGC-GT: Melt-Growth Composite Gas Turbine*
*MGT: Micro Gas Turbine*
*IGCC: Integrated Gasification Combined Cycle*
*IGFC: Integrated Gasification Fuel Cell*
*AHAT: Advanced Humid Air Turbine*
*MGE: Micro Gas Engine*

The following coal-related technologies are central to current Japanese R&D support policy.

- **USC (Ultra Super Critical Coal Combustion)**

The first, 8-year-long R&D project on USC was completed successfully in 2000 with the installation of a 44% (630°C, 25 MPa) plant by Toshiba. However, today efforts are concentrating on the realisation of IGCC technology due to its higher efficiency (48%) and lower $CO_2$ emissions (-20%).

On USC, R&D is being conducted on materials (new ferritic steels), with **Japan leading the market in materials for supercritical reactors**. The goal here is to enable operation at 700°C and thus attain higher efficiencies. The targeted cost of plant is estimated to be ¥200 k/kW (€1,500/kW), compared to ¥270 k/kW (€2,030/kW) for conventional burners [312].

- **PFBC (Pressurised Fluidised Bed Combustion)**

The domestic PFBC development programme spanned 11 years (1989-2000), but the largest commercial plant (360 MW, started in 2001) was built under licence from ABB. Thus, **industrial development of PFBC seems to be lagging behind foreign companies**.

An advanced PFBC system development has been promoted by the Center for Coal Utilization, Japan (CCUJ), targeting a 42% efficiency level for a target cost of ¥220 k/kW (€1,650/kW) by 2020 [312]. However, as for USC, this technology has been superseded for now by IGCC and IGFC.

- **IGCC (Integrated Gasification Combined Cycle)**

In Japan in 2001, 10 power companies jointly created the Clean Coal Power R&D to develop and test air-blown IGCC technology. A 250 MW (1250°C gas turbine), 48% efficiency (LHV) pilot plant is scheduled to operate from 2008 to 2010. This national project is funded by METI to 30%, and by power companies to 70%. The targeted cost of plant is estimated to be ¥290 k/kW (€2,180/kW), with pre-commercial application by 2015.

**The development of IGCC has been central to coal-energy-related policy.**

- **IGFC (Integrated Gasification Fuel Cell)**

In the long term, Integrated Gasification Fuel Cell (IGFC) technology is expected to provide the best efficiency and environmental performance. However, this technology is dependent upon the development of both high-temperature gas turbines and high-temperature fuel cells (ultimately SOFC).

On the gasification side, the EAGLE project -Energy Application for Gas, Liquid and Electricity- (1996-2006) aims to develop a multi-purpose (production of hydrogen, synthetic liquid fuels, power, etc.) coal and gas production plant. In so doing, great stress has been placed on the purification methods and environmental impact. A 150 t/day pilot plant has been operating since 2001, with IGFC its main target application.

As for fossil-fuel-based distributed power or cogeneration, most R&D spending has gone on the development of fuel cells. In Japan today, **US expertise in microturbine technology, as well as fuel cell technology, is considered to be leading the field in distributed generation applications**.

### *Market and Industry (M&I)*

In the field of distributed power, the installed capacity of natural gas cogeneration systems – including fuel cells – was 2,150 MW in 2002, with the official target for 2010 set at 4,640 MW [ANRE]. This is very low compared to Europe or the USA (~100 GW by 2010).

The cogeneration market in Japan was evaluated at 5.0 GW (2.5 GW for natural gas), or in other words ¥65 bn (€488 M) in 2000, and estimates forecast an increase to 10 GW in 2010 [230].

As for micro gas turbines, 529 systems were in operation in 2002 (136 in 2000), amounting to 32.0 MW (8.9 MW in 2000). Estimates for 2010 give 850 systems in operation, corresponding to a ¥15.8 bn (€119 M) market. The main suppliers for microturbines are Capstone (US), Toyota Turbine and Systems (J), Ebara Elliott (J, originally from US), and Bowman (UK).

Finally, Mitsubishi Heavy Industries is leading the market in large gas turbines in Japan with proprietary technology, and has been developing microturbines in recent years.

### *Policies and Measures (P&M)*

NEDO has been subsidising natural gas cogeneration systems for several years now, and local governments, non-profit organisations and individuals can receive **subsidies of up to 50% of the system price**.

The coal price in Japan is low (~¥191/GJ [€1.43/GJ]) and stable, while LNG is much more expensive (~¥480/MJ [€3.59/GJ]) and varies with the price of oil [40].

Although Japan has been promoting the development of clean coal technologies, it should be noted that **both the absolute and relative contributions of coal to electric power generation are scheduled to decrease** slightly over the coming decades. On the other hand, development of these technologies is reportedly aimed at export, for instance towards China [41, 224].

## SWOT analysis for Europe

| | Strengths | Weaknesses |
|---|---|---|
| S&T | • Existence of Centres of Excellence and Networks of Excellence<br>• Hypogen project, test facility for $H_2$ and electricity production<br>• Coordination of national level fossil fuel power technology programmes through FENCO | • FP6 leaves out fossil-fuel-based energy technology development projects<br>• R&D in Europe is too fragmented, need to better organise and combine strengths<br>• Lack of large integrated programmes where OEMs, academics and end-users work together |
| M&I | • Good performance of clean coal combustion technologies (PF and FBC)<br>• EU companies involved in zero-emission plant development<br>• European microturbine makers hold a large share of the (small) European market | • GTs perform less well than those of US makers, and Europe has lost some of its technical expertise.<br>• Wait-and-see position regarding plant commissioning<br>• EU power plant makers cannot financially support fossil fuel technology improvement alone, need for risk share from the government/EC<br>• NMS power plants have low efficiency and low environmental performance<br>• Heavy fuel still used in some countries for electricity production |
| P&M | • Effort made by NMS (e.g. Estonia) to upgrade technologies on schedule<br>• Policies and incentives in favour of DG and cogeneration in many EU countries (especially Germany)<br>• Development of network connection standards at EU level for CHP systems | • EC-level funding attributions and technical roadmaps are driven by academics<br>• Lack of support for the building of large pilot plants<br>• Strong influence of large lobbying organisations on EU FP priorities<br>• EC cannot finance competitive R&D<br>• Uncertainties on future policies and measures |
| | **Opportunities** | **Threats** |
| S&T | • Technical capability to catch up with the USA on gas turbine technology, if financial support and integration of aircraft technologies<br>• Development of small-scale gas turbines (<2MW) for use in DG systems | • EU might miss the Chinese market opportunity because in Japan and the USA R&D benefits from strong government support |
| M&I | • China and India will be the largest markets in coming years<br>• Shortage in energy capacity is expected in Europe<br>• Increase in coal use for power generation expected worldwide | • Chinese industry capable of copying foreign technologies<br>• US leadership in gas turbines<br>• Capstone, the world microturbine leader, is “swamping” the market |
| P&M | • $CO_2$ permits scheme effective since January 2005 | |

## Strengths and weaknesses of Europe

*Science and Technology (S&T)*

Many fossil fuel experts have expressed their disappointment at the decision to **leave projects involving fossil-fuel-based energy technologies out of FP6**, except for development projects on hydrogen production and $CO_2$ capture and storage. According to the energy mix foreseen for 2020, fossil fuels will still represent a major energy source. In this context, the FP6 priorities – large focus on renewables, fuel cells and hydrogen – are felt not to properly address the short/medium-term energy issues.

Experts therefore urge that advanced fossil fuel technologies are put back onto the political agenda, for two reasons: to support European R&D in this field; and to **encourage technology**

**developers and manufacturers to invest** in the development of commercial products. The later such a decision is taken, the more difficult it will be for Europe to catch up with the USA and Japan, who are already engaged in strong support for coal technologies for instance.

**R&D activities in Europe are considered to be overly fragmented**, at the EU and national levels. Coordinating national-level and EU-level activities Europe-wide by **combining strengths would benefit the entire EU energy business**. Some action has been undertaken to improve the situation, such as the EC-supported project "Centres of Excellence for Industrial Gas Turbines" (CE-IGT), which aims to create more co-ordinated and integrated European research activities in the Industrial Gas Turbine (IGT) field. The CE-IGT's first task was to draft an inventory of all European groups working on gas turbines.

In addition, there is a **lack of large, integrated programmes** where academics, OEMs and end-users work together. Such integrated programmes enable advanced, cost-competitive technologies to be developed. A technology platform for gas turbines could be one such project. The US DOE and the Japanese NEDO both launch and support such large programmes, which often directly contribute to the development of a commercial product, e.g. GE's high-efficiency NGCC, now the best gas turbine on the market.

The development of gas turbines was supported within the EU FP4 and FP5. In addition, there was a significant technology transfer between the aero-engine development work supported by the EU and the industrial gas turbine industry. Some of the EU FP5 projects related to gas turbines are:

- The AZEP – Advanced Zero-Emissions Power Plant – project (based on the oxyfuel combustion process and aimed at the development of a $CO_2$-free gas turbine system)
- CAME-GT (Cleaner and more efficient gas turbines), a thematic network project, the objective of which is to co-ordinate RTD projects in industrial gas turbines, covering fossil fuels and biomass and gas turbines in CHP applications and combined cycles. The main participants are Alstom Power, Rolls Royce, MAN, DLR, Vrije Universiteit Brussels, GASTEC, Siemens, Ansaldo, etc.

However, these projects should be contrasted with US support for gas turbine technology in the same period, where the development of the technology was followed up by a planned demonstration phase.

**FP6 does not address the improvement of power production efficiency in gas turbines**. The only support for gas turbines is given as part of a bio-fuel project in the short term and as part of a pre-combustion $CO_2$ mitigation project in the long term (ENCAP project). Consequently, Europe's gas turbine competitiveness is building solely on the basis established under FP5 and various networks such as CAME-GT and CE-IGT.

Besides CAME-GT, there are other EU-level networks which together cover all of the technological themes related to fossil fuel power plant technologies:

- POWERCLEAN, an FP5-funded thematic network focusing on technologies based on coal and other solid fuels. One of the objectives of this network is to help maintain the technical and industrial content of future European energy-related research. The main work of the network is carried out through four thematic groups (combustion, gasification, systems, and materials)
- $CO_2$NET is the European Network of researchers, developers and users of $CO_2$ technology, facilitating co-operation between these organisations and European projects on $CO_2$ geological storage, $CO_2$ capture and zero-emissions technologies

According to POWERCLEAN, those coal-based technologies that are of interest to Europe are advanced ultra-supercritical PF combustion, CFBC (incorporating an advanced supercritical steam cycle), and IGCC.

Currently, the best-performing PF power plants worldwide are located in Japan (5 plants with a maximum steam temperature of 600 °C), the second best being in Europe (3 plants with a maximum steam temperature of 580 °C). Construction of a new PF plant (maximum of 600 °C) in Torrevaldaliga in Italy is planned in replacement of an old fuel oil plant, but due to strong environmental opposition, ENEL seems to be experiencing difficulties in obtaining authorisation.

Intense advanced research has also been carried out on the development of ultrasupercritical boiler technologies. The reference project is the **AD700 project** – Advanced Supercritical PF power plant operating at 700 °C - started in 1998 through an FP4-funded contract. Forty partners from 13 countries joined this integrated initiative, which was of critical importance to EU industry. Funding for Phase 2 continued through FP5, and Phase 3 planned to build a full-scale test facility. However, due to lack of support for fossil-fuel-based technologies in FP6, the test facility could only be built at a smaller scale and was able to demonstrate fewer components of the water/ steam cycle.

Regarding CFBC technology, many subcritical plants are currently in operation in Europe (mainly in Poland), in the USA, and in Asia. The only supercritical plant commissioned to date will be installed in Poland, with commercial operation planned for 2007. Foster Wheeler is supplying the supercritical CFBC, which first gasifies the fuel.

With respect to IGCC systems, Europe has developed large-scale pilot plants with funding from industry, Member States and the EC. Of the 4 commercial-scale pilot plants in operation in the world, 2 are located in Europe, at Buggenum in the Netherlands and at Puertollano in Spain. Both plants, which run on coal, show an efficiency of 43%, and it has been proven that the efficiency of the Puertollano plant could be improved to 50% with simple design changes.

As mentioned above, FP6 is supporting ENCAP (Enhanced Capture of $CO_2$), a major project addressing fossil fuel plant technologies. This project involves research into the development of pre-combustion decarbonisation technologies in power cycles operated by fossil fuels. The objective is to achieve a capture rate of at least 90% and 50% capture cost reduction. The project is being coordinated by the Swedish power company Vattenfall and some of the partners are RWE, Statoil, Alstom, Siemens, Mitsui Babcock, Linde, Air Liquide, Lurgi, TNO, Sintef, etc. The project has a total budget of €22 M, with EC support of €10.7 M within the FP6 programme. The planned work is divided into six sub-projects, including Pre-combustion Decarbonisation Technologies, OxyFuel Boiler Technologies, Chemical Looping Combustion, and High-Temperature Oxygen Generation for Power Cycles.

While ENCAP covers pre-combustion capture, CASTOR – Capture and sequestration of $CO_2$ associated with cleaner fossil fuel plants – is an integrated FP6 project aimed at developing all of the innovative technologies needed to capture (at post-combustion stage), transport and store $CO_2$. The general objective is to capture and geologically store 10% of $CO_2$ emissions for Europe (30% for power and industrial plants).

At the beginning of 2004, in the scope of the “quick start” programme of the European Growth Initiative, the Commission decided to launch an implementation-oriented initiative called **Hypogen,** to build a large-scale test facility for the production of hydrogen and electricity from fossil fuels with separation and storage of $CO_2$. The project was launched in 2004, with an EU budget of €1.4 bn over a 10 year-period. Synergies with Community funding, possible research frameworks, and programme and structural funds are to be enhanced. Through this initiative, the EU is taking a major step towards an efficient, cost-effective and environmentally friendly energy supply. In terms of objectives and funding, the Hypogen project is very much equivalent to the US FutureGen project, and should therefore enable Europe to take the lead in advanced fossil fuel technologies for power and hydrogen production.

