International Overviews

RESEARCH PRIORITIES AND PROGRESS IN HYDROGEN ENERGY RESEARCH IN THE EU

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ABSTRACT

The European Commission (EC) fosters and funds under its multi-annual work programme – currently the Seventh Framework Programme (2007-2013) - research, development and demonstration activities on hydrogen and fuel cells. It has also successfully mobilised key European stakeholders via the establishment and operation of the industry-led European Hydrogen and Fuel Cell Technology Platform and most recently with the launching of its follow-up, the Fuel Cells and Hydrogen Joint Technology Initiative (JTI). The JTI is a long-term public-private Joint Undertaking to be funded by the European Community and an Industry Grouping. The aim of the JTI is to explore the potential and accelerate the development and deployment of these key technologies at European level, through integrated, focused actions, with a vision of clean, affordable and secure energy systems based on hydrogen as an energy carrier and fuel cells as energy converters.

The current paper highlights some illustrative EC co-financed R&D projects on hydrogen technologies, the role of materials research in them and their key achievements. It also includes a brief overview of the enabling, supporting functions assumed in this research field by the Commission's Joint Research Centre and in particular by the Institute for Energy. An outlook on hydrogen energy research and respective priorities in the Seventh Framework Programme and under the Fuel Cells and Hydrogen JTI, is also discussed.

INTRODUCTION

The European Union[1] (EU) is a unique, treaty-based, economic and political partnership between currently twenty seven member states. It aims at peace, prosperity and freedom for its almost 500 million citizens. The EU affairs are regulated by a number of Institutions - primarily the European Parliament, representing the people of Europe, the Council of the European Union, representing national governments, and the European Commission. The European Commission is independent of national governments and it embodies the common EU interest as a whole. It is the executive arm of the EU, drafts proposals for policies and it has the sole right to initiate legislation. It also ensures that all abide to European treaties and laws and manages the day-to-day running of the EU.

The EC is divided into Directorate Generals (DGs) handling a number of policy areas and portfolios, such as agricultural policy and economic development, trade, competition, environment, consumers and health, humanitarian aid, energy. Several of these DGs have mandates related to research and development, science and technology. In particular, the following have responsibilities linked to Hydrogen and Fuel Cells (H_2/FC) activities: DG Transport and Energy, DG Enterprise, DG Environment, DG Education and Culture, DG Research and the Joint Research Centre (JRC). DG Research oversees the European Research Area initiative[2], manages the EU Research Programme and administers the respective budget. The JRC with its research activities and services supports the EU policy making. It contributes to the development and operation of an EU scientific reference system for underpinning policy decisions. JRC's knowledge comes by networking within Europe and globally, and from specific application- and issue-oriented research within its seven Institutes. The JRC Institute for Energy focuses on energy issues and runs the JRC Hydrogen and Fuel Cells research activities.

Research and development in this area is also funded, within Europe, regionally, nationally, and by the industry, however the present document concentrates on EU funded H_2/FC activities. The

European Commission (EC) fosters and funds under its multi-annual work programme – currently the Seventh Framework Programme (FP7: 2007-2013) - research, development and demonstration activities on energy-related issues and on hydrogen and fuel cells. Here we present the highlights of some illustrative EC co-financed R&D projects on hydrogen technologies, with emphasis on the related materials research issues, and on the projects' key achievements. Following the recent developments in the energy research policy field, H_2/FC will be covered in the near future only under the industry-led "Joint Technology Initiative" (JTI) and its corresponding "Joint Undertaking in Fuel Cells and Hydrogen". This Undertaking will be responsible for defining the short, medium and long term research agenda on H_2/FC. In what follows we give a brief account of the rationale and the steps to the proposal of the JTI, as part of the evolution of the EU energy policy framework.

EU ENERGY STRATEGY & THE CASE FOR HYDROGEN AND FUEL CELLS RESEARCH

EU Energy Policy – Rationale and Recent Developments

The EU has a strong dependence on fossil fuel sources, while its hydrocarbon reserves are running down and cannot even satisfy the current demand. As a result, the EU is obliged to import 50% of its total energy consumed. This, in geopolitical terms, means dependence on two regions - 45% of oil imports come from the Middle East and 40% of natural gas comes from Russia. According to projections, over the coming years, primary energy production in Europe will decline while demand is going to grow further. Prices for oil and gas are steadily increasing, making the situation more uncomfortable. Moreover, considerable investments are needed to replace the EU ageing infrastructure for balancing the energy supply with the demand. The picture becomes more complicated considering that energy production and use, at the moment, account for 80% of all greenhouse gas (GHG) emissions. These emissions contribute to global warming which has already made the world 0.6°C hotter in the past 100 years, according to the UN Intergovernmental Panel on Climate Change (IPCC). Continuing with the current trend, and for a 'business as usual' scenario, by 2030 energy imports will be climbing to 65% of total consumption in the EU, the electricity demand will raise by 1.5% per year while the greenhouse gas emissions will increase by 55%. This clearly has economic, social, environmental and physical risks for the EU.

