International Partnership for the Hydrogen Economy

Implementation-Liaison Committee

Scoping Papers

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International Partnership for the Hydrogen Economy
Implementation-Liaison Committee

Scoping Papers

Executive Summary

Background

The International Partnership for the Hydrogen Economy (IPHE) was established in 2003 as an international mechanism to organise and implement effective, efficient and focused international research, development, demonstration and commercial utilisation activities related to hydrogen and fuel cells. It provides a forum to accelerate the cost-effective transition to a global hydrogen economy to enhance energy security and environmental protection.

The IPHE partners include Australia, Brazil, Canada, China, the European Commission, France, Germany, Iceland, India, Italy, Korea, Norway, Russia, the United Kingdom and the United States.

At its November 2003 inception meeting the IPHE Implementation-Liaison Committee identified the following priority areas for collaborative research and development among the IPHE partners:

- Hydrogen Production
- Hydrogen Storage
- Collaborative Fuel Cell R&D
- Hydrogen and Fuel Cell Regulations, Codes and Standards
- Socioeconomics of Hydrogen

The Committee, led Dr. Thorsteinn Sigfusson, Professor, University of Iceland, and Dr. Hanns Joachim Neef, Head of Division ERG, Project Management Organisation Jülich (PtJ), Germany, established Task Forces for each research priority area. The Task Forces, composed of a lead author and experts from IPHE countries, produced Scoping Papers that summarize the current state of technology, identify technical barriers to commercial deployment, and further prioritize concrete projects, events and actions to be undertaken by IPHE partners that will advance technology development and deployment.

This report compiles the Scoping Papers for each IPHE research priority. It is a “living” document that will be updated by the Committee as research and demonstration projects are completed and new priorities emerge.

Annex 1 provides a list of the experts of the Task Forces.

Hydrogen Production

Lead Author: Paul Lucchese, Director, CEA, France.
paul.lucchese@cea.fr

The Scoping Paper on Hydrogen Production foresees a four phased transitional process in which production evolves from today's reliance on fossil fuels to more sustainable production using a suite of technologies best suited to the primary energy sources available in a particular production location. In the near-term, the paper recommends research activities to improve the efficiency of traditional reforming techniques, innovations in electrolysis, and a focus on hybrid systems. In the longer term, the paper recommends focusing on pre-competitive research on innovative and clean technologies, defining and promoting hydrogen production demonstration projects, and developing a common methodology to evaluate future hydrogen production processes.

The IPHE will undertake the following action items related to hydrogen production:

1) Create, by mid-2005, a Task Force on Hydrogen Production comprised of research and industry personnel to exchange information on innovative hydrogen production processes.

2) The Task Force on Hydrogen Production will develop at the conclusion of 2005, an annual report on IPHE member hydrogen production research programs and experimental (existing or to be built) platforms and facilities.

3) The Task Force on Hydrogen Production will compile reports and benchmark results on hydrogen production research in IPHE member countries. The Task Force will establish a database on the main results, with a comparison between the primary energy/processes and perspectives.

4) The Task Force on Hydrogen Production will organize the IPHE sanctioned conference, "Hydrogen Production from Renewable Energy Sources" to be conducted in Seville, Spain October 18-20, 2005. The IPHE will also conduct an interdisciplinary workshop on Sustainable Hydrogen Production in 2005.

5) The Task Force on Hydrogen Production will compile and evaluate potential hydrogen production processes from fundamental research projects that are not directly related to hydrogen production.

6) The Task Force on Hydrogen Production will define and promote intermediate (2020-2030) demonstration projects to test the sustainability of industrial based production in such industries as steel and chemical production and refining. The IPHE will develop a methodology to define appropriate demonstration projects in 2005. By 2010, IPHE will identify potential demonstration projects for large-scale hydrogen production.

7) The IPHE will bridge hydrogen production technologies and needs of different countries, especially developing countries where analysis must be carried out to determine how technology transfer will be affected.

8) In 2005, the IPHE will develop a common and agreed approach (set of methodology, definition of criteria, data evaluation and reliability, benchmarking) to assessing future hydrogen production processes. This includes the scientific, technical, economic, environmental and social acceptance of the processes. This task will be linked with Task Force on the Socio-economics of Hydrogen.

Hydrogen Storage

Lead Author: Stanyslav Malyshenko, Deputy Chair, Russian Hydrogen Energy Technology Council, Russia - litp@dataforce.net

Hydrogen storage is clearly one of the key challenges in developing and implementing a hydrogen economy. Storage of hydrogen on-board vehicles must meet minimum requirements in order to achieve consumer acceptance. In addition, off-board hydrogen storage must be viable, cost effective, and efficient, to meet the needs of a global hydrogen economy. The Hydrogen Storage Scoping Paper notes that breakthrough concepts to meet required storage capacities using low cost carbon-based and carbon-metal composed materials are of interest. For chemical storage, a key issue is whether reclaiming and regenerating the spent fuel byproduct off-board is viable in terms of overall efficiency, environmental impact, safety and cost. In addition to a focus on the above hydrogen storage technologies, global collaboration on two additional crosscutting topics is proposed 1) standardized testing of materials and systems for hydrogen storage capacities; and 2) systems analyses which include life cycle, efficiency, safety and environmental impact analyses.

The IPHE will undertake the following action items related to hydrogen production:

1) The IPHE will conduct an International Workshop on Hydrogen Storage in June 2005 in Luca, Italy.

Fuel Cells

Lead Author: Valri Lightner, Lead Engineer, Office of Hydrogen, Fuel Cells and Infrastructure, U.S. Department of Energy, USA - Valri.lightner@ee.doe.gov

The Fuel Cell Scoping Paper notes that fuel cells are a key technology that, when successfully commercialized, can help realize the full potential of the hydrogen economy. Under the Partnership, pre-competitive R&D in the following areas is recommended: polymer electrolyte membrane fuel cells, alkaline fuel cells, high temperature fuel cells and standardized testing methods and protocols for fuel cell systems and components such as stacks and cells.

1) The IPHE will conduct an International Workshop on High Temperature Fuel Cells in Summer 2005.

2) The IPHE will conduct an International Workshop on PEM Fuel Cells in Summer 2005.

Regulations, Codes and Standards

Lead Author: Marc Steen, Unit Head, Clean Energics, European Commission marc.steen@cec.eu.int

The Regulations, Codes and Standards (RCS) Scoping Paper recognizes that IPHE is neither a regulatory nor a standardisation body. It further recognizes that a lot of work has already been and is being done on RCS by IPHE members. Therefore, IPHE activities related to RCS should only be initiated when they (are expected to) provide a clear added value. In this respect, initiatives by IPHE should not duplicate ongoing activities, but rather identify gaps, provide guidance through agreed-upon projects and provide a forum for facilitating progress towards common regulations, codes and standards, and safety protocols.

The IPHE will undertake the following action items related to hydrogen RCS:

1) The IPHE will prepare a final report by February 2006 cataloguing vehicle approval processes in use today in IPHE member countries.

2) The IPHE will complete a final report by February 2006 cataloguing the stationary, domestic and light duty appliance approval processes in use today in IPHE members.

3) The IPHE will conduct an International Hydrogen Safe-Use Workshop that will address approaches to risk and safety modelling.

4) The IPHE will complete a final report by December 2006 containing a comprehensive "meta-gap analysis" on the complete range of Regulations, Codes & Standards across the hydrogen economy that exist, are under development, and need to be developed. As a first step on the meta-gap analysis, the IPHE will prepare a glossary of common definitions, terminology and nomenclature for standardisation and regulatory terms, including terms which are specific to certain IPHE members (e.g. directives, self-certification, etc.). The glossary will be completed by December 2005.

Socio-economics of Hydrogen

Lead Author: Francois Moisan, Director, ADEME, France
francois.moisan@ademe.fr

The Socioeconomics of Hydrogen Scoping Paper was developed to assist members in identifying socio-economic barriers to the hydrogen economy. Socio-economic issues include the evaluation of hydrogen energy chains with regard to efficiency, cost (direct and indirect) and affordability, security of supply, greenhouse gas emissions, local environmental impacts, economic impact, safety, and public acceptance. The socio-economic analysis is intended to illustrate possibilities and propose feasible pathways for the development of hydrogen based energy systems, including fuel cells for stationary, portable and mobile applications.

The IPHE will undertake the following action items related to the socio-economics of hydrogen:

1) The Task Force on the Socio-economics of Hydrogen will identify and describe, by mid-2005, hydrogen energy chains that may form the basis of the future hydrogen economy. Hydrogen production processes, storage technology alternatives, infrastructure for hydrogen delivery, hydrogen conversion technologies and final applications (transport, stationary) will be precisely defined.

2) The Task Force on the Socio-Economics of Hydrogen will assemble a meta-database of IPHE member methodologies of assessing the cost parameters of various energy chains. The meta-database will be used to share the methodology of deriving costs and evaluating the socio-economic impacts, as well as to ensure transparency and objectivity in the evaluation processes.

3) The Task Force on the Socio-economics of Hydrogen will assess potential scenarios for the development of the hydrogen economy. A meeting will be conducted in 2005 to examine existing scenarios. A longer-term work plan for the development of potential hydrogen scenarios will be prepared by the Task Force and adopted by ILC at the conclusion of 2005.

4) The Task Force on the Socio-economics of Hydrogen will, by the conclusion of 2005, identify socio-economic studies conducted in association with hydrogen and fuel cell technology demonstration projects.

Acknowledgements:

The Implementation - Liaison Committee gratefully acknowledges the contributions of the Scoping Paper Lead Authors and the IPHE Secretariat Office in supporting the development of the IPHE Scoping Paper. The members of the IPHE Secretariat staff who contributed to this paper include: Erin Cready, Albert Doub, Michael Mills, William Polen, and Rich Scheer.