2003 FENCO (The Cleaner Fossil Energy Coalition) is a Specific Supporting Action (SSA) within FP6 that aims to lead to a Co-ordination Action that will create a Fossil Energy European Research Area Network (ERA-Net). Such a Europe-wide initiative is expected to help the European fossil fuel industry compete in the expanding world market. Without such support, the FENCO members believe it is likely that the European fossil fuel industry will be increasingly marginalized by both the US and Japanese industries, which benefit from massive governmental support. FENCO was an initiative undertaken by the German and UK governments, and started with four other country partners, namely Greece, Portugal, Denmark and Austria.

With a view to developing near-zero-emission power plants, EC FP6 is funding the development of both pre- and post-combustion capture technologies, as well as $CO_2$ storage, but does not cover the R&D needs of high-efficiency gas and steam turbines nor on highly efficient power plants. To fill the gap, the FENCO project covers these latter R&D themes, by aiming **to co-ordinate national funding** provided by those EU Member States engaged in such research, particularly Germany and the UK.

The German programme COORETEC ($CO_2$ reduction technology), announced in early 2004, aims to study a 3rd generation capture IGCC including an integrated $CO_2$ separation combined cycle, $H_2$ turbine specification and improvement of gasification (power plant gasifier). The main partners are Siemens, Lurgi, RWE, Vattenfall, EoN, IEC and Linde. This programme focuses on both **incremental efficiency improvement** (as much as possible) of fossil fuel technology, **combined with $CO_2$ capture and storage**. While the current EU R&D strategy seems to set aside the development of power plants with improved efficiency, many experts believe that the German approach (i.e. efficiency improvement combined with CCS) is the best way to tackle the $CO_2$ mitigation issue.

The UK DTI launched a similar programme called Carbon Abatement Strategy (CATS) for improved fossil fuel efficiency. Its objectives are threefold: improved efficiency, fuel switch/co-firing and retrofit issues, and $CO_2$ capture and sequestration.

Several EU projects on distributed generation systems address the development of microturbine systems for instance, such as the FP5 Optimised Microturbine Energy Systems (OMES) project.

### *Market and Industry (M&I)*

The energy sources and technologies in the new Member States are variable from country to country (see section on market trends). In Poland, the Czech Republic and Hungary, considerable amounts of coal and lignite are produced and consumed, resulting in increased coal reserves and consumption in the enlarged EU. These figures help confirm that **coal is continuing, and will continue to play a major role in European power generation.**

To replace old plants and satisfy new demand in the EU-15, 300 GW of power plant needs to be built by 2020 and 550 GW by 2030. The corresponding investments required by 2030 will be approximately €430 bn.

The **power plant market is currently in a wait-and-see situation in Europe.** Taking the decision to build a plant is difficult because of the uncertainties related to $CO_2$ taxes and other regulatory constraints, strong public opposition (NIMBY effect), etc. Although the need to increase and replace current capacity is huge, very few new plants have been built or commissioned recently. Today, due to recession, there is excess capacity in Europe, but this situation will probably not last. Plant commissioning decisions should not be put off any longer.

Over the last decade, US gas turbine technologies have reached a dominant position on the market, in terms both of market share and technology performance. During the same period**, European industry has lost some of its technical expertise**.

**Industrial R&D on gas turbines is being continued however**. For instance Alstom Power acted as co-ordinator of the FP5 AZEP (Advanced Zero-Emissions Power Plant) project, based on the oxyfuel combustion process. The project cost for 3 years (Dec 2001-Dec. 2004) was €9.3 M, to which the EU contributed €3.4 M, the Swiss government €1.5 M and Alstom Power €1.3 M.

EU industry, together with Japanese industry, is leading the world scene in advanced PF systems, and some experts consider the USA to be 20 years behind.

Europe also has state-of-the-art CFBC and PCFB plants, and the gasification plant that has been up and running in Puertollano (Spain) since 1998 is world class.

Since the start of energy market liberalisation in Europe, distributed generation has been presented as an opportunity, but it actually only makes sense if there is no existing distribution system, or if the distribution system is not reliable, which is not the case in Europe. DG can help by eliminating network investments, but it can also hinder security of supply if the system is uncoordinated leading to availability issues.

The EU microturbine market is in its very early stages, involved mostly in testing and demonstration installations. About 300 units are installed in the EU, most of which are natural gas fired and are used for cogeneration. Although Capstone is the world leader, the European makers Turbec and Bowman do hold 80% of the European market. Only in the UK is there a significant market, with about 100 units, mostly replacing boilers for hot water production. Some of the reasons for this low market penetration are: the low efficiency of fuel-to-electricity conversion (~30%), large investment costs for total microturbine systems (between 900 and €1,200/kW), high costs of produced kWh (especially with the high gas prices of today), low reliability of components, short lifetime, lack of regulations for distributed systems with low power outputs [118].

### *Policies and Measures (P&M)*

From the viewpoint of fossil fuel technology makers and users, Europe abounds with uncertainties regarding policies and measures. For instance, how and when will $CO_2$ allowances and taxes be implemented, and how is the poor interest in fossil fuel technologies – compared to the current strong support for renewable energies – explained?

Unlike in the USA and Japan, the EU is **not allowed to directly finance competitive technology development** and demonstration projects. Nonetheless, in technological fields other than energy, such as aero engines, it succeeds in circumventing this issue. Under the FP5 Technology Platform EEFAE (*Efficient and Environmentally Friendly Aero Engine*), the aim is to develop engine concepts for both wide- and narrow-bodied aircraft, and to halve the time needed to bring the new technologies to market. The four-year EEFAE project will enable manufacturers to acquire the advanced technology necessary to consolidate their market share in a business now worth €10 bn and forecasted to treble over the next 20 years.

The EC should take similar risks in **supporting technology platforms** for energy technologies.

Current EU policies are not always consistent with the true attainable performance of clean power plants such as NGCC. However, some national-level programmes do target clean fossil fuel power technology R&D.

The EU considers it to be the role of industry to build demonstration plants, but EU companies such as Siemens and Alstom Power **cannot financially support technology** development all the way through to the commercial phase on their own. On the other hand, the demonstration phase is essential, because it limits the risk of having to implement costly repairs on all the units installed, and because it is difficult to convince a user to buy a technology that the manufacturer itself does not even use.

Actually, this is not merely a question of money, as industries can usually cover the capital cost of demonstration plants. But **they do need to be able to rely on the government or EC or other funding** bodies in case unexpected problems occur during development, leading to significantly increased costs.

In the USA, funding is attributed following guidelines given by technical roadmaps that are developed by technical and industrial staff. On the contrary, the technical and funding decisions taken in the EU tend to rely on the **views of academic experts** who may not always have a comprehensive understanding of market needs and expectations. Moreover, **large lobbying organisations have a strong influence** on the definition of EU priorities.

Although sometimes considered as insufficient or unsuitable, the **policies and measures for distributed generation** in Europe are much more favourable than in the USA for instance.

**European legislation and policies are playing an increasingly important role** in defining the framework conditions for the current use of cogeneration in Europe and in shaping its future markets. Two of these Directives are:

- the Directive on the promotion of cogeneration, adopted in February 2004, which simply gives a framework according to which the Member States are to publish the action taken to promote cogeneration and the results obtained. Small-scale (< 500 kW) cogeneration is not specifically encouraged in the Directive, although it would have benefited from a clear differentiation from medium and large cogeneration
- the Directive that has been in force since January 2005 establishing a scheme for greenhouse gas emission allowance trading (ETS), and which is meant to encourage the use of more energy-efficient technologies, including combined heat and power technology, producing less emissions per unit of output.

Regarding distributed generation, **network connection standards are being developed at EU level**, so as to integrate small cogeneration systems into the electricity distribution network and the home energy system [199].

Most European countries favour the installation of cogeneration systems. The best example is Germany, where legislation for small- and medium-scale cogeneration systems (<2 MW) includes exempting those plants from electricity and natural gas taxation, and introducing a bonus for electricity fed into the grid [197, 199]. In some EU countries however, the situation is not as encouraging for cogeneration. In the UK, for instance, where there are no specific feed-in tariffs for electricity produced from CHP, selling electricity to the grid is not profitable. Therefore the CHP owner usually prefers to sell it directly to the end-user (e.g. in the case of residential CHP units).

## Opportunities and threats for Europe

### *Science and Technology (S&T)*

In Europe, up until the EC's Fifth Framework Programme (1998-2002), intense advanced research was carried out on fossil energy technologies, e.g. on ultrasupercritical boiler technologies (AD700 project) and IGCC systems. FP5 was followed **by FP6 (2002-2006),** designed to establish a sustainable energy base for Europe, with an emphasis on the development of renewable energy sources and near-zero-emission fossil-fuel-based energy conversion systems anchored in the capture and sequestration of $CO_2$. **This left out the conventional fossil fuel technologies. Unless FP7 brings fossil fuels back into the EU research strategy, this lack of R&D support for fossil-fuel-based technologies will have unfortunate consequences**, affecting both the sustainability of EU security of supply and the competitiveness of the European power generation equipment industry. In a context where 70% of the energy supply will still be fossil fuel based for several decades, and 550 GW in power plant capacity will have to be built in Europe before 2030, including support for fossil fuel-fired technologies in the next framework programme is essential.

**Sustained support for R&D would also strengthen current action** such as that of the FENCO coalition (which coordinates the fossil energy programmes of the Member States) or the E-max group (AD700 project). It would also help Europe to remain in a leadership position regarding several clean coal technologies (European manufacturers commercialise high-performance PF and CFB systems on the world market, and Europe is a world leader in the demonstration of integrated gasification combined cycles (IGCC), together with the USA).

In terms of gas turbines, the **EU has the capability to catch up with the USA,** provided that financial support is allotted and aircraft technologies are integrated.

The significant **increase in coal use for power generation expected worldwide** is an opportunity for European manufacturers to strengthen their leading technological position in advanced PF, CFBC power plants, and also boost the development of commercial IGCC and PCFB power plants.

### *Market and Industry (M&I)*

The IEA foresees that 3,055 GW of new capacity will be installed in the world by 2020, about 60% of which will be in developing countries, and over 1,000 GW in Asia alone [IEA]. **China and India will be the largest markets** in the coming years. But these countries are strongly distorting the technology market and they will place enormous strain on oil, gas and coal. The EU and Germany are currently discussing with these countries, however Japan and the USA are a step ahead on these markets as they have already sold several plants.

Although the market prospects in China are high, **Chinese technological capacity** is good enough for the local industry to be able to build a power plant on its own after having bought just one foreign plant and several licences. A good example of this is the first supercritical coal-fired plant of Chinese origin, consisting of a 600 MW unit that started full-scale operation at the end of 2004. Under such conditions, the only way for foreign industries to keep a foot in the Chinese market is by regularly introducing advanced technologies.

Therefore, for the EU to benefit from the huge market potential in China, **it is essential to maintain a strong capacity to innovate** to be able to offer new, clean and efficient technologies every five years or so. European industry cannot support such intensive developments on its own, and this puts them in a weak position compared to their main competitors (Japan and USA) who benefit from substantial government support.

In this respect, one major advantage US industry has over its European competitors is that if a technology needs to be pushed, strong public R&D efforts can be targeted on early-stage programmes involving a high risk but promising technologies. FutureGen, an integrated modular approach to showcase the best technology options for using coal to produce electricity and hydrogen with zero emissions, is supported by the US DOE, which has officially stated that public investment is required to offset the high risk associated with such projects in sectors where the coal and utility industries are generally conservative and risk adverse. Public funding should provide about 65% of the overall project cost, up to the full-scale prototype plant, while private industry investment should be limited to about 25% (and international partners the remaining 10%).

Gas turbines will be a key technology up to 2030 and beyond. Therefore Europe's competitiveness on the international market is a critical issue: will gas turbines in the future power fleet be 100% US technology or is Europe still in a position to compete? To do so, technology development and demonstration plants are essential, but they must be government or EC supported to reduce the risk related to commercialisation of new systems.

Against a backdrop of low grid reliability in some parts of the country, there is significant niche market potential in the USA for small power generators (main or backup). Capstone, the world leader in microturbine technology, is benefiting from this market, as shown by the contract with the restaurant chain McDonald's (which was eventually abandoned), which was willing to install a microturbine unit in each restaurant in the USA. With such market perspectives, Capstone will be able to decrease its unit costs and with that confirm its leading position, making it all the more difficult for European companies to be competitive. It is however important to point out that the microturbine manufacturers in the USA are able to sell their products below production price because they are backed up by investors prepared to put in large amounts of money although the market is not developing yet. In a similar financial context, Europe would be able to regain a leading position fairly quickly.

### *Policies and Measures (P&M)*

A shortage in energy capacity is expected in Europe by 2010, because procedures to build facilities are very long on the one hand, and policies and measures are unclear on the other hand. Therefore, in the short to medium term, all types of power production available will be needed and none of them should be discarded in government strategies. In other words, as an expert puts it: if we chose the winners today, we will be the losers tomorrow.

One of the benefits of implementing the **$CO_2$ permits** trading system is that the industries ($CO_2$ producers) are to start taking action in terms of $CO_2$ mitigation. Depending on the price of the $CO_2$ tax, they may decide to keep their current technologies and pay the tax, or they may decide to build advanced power technology plants to avoid paying the tax. In any event, the recently launched Emissions Trading Scheme should have a positive effect by stimulating the commissioning of clean power technologies. This should thereby give an advantage to European fossil fuel power plant developers over their US and Japanese counterparts in terms of number of power plant orders and competitiveness.

## References


[21] Vision 21 Technology Roadmap. US National Energy Technology Laboratory (NETL). 2001.

[40] Thinking the future of energy. Central Research Institute of Electric Power Industry (CRIEPI), Japan. November 2003.

[41] Energy in Japan 2003. Agency of Natural Resources and Energy (ANRE), Japan. November 2003.

[70] President's 2005 budget includes nearly 729 MUSD for fossil energy programs. US Department of Energy, Office of Fossil Energy. 2004.