For tackling this situation and fulfilling the EU vision for an efficient, diversified, decarbonised energy future, the EU leaders, being inspired by the EC Green** Papers[3] and following the EC proposal[4], decided to combine action at European and member states' level. They therefore endorsed an EU-integrated approach to climate and energy policy, the 'Energy Policy for Europe' (EPE), in March 2007. The EPE has a comprehensive package of measures, the 'Action Plan' 2007-2009, attending to priorities, while respecting the Member States' choice of energy mix - the share of coal, nuclear, gas or renewables – and sovereignty over primary energy sources. The priorities addressed are the internal gas and electricity market, the security of energy supply and the response to potential crises. EPE also makes concrete recommendations for expanding and strengthening the EU's international energy relations by speaking with a 'common voice'. Moreover, it sets highly ambitious quantified targets: the so-called 20%s by 2020 – 20% reduction of GHG emissions, 20% energy efficiency improvements and 20% renewables in the energy mix (with 10% biofuels in transport).

To assist the implementation of the Action Plan, the EC proposed a coordinated set of strategic actions on a number of key technologies, under the European Strategic Energy Technology (SET) plan[5]. This was recently endorsed (28th February 2008) by the EU Energy Ministers. The technological sectors identified can be instrumental in reaching EPE's objectives and are those for which the barriers, the scale of the investment and risk involved can be better tackled collectively. Examples are: second generation biofuels, CO_2 capture and storage, wind energy, solar energy, fission, energy storage technologies, fuel cells and hydrogen, etc. EU efforts in these areas are currently scattered and fragmented. The SET plan aims to coordinate them and exploit the added value of European-level intervention by mobilising the critical mass of R&D investment from public and private sources and coupling research tightly to innovation. It also establishes a watch and alert European Energy Technology system, and ensures better communication and correspondence between developments in these technologies and energy policy goals. The tools proposed for implementing these actions are the 'European Industrial Initiatives' - strategic technology alliances between researchers, key economy operators and decision makers at different levels. One form for such an alliance are the Joint Technology Initiatives (JTIs), introduced in FP7. The JTIs are long-term public-private partnerships, with industry in the lead, for technology fields of high industrial and policy relevance across Europe and therefore prioritised as such by all member states. They ensure a long-term work programme, guarantee linking of fundamental research and demonstration projects and an agreed, long-term budget plan and strategy – these are prerequisites for the industry to commit more resources.

H_2/FC research under the JTI, beyond 2008

The Fuel Cells and Hydrogen Joint Technology Initiative was adopted by the Commission on the 9th of October 2007[6]. The Commission is expected to fund M€ 470 from the FP7 programme for a period of six years with at least the matching amount coming from the private sector. The JTI will be established as a Joint Undertaking for a period of ten years with its seat in Brussels. The founding members are the European Community represented by the EC and the Industry Grouping, a non-profit association of European industry interests. A similar grouping representing the research community will also be formed and will become member of the JTI. The Fuel Cells and Hydrogen JTI aims to boost the development of hydrogen technologies to the point of commercial take-off between 2010 and 2020. It will do this via the implementation of streamlined, basic and large-scale, industrial and applied R&D activities, demonstration and support actions focused on the most promising applications. This is in line with the needs identified by the JTI's predecessor, the European Hydrogen and Fuel Cell Technology Platform (HFP)[7] and its vision for hydrogen and fuel cells, as seen in its "Deployment Strategy" document. Extracted from this document is the so-called "Snapshot 2020" with market forecasts for H_2/FC technologies in all end-use applications, stating what is needed to move technology from prototype through demonstration to commercialisation by 2020.

Table I. Key assumptions on Hydrogen and Fuel Cell Applications for a 2020 reference market scenario ("Snapshot 2020") for the Implementation Plan – references 7, 8

	Portable FCs for handheld electronic devices	**Portable Generators & Early Markets**	**Stationary FCs** Combined Heat and Power (CHP)	**Road Transport**
EU H2/ FC units sold per year projection 2020	~ 250 million	~ 100,000 per year (~ 1 GW_e)	100,000 to 200,000 per year (2-4 GW_e)	0.4 million to 1.8 million
EU cumulative sales projections until 2020	n.a.	~ 600,000 (~ 6 GW_e)	400,000 to 800,000 (8-16 GW_e)	1-5 million
EU Expected 2020 Market Status	**Established**	**Established**	**Growth**	**Mass market roll-out**
Average power FC system	15 W	10 kW	<100 kW (Micro HP) >100 kW (industrial CHP)	80 kW
FC system cost target	1-2 €/ W	500 €/kW	2,000 €/kW (Micro) 1,000-1,500 €/kW (industrial CHP)	< 100 €/kW (for 150,000 units per year)

The JTI Work Programme will be built to achieve this scenario in line with the HFP devised Strategic Research Agenda and the respective Implementation Plan[8] for applied R&D and demonstration actions. The ultimate aim is to pave the way for the realisation of the High Level Group*** (HLG) vision for Europe in 2050[9], through activities concentrating on four main Innovation and Development Actions, IDA's, as defined in the Implementation Plan. These are all necessary, comprehensive sets of actions for technology development and acquisition that have to happen by 2010 and 2015 in order to achieve a timely, smooth transition from now to 2020 for the market entry of transport, stationary and portable hydrogen and fuel cell applications. From now on, all EU funded research work related in the field of Fuel Cells and Hydrogen will fall under the umbrella of the JTI