Annex 1

Task Forces for ILC Scoping Papers

	Task Force Experts	E-Mail
Hydrogen Production		
Australia	John Wright	john.wright@csiro.au
Brazil	Ennio Perez Silva	lh2ennio@ifi.unicamp.br
Canada	Dr. Vesna Scepanovic	vscepan@nrcan.gc.ca
France	Paul Lucchese (lead author)	lucchese@zoe.cea.fr
Germany	Joachim Wolf	joachim.wolf@linde.de
Iceland	Bragi Arnason	Arnason@raunvis.hi.is
Italy	Adolfo Parmaliana	Adolfo.parmaliana@unime.it
Japan	Nobuhiro Kuriyama	kuriyamanbh@nedo.go.jp
Norway	Helle Mostad Brage W. Johansen	helle.brit.mostad@hydro.com bwj@statoil.com
Republic of Korea	Jae Sung Lee	jlee@postech.ac.kr
United States	Pete Devlin	Peter.devlin@ee.doe.gov
Fuel Cell R&D		
Australia	Sukhvinder Badwal	sukhvinder.badwal@csiro.au
Brazil	Paulo Emilio Miranda	pmiranda@labh2.coppe.ufrj.br
Canada	Rod McMillan	Rod.McMillan@nrc-cnrc.gc.ca
Germany	Detlef Stolten	d.stolten@fz-juelich.de
Italy	Agostino Iacobazzi	iacobazzi@casaccia.enea.it
Japan	Mr. Tomohide Satomi	satomito@mx8.ttcn.ne.jp
Norway	Steffen Møller-Holst	steffen.moller-holst@sintef.no
Republic of Korea	Jung Myun Bae	jmbae@kaist.ac.kr
United States	Valri Lightner (lead author)	Valri.lightner@ee.doe.gov
European Commission	William Borthwick	william.borthwick@cec.eu.int
Hydrogen Storage		
Australia	David Rand	david.rand@csiro.au
Brazil	Maria Helena Frank	mhelena@cenpes.petrobras.com.br
Canada	Dr. Vesna Scepanovic	vscepan@nrcan.gc.ca
Germany	Jurgen von Wild	Juergen.Von-Wild@bmw.de
Iceland	Hannes Jonsson	hj@hi.is
Italy	Mario Conte	conte@enea.it
Japan	Dr. Nobuhiro Kuriyama	kuriyamanbh@nedo.go.jp
Norway	Øystein Ulleberg	oysteinu@ife.no
Republic of Korea	Ki Suk Nahm	nahmks@moak.chonbuk.ac.kr
Russia	Stanislav Malyshenko (lead author)	litp@iht.mpei.ac.ru
United States	Sunita Satypal	sunita.satyapal@ee.doe.gov
European Commission	Marc Steen	Marc.Steen@cec.eu.int

Socio-Economics		
Australia	Randall Wilson	randall.wilson@industry.gov.au
Brazil	Mauricio Cantao	cantao@lactec.org.br
Canada	Peter Reilly-Roe	peterrr@nrcan.tc.ca
France	Francois Moisan (lead author)	Francois.Moisan@ademe.fr
Germany	Klaus Willnow	klaus.willnow@siemens.com
Iceland	Jon Bjorn Skulason	skulason@newenergy.is
Italy	Pierpaolo Garibaldi	Pierpaolo.garibaldi@tiscali.it
Japan	Dr. Kenzo FUKUDA	fukuda@iae.or.jp
Norway	Erling Holden	erling.holden@vestforsk.no
Republic of Korea	Jong Wook Kim	jongwkim@kier.re.kr
United States	Pat Davis	pat.davis@ee.doe.gov
Regulations, Codes and Standards		
Australia	John Henry	John.Henry@standards.org.au
Brazil	Sergio Pinheiro de Oliveira	spoliveira@inmetro.gov.br
Canada	Ian MacIntyre	imacinty@nrcan.gc.ca
Germany	Franck Gröschl Christoph Albus	groeschl@dvgw.de christoph.albus@bmvbw.bund.de
Iceland	Agust Agustsson Tryggvi Axelsson	agust@ver.is tryggvi@ls.is
Italy	Romano Borchiellini	Borchiellini@polito.it
Japan	Kazuo Koseki Kazuyuki Narusawa	koseki@enaa.or.jp narusawa@ntsel.go.jp
Norway	Ståle Selmer-Olsen	Stale.Selmer-Olsen@dnv.com
Republic of Korea	Sung Ho Shin	shshin@ats.go.kr
United States	Pat Davis Duane Pfund	pat.davis@ee.doe.gov duane.pfund@rspa.dot.gov
European Commission	Marc Steen (lead author)	marc.steen@cec.eu.int

International Partnership for the Hydrogen Economy

HYDROGEN PRODUCTION
SCOPING PAPER

Background and General Vision

At its November 2003 inception meeting, the Implementation-Liaison Committee (ILC) of the International Partnership (IPHE) for the Hydrogen Economy identified hydrogen production as a priority for collaborative research among members. This Scoping Paper discusses technical barriers to hydrogen production on a scale necessary to develop a hydrogen based economy. It proposes an integrated approach to cooperation among IPHE members aimed at furthering collaborative research on hydrogen production.

One of the advantages of hydrogen is that it can be produced from a variety of feedstocks and with a variety of production technologies. Hydrogen is currently produced on a large scale (approximately 600 billion M3/year) mostly from hydrocarbons using mature reforming technologies. However, these processes emit carbon dioxide (CO_2) in the reforming process.

Figure 1 (see Attachment 1) describes the possible qualitative phases for a transition from today's liquid fuel to the hydrogen economy in the 21st century:

Phases 1 and II

In phases I and II, oil and especially natural gas are necessary to produce large quantities of hydrogen. In the very short term, small units will be needed for local production. These units will employ small electrolysers and reformers using natural gas, LPG or others fossil products. In some cases, reforming process will be integrated with fuel cell systems such as Solid Oxide Fuel Cells or high temperature fuel cell systems developed for the generation of electric power and/or thermal energy. For the long term use of fossil fuels for hydrogen production, CO_2 capture and sequestration processes will be required. Large scale production of hydrogen (with CO_2 sequestration and/or use of low carbon processes such as nuclear and renewable resources) could be accomplished in centralized facilities involving the co-production of electricity and thermal energy for combined heat and power applications. It is likely that hydrogen from renewable energy sources through electrolysis will be produced at a decentralized level in some countries.

It is also possible that in some regional cases and in a few niche markets, renewables or nuclear production methods may quickly become the optimum solution for hydrogen production. Local requirements will drive the method of production in off-grid isolated communities. In some cases, centralized production could be demonstrated from renewables through off-shore wind farms and when large, inexpensive quantities of electricity (hydro, nuclear) are available. Hydrogen could be produced locally by intermittent renewable energy and used as an energy storage medium to improve energy efficiency. But, from a global perspective, during Phase I and II, natural gas will be the main bridge to the hydrogen economy (e.g., through central and local reforming, and hydrogen enriched natural gas.)

Phases III and IV

In phases III and IV, renewables, nuclear and coal or others fossil fuels with long-term reserves (with clean processes) will substantially replace natural gas for producing hydrogen. For hydrogen produced by fossil fuels, CO_2 capture and sequestration will be used and industrially deployed at large scale. Similar to previous phases and depending on local conditions, different renewable solutions (high temperature solar energy in the sun belt, biomass, geothermal, wind, hydro,) and nuclear and coal could be preferred. In some cases, in isolated sites, islands or in some countries where large parts are off-grid or where renewables are available easily (sun, biomass, hydro), decentralized solutions could provide most of the energy needed for primary applications. In others countries, where nuclear energy is developed or where large centralized renewable sources are available (sunbelt, large wind farm, large biomass plant, large hydro or geothermal), massive hydrogen production associated with transportation infrastructure are possible to supply large cities.

Barriers and Needs

Temperature level is a good parameter to distinguish the two main families of hydrogen production:

High Temperature Processes

We can separate these processes into two sub-families. The first is zero-carbon high temperature processes, including:

- Thermo chemical cycles (from 600 °C to 2000 °C) and high temperature electrolysis;
- Hybrid systems coupling thermal decomposition and electrolytic decomposition;
- Direct catalytic decomposition of water with separation by a ceramic membrane; and
- Plasma-chemical decomposition of water in double stage CO2 cycle.

The main technical barriers to solve for zero carbon high temperature processes are:

- Materials developments (high temperature, corrosion resistant);
- High temperature membrane and separation processes;
- Heat exchanger; and
- Heat storage medium development.

The second high temperature sub-family is hydrogen production using carbon feedstock, including:

- High temperature processes for biomass transformation (gasification, pyrolisis, high pressure aqueous process, supercritical water or CO2 processes, plasma processes);
- Fossil fuels and hybrid processes combining clean energy sources for supplying heat with hydrocarbon feedstock to decrease greenhouse gas emissions;
- Direct racking/decomposition of hydrocarbons; and
- Plasma catalytic reforming and gasification of hydrocarbons and carbon containing materials.

The technical barriers to resolve for high temperature carbon based hydrogen production:

- Material development (resistant to high temperature, corrosion, temperature cycling, etc.);
- Efficiency of multi-phase separation processes (in liquid phase, vapor phase, high temperature membrane);
- Heat exchanger design;
- Development of new advance plasma chemical reactors;
- Gas purification;
- Design of large plants and adequate flow sheets;
- Safety of complex plants, and
- Coupling large plants with hydrogen infrastructure (liquefaction plant, compressor, pipe lines).

Low Temperature Processes

Low temperature processes include:

- Low temperature electrolysis;
- Photo electrochemistry processes;
- Photo biological processes; and
- (Biophotolysis) anaerobic or fermentation processes.

The principle technical barriers to low temperature hydrogen production are:

- Improving reliability;
- Sensitivity of living support (bacteria, algae) to non-hydrogen materials;
- Photosynthetic efficiencies; and
- Increasing the overall efficiency of process (biological and photo electrolytic).

Proposed Areas for Collaboration Under the IPHE

Collaboration should focus on pre competitive research and development. These efforts should be linked with CO2 sequestration (treated outside this group, in other international collaboration). This will include major improvements or breakthroughs on fossil fuels processes, electrolysis innovations and hybrid systems.

1) A Task Force on Hydrogen Production comprised of research and industry personnel will be created to exchange information on innovative hydrogen production processes. The Task Force on Hydrogen Production will be linked with the future High Temperatures Processes Group at IEA, under which an Annex of the Hydrogen Implementation Agreement will soon be created.

Milestone

- The Task Force on Hydrogen Production will be formed by mid-2005.

2) The Task Force on Hydrogen Production will develop an annual report on programs and different experimental (existing or to be built) platforms and facilities devoted to hydrogen production to promote greater sharing of information on research, demonstration and deployment projects.

Milestone

- The first annual report will be produced at the conclusion of 2005.

3) The Task Force on Hydrogen Production will compile reports and benchmark results. The group will establish a database on the main results, with a comparison between the primary energy/processes and perspectives. Input from IEA technical groups is required.

4) The Task Force on Hydrogen Production will organize workshops and exchange of researchers, students in this field to promote exchange of knowledge and common issues and to promote synergies between different sectors of research. The workshops will focus on mixing different interdisciplinary experts (low and high temperature, chemistry and physic, biologist and physics), different energy experts and industrial/research sectors (fossil, nuclear, renewables, chemistry industry, etc.)