[74] IGGC Technologies (coal gasification). Conference on "Innovative Technologies for Generating Electricity - towards zero-emission coal-fired and gas power plants", Berlin. May 2004.

[82] The EU research strategy for $CO_2$ capture and storage. EC-DG Research. April 2004.

[118] Roadmap for the biomass technologies in the United States. Biomass R&D Initiative. December 2002.

[155] The impact of emissions trading on the coal industry. IEA Clean Coal Centre. June 2004.

[197] Micro CHP: a sustainable innovation? 8. Symposium Energieinnovation: Erfolgreiche Energieinnovationsprozesse, Graz. February 2004.

[199] MICRO-MAP: mini and micro CHP market assessment and development plan: summary report. European Commission SAVE Programme, DG-TREN. April 2002.

[211] Uncertainties in relation to $CO_2$ capture and sequestration. International Energy Agency (IEA) - EET. March 2003.

[224] Long-Term Outlook of Energy in Japan. Institute of energy Economic, Japan (IEEJ). November 2002.

[230] Micro Gas Turbine. Institute of Applied Energy (IAE), Japan. March 2001.

[289] FutureGen: integrated hydrogen, electric power production and carbon sequestration research initiative. US DOE, Office of Fossil Energy. March 2004.

[290] Department of Energy FY 2005 Congressional Budget Request. US DOE, Office of Management, Budget and Evaluation. February 2004.

[291] DOE's Fossil Energy Turbine Program. US DOE, NETL. July 2003.

[292] Decentralised generation - Technologies and Market perspectives. Imperial College London. March 2004.

[293] A power generation strategy for Europe. CAME-GT, Dr. Peter Holmes. July 2004.

[294] Committee on new power technology. New Energy and Industrial Technology Development Organization (NEDO), Japan. March 2002.

[295] Distributed generation as a potential solution to United States electricity transmission bottlenecks. WISE, University of Arizona. August 2004.

[296] Distributed energy services, the world's power and transportation industries: set for a revolution. Bear Stearns, USA. November 2000.

[297] Distributed power generation in the US - practical issues affecting project development. Thelen Reid and Priest LLP. August 2004.

[310] Emissions trading and its possible impacts on investment decisions in the power sector. International Energy Agency (IEA). 2003.

[311] Future power generation perspectives from manufacturer's side. Siemens AG Power Generation. June 2004.

[312] Clean Coal Committee. Agency for Natural Resources and Energy (ANRE), Japan. January 2004.

# Carbon dioxide capture and sequestration technologies

## Technology and market trends

The Kyoto Protocol established binding obligations for the reduction of emissions of greenhouse gases in an attempt to stabilise anticipated changes to the global climate. Whatever the position of governments toward this text, all countries recognise the necessity to reduce these emissions and have each decided on priority methods and timeframes – which are sometimes highly contrasted.

One of the challenges faced is to be able to continue to use fossil fuels while both eliminating $CO_2$ and other polluting emissions and, at the same time, maintaining industrial competitiveness. In this respect, cost-effective $CO_2$ capture and sequestration (CCS) is of essential importance. Indeed, even under the most optimistic scenarios for energy efficiency gains (see section on fossil fuel technologies) and the greater use of low- or no-carbon fuels, **sequestration will likely be essential** in order to stabilise atmospheric concentrations of greenhouse gases at acceptable levels.

Nevertheless, one should keep in mind that the concept of **capturing and storing $CO_2$ is an end-of-pipe solution**, and should therefore be considered **only once a maximum efficiency improvement has been achieved on the power production process.**

## Technology trends

### *$CO_2$ capture technologies*

Three types of processes can be used to capture $CO_2$ at the main industrial emission sources:

- **Post-combustion capture**, where $CO_2$ is extracted from flue gas, and which is highly suited for retrofitting
- **Pre-combustion capture**, which leads to a high $CO_2$ concentration stream, enabling simple separation techniques to be applied and allowing hydrogen to be produced
- **Oxy-fuel technologies**, using combustion in almost pure oxygen which leads to a high $CO_2$ concentration in the flue gas.

$CO_2$ is routinely separated and captured as a by-product from industrial processes such as synthetic ammonia production, $H_2$ production, and limestone calcination. The existing capture technologies, however, **are not cost-effective** when considered in the context of capturing $CO_2$ from power plants, where **flue gases contain only 5 to 15% $CO_2$**. For effective carbon capture, the $CO_2$ in these exhaust gases must be separated and concentrated.

$CO_2$ capture technologies involve **adsorption, absorption** (chemical or physical), **membrane separation**, or **cryogenics**. All of these processes consume a significant amount of energy, and thus entail cost. This is referred to as the “energy penalty” of the capture process.

**Absorption** technologies, based on either chemical or physical absorption, are well established and have been in use for decades. The two main manufacturers of chemical-based methods, Fluor and Mitsubishi, commercialise industrial absorption facilities for specific applications. Although these systems are adapted to $CO_2$ capture applications, they are unattractive because of their high cost. The main technological barriers are: development for large-scale power generation, cost reduction, and innovative solvents. A number of commercial-scale physical absorption-based technologies are also in use and are generally applied to systems operating at higher pressure levels. The proprietary solvents used (e.g. Union Carbide’s Selexol) are favoured where high concentrations of $CO_2$ are present in the flue stream.

Although capture by physical **adsorption** is a commercially available technology, it is not expected to be mature for large-scale separation of $CO_2$ from flue gas before 2015 because the capacity and $CO_2$ selectivity of available adsorbents are low. The main technological barriers to use of this technology are: development of adsorbing materials and development of processes.

**Membrane separation** technology could be used to separate $CO_2$ at various locations in power generation processes. Membranes cannot usually achieve high degrees of separation, so multiple stages are necessary, leading to increased complexity, energy consumption and cost. **Membranes are, however, unanimously considered to be the most promising** of the capture technologies, mainly because they enable to separate both $CO_2$ and hydrogen. Capture plants would thus be profitable since the hydrogen could be sold for fuel cell applications. However, such plants are still being developed and are not expected to be mature before 2019. The main technological barriers for large-scale application are: development of new membranes, development for large-scale power generation conditions, reduction of the energy required for separation.

**Cryogenics-based systems** are another possible technology for $CO_2$ capture, though uneconomical for low $CO_2$ concentrations (e.g. in flue gas). They could be worthwhile for systems that increase the $CO_2$ concentration in the flue gas, as in oxy-fuel combustion.

### *$CO_2$ storage technologies*

Carbon dioxide sequestration in geologic formations includes **depleted oil and gas reservoirs, unmineable coal seams**, deep saline reservoirs (**aquifers**), etc. The primary goal of $CO_2$ sequestration research is to understand its behaviour when stored underground, in order to determine the extent to which the $CO_2$ moves within the geologic formation, what physical and chemical changes occur to the formation when it is injected, and ultimately ensure that sequestration will not provoke safety or environmental problems.

The **estimated geological reservoir capacities** are 900 Gt $CO_2$ in disused oil and gas fields, 40 Gt $CO_2$ in unmineable coal beds and 400-10,000 Gt $CO_2$ in deep saline reservoirs. To put these capacities in perspective, in 2002 global $CO_2$ emissions from fuel combustion amounted to about 24 Gt-$CO_2$ and are projected to reach 38 Gt-$CO_2$ per year in 2030 [229].

With respect to storage in depleted oil reservoirs, one option consists in injecting $CO_2$ into almost-depleted oil fields so as to enhance oil production. This process, called the **Enhanced Oil Recovery process** (EOR), currently uses about 45 Mt $CO_2$/year and is most commonly used in the USA [211]. Transposing this process for Enhanced Gas Recovery (EGR) is not currently used, although such projects have been proposed in Canada and the Netherlands [212]. $CO_2$ can also be injected into suitable coal seams, producing methane that is pushed out by the incoming $CO_2$. There have been few **Enhanced Coal Bed Methane** (ECBM) trials in the world to date.

Apart from those options that would create profit, there are other options that would not provide any revenue. The most promising of these is storage in saline aquifers (deep sub-sea or on-shore), where the $CO_2$ is dissolved in the aquifer. The main technological barriers here are: long-term stability of the stored $CO_2$, energy consumption, safety aspects, and public acceptance.

Another option is oceanic storage of $CO_2$, which is still very controversial in Europe, partly because the impact of increased $CO_2$ concentration on the oceanic ecosystem is unknown. The main technological barriers are: injection and dispersion techniques, long-term stability of the stored $CO_2$ and public acceptance.

For all these projects, major energy companies in Europe, Japan and the USA have joined with national research centres to understand the behaviour patterns and evaluate the viability of $CO_2$ sequestration as a cost-effective option for environmental protection. In 2003, the USA launched the **Carbon Sequestration Leadership Forum** (CSLF), designed to improve carbon capture and storage technologies through coordinated R&D with international partners (Canada, Japan, Australia, Russia, China, the EC and some EU Member States) and private industry. Three types of cooperation are currently envisioned within the framework of the Forum: data gathering, information exchange, and joint projects.

Although the **estimated reservoir capacity** of disused oil and gas fields (900 Gt $CO_2$) and unmineable coal beds (40 Gt $CO_2$) is low compared to that of deep saline reservoirs (400-10,000 Gt $CO_2$), EOR and ECMB processes are expected to be implemented first since they could bring benefits thanks to enhanced fossil fuel production. These benefits would amount to $0-35/t $CO_2$ (€0-29/t); compared to capture costs of $19-51/t $CO_2$ (€16-42/t). **This offers the opportunity to offset part or even all of the capture costs**. [211].

The $CO_2$ transport issue is often omitted, although generally inevitable since $CO_2$ source locations are far from the prime locations for underground storage. $CO_2$ could be transported either via pipeline technology (an established technology) or by ship (non-established technology). In both cases, the cost would depend on the distance and volume, ranging from $1-10/t $CO_2$ (€0.8-8/t) [211].

## Market trends for $CO_2$ capture technologies

From a market perspective, **chemical absorption-based processes, which are readily available, will be the first** to fulfil the needs of the $CO_2$ capture technology market. Once **membrane technology** is fully developed, it **will progressively replace** absorption technology.

**Although capturing is technically feasible today, the cost of this process is a major issue. Capture costs are currently estimated at €50-60/t, whilst the target costs are €30-40/t for Japan, €20-30/t for Europe and $10/t for the USA** [82].

Besides the use of $CO_2$ for EOR, other unsuspected applications may appear for $CO_2$, as was the case for $SO_2$ when the $SO_2$ permits trading system was introduced in the USA (1990 Clean Air Act). A whole new business was created and today the coal power plants make money from the $SO_2$ they produce.

## Trends in policies and measures for $CO_2$ sequestration

**From a regulatory standpoint, many issues remain unresolved**. Two of the relevant multilateral environmental agreements/treaties are the London Convention and Protocol (regulating dumping of wastes and other matters at sea) and the OSPAR Convention (regional agreement covering the maritime area of the North East Atlantic). Interpreting these treaties for application to $CO_2$ storage raises issues such as whether captured $CO_2$ is being stored or disposed of, whether the $CO_2$ contains impurities resulting from its capture, etc. This issue currently needs to be resolved at the political level, with subsequent treaty amendment [209].

The **European Emissions Trading Scheme** was launched in January 2005. Many companies consider it to have a negative impact on the economy, since the cost of $CO_2$ sequestration will increase the cost of power and manufactured products. However, the implementation of **this trading system should be seen as an opportunity**: $CO_2$ permits will lead to more efficiency in processes, will enable capture and storage systems to be developed in a cost-effective way, will prompt the industries to actually start manufacturing and using CCS processes, and may also generate many unknown benefits.

The US Coal Utilisation and Research Council has estimated that the development of $CO_2$ capture systems for coal-powered plants will cost $0.94 G up until 2020. Demonstration systems will cost a further $1.35 G. The next step would be to bring costs down through deployment. These R&D costs are rather limited compared to the quantities of $CO_2$ involved. If a cumulative quantity of 2 Gt $CO_2$ is stored (a low estimate), the **R&D costs should amount to $1/t $CO_2$**, which is negligible [211].

Unlike capture technology development, **storage-related research is an international issue;** the parties involved collaborate freely worldwide and there is no real competition. The day intellectual property and related issues appear, this will mean that business, and thus competition, is beginning; that will be a sign that the technology is mature.

Finally, **public acceptance** of $CO_2$ transport and storage is an issue that must be tackled immediately and carefully to avoid possible confusion of **$CO_2$ storage with other issues like nuclear waste**.

It follows that the technology opportunities/challenges are $CO_2$ capture by absorption and geological storage with EOR in the short term, storage in aquifers in the medium term, and capture by membrane separation in the long term.

## Main strengths and weaknesses of the USA and Japan

### USA

| | Strengths | Weaknesses |
|---|---|---|
| S&T | • Strong CCS portfolio of research projects with over 40% private-sector cost share (e.g. membrane separation technologies)<br>• Weyburn $CO_2$ Monitoring and Storage project | |
| M&I | • A commercial absorption-based process<br>• 30-year experience of EOR; $CO_2$ pipelines domestically available | • Launch of large-scale EOR determined by guarantee of profitability<br>• Belief that climate change is more complicated to tackle than just decreasing one input (i.e. $CO_2$) |
| P&M | • Tax incentives to defray higher costs<br>• Existence of a legal framework for storage<br>• Experience in Sulfur Dioxide Allowance Trading Program since 1992<br>• Environmentalists communicate positively on geological storage | • Federal Government not environmentally proactive |

#### *Science and Technology (S&T)*

The USA has a **strong CCS portfolio of research projects** with over 40% private-sector cost sharing [17]. For instance, major R&D efforts are being undertaken on membrane separation technologies in the US.

The **Weyburn $CO_2$ Monitoring and Storage project** is an IEA project in which governments, industries and researchers from the USA, Canada, Europe (e.g. the EC) and Japan are taking part. Since 2000, 5000 t $CO_2$ per day have been transported through a 330 km pipeline and used for EOR.