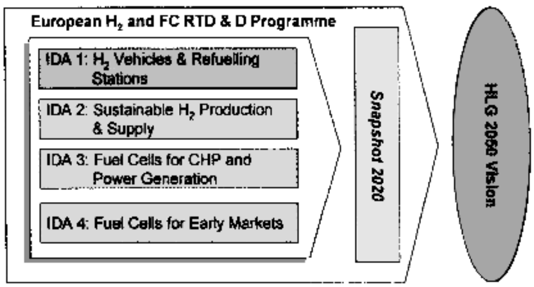


Figure 1. Key elements of the European Hydrogen and Fuel Cell Research and Technological Development and Demonstration Programme for meeting the "Snapshot 2020" targets and the 2050 Vision of the High Level Group

Concerning regulatory issues for the establishment of the Fuel Cells and Hydrogen JTI, on the 25th February 2008, the EU Competitiveness Council reached an agreement of the main elements for its launching and the final decision is expected still by summer 2008. In the mean time and to ensure a quick start-up of the activities, a 'bridging structure' has been put in place and the first call for proposals is planned immediately after the Council decision[10].

HYDROGEN ENERGY EU FUNDED RESEARCH

As stated earlier, research on hydrogen and fuel cells has been co-funded over the years through the EC multi-annual work programme, the so-called Framework Programme (FP): the main EU instrument for funding RTD activities since 1984. We are currently in the Seventh Framework Programme[11], which has a number of novelties compared to the previous FPs. FP7 is of longer duration (2007-2013), with an increased annual budget and a new structure. It also has novel mechanisms for managing R&D – the European Research Council[12] dedicated to Frontier Research issues; the Technology Platforms on a number of selected areas for defining R&D priorities and the newly created JTIs. It should be also mentioned here that the EC is a member in the International Partnership for the Hydrogen Economy[13] (IPHE), since its establishment in 2003. The IPHE is leveraging international funds and it is coordinating focused international research, development, demonstration and commercial utilisation activities for advancing the transition to the hydrogen economy. Many European-funded projects have already gained IPHE recognition for their lead and innovation level in the area of hydrogen and fuel cells research.

Over the successive Framework Programmes for research, the European Commission has increased its financial support to fuel cells and hydrogen, rising from M€ 8 in FP2 (1986-1990) to M€ 315 in FP6, with a total of M€ 558 invested in the field from 1986 to 2006, matched by an equivalent amount of participating stakeholder investment. To put things in perspective, the EC will contribute, over six years, M€ 470 to the Joint Undertaking- the legal entity entrusted with the coordination and the efficient management of the funds committed to the JTI, and the private sector will at least match this amount.

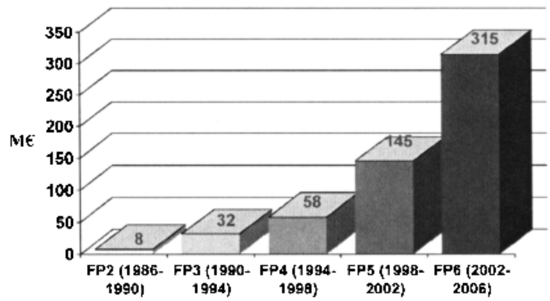


Figure 2 EC Support to Fuel Cell and Hydrogen RTD in Framework Programmes

Looking at the most recent programme, the FP6, more than eighty H_2/FC projects[13] were funded with a significant part of this funding dedicated to transport applications, to the hydrogen production and distribution, to validation and demonstration activities and then to storage of hydrogen. A balanced approach to fundamental and applied research and demonstration was always sought, and attention was paid to better coordination among national and regional research programmes.

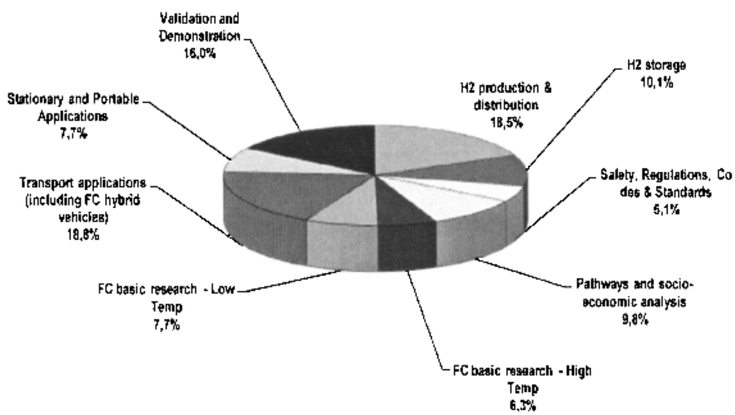


Figure 3. FP6 budget breakdown for H_2/FCs - total EC Contribution ~M€ 315

From all these projects, there are several worth mentioning as a result of their achievements, however our present overview only addresses the salient points of some illustrative examples. Emphasis, as stated earlier, is placed on those projects where materials issues took centre stage in the research activities or material innovations were considered instrumental for further progress. A more detailed account of the recent achievements of the currently running EU hydrogen and fuel cells projects can be found in a recent publication[15] discussing the highlights from these projects, as presented in the Review Days'07 Meeting[16] co-organised by the EC and the European Hydrogen and Fuel Cell Technology Platform.

Hydrogen Research Projects

A number of strategic research topics were pursued for hydrogen in FP6[14] but are also still central to the current FP7. These are summarised below.