Milestone

- The IPHE sanctioned conference, “Hydrogen Production from Renewable Energy Sources” will be conducted in Seville, Spain October 18-20, 2005.

5) Compile and evaluate potential processes from fundamental research, not directly involved in hydrogen production.

6) The IPHE will define and promote intermediate (2020-2030) demonstration projects to test the sustainability of industrial based production in such industries as steel and chemical production and refining. This work will examine how to scale up the processes (from 1l/h to 100 000 M3/h), and how to test critical components (heat exchangers, photobiological reactors, high temperature membranes.)

Milestones

- The IPHE will develop a methodology to define appropriate demonstration projects in 2005; and

- By 2010, IPHE will identify potential demonstration project for large scale hydrogen production.

7) The IPHE will bridge technologies and needs of different members of IPHE, especially developing countries where analysis must be carried out to determine how technology transfer will be affected.

Milestone

- The IPHE will conduct an interdisciplinary workshop on Sustainable Hydrogen Production in 2005.

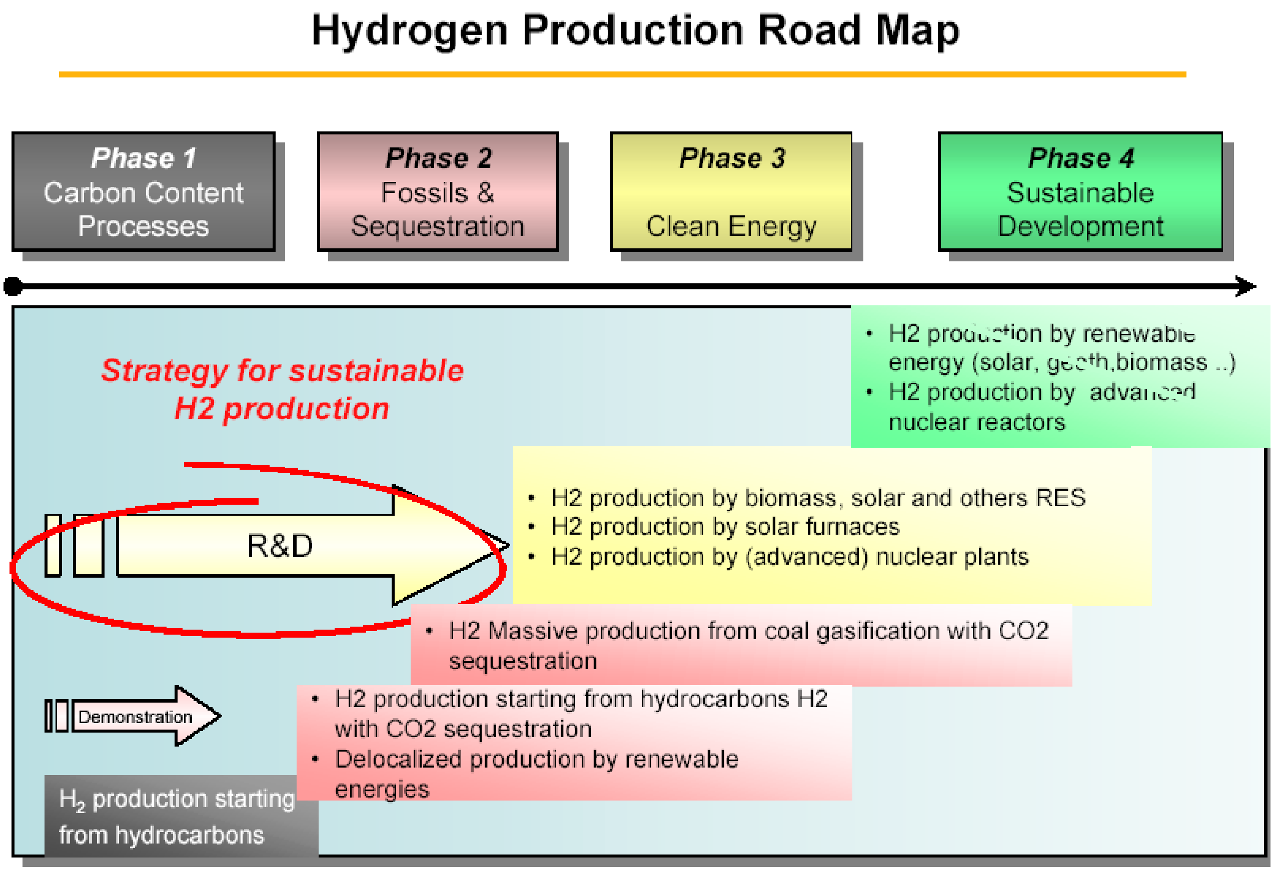
8) The IPHE will develop a common and agreed approach (set of methodology, definition of criteria, data evaluation and reliability, benchmarking) to assessing future hydrogen production processes. This includes the scientific, technical, economical, environmental and social acceptance of the processes. This task will be linked with Task Force on the Socio-economics of Hydrogen.

Milestone

- The IPHE will create a working group dedicated to developing definitions and common approaches to long-term hydrogen production processes in 2005.

ATTACHMENT 1

Figure 1: Hydrogen Production Roadmap



Hydrogen Production Road Map

- H2 production by renewable energy (solar, geoth,biomass ..)
- H2 production by advanced nuclear reactors

- H2 production by biomass, solar and others RES
- H2 production by solar furnaces
- H2 production by (advanced) nuclear plants

- H2 Massive production from coal gasification with CO2 sequestration

- H2 production starting from hydrocarbons H2 with CO2 sequestration
- Delocalized production by renewable energies

H_2 production starting from hydrocarbons

International Partnership for the Hydrogen Economy
Implementation - Liaison Committee

HYDROGEN STORAGE

SCOPING PAPER

Background and General Vision

Hydrogen storage is clearly one of the key challenges in developing and implementing a hydrogen economy. Both on-board and off-board storage of hydrogen must be viable, cost effective, and efficient, to meet the needs of a global hydrogen economy, covering transportation, stationary and portable applications.

This Scoping Paper summarizes the key technical barriers for on-board and off-board hydrogen storage technologies and proposes areas of research and collaboration for the international community under the auspices of the International Partnership for a Hydrogen Economy (IPHE). The proposed areas of international collaboration focus on storage technologies that have potential to meet the *long-term goals* required for a viable global hydrogen economy. Therefore, a major R&D focus on conventional compressed gas and cryogenic liquid systems is not proposed as they are already near commercialization. Such systems are in use for prototype vehicles and off-board storage and the primary focus is on cost reduction rather than on developing technology breakthroughs.

The proposed R&D areas also take into consideration the various international efforts already underway. For example, the International Energy Agency's (IEA) Hydrogen Implementing Agreement (hydrogen storage activities, currently through Annex 17) is already promoting substantial international collaboration on carbon nanotubes and metal hydrides. To avoid duplication of current work and to focus on areas with significant technical challenges, the following key areas are proposed:

- Materials-based systems that are truly reversible, such as metal hydrides, high surface area sorbents, and carbon; and
- Chemical hydrogen storage systems, such as chemical hydrides, which must be regenerated off-board.

In addition, global collaboration on two additional cross-cutting topics is proposed:

- Standardized testing of materials and systems for hydrogen storage capacities, including standardization of units of measure; and
- Systems analyses that include life cycle, efficiency, safety and environmental impact analyses.

Barriers and Need

While high pressure / cryogenic hydrogen storage may be an Interim approach, it is recognized that they will not meet all the requirements of a global hydrogen economy. The barriers that must be addressed are summarized below.

General

- **Cost**. The cost of hydrogen storage systems is too high, particularly in comparison with conventional storage systems for petroleum fuels. Low-cost materials and components for hydrogen storage systems are needed as well as low-cost, high-volume manufacturing methods.
- **Weight and Volume**. The weight and volume of hydrogen on-board storage systems are presently too high, resulting in inadequate vehicle range compared with conventionally fueled vehicles. Materials and components are needed that allow compact, lightweight, hydrogen storage systems while meeting customer expectations for driving range. Off-board storage has less stringent requirements for weight and volume.
- **Efficiency.** Energy efficiency is a challenge for all hydrogen storage approaches. The energy required to get hydrogen in and out of storage is an issue for reversible solid-state materials. Life-cycle energy efficiency is a challenge for chemical hydride storage in which the by-product is regenerated off-board. The boundaries for efficiency should be clearly defined.
- **Durability**. Durability of hydrogen storage systems is inadequate. Materials and components are needed that allow hydrogen storage systems with a lifetime of 1500 cycles.
- **Refueling Time**. Refueling times are too long. There is a need to develop hydrogen storage systems with refueling times of less than three minutes, over the lifetime of the system.
- **Safety, Codes & Standards**. Achieving safety, codes and standards for hydrogen storage systems and interface technologies, which will facilitate implementation/ commercialization and assure safety and public acceptance, is yet to be accomplished.

- **Life Cycle, Environmental Impact, and Efficiency Analyses**. There is a lack of analyses of the full life-cycle cost, environmental impact, and efficiency for hydrogen storage systems within the context of the entire hydrogen production/ delivery/ storage/ utilization framework. Such studies should look at the cost and performance of each component in the system.

In addition to all the general barriers described above, each category of storage technology has additional unique barriers as summarized below:

Reversible Solid-State Material Storage Systems (Regenerated On-Board)

- **Hydrogen Capacity and Reversibility**. Hydrogen capacity and reversibility are inadequate at practical operating temperatures and pressures and within refueling time constraints. Adequate cycle life of these systems has not been demonstrated.
- **Kinetics of Hydrogen Storage:** Fundamental understanding of hydrogen physisorption and chemisorption processes is lacking. Improved understanding and optimization of absorption/desorption kinetics is needed to maximize hydrogen uptake and release and to provide sufficient flow rates of hydrogen for vehicle use.
- **Heat and mass transfer in storage media**. There is a poor understanding of the heat and mass transfer characteristics in micro- and nano-structured materials that experience large volumetric and thermal effects during sorption/desorption of hydrogen. Improved mathematical models are required to achieve maximum performance from these materials. For metal hydrides, heat rejection during charging is a significant issue.
- **Test Protocols and Evaluation Facilities**. Standard test protocols and independent facilities for evaluation of hydrogen storage materials are lacking.
- **Dispensing Technology**. Dispensing technology has not been defined.