Although the R&D effort on CCS is significant, the government is **not environmentally proactive**. It prefers to put relatively small amounts of money into R&D (in 2004, the US DOE Budget for **Sequestration R&D was** $40 M) rather than take action to oblige industries to decrease emissions, for example, which would cost much more.

### *Market and Industry (M&I)*

The company Fluor markets **absorption-based processes**. Other companies have also been developing advanced absorption processes, such as Praxair which has come up with a process that uses concentrated amine blends [210].

The USA has 30 years of **experience in EOR,** with an infrastructure of over 3000 km of $CO_2$ – mainly natural $CO_2$ – pipelines. There are **tax incentives** to defray high costs related to the implementation of $CO_2$-EOR projects. Over the past 30 years, federal government tax credits and specific state allowances have created the prerequisite incentives for the initiation of tertiary oil production using $CO_2$ [212].

In the USA, it is not widely believed that there is a link between climate change and the use of fossil fuels. People (public opinion and part of the scientific and political community) consider that climate change is complex and that there are many inputs into it, so acting on only one input (i.e. man-made $CO_2$) is not really useful. On the other hand, most **environmentalists do communicate positively** on geological storage, presenting it as a solution for the continued use of fossil fuels without affecting current lifestyles.

### *Policies and Measures (P&M)*

The **current legal framework** could allow the storage of $CO_2$ underground. Facilities across the USA already discharge a variety of hazardous and non-hazardous fluids into more than 400,000 injection wells. The US EPA Underground Injection Control (UIC) Program works with state and local governments to oversee the underground injection of waste.

Today in the USA there are no legal barriers to the application of EOR, the only hindrance being cost. For companies to start adopting EOR, it needs to be made clear to them that the **use of $CO_2$ can be profitable**. Since there is currently no indication that a $CO_2$-related business may develop, no-one wants to take the risk of making the first move. However, once the worldwide $CO_2$ emissions trading market gets off the ground, the USA will benefit from its unique hands-on experience gained over the last decade with the sulphur dioxide ($SO_2$) **allowance trading system.** This market was initiated in 1992 in the scope of the Clean Air Act. Through this system, the utilities regulated under the programme, rather than a governing agency, decide on the most cost-effective way to use available resources to comply with the acid rain requirements of the Clean Air Act. Once allocated, allowances may be bought, sold, traded, or banked for use in future years.

## Japan

| | Strengths | Weaknesses |
|---|---|---|
| S&T | | • Late start compared to Europe and the USA |
| M&I | • Strong industrial competences in plant engineering and oil exploitation<br>• MHI is one of the leaders in the field of $CO_2$ capture | |
| P&M | • Willingness to tax $CO_2$ emissions to finance sequestration measures | • Underground storage of $CO_2$ is an unpopular topic [40]<br>• International acceptance of ocean storage is an issue |

$CO_2$ mitigation R&D programmes were started in Japan in the late 90s and **focused on innovative $CO_2$ utilisation technologies**, such as fixation by biological functions or fabrication of synthetic fuels through Fischer-Tropsch processes [38]. Indeed, as the R&D programmes are set by the Ministry of Economy, Trade and Industry (METI) – which is also in charge of all energy-related R&D – priority is given to solutions with a potential to create new market opportunities, thus focusing on $CO_2$ valorisation rather than storage.

It should be noted that some of the advisers to METI believe that Japanese policy should promote the development of high-efficiency technologies and energy conservation technologies as a priority, rather than $CO_2$ capture and storage technologies [231].

For other sequestration options, the RITE, Research Institute of Innovative Technology for the Earth, has been entrusted with conducting and managing most R&D related to $CO_2$ mitigation.

### *Separation and Capture*

**The NEDO has been funding basic R&D aiming at reducing the cost of separation and capture to 60~70% of the total sequestration process cost (¥6000~8000/t-$CO_2$)** [231]. These are three-year projects, each with a total budget of ¥60 M [NEDO, RITE]. The most original project involves studying reversible capture in solid ceramics, based on a technology developed by Toshiba.

**Mitsubishi Heavy Industries (MHI) is already offering an industrial solution for $CO_2$ capture,** and is world leader in this respect alongside US company Fluor.

### *Storage*

Two main storage technologies are being investigated: geological storage in aquifers and intermediate water ocean storage. This research has also been also entrusted to the RITE.

**Storage in aquifers** is the preferred option for underground $CO_2$ storage in Japan since estimated capacity is 88 Gt-$CO_2$, compared to only 2 Gt-$CO_2$ for oil and gas fields. Thus a pilot project (fiscal 2000 to 2004, injection of 20 t/day supercritical $CO_2$ for 18 months) has been initiated, the goal of which is to study the behaviour of $CO_2$ in aquifers, as well as to build a model based on actual data.

Japan being a volcanic archipelago, safety issues related to volcanic eruptions and earthquakes are dominant concerns when considering geological storage; a major earthquake occurred near the test site in October 2004, which will give researchers first-hand experience on $CO_2$ behaviour following such events.

The **ocean storage** project (first stage from fiscal 1997 to 2001, second stage from 2002 to 2006) explores the dilution potential of oceans when releasing $CO_2$ in intermediate water from a moving ship. It involves simulation of droplet dilution, efficiency and cost analysis, as well as an environmental safety evaluation. The cost of the total process is estimated today at ¥6500~8200/t-$CO_2$.

This project is being conducted with the collaboration of the US, Canadian, Norwegian and Australian authorities.

## SWOT analysis for Europe

| | Strengths | Weaknesses |
|---|---|---|
| S&T | • Sleipner storage (in aquifer) project is world class, commercial scale and unique in the world | • Lack of industrial partners for S&T and interaction with policy-makers<br>• Insufficient funding and government support for R&D<br>• No Network of Excellence on capture<br>• No experience in EOR<br>• Lack of industry/government risk sharing in large-scale demonstrations |
| M&I | | • No capture technology manufacturers<br>• Low strategic outlook of industries, which are waiting for market incentives |
| P&M | • $CO_2$ permits scheme effective since January 2005 | • No legal framework for transport and storage |
| | **Opportunities** | **Threats** |
| S&T | | • Strong R&D effort on membrane separation technologies in the USA<br>• Non-EU countries could have access to EU R&D results by participating in EC RTD |
| M&I | • Create a new industry with $CO_2$ capture technologies (absorption, then membrane in the longer term)<br>• Create a business with the expertise built up in $CO_2$ storage<br>• Strong $CO_2$-EOR potential in the North Sea<br>• Need for infrastructure for $CO_2$ collection and transport | • Absorption technologies commercialised by US and Japanese companies only<br>• EU not well positioned for EOR, which should be the market "door-opener"<br>• Price of oil and price of $CO_2$<br>• Public acceptance |
| P&M | • Need for specifications on $CO_2$ to be stored<br>• Use Europe's expertise in dealing with nuclear waste to tackle some $CO_2$ storage issues? | • USA could quickly start storing $CO_2$ thanks to an existing legal framework |

## Strengths and weaknesses of Europe

### *Science and Technology (S&T)*

One of the conclusions of the Annual Seminar of the European Carbon Dioxide Thematic Network ($CO_2$NET) held in April 2004 was that, although multiple capture technologies are showing results at laboratory scale, and several projects are moving to small pilot scale, **continued funding** is needed to demonstrate technologies at commercial scale. On the whole, researchers consider that there is a **lack of both industrial partners** to take over the laboratory research, and of **interaction with policy-makers.**

The total expenditure on $CO_2$ capture and storage research within FP5 was approximately €32 M, with a maximum EC contribution of €16 M. Currently, €37 M of EU funding, matched by an equivalent amount of public and private investment, has been awarded to RTD and demonstration projects for $CO_2$ capture and storage in FP6 (1$^{st}$ call). This will be reinforced via further calls.

Although FP5 initiated the $CO_2$NET Thematic Network covering capture and storage, FP6 is solely funding a **Network of Excellence** on geological sequestration ($CO_2$GEONET). Such a network would be useful for capture technologies, as it is a good instrument in promoting communication among stakeholders and often encourages good participation of industries.

The **Sleipner project**, initiated by the Norwegian company Statoil, has become an international level full-scale demonstration plant for $CO_2$ storage in aquifers. Many partners are involved in this project, including the EC (FP4, FP5, FP6), companies (BP, Shell, ExxonMobil, TotalFinaElf) and also the DOE. It is a world-class project from which **hands-on experience** is being gained in terms of processes, safety and reliability.

### *Market and Industry (M&I)*

From the point of view of **the capture technology industry**, a key component in all chemical absorption plants is the organic solvent (alkanolamine). The German company BASF produces a solvent equivalent to that of Fluor and Mitsubishi, but is not in a position to market a comprehensive $CO_2$-capture process. European engineering companies (e.g. Lurgi, Linde) could develop such processes, but do not seem interested in doing so unless a chemicals company such as BASF develops a better-performing solvent than those produced in the USA and Japan.

It is generally admitted that EOR and ECBM technologies will be used to store $CO_2$ before storage in aquifers is launched, and that **they will be the "door-openers"** to the market thanks to the benefits they create. Unfortunately though, **there is no $CO_2$-EOR production in Europe** and only one experimental $CO_2$-ECBM in Europe today. The major North Sea operators have nonetheless recognised that $CO_2$ could have a beneficial effect if it were available in sufficient volumes and at a cost compatible with alternate technologies for EOR [212]. A project is being developed in that direction. The CENS ($CO_2$ for EOR in the North Sea) project plans to begin operating $CO_2$ capture facilities at five large coal-fired power plants in Denmark in 2007. There is also an EC-supported large-scale demonstration project for ECBM in a Polish coalfield.

### *Policies and Measures (P&M)*

The benefits of implementing the **$CO_2$ permits** trading system are threefold:

- Europe has the opportunity to develop storage technologies in the North Sea in a cost-effective way
- The industries ($CO_2$ producers) are shifting from a wait-and-see policy to a more active attitude in terms of $CO_2$ mitigation actions
- The CCS technology developers are assured that there will be a market.

The stakeholders generally acknowledge a **lack of support for early technology dissemination**, for instance in the form of funding «lighthouse» commercial demonstration projects. By sharing the risk with the industrial sector, the government has proven its commitment to these new markets. Without such signs, like market incentives for instance, the industrial sectors usually adopt a wait-and-see attitude, with a **low-key strategic outlook**.

## Opportunities and threats for Europe

### *Market and Industry (M&I)*

In terms of business, the situation is rather different between capture technologies and storage technologies. For the latter, **new business opportunities** will be small from a technological point of view – the storage technologies being rather low-tech – but probably very large in the field of storage plant exploitation, e.g. transport, site monitoring and risk assessment. In this respect, the experience Europe is gaining with the various $CO_2$ storage projects, and the recent launch of an emissions trading system, should prove rewarding.

As for $CO_2$ capture processes, a whole new industry needs to be created for the market in both the industrialised and developing countries. However, looking at the current technological know-how worldwide, Europe is lagging behind, considering the fact that the **USA and Japan are leaders** in commercially available absorption technologies and that the USA is undertaking robust R&D efforts in the development of membrane technologies. Moreover, the USA is taking advantage of the **opportunities for non-EU countries to participate in European R&D** programmes. This benefits the EU since the non-EU country then finances its share of the research, but is also a drawback since the co-funding country has direct access to the EU R&D strategies and results.

As for fossil-fuel-based power production systems, China represents a great potential market for capture technologies. In this respect, the estimate that emissions in China will be equal to those in the USA by 2012 speaks for itself.

The **$CO_2$-EOR potential** in the North Sea is significant. On the Norwegian Continental Shelf alone, the potential incremental oil from $CO_2$-EOR projects has been estimated to be in the region of 1.5-2.0 milliard barrels, thereby inferring a requirement for 500-650 Mt $CO_2$ in the Norwegian sector until 2025. Similar figures are anticipated for the UK offshore oil sector. The required technologies have already been tried and tested, although not for specific offshore application. Other issues such as logistics, operations and maintenance of the whole $CO_2$ supply chain may pose engineering challenges. For the offshore industry, therefore, economic incentives need to come into play before the necessary capital investments can be made [212]. The oil industry will start investing in $CO_2$ storage only when it becomes profitable, i.e. when the regulatory context and tax incentives make that option attractive. In the meantime, so as to reassure future investors, it is important to assess the related risks by implementing demonstration programmes for capture and storage, both inland and off-shore.

Taken individually, the oilfield operators have limited opportunities to gather sufficient $CO_2$ for an economic EOR project. Therefore, with the consent and support of the governments of the surrounding countries, **implementation of a major infrastructure for $CO_2$ gathering and transportation** is needed that can provide the necessary background for participation of a wider number of sectors and thus ensure that the economies of scale are realised rapidly [212].

### *Policies and Measures (P&M)*

Some countries already have a legal framework that can be applied directly to $CO_2$, as in the USA with “underground waste injection”, or in Norway with the regulations related to natural gas (any natural gas, even if incombustible like $CO_2$). The absence of a legal framework compatible with that of the neighbouring countries, for example, will probably turn out to be the main barrier to the development of a $CO_2$ transport and storage market in any one country or area.

Another problem is the purity of the $CO_2$ to be stored, since it often contains other compounds such as sulphur. **Specifications thus need to be defined for a category of “$CO_2$ to be stored”**. As suggested by some specialists, using Europe’s expertise in dealing with nuclear waste could facilitate the establishment of $CO_2$ specifications – in fact it took 15 years to define specifications for the handling of nuclear waste.

Leakage of $CO_2$ stored underground remains a major issue, which is being tackled through two ongoing projects in Germany and in Poland.

## References


[17] US Climate Change Technology Program: Technology options for the near and long term. US Department of Energy. November 2003.

[38] Outline of NEDO. New Energy and Industrial Technology Development Organization (NEDO), Japan. June 2003.

[40] Thinking the future of energy. Central Research Institute of Electric Power Industry (CRIEPI), Japan. November 2003.

[82] The EU research strategy for $CO_2$ capture and storage. EC-DG Research. April 2004.

[209] Storage - making it legal under international law. Department for Environment, Food and Rural Affairs, UK. 2004.