(i) Clean, competitive and sustainable production of hydrogen from existing and novel processes including the techno-socio-economic assessment.

(ii) Preparing for a transition to a hydrogen energy economy – aiming at the consolidation of efforts on hydrogen pathway analysis and road mapping and exploration and sharing the wealth of information coming from the significant investment made in the field. This way the researchers can underpin sound transition strategies and provide a rational basis for policy decisions and market framework development. This proved to be an excellent field for joining forces also at international level, as was demonstrated by the IPHE recognised projects - the European led HYWAYS[17] - development and detailed evaluation of a harmonized European hydrogen energy roadmap, the Clean Urban Transport for Europe (CUTE[18]); and the Ecological City Transport System (ECTOS[18]).

(iii) Safety - in a sustainable hydrogen energy economy this is paramount for the introduction of new technologies for hydrogen storage and energy conversion. In the absence of harmonised European and worldwide regulations, codes and standards, pre-normative research and development were and still remain essential. Projects around these lines made a contribution towards filling knowledge gaps and supplying the necessary information for certification issues (see storage vessels) and preparation for regulations, codes and standards (RCS) at EU and global level. They also offered the opportunity to form strong international partnerships for solving such pre-competitive issues. Illustrative examples are the safety recognised IPHE projects, HYSAFE[19] (Safety of Hydrogen as an Energy Carrier), and Fuel Cell Testing, Safety and Quality Assurance (FCTES[QA])[20].

(iv) Basic materials research - a number of fundamental issues were addressed such as the development of functional materials for electrolysers and fuel processors, novel materials for hydrogen storage and separation membranes and purification. For instance, components, materials for steam reforming and contaminants removal; more stable ion-conducting electrolytes for high temperature electrolysis cells and new materials for advanced performance electrolysers; new materials for high temperature reactors.

An illustrative example is the HI2H2[21] (Highly efficient, High temperature, Hydrogen production by Water Electrolysis, coordinated by EdF, France, 2004-2007). HI2H2 was checking the feasibility of increasing the efficiency of the electrolysis up to potentially 90% by using a planar Solid Oxide Electrochemical Converter, based on material cell components and fabrication processes of advanced thin-film SOFC technology. It also analysed the limitations and degradation mechanisms of such cells, in order to develop new corrosion resistant materials (cells, membrane, interconnects) to be used in high temperature electrolysis mode. The project, completed now, achieved a remarkable performance and durability for single cells. However, teething issues such as cell degradation, due to sealant problems, and heat management, particularly for scale-up applications to the level of MW plants, remain to be addressed as part of a possible future strategic research in this field.

(v) Hydrogen storage - exploring innovative methods, including hybrid storage systems, which could lead to breakthrough solutions, particularly for the most demanding on-board storage for road transportation. In spite the technical progress made, none of the storage options can satisfy the stringent requirements. A number of scientific and technical issues related to materials, which could make a difference, were identified.

(v.1) Gaseous storage: there is still the need to develop high strength fibres and liners impermeable to hydrogen for use in vessels that can allow higher pressure tanks, under safe conditions, for longer driving range road vehicles; address the issue of up-scaling, recycle-ability of materials and develop cost and time effective laminating processes.

(v.2) Liquid storage: the issues of high energy penalties due to liquefaction and boil off remain unsolved, whereas materials research could enable the exploration of novel insulations and the building of the next generation of cryogenic lightweight/low volume tanks.

(v.3) Solid state storage: this is the area where materials are indeed the focal point: it was shown that passing efficiently this technology from the laboratory to application requires a lot more than our current limited understanding of the mechanisms of chemi- and physi-sorption of hydrogen in the different material classes. Therefore the need for fundamental research is still pressing. Under hydrogen storage, the EC has funded five FP6 projects and three research training networks (investing around M€ 32 in grants) for educating the future technologists – all of them are still running. NESSHY[22] was recognised by the IPHE as a leading international project. Under FP7, a new collaborative project (around M€ 2.4) started in January 2008: this is NANOHY (Novel Nanocomposites for Hydrogen Storage Applications), coordinated by FZK, Germany.

Table II. EU funded research projects on hydrogen storage under FP6 and FP7

Project Acronym	Co-ordinator	Duration (months) Running since	Topic	EU indicative funding (M€)
Hydrogen Storage Projects under the Energy Programme				
STORHY	Magna Steyr, Austria	54 since 01/03/04	Next generation storage technologies for vehicle on-board applications	10.7
NESSHY (+ HYSIC)	NCSR Demokritos, Greece	60 since 01/01/06	Novel efficient solid storage for hydrogen	7.5 (+ 0.3)
NANOHY (under FP7)	FZ Karlsruhe, Germany	45 since 01/01/2008	Novel nanocomposites for hydrogen storage applications	2.4
Hydrogen Storage Projects under the Materials Programme				
HYCONES	NCSR Demokritos, Greece	36 since 01/11/06	Hydrogen storage in Carbon cones	1.55
SURMOF	Rhur University, Germany	36 since 01/10/2006	Anchoring of MOFs to surfaces	2.5
MOFCAT	SINTEF, Norway	36 since 01/09/2006	Functional MOFs as heterogeneous catalysts and adsorbents	2.2
Research Training Networks (RTN) on Hydrogen Storage under the Marie Curie Programme				
HYTRAIN	University of Salford, UK	48 since 01/01/2005	Mg-based, complex hydrides (e.g. alanates,borohydrides), novel light hydrides (Li nitrides, amides)	2.65
COSY	GKSS, Germany	48 since 01/11/06	Sorption kinetics and reactive hydride composites, for energy efficient hydrogen storage	2.5
HYDROGEN	Leiden University, Netherlands	48 since 01/09/06	Alanates, borohydrides, & new material classes in form of ammonia	3.54 (only 50% to H_2 storage