Chemical Hydride Storage Systems (Regenerated Off-board)

- **Regeneration Processes for Irreversible Systems**. Low-cost, energy-efficient regeneration processes for irreversible systems have not been established. Full life-cycle analyses need to be performed to understand cost, efficiency, safety and environmental impacts.
- **By-Product Removal**. The refueling process is potentially complicated by byproduct removal. Better system designs must be developed.

Proposed Areas for Collaboration Under the IPHE

For metal hydrides, despite the significant advances in recent years, there is still no technology that meets the weight, volume and cost requirement for vehicles. New reversible solid materials with hydrogen storage capacities significantly higher than 6 wt. % should be developed.

Innovation beyond the current state-of-the-art in complex metal hydrides (and beyond IEA activities) is sought in order to attain truly reversible systems that also meet the weight, volume, and cost targets for vehicles. Although significant effort is underway through the IEA on carbon materials (such as carbon nanotubes), breakthrough concepts to meet required storage capacities using low cost carbon-based and carbon-metal hybrid materials would be of interest. For chemical storage, a key issue is whether reclaiming and regenerating the spent fuel byproduct off-board is viable in terms of overall efficiency, environmental impact, safety and cost. In all cases, both fundamental R&D and systems level engineering are required to achieve the storage capacities to meet the volume, weight, safety and cost constraints in vehicular applications.

Because the measurement of storage capacities and other required properties for hydrogen storage pose significant technical challenges, there is often controversy in the scientific community as to the validity of published data on hydrogen storage. It is thus critical that standardized test and measurement protocols be established. These standardized methods will permit materials to be evaluated systematically to ensure accurate and reproducible data worldwide.

In terms of systems analyses, it is imperative that the complete hydrogen storage system within the context of the infrastructure required for a hydrogen economy be evaluated. Both on-board and off-board storage systems must be evaluated in terms of environmental impact, overall energy efficiency, safety and cost, from a complete life-cycle standpoint.

Finally, a specific recommendation to promote international collaboration beyond the scope of the IEA and advance the current status of hydrogen storage technologies is to organize an International Conference/Workshop on Hydrogen Storage. The meeting would provide a framework for providing baseline information on various technologies, tracking worldwide progress, and identifying critical areas that would benefit from leveraging the efforts of multiple countries.

Measuring Success and Defining Progress

In conclusion, a critical aspect of the proposed collaboration is a **results-driven** approach to ensure that efforts are continually focused on technologies that are most likely to achieve the goal of commercially viable hydrogen and fuel cell systems in the 2015 timeframe. Technical targets will be formalized to provide clear quantifiable measures, which can be used to track progress. Periodic milestones and go/no-go decision points will ensure that funds are used only for the most promising approaches and that performance goals are being met throughout the effort. In addition, both fundamental and applied R&D will be conducted by building partnerships between government laboratories, universities, and industry to accelerate the development of hydrogen storage technologies for the future.

Milestone

- The International Workshop on Hydrogen Storage - June 2005 – Luca, Italy.

International Partnership for the Hydrogen Economy
Implementation - Liaison Committee

COLLABORATIVE FUEL CELL R&D
SCOPING PAPER

Background and General Vision

Fuel cells are a key technology that, when successfully commercialized, can help realize the full potential of the hydrogen economy. Under the Partnership, pre-competitive R&D in the following areas is recommended: polymer electrolyte membrane fuel cells, alkaline fuel cells, high temperature fuel cells and standardized testing methods and protocols for fuel cell components such as stacks and cells. Research will build on the foundation for collaboration established by the IEA and will strive for public-private consensus on establishing research needs, approaches, milestones, teaming arrangements, and deliverables. The most likely mechanism for teaming will be task sharing where collaboration occurs without the transfer of funds across country lines, i.e. individual countries fund the R&D activities within their own country. Commercialization of fuel cells in general requires scientific and technical breakthroughs to improve reliability and durability of the stacks and systems and to reduce the costs. To be competitive with current technologies, fuel cell systems for transportation applications require 5,000 hours durability at a cost of less than $50/kW, and for stationary applications 40,000 hours durability at a cost of less than $750/kW.

Polymer Electrolyte Membrane Fuel Cells (PEMFC)

PEMFC are being primarily developed for transportation applications and some stationary applications. Due to their fast startup time, low sensitivity to orientation, and favorable power-to-weight ratio, PEMFC are particularly suitable for use in passenger vehicles, such as cars and buses. PEMFC operate on hydrogen and oxygen (which can come from air) and generate water. The barriers and technology needs of direct methanol fuel cells, direct ethanol fuel cells and regenerative fuel cells are similar to those of PEMFC. Direct methanol fuel cells and direct ethanol fuel cells are primarily being developed for portable power applications. Regenerative fuel cells are primarily being developed for stationary applications. In this case the fuel cell can be run reversibly to generate hydrogen when electricity is available and can provide electrical power from the hydrogen generated as needed for back-up or peak power demand.

Advanced Membranes

PEMFC (polymer electrolyte membrane fuel cell) systems are currently operated at 80^{o} C or less primarily due to the durability limitations of Nafion membranes. Higher temperature fuel cell operation would facilitate heat rejection and reduce the weight and complexity of the fuel cell radiator system as well as increase stack tolerance to carbon monoxide. Fuel cells for automotive applications could reach temperatures as high as 120 ^{o} C for brief periods of time when operated at full load without requiring changes to the glycol-based coolants currently used. Fuel Cells for distributed generation could operate above 150^{o} C and up to 300^{o} C nearly continuously to increase the overall efficiency in a combined heat and power operation. Nafion membranes dry out and lose proton conductivity as the relative humidity decreases with increasing operating temperature. Membranes that maintain conductivity at low relative humidity levels (25%) across the temperature range of operation would minimize thermal management issues in the fuel cell stack. Direct alcohol fuel cells in particular DMFC employing nafion membranes suffer from fuel cross-over. This presence of methanol at the cell cathode results in low cell efficiency due to oxidation of methanol on the platinum of the cathode and mixed potentials developed there.

Barriers and Needs

For transportation applications, membranes that are compatible with electrodes and have adequate conductivity, strength, stability and performance at low humidity (25%) and across the full operating range of temperature from start-up (as low as -20°C) to full power (up to 120-150°C) are needed. For distributed energy applications, membranes that are compatible with electrodes and have adequate conductivity, strength, stability and performance at high temperature (150-300°C) are needed. For portable applications membranes for DMFC's must have low methanol permeability.

Proposed Approaches

Near-term focus:

- Identify and understand higher temperature (non-aqueous) proton conducting mechanisms;
- Identify and synthesize materials with high conductivity, thermal and mechanical stability across all operating conditions;
- Devise methods of fabricating membrane electrode assemblies (MEA) with advanced membrane materials. Materials of interest include:
    - Composite fluorocarbon materials and additives to improve water retention.
    - Thin ceramic materials.
    - Innovative material.
    - Sealing materials for extreme temperature conditions; and

- Identify membrane materials which restrict methanol transport and have adequate proton conductivity, and thermal and mechanical properties.

Milestones

Near-term focus:

- The IPHE will conduct an International Workshop on PEM Fuel Cells in Summer 2005;
- Have an adequate understanding of high temperature proton conducting mechanisms in order to develop polymer membranes that can operate at low relative humidity conditions (25%) and temperatures up to 120^{o} C;
- Have adequate knowledge of proton conduction in ceramics and a means to fabricate stable MEA with thin ceramic membranes operating at high temperatures (150-300°C); and
- Have an understanding of the reduction of methanol transport in existing and new membranes.

Catalysts

Current precious metal-based PEMFC catalysts are expensive. The impact of high volume production of fuel cells on world Pt price, production, and reserve is a concern. Non-precious metal catalysts (platinum, ruthenium, rhodium, etc.) or reduced loading of precious metal in catalysts are sought that are capable of significantly lowering system cost while maintaining performance and durability. Reduced loadings of precious metal catalysts for DMFC's are sought for the same reasons. A possible solution for methanol cross-over is the development of a methanol tolerant cathode eliminating low mixed potentials at the cathode.

Barriers and Needs

Non-precious metal catalysts systems have been studied. The primary barriers to their use are the low catalytic activity for the anode and cathode reactions and their stability in the PEMFC environment. Power density is very important. Non- precious metal catalysts will increase stack weight, lower efficiency and negatively influence the balance of plant (i.e. radiator size, air module, piping, etc.). Fuel economy and power density have to be considered in trade off with catalyst selection. Catalyst recycling would be required to achieve cost targets using catalysts containing precious metal. For DMFC's anode catalysts and structures with enhanced power density at low catalyst loadings able to use 1:1 MeOH/Water fuel and provide powers above 200 mW/cm^2 at cell temperature < 40^{o} C are needed to allow further development of DMFC's for portable applications. Methanol tolerant cathodes would employ non-precious metals and may be the same materials as developed for PEMFC's.

Proposed Approaches

Near-term focus:

- Understand Pt's unique catalytic properties and opportunities for recycle/reuse;

- Identify and understand the nature of Non-precious metal catalytic sites for O_2 reduction;
- Improve the chemical stability of Non-precious metal catalytic sites in PEMFC environments. Materials of interest include:
    - Macrocyclic organic materials with Fe-N-C catalytic sites;
    - Microbiologic hydrogenase enzymes with Ni-Fe catalytic sites for hydrogen oxidation;
    - New inorganic catalysts such as RuS_2, WC, and FeCN compounds;
- Determine controlling mechanisms at low catalyst loadings to enable enhanced activity;
- Identify catalysts and electrode structure for higher power, possible structures include Pt and Ru at low loadings on carbon substrates; and
- From the list of non-precious metal PEMFC cathode catalysts identify those which ate not electrochemically active to methanol.

Milestones

Near-term focus:

- Identify candidate non-precious metal catalyst materials that can meet 2010 electrode cost target;
- Evaluate precious metal recycling processes;
- Understand the fundamentals of Fe-N-C catalytic sites in macrocyclic organic materials and hydrogenase enzymes;
- Understand the fundamentals of inorganic non-precious metal catalytic sites;
- Improve the chemical stability of non-precious metal catalysts in PEMFC conditions;
- For DMFC by 2008 understand how to fabricate anode electrodes with good power density incorporating water management; and
- By 2010 identify candidate catalysts for oxygen reduction selectively in the presence of methanol and without electrochemical interaction.