[210] Advanced technology for capture of dioxide from flue gases. Praxair Inc. 2001.

[211] Uncertainties in relation to $CO_2$ capture and sequestration. International Energy Agency (IEA) - EET. March 2003.

[212] Mechanisms and incentives to promote the use and storage of $CO_2$ in the North Sea. $CO_2$-Norway AS. 2004.

[229] Carbon dioxide capture and storage issues - accounting and baselines under the UNFCCC. International Energy Agency (IEA). May 2004.

[231] Energy Supply and Demand up to 2030. Agency for Natural Resources and Energy (ANRE), Japan. April 2004.

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# Glossary

| | |
|---|---|
| ADM | Archer Daniels Midland |
| AEBIOM | European Biomass Association |
| AHAT | Advanced Humid Air Turbine |
| ANRE | Agency for Natural Resources and Energy (Japan) |
| APU | Auxiliary Power Unit |
| ARES | Advanced Reciprocating Engine Systems (US) |
| ATP | Advanced Technology Program |
| AZEP | Advanced Zero-Emissions Power Plant |
| BERA | Biomass Energy Research Association (US) |
| BFBC | Bubbling Fluidised Bed Combustion |
| BOS | Balance of Systems |
| CAME-GT | Cleaner And More Efficient Gas Turbines (Europe) |
| CATS | Carbon Abatement Strategy (UK) |
| CCPI | US Clean Coal Power Initiative |
| CCS | $CO_2$ capture and sequestration |
| CCUJ | Center for Coal Utilization, Japan |
| CEA | Commissariat à l'Energie Atomique (France) |
| CE-IGT | Centres of Excellence for Industrial Gas Turbines (Europe) |
| CENS | $CO_2$ for EOR in the North Sea |
| CFB | Circulating Fluidised Bed |
| CFBC | Circulating Fluidised Bed Combustion |
| $CGH_2$ | Compressed Hydrogen |
| CHP | Combined Heat and Power |
| CIGS | Copper Indium Gallium Selenide |
| CIS | Copper Indium Diselenide |
| CNG | Compressed Natural Gas |
| $CO_2$GEONET | European Network of Excellence on Geological Storage of $CO_2$ |
| $CO_2$NET | European Carbon Dioxide Thematic Network |
| COORETEC | $CO_2$ Reduction Technology (German programme) |
| CPG | Centralised Power Generation |
| CSLF | Carbon Sequestration Leadership Forum |
| CUTE | Clear Urban Transport for Europe |
| DARPA | The Defense Advanced Research Projects Agency (US) |
| DG | Distributed Generation |
| DME | Dimethyl Ether |
| DMFC | Direct Methanol Fuel Cell |
| DOC | US Department of Commerce |
| DOE | US Department of Energy |
| DOE – DE | US Department of Energy, Distributed Energy Program |
| DOE – EERE | US Department of Energy, Energy Efficiency and Renewable Energy |
| DOE – OBP | US Department of Energy, Office of the Biomass Program |
| DPG | Distributed Power Generation |
| EAGLE | Energy Application for Gas, Liquid and Electricity |
| ECBM | Enhanced Coal Bed Methane |
| EEFAE | Efficient and Environmentally Friendly Aero Engine |
| EGR | Enhanced Gas Recovery |
| ENCAP | Enhanced Capture of $CO_2$ (Europe) |

| | |
|---|---|
| EOR | Enhanced Oil Recovery |
| EPIA | European Photovoltaic Industry Association |
| ERA-Net | European Research Area Network |
| EREC | European Renewable Energy Council |
| EREEC | European Renewable Energy Export Council |
| EtOH | Ethanol |
| EU-ETS | European Union Emission Trading Scheme |
| FBC | Fluidised Bed Combustion |
| $FCTES^{QA}$ | Fuel Cell Testing, Safety and Quality Assurance (Europe) |
| FCTESTNET | Fuel Cell Testing and Standardisation thematic Network |
| FCV | Fuel Cell Vehicles |
| FENCO | The Cleaner Fossil Energy Coalition (Europe) |
| FERC | Federal Energy Regulatory Commission (US) |
| FP | European Framework Programme |
| GE | General Electric |
| GHG | Greenhouse Gas |
| GM | General Motors |
| GT | Gas Turbines |
| HHEG | High-pressure Hydrogen Energy Generator |
| HHOG | High-purity Hydrogen and Oxygen Generator |
| HHV | Higher Heating Value |
| ICBR | Integrated Corn-Based Bioproducts Refinery |
| ICE | Internal Combustion Engines |
| IEA | International Energy Agency |
| IGCC | Integrated Gasification Combined Cycle |
| IGFC | Integrated Gasification Fuel Cell |
| IPHE | International Partnership for Hydrogen Economy |
| ITM | Ion Transport Membranes |
| JHFC | Japan Hydrogen and Fuel Cell Demonstration Project |
| JPEA | Japan Photovoltaic Energy Association |
| LEV | Low Emission Vehicle |
| LHV | Lower Heating Value |
| LNG | Liquefied Natural Gas |
| M&I | Market and Industry |
| MCFC | Molten Carbonate Fuel Cell |
| METI | Ministry of Economy, Trade and Industry (Japan) |
| MGC-GT | Melt-Growth Composite Gas Turbine |
| MGE | Micro Gas Engine |
| MGT | Micro Gas Turbine |
| MHI | Mitsubishi Heavy Industries |
| MoE | Japanese Ministry of the Environment |
| NEDO | New Energy and Industrial Technology Development Organization (Japan) |
| NFPA | National Fire Protection Association (US) |
| NGCC | Natural-Gas-fired Combined Cycle |
| NGNP | Next Generation Nuclear Plan |
| NHA | National Hydrogen Association (US) |
| NIMBY | Not In My Back Yard |
| NMS | EU New Member States |
| NRDC | US Natural Resources Defense Council |

| | |
|---|---|
| NSF | US National Science Foundation |
| OEM | Original Equipment Manufacturer |
| OMES | Optimised Microturbine Energy Systems (Europe) |
| OSPAR | Convention for Protection of the Marine Environment of the North-East Atlantic |
| P&M | Policies and Measures |
| PAFC | Phosphoric Acid Fuel Cell |
| PATH | Partnership for Advancing the Transition to Hydrogen |
| PEMFC | Proton Exchange Membrane Fuel Cell |
| PF | Pulverised Fuel |
| PFBC | Pressurized Fluidised Bed Combustion |
| PFCA | Public Fuel Cell Alliance (US) |
| PFI | Private Finance Initiative |
| PSDF | Power Systems Development Facility (US) |
| PUHCA | Public Utility Holding Company Act (US) |
| PV | Photovoltaic |
| PVTEC | Photovoltaic Power Generation Technology Research Association |
| RES-E | Electricity from Renewable Energy Sources |
| RITE | Research Institute of Innovative Technology for the Earth (Japan) |
| RPS | Renewable Portfolio Standards |
| S&T | Science and Technology |
| SBIR | Small Business Innovation Research Program (US) |
| SECA | Solid State Energy Conversion Alliance (US) |
| SME | Small and Medium-sized Enterprise |
| SOFC | Solid Oxide Fuel Cell |
| SSA | Specific Supporting Action |
| STTR | Small Business Technology Transfer Program (US) |
| SWOT | Strengths, Weaknesses, Opportunities and Threats |
| UIC | Underground Injection Control (US EPA) |
| UPS | Uninterruptible Power Supply |
| USC | Ultra Supercritical |
| USDA | US Department of Agriculture |
| VHTR | Very High Temperature Reactors |
| WE-NET | World Energy Network (Japan) |
| ZEV | Zero-Emission Vehicles |

# Appendix 1 – Methodology

## Methodology

A common methodology was applied to the different key technology areas covered by the study in order to conduct a sound and consistent analysis and to draw up a final report with a coherent structure and content.

The work was divided into four phases and conducted according to the following timetable.

| | | |
|---|---|---|
| **Phase 1**<br>Selection of important energy technologies<br>⇓<br>List of important technologies | Desktop research and analysis<br>Review of important energy technologies for Japan and USA | **May<br>-<br>June 2004** |
| **Phase 2**<br>Position of the technologies in an attractiveness/competit-iveness portfolio matrix<br>⇓<br>Identification of priority technologies | Literature review and survey sent to more than 500 experts/stakeholders, in order to:<br>- rate the attractiveness of each technology, its potential impact and performance on the market, and expected developments within 5, 10 and 15 years<br>- assess the strengths and weakness of Europe with regard to its main competitors in terms of industries, markets and regulation<br>- identify some priority energy technologies | **July<br>-<br>October 2004** |
| **Phase 3**<br>SWOT and trends analysis on priority energy technologies | SWOT and trends analsis on the technology areas, focusing on the most attractive technologies<br>Research on the market, indutry and regulation environment for these key priority technologies<br>Interviews with experts/stakeholders<br>Analysis of opportunities to be seized and threats to overcome | **October<br>-<br>November 2004** |
| **Phase 4**<br>Gap identification | Draft of the final report<br>Meeting with stakeholders<br>Key findings: identification of the most important gaps between Europe, Japan and the USA | **December 2004<br>-<br>January 2005** |

## Technology screening

In order to focus the SWOT analysis on the most promising energy technologies, an initial selection of technologies was carried out at the very start of the study. The selection was undertaken on the basis of a literature review, and particularly through examination of Japanese and US reports presenting the key energy technologies of current and future R&D programmes, as well as an analysis of the relevance of these with respect to the European Union environment.

A total of 48 technologies were finally selected in agreement with the EC, for power and transport applications, and grouped into 6 technology areas, corresponding to the different parts of the report:

- photovoltaic: 6 technologies
- biomass: 7 technologies
- fuel cells: 8 technologies in 2 groups (power generation, transport)

- hydrogen: 15 technologies in 3 groups (production, storage, end use)
- fossil fuels: 7 technologies
- $CO_2$ mitigation: 5 technologies in 2 groups (capture, sequestration).

## Attractiveness and competitiveness assessment

In addition, a survey was conducted asking more than 500 experts to evaluate the attractiveness of the 48 technologies listed, and the strengths and weaknesses of the European situation compared to its main competitors (Japan and the USA). The results of this survey are presented in Appendix 1.

### *Content of the survey*

A questionnaire was developed for each technology area, including the following items:

- an introductory note, explaining the context and objectives of the study
- some background questions referring to the respondents' expertise, type of organisation, and country
- closed questions for each technology, in order to rate from 1 to 4 the different criteria related to "technology attractiveness" and "European competitiveness"
- some open questions, in order to obtain additional points of view from the experts that could be helpful for the SWOT analysis and recommendations (expected future developments, action needed to enhance the European situation in terms of industry, market and regulation, etc.).

The survey was conducted electronically, through an online questionnaire

### *Experts contacted*

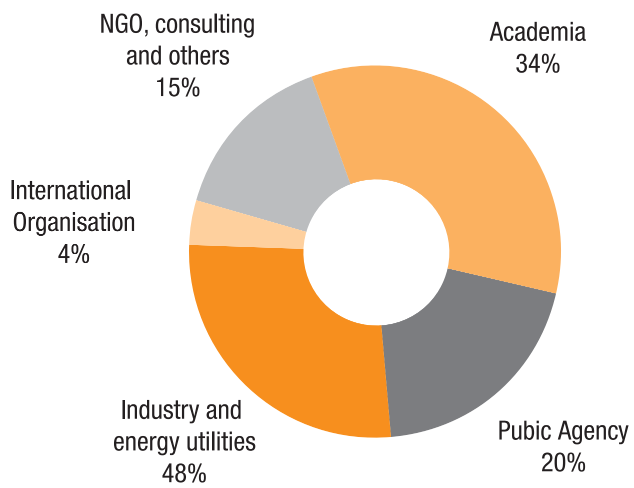
The selection and identification of key experts was very important for the results of the survey. The experts were identified by:

- selecting from an existing Jitex experts database, comprising people who had already been contacted for the purposes of other studies
- selecting speakers in energy congresses
- selecting authors of energy publications
- completing the missing fields through direct research (internet, telephone calls, etc.).

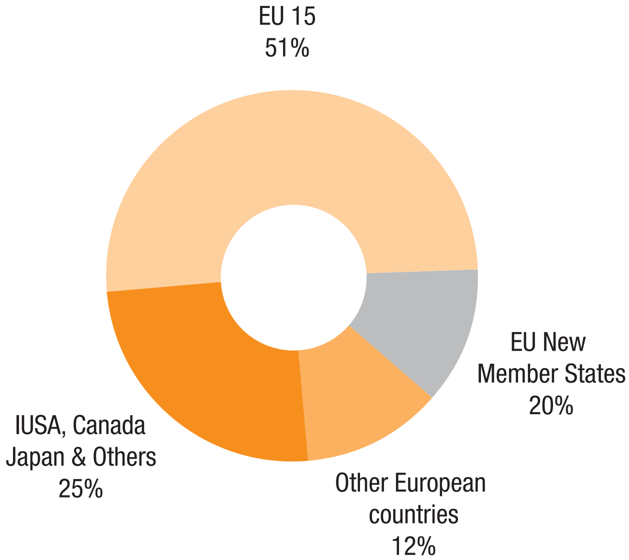
In the end, we sent the questionnaire to 515 qualified experts, representing the diverse technology fields, applications (transport/power), geographical areas (EU 15, New Member States, Other European Countries, USA/Japan, etc.), and institutional backgrounds (academia, public agencies, industry, etc.).

As shown in the following figures, the objective of covering a broad mix of backgrounds, geographical origins and areas of expertise was achieved in the survey results. At the time the website was closed (October 8th), we had received answers from 93 respondents, equivalent to an 18% response rate.

Institutional background of the respondents
Total: 93 repondents




Geographical origin of the respondents
Total: 93 repondents




*Matrix representation*

For each technology area, a portfolio matrix was used to present the results of the survey so as to position the technologies according to their attractiveness and their European competitiveness. Each matrix is presented and explained in Appendix 1.