The hydrogen storage portfolio covers on-board and off-board hydrogen storage systems and it has basic research and application-oriented projects. STORHY[23], "Hydrogen Storage for Automotive

Application", is one of the automotive application projects aiming at developing robust, safe and efficient on-board hydrogen storage systems, suitable for use in hydrogen fuelled FC or ICE vehicles. It addresses all three hydrogen storage solutions: high pressure compressed gas ($C\text{-}H_2$), cryogenic liquid ($L\text{-}H_2$), and solid concentrating on advanced alanates. STORHY has thirty four partners coming from thirteen European countries and a total budget of M€ 18.7 (EC contribution: M€ 10.7). It is near to completion now and it has so far the best performing solution for $C\text{-}H_2$ and $L\text{-}H_2$. For the 700 bar hydrogen pressure tank, STORHY data reach capacities of 4.5 wt.% (for 2.4 kg H_2/100 l, at system level) and for $L\text{-}H_2$, 14 wt.% (corresponding to 4 kg H_2/100 l) at system level for metal design, and even up to 18 wt.% with advanced composite materials [15-16].

However, there is still room for improvement on all storage solutions with respect to a comprehensive safety assessment of the technologies using probabilistic theory tools; tackling energy and storage losses through evaporation-liquefaction of the gas and 'boil-off'; addressing issues of permeability and tank design optimisation using theoretical simulations. New designs, new concepts need to be certified to be commercialised, and they require validation and possible changes in regulations, codes and standards. Finally, environmental issues, recycle-able materials and ultimately overall costs, need to be also addressed. There is a need for fundamental research and understanding of material properties for reducing ageing, fatigue and associated failure in gas cylinders and also for liner materials. Hydrogen compression for increasing the volumetric energy in $C\text{-}H_2$, is a rather mature technology nowadays but remains energy consuming; it reduces the total system efficiency and adds to the overall expense of this technology. Further work may be required on the development of compressors considering new materials, improved efficiency, and even more compact designs. Any additional cost reduction, particularly for up-scaling, calls for completely novel industrialisation concepts. For $L\text{-}H_2$, STORHY demonstrated a compact, light, free-form tank design with improved conformability for vehicle integration and with considerable potential in combination with new hydrogen ICE. Nevertheless, the overall cost is still prohibitive for commercialisation.

Concerning solid-storage, the state-of-the art in Europe is at the moment with the FP6 project NESSHY, recording for alanates, and at room temperature, a maximum of 1.8 wt.% and higher values for 80-100°C. Despite being the safest and most energy saving method, because of these storage capacities and the inadequate overall performance with respect to a number of technical and economic criteria, solid-state storage is far away from the targets for transport applications[15]. What is still required are novel materials with improved storage densities, kinetics and thermodynamic behaviour, to make the difference. The researchers need to adapt a multi-disciplinary approach and explore the full potential of theoretical modelling, experimentation and the lessons learnt from fundamentals and basic research. As an example HYCONES[24] is looking at the improvement of hydrogen sorption properties of carbon cone materials through a better understanding of the hydrogen-carbon interactions. NESSHY itself uses diverse analytical, computational and characterisation tools and pools resources from twenty two partners in twelve European countries and the USA. Moreover, NESSHY organises integrating activities amongst its partners, coordinated by the JRC-IE. These aim at the establishment of a common European infrastructure, a Virtual Laboratory, for exchanging and sharing experimental data, measurement techniques, for calibration purposes, standardisation and for addressing safety issues. As part of these activities, inter-laboratory comparison exercises are currently running and a database is being developed for the management of the experimental material properties data generated in the project and of the physical and engineering data required for the tank design.

Fuel Cells, Systems and Applications - Research Projects

A number of strategic research topics were pursued for fuel cell systems in the EU funded projects, ranging from basic research to validation and demonstration activities for gaining 'field experience'. All activities were targeting systems which could be commercially viable by 2020 for many applications, with focus on the high temperature technologies (mainly Solid Oxide, SOFC) and low temperature technologies (mainly Polymer Electrolyte, PEFC)[14-16]. The most challenging objective for Fuel Cells research was, and still remains, the reconciliation of the cost and the high performance, durability, safety and reliability, for making the FC technology competitive with conventional technologies. The key areas addressed were:

(i) Cost – investigation of possibilities for cost reduction with respect to materials and processes; looking for low cost materials and inexpensive electrolyte membranes and catalysts and minimising the use of precious metals. Examples of such approaches we find in the road transport applications projects for developing high temperature PEMFC (Proton Exchange Membrane Fuel Cells) operating at 130-200°C [see FCANODE (2007-2010)] but also low temperature PEMFC (see FURIM[25]). AUTOBRANE[26] – Automotive High Temperature Fuel Cell Membranes (running 2005-2009; coordinated by DaimlerChrysler)-is aiming at developing apart from catalysts also Membrane Electrode Assemblies (MEAs) for high temperature automotive applications. First tests on perfluorosulphonate ionomeric MEAs and on inexpensive catalysts have not yet resulted in any promising alternatives. To effectively tackle such persisting problems, projects in this field are inter-collaborating. For instance, AUTOBRANE is in close contact with two other Consortia also IPHE recognised for their leading research programmes, namely: CARISMA[27] (Coordination Action of Research on Intermediate and high temperature Specialised Membrane electrode Assemblies; 2007-2009) - and IPHE-GENIE (IPHE for GENeration of new IonomEr membranes, started in December 2006) which aims at developing an AUTOBRANE-relevant MEA using materials and methods complementary to those of AUTOBRANE.

(ii) Durability - material development to guarantee performance in terms of corrosion resistance and exhaustion of catalytically active components; reduced ageing and ruggedness in everyday operation, long lifetime, low degradation, tolerance to impurities. And these refer also to stacks and balance of plant components. Projects were also asked to address mechanical durability (40,000 hours for stationary applications and "maintenance free for life" for smaller portable units)[14-16]. Examples of projects looking at such issues are REAL-SOFC[28] (2004 -2008) for 600-800°C operation and the IPHE recognised SOFC600[29] (2006-2010) looking at operation at 600°C. They investigate generic problems with planar Solid Oxide Fuel Cells (SOFC) in a concerted action involving the European fuel cell industry and research institutions. They resort to methodical material research to achieve enhanced lifetimes, ease of operation, cost effectiveness and sustainability. Unfortunately the results so far do not demonstrate any significant improvement on performance with respect to voltage (and efficiency) degradation[15]. Nevertheless one of the valuable lessons learnt is the need for agreeing on standard definitions of requirements and of indicators with respect to degradation.

(iii) Upscaling and manufacturing – projects were targeting standardised, mass-production, high volume manufacture at lower costs, at material and component level. They looked at ways for optimising and simplifying FC components while keeping a high standard performance. Their investigations showed that there is a need for using new analysis tools and quality assurance methodologies for controlling the industrialised process.

(iv) Weight and packaging issues- this was more challenging for portable applications which require the miniaturisation of the fuel cell stack and balance of plant components at application level. Issues such as components integration and thermal, air and water management were seen as instrumental for moving the technology to the next level.

HYTRAN[30] (2004 -2009), "Hydrogen and Fuel Cell Technologies for Road Transport", coordinated by Volvo Technology Corporation, is addressing such issues when integrating components and subsystems into two innovative fuel cell system platforms: one for traction power by an 80 kW direct hydrogen PEM fuel cell system implemented on a passenger car and the other one for Auxiliary Power Units of 5 kW including a micro-structured diesel oil steam reformer, clean-up reactors, a reformate hydrogen stack and balance of plant components. This project gives the opportunity to identify technological bottlenecks, and to test-drive and characterise the existing state-of-the art and finally identify research and development gaps for reaching the targets.

(v) Performance characterisation and benchmarking of materials/systems/components.

One of the conclusions drawn from the projects funded in this area, was that it is imperative to use advanced predictive modelling and simulation tools to complement and refine the experimental work. Equally important is the development of testing and characterisation protocols for sufficient testing capacity and comparative assessment of materials, cells, stacks, components and sub-systems. Indeed, as demonstrated by the REAL-SOFC project, which was recently completed, standardisation issues are critical for the materials and component development. To systematically research this field, particularly when several laboratories are involved, as is the case in these multi-partner projects, it is essential that a coordinated testing programme is drawn to effectively mobilise all. The testing conditions must be standardised and the respective handling and testing protocols have to be agreed in order to ensure comparability of the results between different laboratories and to enable sharing of testing resources. Reproducibility and quality assurance are critical for having reliable data. This is an element of great importance and recognised as such also in the work performed at the Institute for Energy of the Joint Research Centre of the European Commission.