Stack Components

Materials for bipolar plates and gas diffusion layers have been optimized for Nafion-based MEA and an operation temperature of 80°C. In parallel to a development of HT-membranes, an adaptation of the stack components is required. While the requirements for water management are reduced, the need for corrosion resistance and thermally stable materials is increased. The fuel for a DMFC is stiochiometrically a 1:1 mole mixture of methanol and water. The actual fuel supplied may be less rich in methanol to optimize cell performance (methanol crossover etc.) Controlling water management in the cell and minimizing fuel balance of plant will necessitate management of the composition of the fuel. Efficient low cost methanol sensors are needed.

Barriers and needs

Select and develop materials for operation at temperatures above 100°C according to the properties of the new membranes, in order to be able to implement new MEAs in a fuel cell stack. For DMFC low cost reliable methanol sensors are needed.

Proposed approach

- Investigate corrosion protective layers for metallic bipolar plates;
- Develop carbon/polymer binder composites for high temperature application;
- Define requirements for gas diffusion layers and investigate performance in test cells;
- Adapt sealing materials and technology for high temperature operation; and
- Identify methanol sensor materials and fabricate sensing system.

Milestones

Near Term Focus:
- Propose a stack concept for the high temperature MEA; and
- By 2008 demonstrate a fully operation sensor system for fuel composition management.

Alkaline Fuel Cells

Alkaline Fuel Cells (AFC) are primarily being developed for space applications. Two distinctly different designs have evolved. ***Immobilized electrolyte*** systems are similar to PEMFC designs and are used by NASA (U.S. National Aeronautics and Space Administration) in the space program. ***Recirculated electrolyte*** systems continuously pump the KOH solution through the cell; originally developed by Union Carbide in the late 1950s and later by Da Capo FC Ltd. (owner of Elenco and Zevco technologies), Astris Energy, and Apollo Energy Systems Inc.

Barriers and Needs

Non-Pt catalysts cannot be run at the same current density as Pt. Trade-off is cost saved on other materials compared to the amount spent to make the hardware larger to obtain the same output power. Results to date on hydroxide conducting membranes are disappointing. Alkaline electrolytes, even at low temperatures are very corrosive and will attack all polymeric and graphite parts. Peroxide forms at the cathode and is a concern because of its reactivity. High-purity nickel or other coated metals have demonstrated lifetimes of 5000-7000 hours, which is considerably short of that required for stationary systems (40,000 hours).

Proposed Approaches

- Continue to investigate non-Pt catalysts to determine what trade-offs can be made that reduce cost and maintain power level;
- Identify lower cost materials that can withstand alkaline electrolytes;
- Identify and investigate CO_2 tolerant cathodes;
- Optimize recirculated electrolyte AFCs for their intended application; and
- Investigate methods to lower cell resistance to improve AFC stack performance.

Milestones

Near-term focus:

- Complete non-Pt catalyst trade-offs Studies;
- Develop lower cost materials that are resistive to alkaline electrolyte corrosion;
- Optimize recirculated electrolyte AFC designs;
- Improve/optimize AFC stack performance; and

High-Temperature Fuel Cells: MCFC and SOFC

High temperature fuel cells include solid oxide and molten carbonate. Solid oxide fuel cells (SOFC's) use a ceramic electrolyte which results in a solid state unit, an important aspect. The conduction mechanism is solid state conduction of O^{2-} ions. The reaction is completed by the reaction of oxygen ions and hydrogen to form water. In a molten-carbonate fuel cell (MCFC), molten carbonate salts are the electrolyte. At 650°C , the salts melt and conduct carbonate ions (CO_3) from the cathode to the anode. At the anode, hydrogen reacts with the ions to produce water, CO_2, and electrons that flow through the external circuit. At the cathode, the electrons react with oxygen from air and CO_2 recycled from the anode to form CO_3^-ions that replenish the electrolyte and transfer current through the fuel cell. SOFC's and MCFC's can extract hydrogen from a variety of fuels using either an internal or external reformer. They are also less prone to CO poisoning than other fuel cells and thus are attractive for coal-based fuels. SOFC 's and MCFC's work well with catalysts made of nickel, which is much less expensive than platinum. SOFC 's and MCFC's can achieve an efficiency of 60% stand-alone, or over 80% (net) if the waste heat is used for cogeneration. Currently, demonstration units exist up to 2 MW (MCFC).

Barriers and Needs

Challenges with SOFC's are development of materials and stacks with high power density, better seals, metallic interconnects, extensive thermal cycling capability and cost reduction. Significant technical challenges with MCFCs are the complexity of working with a liquid electrolyte rather than a solid, and the relatively inherent low power density, as well as high cost. Advantages of both fuel cells are the fuel flexibility, using coal, natural gas, or heavy fuels with small modification. R&D funding by the public sector for MCFC has been concluded as is not discussed. Research is continuing by industry to optimize costs of materials and production processes to enable market entry. R&D for SOFC is described below.

Proposed Approaches

- Develop and characterize lower-temperature oxide-ion conductors. Lower-temperature operation would reduce the thermal durability problems and allow use of cheaper materials;
- Develop electrodes with reduced thickness, improved sulfur tolerance, CTE match, and good interface performance;
- Develop low cost durable seals; and
- Develop light-weight, oxidation resistant metallic interconnects.

Milestones

Near-term focus:

- The IPHE will conduct an International Workshop on High Temperature Fuel Cells in Summer 2005;
- Conduct prototype testing of SOFC systems capable of being manufactured for $800/kilowatt by 2005-2007;
- Operate SOFC systems using advanced materials in the temperature range of 500 to 800°C to enable thermal cycling and better anode and cathode performances;
- Improve and optimize SOFC stack performance and durability; and
- Improve and optimize MCFC stack performance and durability while lowering cost.

Standardized Testing Procedures/Protocols

In the U.S. the ASME and SAE have developed standardized test procedures for stationary and transportation fuel cell systems, respectively. The U.S. Fuel Cell Council is developing testing protocols for fuel cell components as the groundwork for an overarching Single-Cell Testing Protocol, and the Japanese Automotive Research Institute (JARI) has recently developed a single cell test protocol. The European Union has established the Fuel Cell Testing and Standardization Network to harmonize testing procedures applicable to fuel cell systems, down to the stack and cell levels. Australia also has facilities established for the testing of single cells and stacks using hydrogen generated from a range of fuel sources which can be used for establishing codes and standards for fuel cells. Several of these standards are being advanced to the international level through the fuel cell and hydrogen working groups within International Standards Organization (ISO) and International Electrotechnical Committee (IEC) such as ISO 197 and IEC TC 105. Several committee drafts have been developed and soon will become worldwide international standards. Protocols for testing fuel cell stacks or stack components are being developed within the fuel cell activity.

Barriers and Needs

A quantitative comparison of the performance of different fuel cells that are tested using different procedures is not possible. Global standard test procedures are needed that enable fuel cell performance to be assessed on a common basis. A consistent set of engineering definitions and practices will accelerate the commercialization of fuel cells for both transportation and stationary applications. This comparison should include innovative fuel cell technologies (i.e., direct sodium borohydride, ammonium, intermediate temperature, etc.) in addition to those identified in sections 1 – 3.

Proposed Approaches

Near-term focus:

- Compilation of reports on testing methodologies which have been or are being developed by numerous organizations around the world;
- Benchmarking and validation of results from round robin testing; and
- Harmonization of existing test methods.

Milestones

Near-term focus:

- Compile and compare testing protocols; and
- Reach agreement on global fuel cell test procedures. Complete initial assessment of fuel cell systems against user requirements for stationary, portable, and transportation applications.

International Partnership for the Hydrogen Economy

International Partnership for the Hydrogen Economy Implementation - Liaison Committee

REGULATIONS, CODES AND STANDARDS

SCOPING PAPER

Background and General Vision

The Terms of Reference for the International Partnership for the Hydrogen Economy (IPHE) describe IPHE, among other purposes, as a forum for analysing and developing policy recommendations on technical guidance, including common codes and standards and regulations in the transition towards a hydrogen economy. The IPHE Implementation and Liaison Committee (ILC) will make recommendations to the Steering Committee on actions to achieve this, which can be implemented under IPHE.

The first meeting of the ILC echoed and supported the request for common codes, standards and regulations voiced by many speakers at the IPHE Ministerial, Washington, DC, 19 - 21 November 2003. Harmonized regulations, codes and standards are key factors for developing a hydrogen economy. At the ILC meeting, many delegates gave a high priority to the opportunities which the IPHE could offer in this respect, and the drafting of a targeted scoping paper on this topic was decided.

The present scoping paper provides basic considerations and points of view on possible ways forward by IPHE and IPHE-ILC on regulations, codes and standards. It does not deal with specific regulations, codes and standards issues related to a particular application or topic, which may be covered in the other ILC Scoping Papers.

Basic Considerations Guiding IPHE Involvement in Regulations, Codes and Standards (RCS)

The following principles should govern IPHE involvement in regulations, codes and standards:

1) In view of the fact that a lot of work has already been and is being done on RCS by IPHE members, IPHE activities should only be initiated when they (are expected to) provide a clear added value. In this respect initiatives by IPHE should not duplicate ongoing activities, but rather identify gaps, provide guidance through agreed-upon projects and provide a forum for facilitating progress towards common regulations, codes and standards, and safety protocols.

2) IPHE is neither a regulatory nor a standardisation body. Hence the ILC and its points of contact on RCS do not have any direct function or responsibility in (contributing to) drafting of standards and regulations, nor in their harmonisation. Also, IPHE does not have its own funding mechanism. Based on these two factors, possible functions for ILC in the area of RCS are:

    - Providing a forum where standardisation or regulatory issues which are identified as possibly contentious and which may require streamlining among IPHE members can be voiced and discussed, and from where subsequently recommendations can be forwarded to policy- and decision makers of IPHE members.

    - Acting as a catalyst for cooperation and for facilitating harmonisation of activities by IPHE members related to standardisation and regulation. Recommendations for IPHE actions in this area should not be prescriptive in terms of the means, procedures and of the schedule for implementation, but should rather contain specific deliverables, milestones and target completion dates.

3) For realising the above tasks ILC may initiate, when deemed necessary, an “RCS Task Force” composed of specific policy and technical experts, as indicated in the action list from the Beijing SC and Reykjavik ILC meetings. However, in view of the wide range of RCS activities needed for furthering the transition towards a hydrogen economy and of their specialised nature, a single expert group, which is then necessarily composed of non-specialists in a number of areas, is not considered to be the most appropriate means. Instead, if deemed necessary and useful, ILC may recommend the set-up of a dedicated task force for executing specific actions stemming from the recommendations in the RCS scoping paper. Where necessary and/or relevant this will include:

    - Establishment of a template to ”guide” the collection of information for maximum effectiveness; and
    - Identification of deliverables and of target dates;

4) Execution of IPHE actions in RCS following the recommendations from ILC requires resources which have to be provided through the IPHE Partners. IPHE members will implement such actions through existing national instruments or international agreements.