The vertical axis of the matrix represents the attractiveness of the technology, measuring its importance for the near and medium-term future. Each technology attractiveness score has been determined by combining the scores attributed to the following criteria in the survey:

- current level of maturity (from “few basic research activities” to “already in use and competitive”)
- expected level of contribution to energy independence (from “no true impact on reducing dependency on foreign resources” to “breakthrough technology that could lead to a strong substitution phenomenon”)

- expected level of contribution to environment protection (from “no true impact on $CO_2$ emissions” to “strong potential reduction of total $CO_2$ emissions”)
- expected market potential (from “small business potential” to “huge market potential worldwide”)
- expected level of adaptability to future market needs (from “very rigid and limited number of applications” to “high versatility of the technology, which could be applied in many systems”)
- level of social acceptance (from “low, e.g. strong opposition and public concerns about this technology, which could curb its business potential” to “no opposition or favourable bias”).

The horizontal axis of the matrix represents current European competitiveness, measuring the position of Europe with regard to its main competitors, especially Japan and the USA. This competitiveness was determined by scores attributed through the survey in response to a question on leading countries, followed up by questions on the following criteria:

- scientific and technological capabilities
- potential of market opportunities (size, responsiveness, etc.)
- know-how and international leadership of industries and utilities
- current policies and measures.

A scoring system was developed and used in the questionnaires (marks from 1 to 4). The participants were asked to objectively rate each of the selected criteria and finally give two overall scores (out of 10) per technology, one for the “technology attractiveness” criteria and one for “European competitiveness”. Each technology is portrayed as a circle plotted on the matrix. Those technologies at the upper level of attractiveness, whether of high or low European competitiveness, can be considered as priority energy technologies, and were therefore more thoroughly analysed during the third phase of the study.

Alongside the questions regarding “attractiveness”, the experts were also asked to give a forecast of the year in which each technology is expected to be either cost-competitive or market-ready. The various answers to this question have been compiled and presented in a “time maturity” figure with, for each technology, a mean value of the results for maturity year, as well as values for the 1st and 3rd quartile.

Even though we did receive a large number of answers with a broad mix of background, geographical origin and expertise, **we have been extremely cautious about drawing conclusions from this survey.** In many cases, the proposed technologies had been classified into overly broad and imprecise families, making it difficult to obtain specific results.

**The matrices and figures were used as one input among others for the full SWOT analysis.**

**Besides the matrices, the survey enabled us to collect valuable information through the “open questions”, and identify a panel of experts who were interviewed during the third phase of the study.**

### *SWOT analysis and key findings*

The third phase of the work consisted of a SWOT and trends analysis of the different technology areas, focusing, when possible, on the key priority energy technologies selected from the upper level of the matrix representation.

Additional literature research was conducted on the market, industry and regulation environment of these priority energy technologies.

About 50 experts (from different countries, including the USA and Japan), most of whom replied to the survey, were interviewed in order to gain a more extensive understanding of their judgments on European strengths and weaknesses, of their point of view on future developments (short to medium terms), and on the opportunities to be seized and threats to overcome.

For each technology area, the results from the literature review and the different expert opinions were combined in order to provide an analysis of the trends, the internal and external environment (SWOT) and identify the most important gaps between Europe, the USA and Japan.

A draft final report, with the full SWOT analysis, was discussed in detail during a panel meeting with stakeholders held on December 17, 2004, in Brussels.

# Appendix 2 – Survey results

**In the following appendix, the survey results are presented and commented on.**

As described in the methodology chapter, a survey was conducted during the second phase of the work, asking more than 500 experts how they would evaluate the attractiveness of the 48 technologies listed in phase 1, and the strengths and weaknesses of the European situation compared to its main competitors (Japan and the USA).

For each technology area, a portfolio matrix has been used to present the results of the survey, so as to position the technologies according to their attractiveness (vertical axis) and their European competitiveness (horizontal axis).

Scores have been attributed according to the criteria described in the methodology chapter. Each technology has been portrayed as a circle plotted on the matrix.

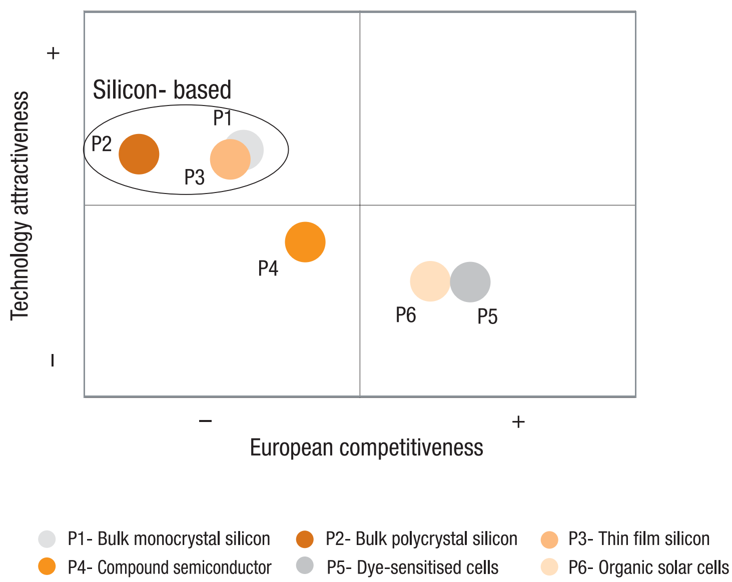
Alongside the questions regarding attractiveness, the experts were also asked to give a forecast of the year in which they expect each technology to be either cost-competitive or market-ready. The various answers to this question have been compiled and presented in a "time maturity" figure with, for each technology, a mean value of the results for maturity year, as well as values for the 1st and 3rd quartile.

Even through we received answers from 93 respondents (equivalent to an 18% response rate) with a broad mix of backgrounds, geographical origins and fields of expertise, **we have been extremely cautious about drawing conclusions from this survey.** In many cases, the proposed technologies had been classified into overly broad and imprecise families, making it difficult to obtain specific results.

**The following matrices and figures were used as just one input among others for the full SWOT analysis.**

**In addition to the matrices, the survey enabled us to collect valuable information through the "open questions", and identify a panel of experts who were interviewed during the third phase of the study.**

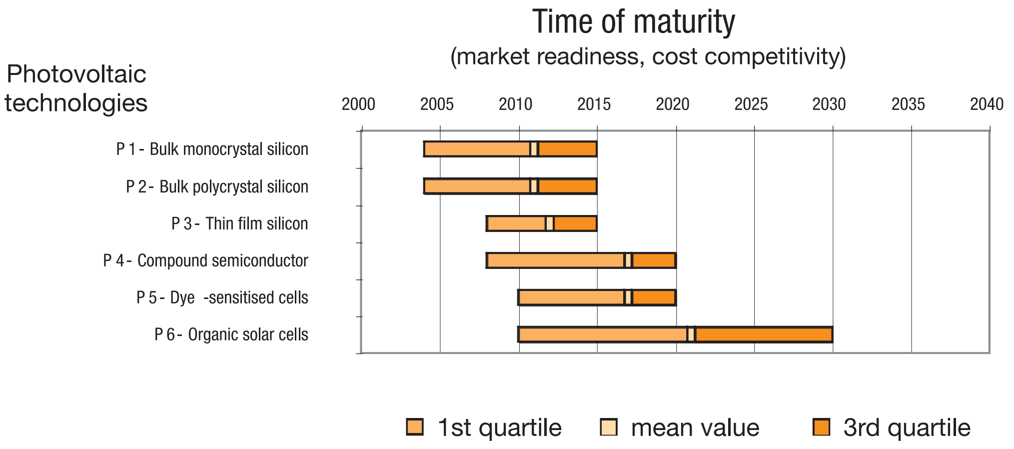
## Photovoltaic technologies



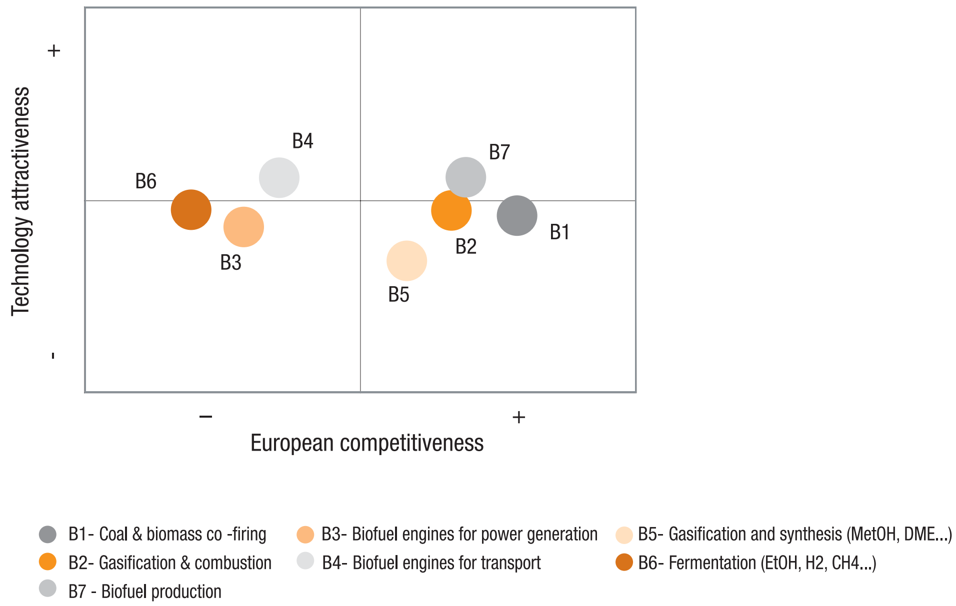
The higher attractiveness of bulk silicon technologies is mainly due to higher scores for the "maturity", "social acceptance" and "adaptability to market needs" criteria. The relatively low attractiveness of dye-sensitised cells and organic solar cells can be explained by a low maturity level. All of the technologies are more or less equivalent in terms of environmental sustainability.

Regarding competitiveness, more than 50% of the respondents agree that Europe is in a leading position for dye-sensitised and polymer cells, while the same proportion sees Japan as the dominating country both in terms of monocrystal and polycrystal silicon technologies.

It can be noted that Europe's competitiveness is higher in the less attractive technologies, suggesting that Europe is a leader in innovative, though perhaps unpromising, technologies.



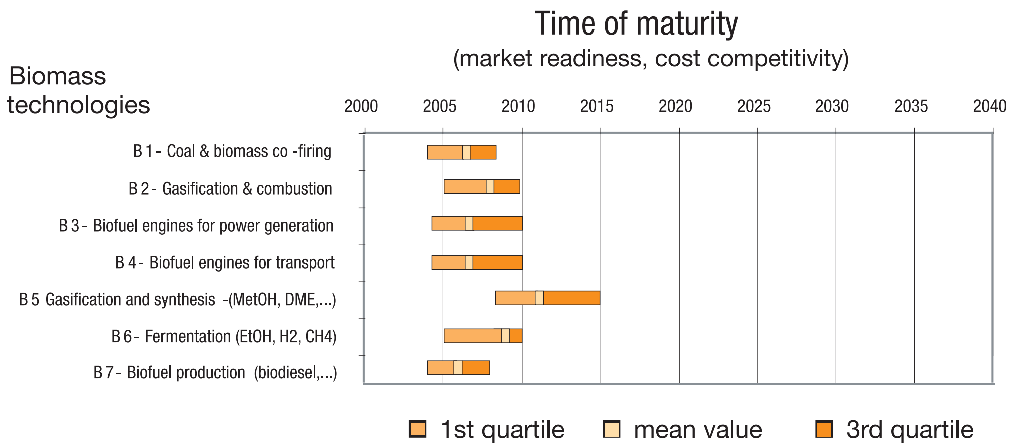

## Biomass technologies




Biomass resources are highly diverse, as are the various processes used for their conversion into biofuels, and the technologies deployed for heat and power generation (engines, turbines, boilers, fuel cells, etc.).

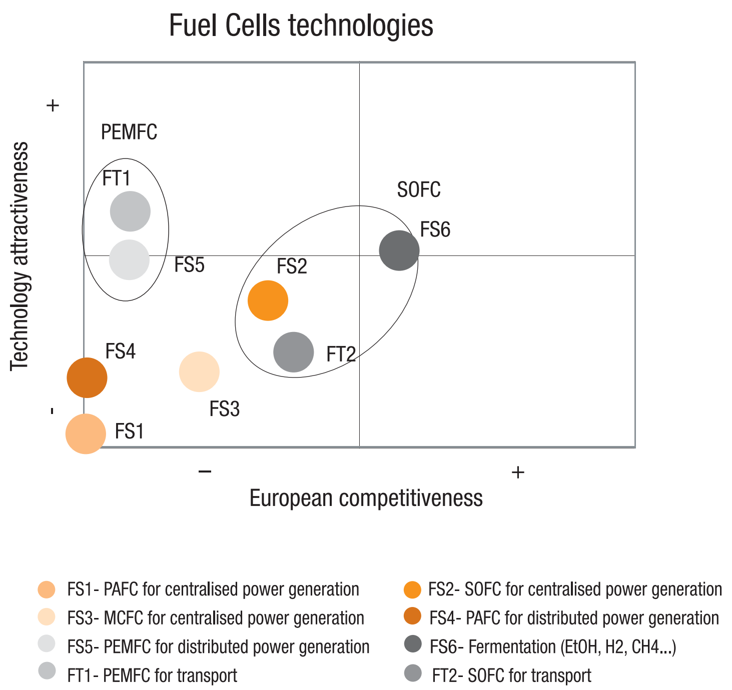
The results of the survey show that the list submitted to the respondents probably classified these technologies into excessively broad and imprecise families, from which it is difficult to draw any conclusions in terms of technology attractiveness since the final scores were all approximately the same (around 5/10).

Looking at the detailed criteria scores, some results are however rather consistent. Coal and biomass co-firing, for example, has been given the best score in maturity (6.6/10), but the worst in terms of adaptability to market needs (4.1/10) and social acceptance (4.4/10). Among the heat and power technologies, the gasification conversion process is considered as having one of the best market potentials (5.4/10), but is still lacking maturity. Many additional comments suggested that fast pyrolysis (for production of liquid fuels) should have been included in the list and is considered to have valuable potential.