The JRC-IE specific H_2/FC experimental programme

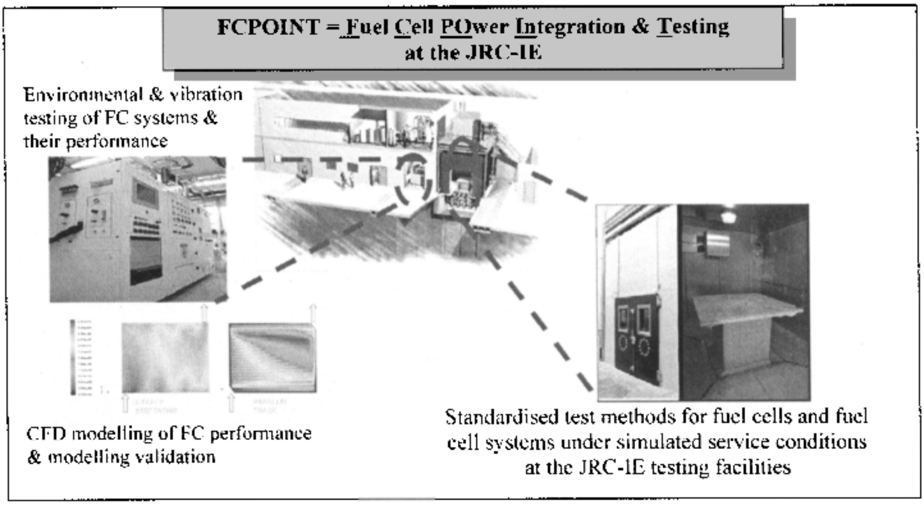
The JRC-Institute for Energy supports the EU energy policy by conducting desktop and experimental activities focused on impact evaluation, assessment and benchmarking of new energy technologies, and hydrogen, in terms of efficiency, safety, reliability and environmental performance. The JRC-IE institutional work is carried out under the umbrella of the EC RTD Framework Programmes. Its output is most appreciated where a European perspective and independence of commercial and national interests are essential. It comes in the form of technological studies or scientific data originating from its state-of-the-art facilities. JRC-IE is aspiring to establish and operate EU reference laboratories for fuel cell, hydrogen storage and safety sensors pre-normative research and performance verification, within the European Research Area, open to the scientific community and industry. The facilities and the activities followed are designed to support developments in Regulation, Codes and Standards (RCS) and to carry out testing campaigns under EU-funded research projects in the related fields.

There are two research projects currently running at JRC-IE relying on experimental facilities for hydrogen storage and fuel cell testing, namely the FCPOINT[31] (Fuel Cell POwer chain Integration and Testing) and SYSAF (SYstemS for Alternative Fuels)[32]. Both are well positioned within their respective area of expertise by networking and collaborating in a number of EU funded research projects, and at international level (participation in the International Energy Agency, Hydrogen Implementing Agreement and in IPHE activities and IPHE recognised projects).

FCPOINT conducts pre-normative research on the validation and benchmarking of test methods for the operational assessment of fuel cells. It also performs testing on fuel cell systems to evaluate their performance in terms of efficiency and emissions and their integration into the power chain. This is done within the EU projects FCTESTNET[33]/FCTES^{QA}, FCANODE and DECODE. A set of fuel cell testing protocols (single cells, stacks and systems) for transport, portable and stationary applications were actually established under the JRC-IE implemented project FCTESTNET. In the mean time, these test procedures are applied by SOFC600 and they are currently under validation within the FCTESTNET follow-up project: FCTES^{QA}. The latter focuses on safety and quality assurance. Its results and gap analysis for pre-normative research on RCS for fuel cells will be disseminated to IPHE members and to international standardisation bodies by the FCTEDI (IPHE recognised project: "Fuel Cell TEsting and Dissemination").

The fuel cell test facility of FCPOINT, where all this activity is performed, allows characterisation of the electrical and environmental performance of Polymer Electrolyte Fuel Cell

(PEFC) stacks, components and entire systems, in off-grid, and grid-connected configurations, with a capacity of up to 100 kW electrical power output. The facility consists of an automated and computerised fuel cell test station, gas analysers, a multi-axial vibration system which is housed in a walk-in environmental chamber (for controlling temperatures, humidity, shocks and vibrations) and ancillary equipment. The data obtained are complementary to and validate fuel cell simulations and models with reference to operation modes, components and system characteristics[31,32].



To facilitate the hydrogen market penetration, it is imperative to establish, benchmark and validate new concepts and technologies also for the safe, efficient, reliable storage and handling of hydrogen. This involves the harmonisation of measurement methods and test protocols for assessing the performance and potential of the different hydrogen storage media and respective solutions in different applications. Such results of pre-normative research could make a valuable contribution to standardisation in the field and support the EC policy makers. They also make available to the industry validated, harmonised information and evaluation tools for designing or assessing the performance of hydrogen storage systems. This is the SYSAF rationale for its work programme which has three experimental pillars covering the high pressure gas storage, the solid-state storage systems and the hydrogen detection by means of safety sensors. There is also a SYSAF task on computational fluid dynamics modelling for the validation and interpretation of the data, particularly with respect to safety.

SYSAF performs part of its activities within European funded and IPHE recognised research projects. The work under the safety and performance assessment of hydrogen commercial sensors, for on-board applications, is conducted under the Network of Excellence HYSAFE [19]. This is done in the form of round robin testing with European partners. The safety sensors are tested at the JRC-IE in-house built Sensors Testing Facility (SenTeF). This facility consists of an automated test bench for gas sensors constructed based on the functional requirements derived from market and gap analyses. The testing parameters investigated are the sensors reaction time, lifetime, sensitivity, specificity, as well as their stability under various environmental parameters (temperature, humidity and altitude), in accordance to the guidelines given by the existing IEC standard for the detection and measurement of flammable gases. The results of the round robin tests checking the practical applicability of the proposed procedure will be fed to the ISO TC197/WG13 on "hydrogen detection apparatus" for the reviewing of the testing methodology.