5) In view of the above, the facilitating function by IPHE-ILC will mostly address pre-normative and pre-regulation research issues: e.g. definition and prioritisation of needs, identification of possible complementary activities and setting scope for cooperation among IPHE members, sharing and discussing results from pre-normative research, identification of appropriate standardisation/regulatory body(ies) and working group(s) for exploitation of the research results and further development of RCS, exploitation of experiences gained in demonstration projects for feedback to RCS-making.

6) In view of the lack of own funding, IPHE workshops, organised by the ILC RCS team or by an aforementioned ILC Task Force constitute the most efficient approach for structuring pre-normative research activities and discussing pre-normative research results.

7) It must be realised that all IPHE activities in support of a worldwide hydrogen economy are based on actual knowledge of hydrogen basics and on current technology. The appearance of a breakthrough hydrogen technology that promotes a paradigm shift could trigger revisions in the present scooping paper.

Proposed Areas for Collaboration Under the IPHE

Hydrogen can be used to provide many energy services, especially in transportation, stationary (including the use in centralized and distributed facilities) and portable applications. A first review on international efforts on codes, standards and regulations suggests using this categorisation for the IPHE activities as well.

Today hydrogen is mostly used in the industrial sector, mainly in the chemical and petrochemical industries. In Europe and North America, several hundred kilometres of hydrogen pipelines are operating. In addition, the gas industry has extensive experience with so-called "town gas," containing up to 67% hydrogen, which was produced and distributed mainly for heating purpose, from the mid-19th century until the late 1960s. Today town gas is used only sporadically.

Driven by major considerations on energy supply security, climate change and air quality, hydrogen in the transportation and in the stationary energy market has a long-term perspective. Therefore regulations, codes and standards should be set in accordance with the progress in the technology. In particular, standardization must be linked closely to R&D, but may not solve technical barriers too early. Also continuous education and awareness building should complement efforts in this area. The following topics should be included in these considerations:

- Hydrogen production in centralized facilities and in distributed facilities (rural areas and community locations);
- Hydrogen transport (pipelines, compressors, materials, sealing, …);
- Hydrogen safety during transport (e.g. tankers on road or rail);
- Hydrogen distribution (networks, pressure regulators, storage, connectors, materials, sealing, …);
- Hydrogen utilization (mobile use, domestic, commercial, industrial, gas appliances, heating systems, fuel cells, cookers, safety in private buildings, …); and
- Hydrogen gas detection e.g. by sensors or by appropriate odorization.

From discussions among the RCS Points of Contact in ILC, six recommended steps have been identified to promulgate hydrogen regulations, codes and standards that should be followed regardless of the end use:

1) Establish a validated database of technical information on hydrogen (i.e. basic properties and behaviour, material compatibility, safety issues, …). This database, especially the entries related to hydrogen safety, should be shared to the greatest extent possible.

2) Emphasize the development of performance-based rather than product-specific regulations, codes and standards.

3) Support the adoption of harmonized international regulations, codes and standards (screening of existing projects, identifying the existing "gaps" for hydrogen RCS, initiate appropriate structures that eliminate gaps within existing groups or organisations i.e. ISO, CEN, UN-ECE…)

4) Collect operational data on and from research, development and demonstration projects. This information should be incorporated to the greatest extent possible in a publicly accessible database and exploited for feedback to RCS.

5) Provide appropriate education and training in codes, standards and safety for elected and appointed officals, regulators, students, users, and the general public (specific workshops, joint studies, summer schools, …)

6) Support public and technical forums and workshops to awareness-building on hydrogen issues.

The RCS Team strongly encourages the ILC to follow these steps in their efforts related to the development of regulations, codes and standards, both nationally and internationally.

Mobile Applications - Road Vehicles

International harmonization of regulations, codes and standards is the basis for the introduction of hydrogen and fuel cell (H2/FC) vehicles into the market as commercially viable alternatives to conventional vehicles and fuels.

Within the framework of the World Forum for Harmonization of Vehicle Regulations, UN-ECE-WP.29/GRPE[1], it is possible to develop Global Technical Regulations (GTRs) under the 1998 agreement. This agreement takes into account the differences in vehicle approval processes in Europe/Asia (type approval) compared to North America (self-certification). Work has started to develop harmonized regulations for H2/FC vehicles, in close cooperation with international standardisation organisations (e.g. ISO and IEC). More detailed information, including a detailed list of the possible elements of a GTR for H2/FC vehicles, is available in the Hydrogen and Fuel Cell GTR road map (informal document no. GRPE-48-17/Rev.1)[1].

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[1] Information is available on the United Nations Economic Commission for Europe (UN-ECE) website: www.unece.org → Transport → Vehicle Regulations → GRPE (Working Party on Pollution and Energy).

Barriers and Need

Since March 2001, the Informal Group Hydrogen-Fuel Cell-Vehicles of the UN-ECE-WP.29/GRPE, consisting of technical experts on H2/FC vehicles, has been addressing the structure and content of globally relevant regulations for hydrogen and fuel cell vehicles. This group has active participation from a number of IPHE member countries, and as such, is an important activity for IPHE to monitor. Because of existing activities related to the development of a road map for global technical regulation(s), there is no immediate need for additional IPHE facilitation of the development of vehicle-related regulations. Clearly, an active exchange of information is very important. In particular, IPHE should be made aware of any policy hurdles that arise regarding the development and implementation of GTR(s) within existing regulatory and approval frameworks.

While the GRPE Informal Group is addressing harmonization of vehicle approval processes and is considering the conflicts between the various vehicle approval methods (e.g. type approval and self certification) a complete understanding of the specific approval processes utilized by IPHE member countries is not documented. It is therefore difficult to discern the full implication of the activities of the Informal Group on GTRs to all IPHE parties.

Proposed Approach

A survey should be conducted to document the approval processes in use today in IPHE member countries. It is also proposed to invite a representative of the Informal Group to report regularly on the progress of its work on GTRs to the ILC.

Expected Outcomes

- Improved understanding of the implementation requirements for GTRs and clarification of potential hurdles in the process of developing GTRs; and
- GTRs are not disruptive upon their implementation.

Deliverable

- Report on the vehicle approval processes in use by IPHE member countries.

Milestones

- Draft report completed, September 2005; and
- Final report published, February 2006

Mobile Applications - Other

The ILC notes that other mobile applications (marine, rail, air, space) of hydrogen and fuel cell technology should be considered as well. Additional work elements may be added to address these specialized transportation applications.

Stationary Applications

Hydrogen and electricity are complementary energy vectors. Electricity is an excellent carrier for short and medium ranges, whereas hydrogen may be transported over longer distances in the future, e.g. by pipeline, ship, train, truck. Hydrogen may also be transported over short and medium distances, e.g. from production sites to refuelling stations for cars, to industry, etc. Which energy vector will be preferred in various settings will depend on the energy situation locally and regionally, on available infrastructure, costs, social issues.

Compared to light-duty transportation, stationary applications of hydrogen are more varied in terms of size, technology and specific applications. For example, the generation of electricity by polymer electrolyte membrane (PEM) fuel cells is projected to include small systems rated at less than one kilowatt in power and systems ranging in size up to hundreds of kilowatts. In addition, these applications may serve industry, local businesses, or residences and may include both continuous operation and back-up power operation. It is clear that the number and extent of regulations, codes and standards required for the full breadth of eventual applications will be significant.

Regulations, codes and standards that cover supply, transport, distribution, storage and use of combustible gases for stationary applications are regularly revised and updated to assure a continued high safety level. This large amount of experience should be exploited where relevant for the establishment of RCS for hydrogen in stationary use.

Barriers and Need

Although a number of activities focusing on global harmonization of codes, standards and regulations for stationary applications of hydrogen are underway, it is difficult to discern the full implication of these activities to IPHE member countries without a complete knowledge base of current practices.

As for road vehicles, a complete understanding of the specific approval processes utilized by IPHE member countries for stationary applications is not documented. In contrast to the approval processes for vehicles, it is the North American market that uses the type approval process for appliances (i.e., Underwriters Laboratory), whereas Europe uses a self-certification process.

Proposed Approach

A survey of IPHE member countries should be conducted to document the approval processes for domestic and light-industry appliances in use today.

Expected Outcomes

- Improved understanding of the implementation requirements for approval processes and clarification of potential hurdles in their development; and
- Approval schemes are not disruptive when they are implemented.

Deliverable

- Report on the stationary approval processes used by IPHE members.

Milestones:

- Draft report completed, September 2005; and
- Final report published, February 2006.

Portable Use

The use of hydrogen and fuel cells in the niche market of portable applications (small appliances or devices such as laptops, cellular phones, …) is an important stepping-stone for further more widespread market penetration of hydrogen and fuel cell technologies. Because of the shorter timescale involved in portable applications and the fact that they are more driven by competitiveness than by energy policy considerations which play the major part for transportation and stationary applications, the need for IPHE action in this area needs careful consideration.

Recently there have been developments aimed at standardization of methanol fuel cartridges, and similar activities may need to be established for hydrogen cartridges. The use of methanol as well as ethanol as a fuel for portable fuel cell applications could be a subject for further work on codes/standards/regulations.

Safety considerations

Like all fuels, hydrogen has specific properties which require particular procedures and precautions to ensure safe use. Some of the issues that require attention in developing procedures for safe operation with hydrogen are:

- Wide range of flammability;
- High diffusivity;
- Non luminous flame (due to high combustion temperature);
- Relatively low calorific value (1/3 of natural gas) and diffusive/penetrating properties which require appropriate adaptation to natural gas infrastructure systems (gas lines, compressors, regulators, refuelling stations etc.);
- Low ignition energy, detonation limits, and higher laminar burning velocity resulting in higher probability of more severe deflagrative explosions for hydrogen than for hydrocarbons;
- Low density and high buoyancy resulting in rapid dispersion;
- Hydrogen-embrittlement and hydrogen-induced microstructural changes in various materials systems;
- Simple, reliable and sustainable leakage detection systems; and
- Storage in metal hydrides may involve combustible materials.