# Fuel cells

## Stationary applications




If we consider one specific technology (e.g. PAFC or SOFC), the attractiveness of **Centralised Power Generation** (CPG) appears lower than that of Distributed Power Generation (DPG). Europe's competitiveness is also lower for CPG mainly due to the fact that the RTD and demonstration programmes in Europe have focused their attention on DPG. It can therefore be assumed that for MCFC the scores for technology attractiveness and for European competitiveness would also have been higher for distributed power generation than for centralised power generation. **Many**

**experts confirm that the potential of MCFC for large decentralised power generation in certain niches is good [216].**

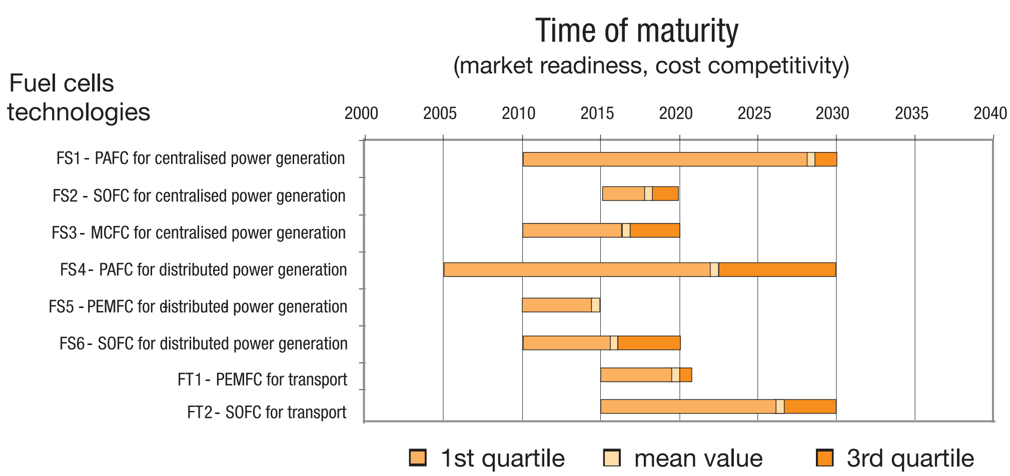
For **distributed power generation**, PEMFC and SOFC are almost equally attractive, although SOFC, which appears to have better market potential, has a slight edge. In terms of competitiveness, Europe is in a better position for SOFC than PEMFC. Considering that Siemens (through Siemens Westinghouse) and Sulzer Hexis are leading companies in **SOFC technology, and that many European RTD programmes have been focusing on SOFC, it is a good sign that Europe's competitiveness** in this area is rather consistent. On the PEMFC side, the USA and Japan are leading the field in the manufacture of fuel cells and membranes.

For both technology attractiveness and Europe's competitiveness, PAFC was ranked at the very bottom. The explanation for this is quite straightforward: of the 350 PAFC units installed worldwide, around 70% were sold by the American company ONSI and only 15 units were installed in Europe, whereas the Japanese have already installed more than 200 units [213]. The very low attractiveness of PAFC can be explained by its declining market position (see page 48) [37, 216].

## Transportation applications

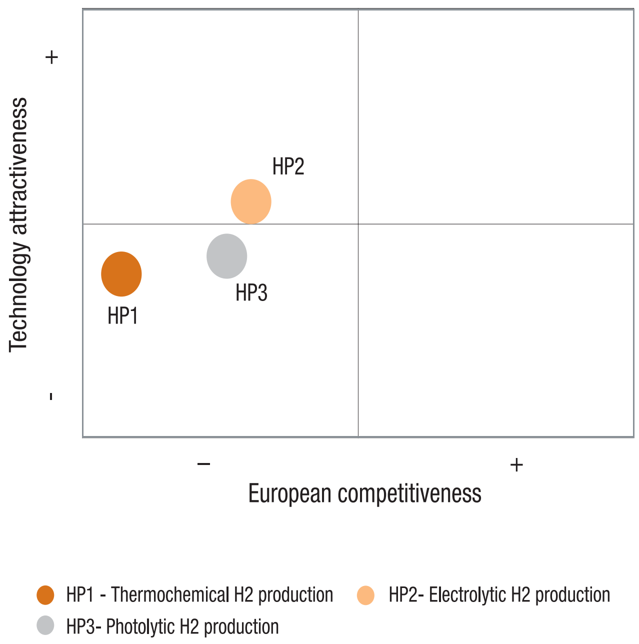
The higher attractiveness of the PEMFC is due to higher scores in the six criteria considered. These scores were particularly high for potential on the global market (7.5/10) and adaptability to future market needs and expectations (6.7/10). The relatively low attractiveness of the SOFC is attributable to a very low maturity level (1.6 /10) and a limited contribution to energy independence (1.7/10). These figures are consistent with the PEMFC and SOFC technical characteristics mentioned in the next chapter. Europe's low competitiveness score for PEMFC is consistent with the fact that the leading companies in the manufacture of PEMFC are based mainly in the USA, Canada and Japan. For the SOFC, the score is slightly better and is most likely linked to German activities in the development of SOFC systems.

**In conclusion, the survey suggests that the most attractive technologies could be PEMFC for transport, SOFC and PEMFC for small decentralised power generation, and SOFC and MCFC (to some extent) for large decentralised power generation. However, in terms of competitiveness, Europe's position is very good only for SOFC (DPG) and major efforts are needed to attain global competitiveness in the MCFC and PEMFC technologies, the most important challenge being in the field of PEMFC for DPG.**



# Hydrogen technologies

## Hydrogen production technologies




The possibilities for producing hydrogen are highly diverse, and the attractiveness of one technology not only depends on its inherent processes but also on other parameters such as the origin of the electricity required for electrolysis, the scale of the production plant for reforming, or the use of $CO_2$ sequestration. In this sense, the results of the survey show that the list submitted to the respondents probably classified these technologies into **families that were too broad**.

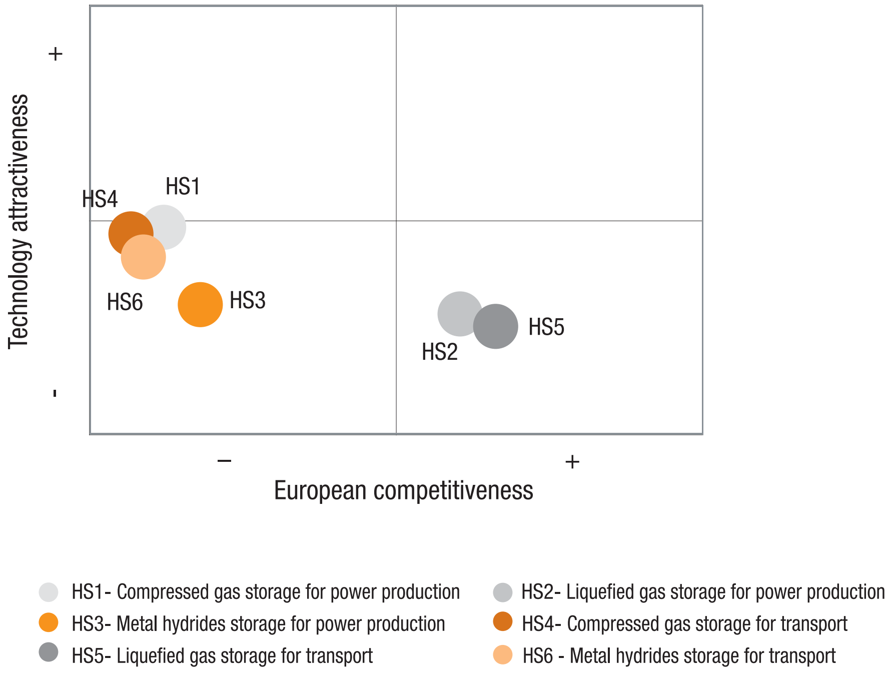
Nevertheless, there are some consistent results. **Electrolysis production** would appear to be the most attractive technology with especially good scores in environmental protection (5.8/10), economic potential on the market (5.6/10) and social acceptance (6.2/10). On the other hand, **photolytic hydrogen production** was awarded the best score in environmental protection (6.2/10) and social acceptance (7.1/10), but the worst (1.2/10) in terms of maturity. **Thermochemical** hydrogen production has the worst attractiveness due to a low score in environmental protection and social acceptance.

Europe's **sound competitive position** in the field of **electrolysis** is consistent with the fact that several leading European companies are active in this area.

It is important to point out that 61% of the respondents were not able to indicate which country leads the field of **photolytic production**. This is probably because this technology is at a very **early stage of development**.

One third of the respondents were not able to answer the question on thermochemical production and further comments suggested that there was confusion with thermochemical water splitting.

## Storage technologies




None of the technologies considered was judged to be highly attractive, as all of the scores given were under 5. Storage is indeed **a current bottleneck in the hydrogen economy**, especially for transport applications.

In this field, **available technologies such as compressed gas** and **liquefied gas** storage are considered to make a **low contribution to energy independence** (3.6 and 2.7/10 respectively) and **social acceptance** (3.3 and 3.5/10 respectively). This is consistent with the fact that compression or liquefaction of hydrogen needs additional energy. Metal hydride storage received good scores in social acceptance (6.3/10) but still suffers from low maturity (1.9/10). Metal hydride storage appears **less attractive for stationary applications**.

Regarding Europe's competitiveness for stationary applications, it is important to point out that 40% or more of the respondents answered "do not know" when asked which country is the current leader in this area.

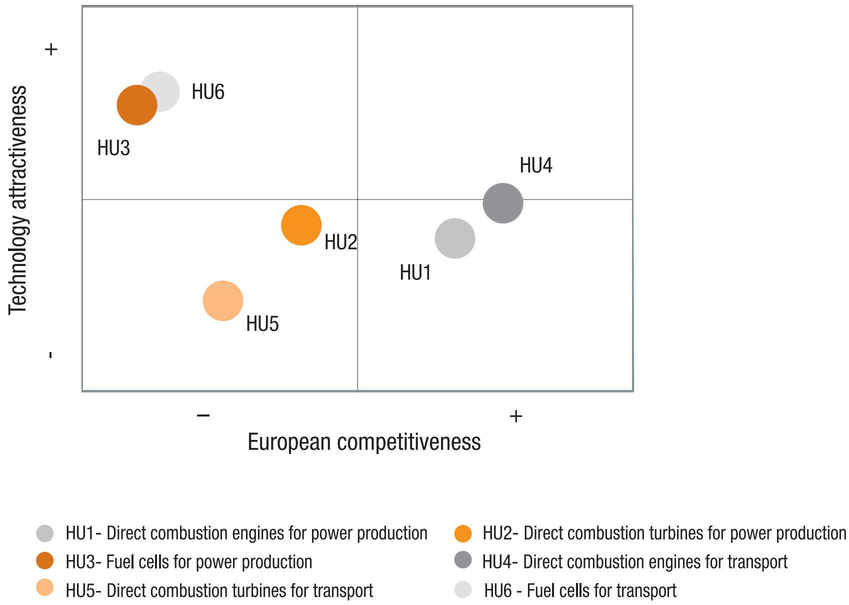
The situation appears clearer for transport applications, with Europe holding the **leading position in liquefied gas storage**, and the USA in **compressed gas**. For **metal hydrides**, both the USA and Japan appear to be **in a leading position**.

## Hydrogen utilisation technologies

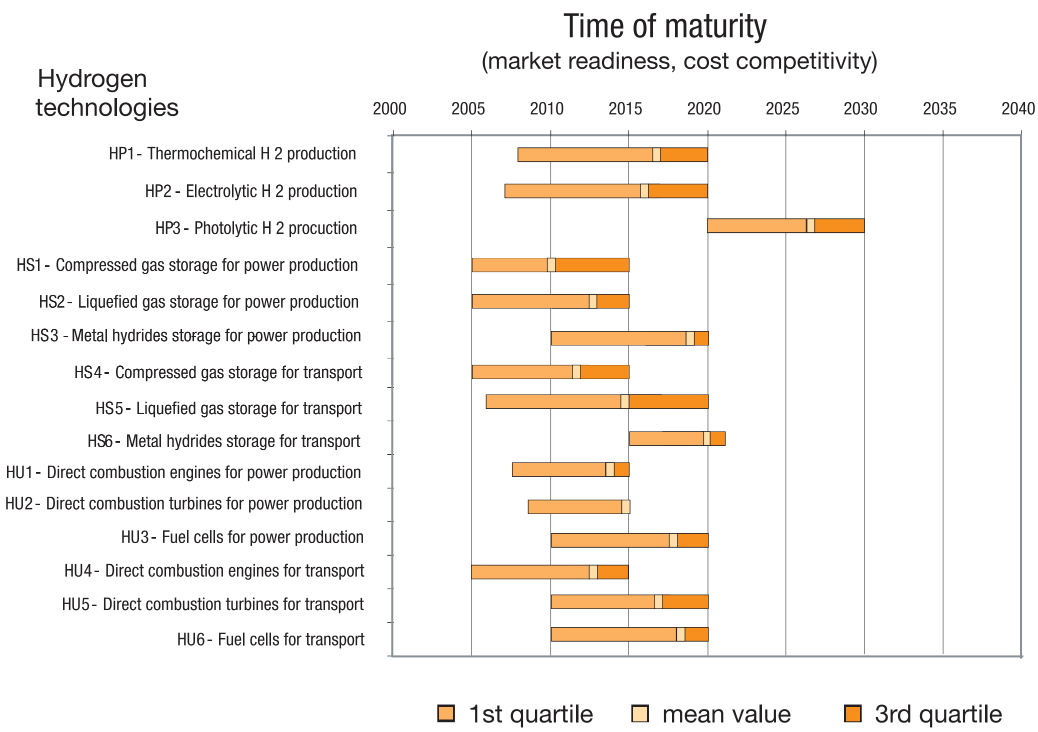
For both stationary and transport applications, **fuel cells appear to be the most attractive** hydrogen use technology with a global score of over 6.6/10, whereas the other technologies were given scores around or over 5. Europe's competitiveness is ranked very low in this field (just under 1) (cf. also the fuel cells chapter).