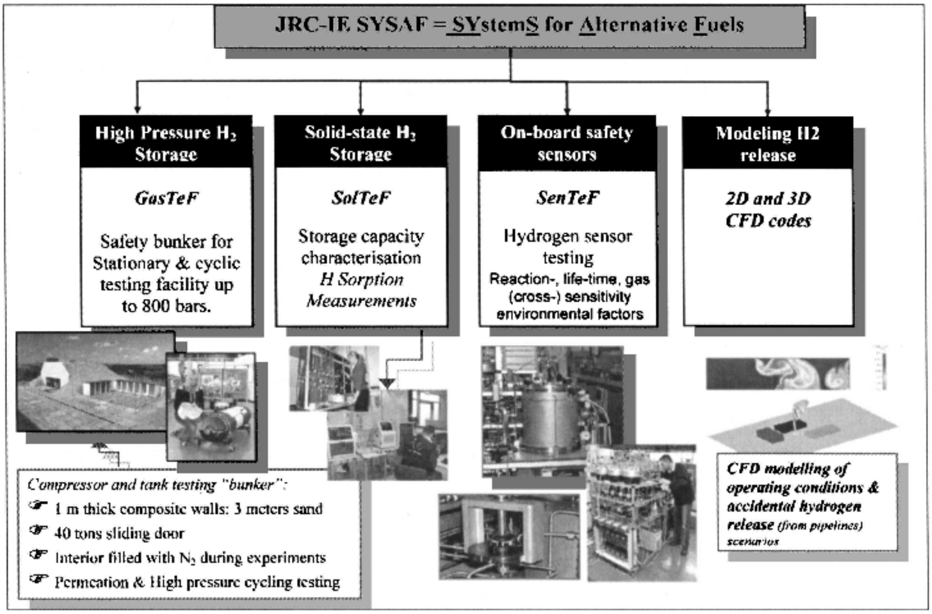


Figure 4. The state-of-the art facilities at EC-JRC-IE for performance characterisation of fuel cells, hydrogen storage and safety sensors

The GasTeF[34], hydrogen high pressure Gas storage Testing Facility, is aspiring to become the EU reference laboratory for safety and performance assessment of high-pressure hydrogen and natural gas storage tanks. This unique facility is housed in a specially-built bunker with N_2-inertised rooms. Targeted testing includes cycling, simulating operation under real conditions with fast filling and hold- or slow-emptying of the tank, and permeation tests on the full scale high-pressure vehicles tanks. The results will give information on long-term structural stability of tanks and their safety-related performance parameters. Such data contribute to the identification of potential safety issues and of possible gaps and needed improvements in the present regulations and standards.

Materials and their interaction with hydrogen are central in the activities at the SolTeF (Solid state hydrogen storage Testing Facility) of the SYSAF project. This is the laboratory aiming at becoming the EU reference experimental facility for hydrogen capacity measurements in solid-state materials, a function suggested by a number of key stakeholders. SolTeF was built for exploring and identifying the most appropriate measurement methodologies, defining best practices and for contributing to the development of testing protocols and standardised procedures for hydrogen (de-) sorption measurements. Its work programme addresses accuracy, repeatability, reproducibility and reliability in measurements. The laboratory is equipped with instruments covering different characterisation techniques, temperature/pressure regimes and sample types and sizes. It therefore caters for a broad range of storage materials and their sensitivity to the sample history and experimental conditions. In parallel, SolTeF participates in European funded projects on solid state storage, offers "second opinion" measurement service to European research centres and university groups who develop materials. It is also engaging in training of future technologists under the Marie Curie Research Training Network HYTRAIN[35]. Moreover, the SolTeF group co-ordinate benchmarking exercises on hydrogen sorption measurements on different materials under the umbrella of the Integrated Project NESSHY. Such an exercise will identify causes for deviations in measurements and enable the development of guidelines and best practices protocols serving future standardisation needs. Finally, and still under NESSHY, SYSAF is developing a web-enabled database for experimental hydrogen capacity parameters and physical engineering properties– this will be made available to European laboratories.

CONCLUSIONS

The European Commission fully supports through its multi-annual work programme research, development and demonstration activities on hydrogen and fuel cells. Recent policy developments in this field are paving the way to the full mobilisation of key European stakeholders. This will materialise by the soon to be established, industry-led, Fuel Cells and Hydrogen Joint Technology Initiative (JTI). The JTI aims at integrated, focused research in the EU in order to facilitate the market penetration of the hydrogen and fuel cell technologies.

So far, hydrogen and fuel cell research results, in spite of the scientific and technical progress made, show that these technologies are not mature enough and they are not able yet to reach the strategic targets. There seems to be a strong need for breakthroughs and return 'back to basics'. Fundamental research for understanding materials and their issues appears to be instrumental for any further progress. There is also a persisting requirement for harmonisation, validation and standardisation of data and test procedures and underpinning pre-normative research in this area. This is an activity endorsed by the European Commission in its work programme. It is also supported by the EC-Joint Research Centre, Institute for Energy via its state-of-the art testing facilities aspiring to become the EU reference laboratories in the field of fuel cells and hydrogen storage performance assessment.

FOOTNOTES

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** Green papers - they are discussion papers published by the Commission on a specific policy area. They are primarily addressed to interested organisations and individuals who are invited to participate in consultation and debate process. In some cases they provide an impetus for subsequent legislation.

*** The High Level Group for Hydrogen and Fuel Cells Technologies was initiated in October 2002 by the EC Vice President, Loyola de Palacio, Energy and Transport Commissioner, and Philippe Busquin, Research Commissioner. The group was invited to formulate a collective vision on the contribution that hydrogen and fuel cells could make to the realisation of sustainable energy systems in future.

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