Proposed Approach

The following topics for IPHE facilitation are proposed for structuring cooperation and complementary activities in safety topics:

- Compilation and sharing of experimental data and development of a database for hydrogen safety assessment of different applications, including full-scale test data;
- Collection of already available industry standards and establishment of a common basis for risk assessment, for risk acceptance criteria, for definition of hazard zones, for modelling and experimental activities on a worldwide scale by taking into account different regional requirements and levels of technical and educational advancement;
- Prioritisation of development and validation needs for analytical and numerical models required for the safe use of hydrogen in different applications, definition of scenarios for computational modelling; and
- Consideration of joint programs in large (full scale) experimental work within safety, e.g. crash tests of vehicles, hydrogen leaks in tunnels and garages, etc.

Expected Outcomes

- Improved leverage of resources among IPHE partners in terms of required budgets and research infrastructures; and
- Promotion of common approaches for risk and safety assessment and risk management in similar applications.

Deliverable

- International Hydrogen Safe-Use Workshop, covering risk approaches and modelling.

Milestone:

- Workshop Fall 2005.

A "meta-gap analysis" for furthering IPHE activities

From the above it can be concluded that "Regulations, Codes & Standards; Safety Considerations" covers a complex field of activities. Significant efforts towards codes, standards and regulations have been made and are currently being pursued. Many of these activities cover a specific area within the total picture of hydrogen usage. However, no single analysis has covered the requirements of the entire hydrogen economy in terms of required regulations, codes and standards across all hydrogen production, delivery, storage and use scenarios.

Proposed Approach

A comprehensive "meta-gap analysis" is suggested to cover the complete range of Regulations, Codes & Standards across the hydrogen economy: existing, under development, and needed to be developed. (The use of a "traffic lights" framework as developed by the International Hydrogen Infrastructure Group (IHIG) in the US might serve this purpose well). This analysis should detail specific needs related to:

- Codes, laws, …;
- Regulations, directives, …;
- Standards;
- Safety; and
- Public awareness.

The analysis should examine the above criteria across the spectrum of hydrogen production and use:

- Hydrogen production;
- Hydrogen distribution / storage/ transport / trade;
- Stationary use (including centralized and distributed electric energy facilities);
- Mobile use (filling stations, fuel dispensers, other infrastructure, …);
- Mobile use (vehicles, ...); and
- Portable use (containers, interface, handling, …)

In a first urgent step, agreed common definitions, terminology and nomenclature for standardisation and regulatory terms, including terms which are specific to certain IPHE members (e.g. directives, self-certification, etc.) must be established.

Expected Outcomes:

- Comprehensive information on ongoing activities;
- Identification of gaps that potential IPHE activity could help eliminate; and
- Recommendations from the forum or groups as to the most appropriate items for taking action to eliminate gaps.

Deliverables:

- Glossary of commonly agreed RCS-terms; and
- Meta-gap analysis.

Milestones

- Draft glossary July 2005;
- Final glossary December 2005;
- Draft of analysis July 2006; and
- Final draft December 2006.

International Partnership for the Hydrogen Economy
Implementation - Liaison Committee

SOCIO-ECONOMICS OF HYDROGEN
SCOPING PAPER

Background and General Vision

At its November 2003 inception meeting, the Implementation-Liaison Committee (ILC) of the International Partnership (IPHE) for the Hydrogen Economy identified the analysis of socioeconomics factors related to the development of the hydrogen economy as a priority for collaborative research and evaluation among the IPHE members. This Scoping Paper discusses a set of socio-economic factors related to the development of the hydrogen economy that require further analysis and evaluation. It proposes an integrated approach to cooperation among IPHE members aimed at gaining a greater understanding of the social, economic, environmental, safety and political factors that will influence or will be influenced by the development of the hydrogen economy.

The evaluation of socio-economic factors related to the hydrogen economy requires the evaluation of energy production, storage, transportation distribution and end use chains using the following criteria:

- Efficiency
- Cost (direct and indirect) and Affordability
- Security of Supply
- Greenhouse Gas (GHG) Emissions
- Local Environmental Impacts
- Economic Criteria: Employment, International Trade
- Safety
- Drivers of Public Acceptability
- Availability and Reliability

These criteria, which may be used to qualify the sustainability of the hydrogen economy, are significant and intentionally broad. They will be defined in greater detail as the future work of the Implementation-Liaison Committee progresses.

Barriers and Needs

Hydrogen energy chains involve the following elements:

- Production
- Storage
- Transport
- Infrastructure
- End Use in Transportation and Stationary Applications

Each element of the chain has an associated set of determining socio-economic issues. These issues must be addressed if a hydrogen economy is to be realized. The key points relevant to each element, the technical challenges and barriers, and proposed pathways to their resolution are treated in the thematic scoping papers on hydrogen production, storage, fuel cells, and codes and standards. This paper focuses on transversal approaches and research needs that are cross cutting in nature.

Proposed Areas for Collaboration Under the IPHE

Socio-economic analysis of hydrogen will illustrate both possible and viable pathways for the development of hydrogen-based energy systems. These systems may include, but not be limited, to fuel cell technologies. It is important to keep in mind that hydrogen is an energy carrier, similar to electricity. These two carriers may, in the future, be use in conjunction to power a broad range of applications from the transportation, stationary, and portable sectors, leading to the development of multiple energy pathways (See Annex 1).

To identify hydrogen technology pathways, hydrogen options need to be assessed within a dynamic framework accounting for interdependencies between energy sources, energy carriers, and technology markets. The socio-economic evaluation of hydrogen energy chains should be done comparative to other alternatives (existing or foreseen), which rely upon other energy resources.

The IPHE will establish a Task Force to study the Socio-economics of Hydrogen in cooperation with the IEA, as agreed to at the second ILC meeting in Reykjavik, Iceland, September 2004. Each IPHE member will designate experts to participate in the task force. The task force will be charged with analyzing and evaluating the socio-economic factors related to the development of the hydrogen economy, as recommended by the ILC.

The following five items are core elements of such an analysis and should be addressed with priority.

1) Identification and description of relevant hydrogen energy chains

The first task involves identifying the hydrogen energy chains that will be evaluated. Hydrogen production processes, storage technology alternatives, infrastructure for hydrogen delivery, hydrogen conversion technologies (such as fuel cells or internal combustion engines), and final applications (transport, stationary) should be precisely defined.

Each energy chain accounts for different volumes of energy produced, transported, stored, distributed and used for specific applications. An overview of these chains, initially differentiated between decentralized and centralized energy systems, will bring clarity to the evaluation of how hydrogen will be derived and for which applications it will be used. "Reference" and alternative solutions for the same end-use applications should be identified to assess, concurrently, different hydrogen energy chains.

The hydrogen energy chains considered to be relevant should be described in detail (See Annex One for a Non-Exhaustive Presentation of Some Hydrogen Chains). The hydrogen applications and production processes considered priorities by the Implementation and Liaison Committee should likely be considered first. For every hydrogen energy chain, each elemental node should be described for the techno-economic evaluation.

Milestone

- Identification and description of relevant hydrogen chains based on the proposals of IPHE Members – to be completed by mid-2005.

2) Elaboration of a meta-database among IPHE members

In order to complete a sound assessment of the variety of hydrogen pathways, it is important to establish a comprehensive meta-database that is both accepted by and shared with all IPHE member countries. Creating such a database will benefit scientists, policy makers and businesses, as it will enable them to conduct their assessments with information that is globally-accepted.

The development of a meta-database will also lead to the development and of a hierarchy among the different hydrogen energy chains and will also point out research priorities (through items such as cost, capacity or environmental bottlenecks). Indicators specific to local socio-economic conditions should be identified, especially for applications in developing countries.

The meta-database will be used to share the methodology of deriving costs and evaluating socio-economic impacts, as well as to ensure transparency and objectivity in the evaluation processes. Its objective is not intended to reach consensus on "primary data".

The Task Force on the Socio-economics of Hydrogen may be instructed to identify existing databases in different countries or organizations (such as IEA) that are relevant for inclusion into the IPHE database. The Task Force should consider the conditions under which IPHE members may access databases in non-IPHE member countries or organizations.

Milestone

- The Task Force will identify the existing databases and analyze the methods and processes currently used in each country to determine the cost parameters of various energy chains.

3) Elaboration of Hydrogen Energy Implementation Scenarios and Tools for Dynamic Systems Analysis

An integrated assessment of the future role of hydrogen within sustainable energy systems will be conducted utilizing the information provided in the meta-database. A dynamic assessment involving quantitative analysis will be required to consider the possible outcomes of various technology implementation scenarios. Such scenarios should take into account the present value of technical and economic parameters in each hydrogen chain and their prospective evolution in comparison to other solutions. Scenarios should also consider the potential impact of implementing several policy options (assessing the penetration pace of technologies in the society).

An initial task is to identify the analytical framework and resulting questions that must be addressed by the modelling tools. Under the guidance of the Task Force on the Socio-Economics of Hydrogen, a comprehensive analysis of existing hydrogen energy modelling scenarios and their output should be conducted . The IEA's Energy Technology Perspectives Model is one of the available tools for evaluating implementation scenarios. The IEA Hydrogen Co-ordination Group (HCG) is launching an analytical policy study on hydrogen and fuel cells to explore technology deployment strategies through long- term scenarios. This work will provide input for an analysis of hydrogen scenarios among IPHE members (Terms of reference of the IEA-HCG are presented in Annex 2).

Milestones

- A meeting of the Task Force on the Socio-economics of Hydrogen will focus on examining currently-existing hydrogen scenarios. The meeting will be conducted in 2005 in coordination with the IEA-Hydrogen Coordinating Group study; and

- A longer-term work plan for the development of potential hydrogen scenarios will be prepared by the Task Force on the Socio-economics of Hydrogen and adopted by the ILC (end 2005).

4) Dissemination and Market Implementation

Aside from the technological progress induced by R&D, the scenarios of hydrogen deployment in the economy will also be dependant on market transformation policies. The IEA analysis on market transformation policy evaluation and the related research on barriers to technology diffusion should be shared. Public policies and measures such as technology procurements, fiscal incentives, and standards should be analyzed to overcome barriers.

5) Sociologic Issues: Drivers of Acceptance

Sociological issues address different approaches that should be considered at an early stage of research and development. These issues extend to *non-technical factors.* To increase our knowledge in this field, the following issues must be addressed:

- What are the main non-technical issues?
- What are the relationships between non-technical issues?
- What are the relationship between non-technical issues and technical issues?
- How can knowledge be used in developing strategies and policy measures to overcome the non-technical barriers and to utilize all available options?