For **transport applications, direct combustion engines** may be of interest, since Europe is considered to be in a leading position for this technology, which benefits from average attractiveness.

It would seem that the use of **turbines for hydrogen** is not as well known as fuel cell or direct combustion engine solutions, since for most of the questions concerning this technology, around 50% (and sometimes more) of the respondents were not able to answer. In this area, the USA was given the leading position and turbines appear to be more attractive for stationary applications.

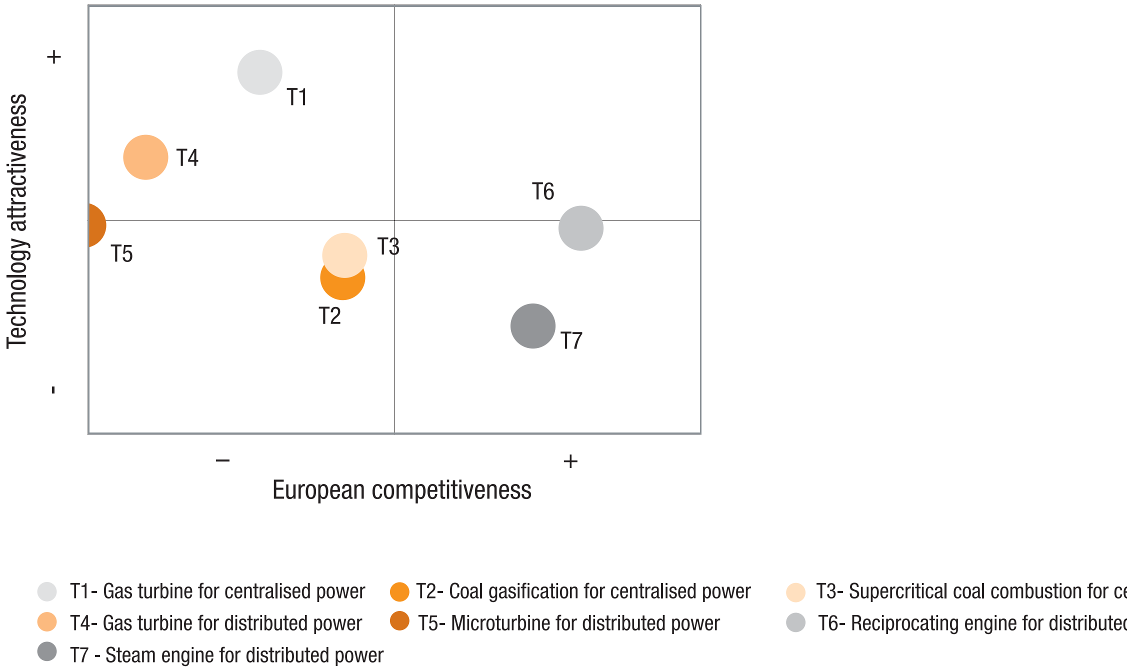


Technology attractiveness
+
-
European competitiveness
–
+
HU1
HU2
HU3
HU4
HU5
HU6
HU1- Direct combustion engines for power production
HU2- Direct combustion turbines for power production
HU3- Fuel cells for power production
HU4- Direct combustion engines for transport
HU5- Direct combustion turbines for transport
HU6 - Fuel cells for transport

Time of maturity
(market readiness, cost competitivity)
Hydrogen technologies
2000
2005
2010
2015
2020
2025
2030
2035
2040
HP1 - Thermochemical H 2 production
HP2 - Electrolytic H 2 production
HP3 - Photolytic H 2 procuction
HS1 - Compressed gas storage for power production
HS2 - Liquefied gas storage for power production
HS3 - Metal hydrides storage for power production
HS4 - Compressed gas storage for transport
HS5 - Liquefied gas storage for transport
HS6 - Metal hydrides storage for transport
HU1 - Direct combustion engines for power production
HU2 - Direct combustion turbines for power production
HU3 - Fuel cells for power production
HU4 - Direct combustion engines for transport
HU5 - Direct combustion turbines for transport
HU6 - Fuel cells for transport
1st quartile
mean value
3rd quartile

## Fossil fuel technologies




A trend common to all seven fossil-fuel-based technologies/applications is:

- the low scores for "contribution to environment protection" (ranging from 2.6/10 for steam engines to 5.8/10 for gas turbines)
- the very low scores for "contribution to energy independence" (ranging from 1.9/10 for steam engines to 3.7/10 for microturbines). Higher scores had been expected for the coal-based technologies (2.9 and 3.2/10), coal usually being considered as having a stronger "security of supply" potential than other fossil fuels since it is rather fairly distributed in the world. Such low scores are consistent considering that, of all the energy technology areas examined in this study, the family of fossil fuel technologies offers the worst environmental performance.

## Centralised power production technologies

Europe would appear to have low to average competitiveness in the three technologies examined, i.e. gas turbines, coal gasification and supercritical coal combustion. This result was expected for gas turbines in view of the USA's well-established leadership and market share in gas turbine technology.

In addition, the two coal-based systems show rather low attractiveness, mainly due to low scores for the "maturity" criterion and very low scores for the "social acceptance" criterion. The general opinion that "coal is dirty" is probably sufficient to explain the coal-based technologies' "social acceptance" scores (2.8 and 3.4/10), which are much lower than for gas turbines (7.8/10).

High scores for maturity (7.8/10), adaptability (8/10), and market potential (8.3/10) all contribute to positioning gas turbines at the highest attractiveness level on the chart.

The very low attractiveness of steam engines is the result of very low scores for "energy independence" (1.9/10) and "environment protection" (2.6/10).

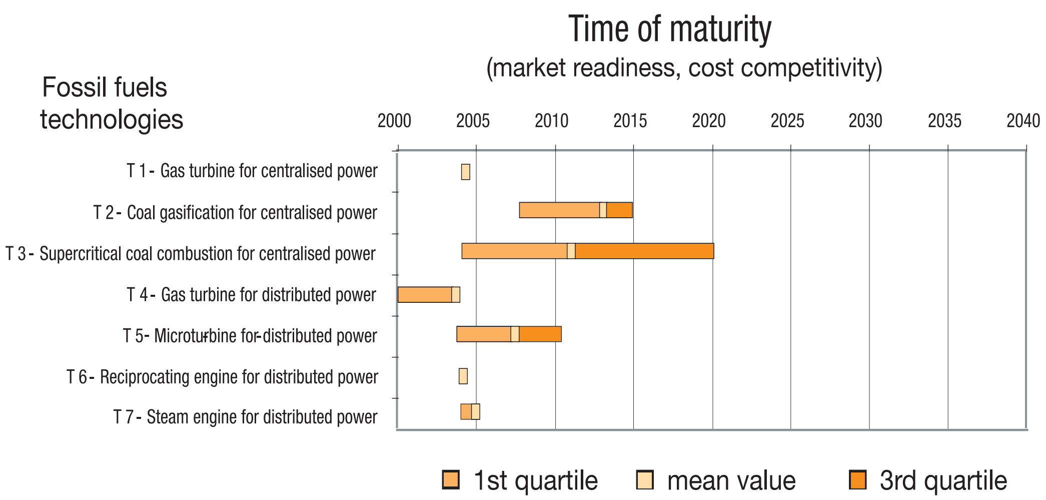
## Distributed power production technologies

Compared to those for centralised production, gas turbines for distributed production are considered slightly less attractive and are given a lower score for European competitiveness. They do, however, appear as the most attractive technology for distributed power generation, thanks to high levels of "maturity", "adaptability to market needs" and "social acceptance".

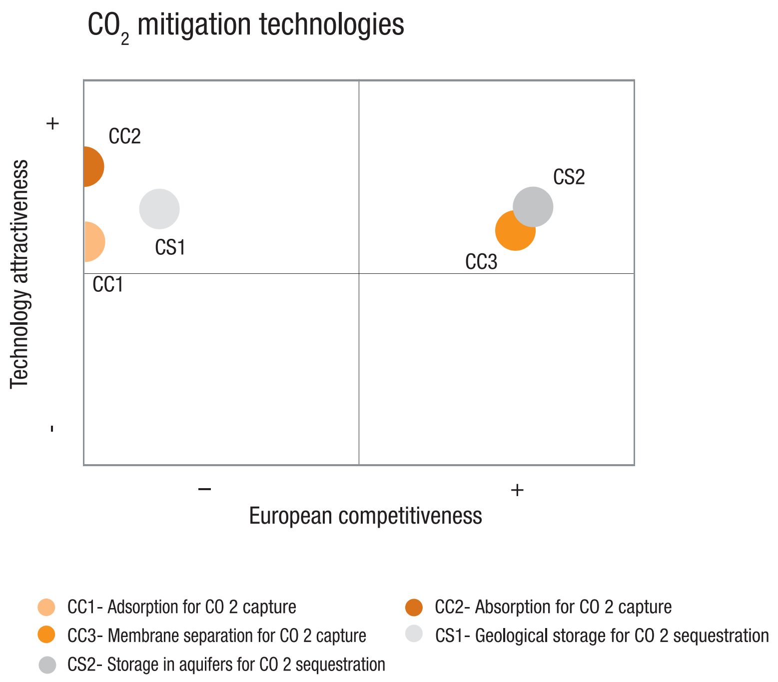
Although the attractiveness of both microturbines and reciprocating engines is equivalent, with an average score close to 5/10, the breakdown of the scores for each of the criteria is very different. Reciprocating engines have a higher score only for the "maturity" criterion (7.1/10 against 3.7/10 for microturbines), but score lower than microturbines for all the other criteria. Both technologies have a high "social acceptance" score (6.3 and 7.8/10).

Steam engines are by far the least attractive, mainly due to very low "environment protection" (2.6/10), "energy independence" (1.9/10) and "global market" (2.3/10) potential.

European competitiveness is highly contrasted depending on the technology. For both reciprocating and steam engines, Europe is considered to be in a leading position (7.5 and 7.8/10). On the other hand, Europe's competitiveness is extremely low for gas turbines (1.1/10), because of the US leadership mentioned earlier, and probably also because of the lack of small (<5 MW) gas turbine manufacturers in Europe. All of the respondents positioned the USA as the leader for microturbines, resulting in a score of 0/10. But although US manufacturer Capstone does have a dominant position (>80%) on the world microturbine market, a higher score would have been expected for European competitiveness considering that the two European makers – Turbec and Bowman – together hold over 80% of the market share in Europe.



## Carbon dioxide capture and sequestration technologies




## Capture technologies

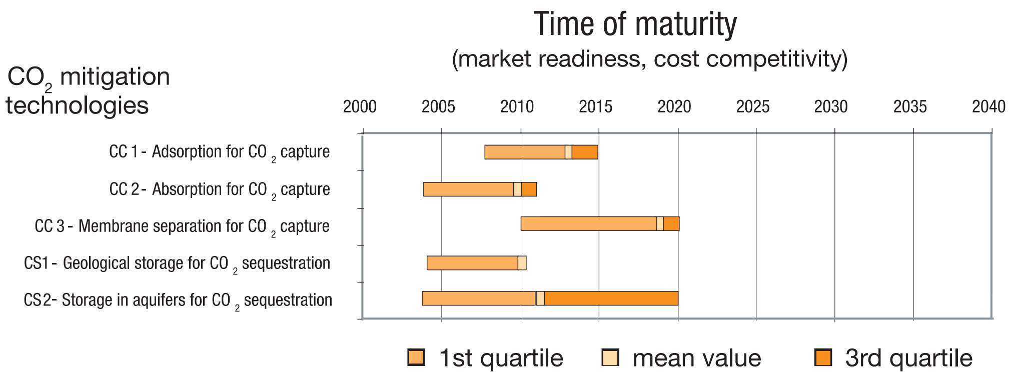
The three capture technologies are positioned with a high attractiveness level. The higher attractiveness of absorption technologies is mainly due to higher scores for the "maturity" and "adaptability to market needs" criteria.

Regarding European competitiveness, it is important to point out that 50% or more of the respondents answered "do not know" when asked which country/area is the current leader for each of the capture technologies suggested. In view of the two main manufacturers of absorption-based systems, Fluor (USA) and Mitsubishi (Japan), a very low score for Europe's competitiveness is essentially consistent. On the other hand, European competitiveness is considered to be high for membrane separation technologies.

## Storage technologies

Both geological storage and storage in aquifers appear equally attractive (6/10), whereas the European competitiveness score diverges significantly (1.4/10 and 8/10 respectively). The explanation for this is quite straightforward: the only commercial-scale geological storage unit in the world is operated in Canada (Weyburn) for EOR using $CO_2$ from the USA, whereas the only large-scale plant storing $CO_2$ in aquifers is located in the North Sea (Sleipner).

Looking at the attractiveness criteria, storage in aquifers was regarded as slightly more adaptable to market needs than geological storage.


Time of maturity
(market readiness, cost competitivity)
CO2 mitigation technologies
2000
2005
2010
2015
2020
2025
2030
2035
2040
CC 1 - Adsorption for CO 2 capture
CC 2 - Absorption for CO 2 capture
CC 3 - Membrane separation for CO 2 capture
CS1 - Geological storage for CO 2 sequestration
CS2 - Storage in aquifers for CO 2 sequestration
1st quartile
mean value
3rd quartile

European Commission

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All countries are facing the increasing challenges of climate change, depletion of fossil fuel resources and growth of global energy use. Europe competes with USA, Japan and other industrialised countries for finding the new energy technologies which their market will need, ensuring them technological edge and economic benefits.

In this context, this study provides a view of future trends, risks and opportunities for the short, medium and long term and a picture of Europe's comparative strengths and weaknesses in key energy technology areas, especially with respect to the USA and Japan.

These key technologies are:

- Fuel cells and hydrogen technologies
- Photovoltaic technologies
- Biomass-based technologies (utilisation of biofuels and biomass)
- Use of fossil fuels for heat and power (including technologies for carbon dioxide capture and sequestration technologies).

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