A two-stage process can be used to address these questions. First, we must draw on existing theoretical knowledge about general strategies to implementing new technology, and then strategies for hydrogen in particular. In this analysis, it is possible to draw upon two related theoretical traditions: *actor-network theory* and *interactive technology policy*. Second, these theoretical positions must be supplemented with empirical investigations from a large ongoing demonstration project.

This approach includes:

- Analysis of stakeholder behaviour and strategy toward hydrogen energy technologies to gain an understanding of potential "allies" or "opponents"; and
- Analysis of acceptance conditions by examining field experience. Sociological field analysis should accompany all demonstration projects.

Milestone

- Identification, by the Socio-economic Task Force, of existing sociological studies conducted on demonstration projects by the end of 2005.

6) Sharing Information on RD&D Conducted in each IPHE Member

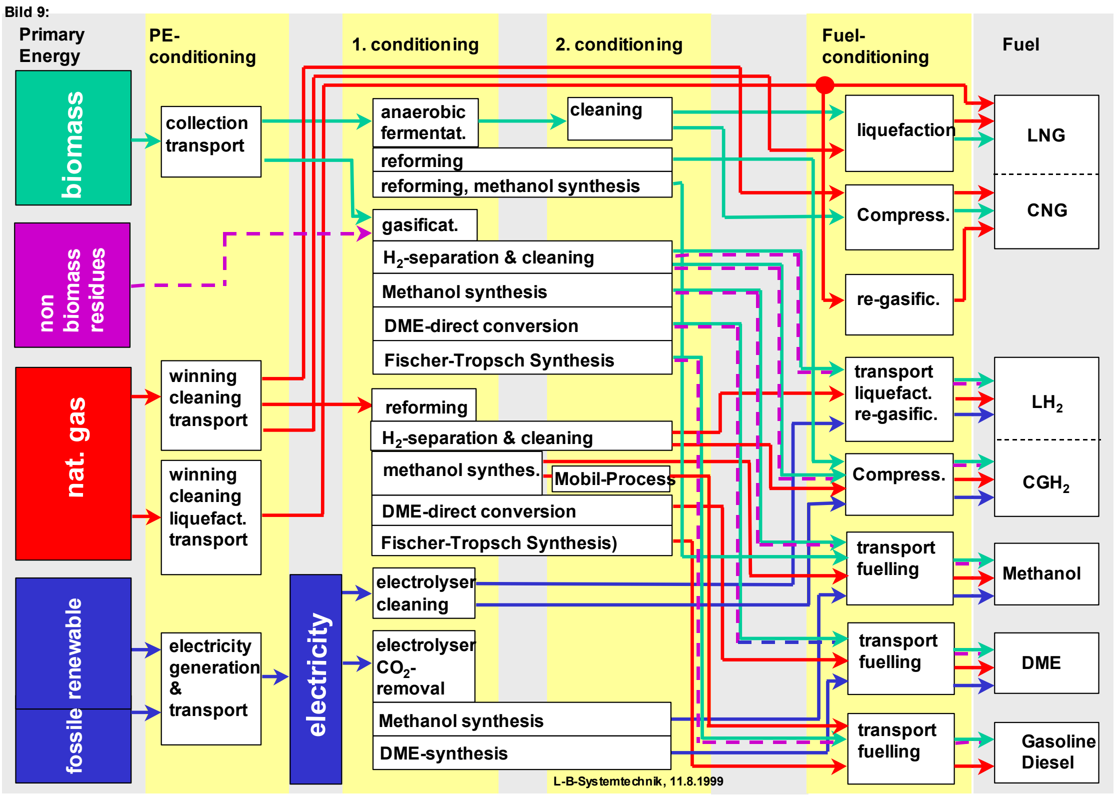
To avoid duplication and to enhance cooperation, it is essential to share information on hydrogen research, development and demonstration programs and implementation policies of IPHE members. An IPHE reporting process should be established to enable member countries to discuss their domestic programs (the Steering Committee will decide which Committee or working group should be charged with organizing this process).

The Implementation-Liaison Committee should define precisely the means dedicated to the tasks elaborated above.

ANNEX 1

Figure 1: Hydrogen Energy Chains

Source : Holger Braess, BMW, Germany
Klaus Willnow, Siemens, Germany



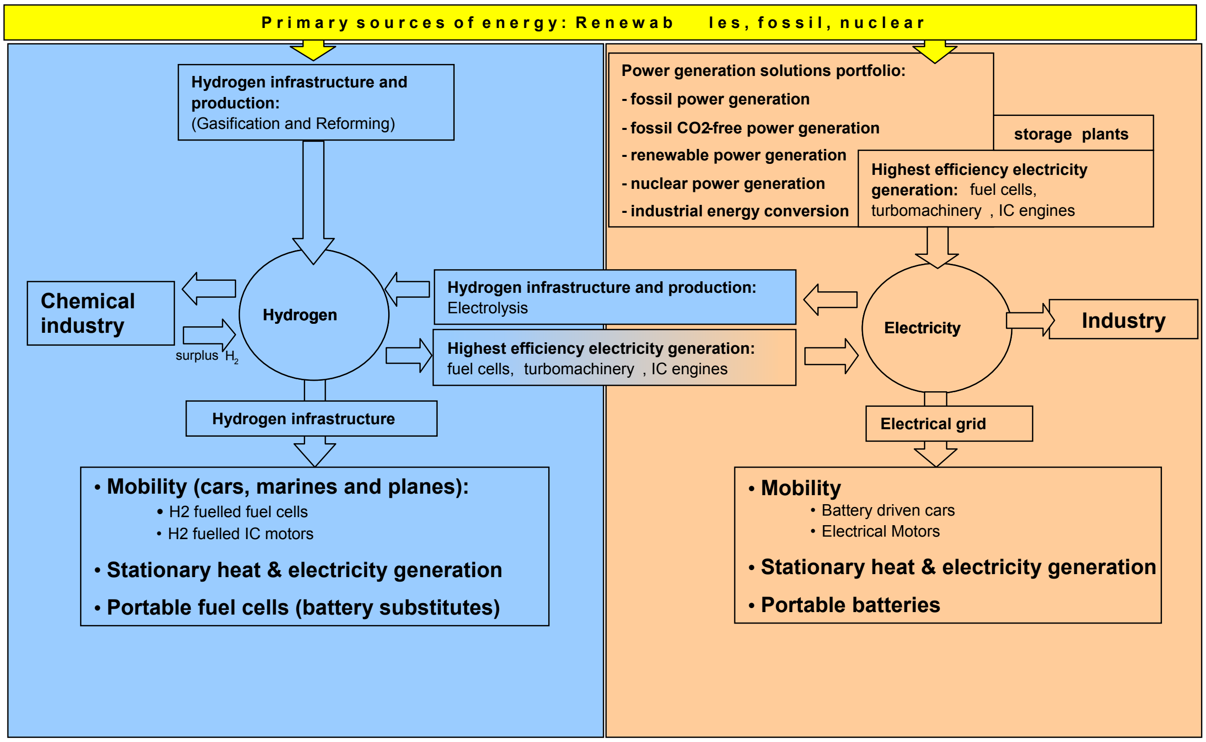
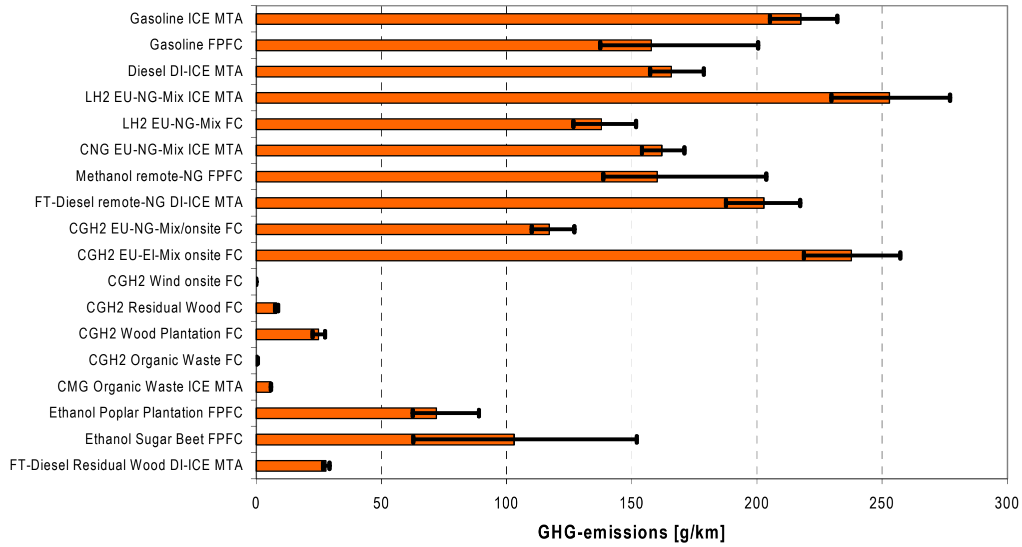


Figure 2: Well to Wheel GHG Emissions for Ddifferent Hydrogen Energy Chains

Source: Holger Braess, BMW, Germany



ANNEX 2

IEA ANALYTICAL POLICY STUDY ON HYDROGEN AND FUEL CELLS SPONSORED BY THE HYDROGEN CO-ORDINATION GROUP

(Note by the Secretariat)

BACKGROUND

The current program of work of the IEA Hydrogen Co-ordination Group (HCG) includes the following tasks as indicated by the IEA Executive Director Mr Claude Mandil when the HCG was established in April 2003:

1) Comparative review of national R&D and policy programs on hydrogen and fuel cells in the IEA Member countries
2) Review of the activities of the IEA Implementing Agreements to identify priorities and needed work on critical-path technologies;
3) Recommend additional collaborations within the IEA framework;
4) Identify analysis to help guide the IEA work.

To accomplish the task No 4, the HCG is considering selected policy analysis studies to be carried out by the IEA Secretariat to investigate the potential impact of hydrogen and fuel cells on future energy scenarios. The analyses would be performed using the IEA Energy Technology Perspective (ETP) model - a quantitative tool to support decision making on energy and technology strategies - and involve members of both the IEA Technology Collaboration Division and IEA Technology Policy Division.

Hydrogen Co-ordination Group: Ongoing Work and Conclusions So Far

Building on the R&D expertise of the IEA Implementing Agreements and policy analysis studies already carried out by the Secretariat, the HCG is assessing priorities and gaps in the IEA R&D program on hydrogen and fuel cells. The aim is to identify whether additional efforts and collaborations are needed in specific R&D areas (HCG task 2 & 3). The result of this work indicates so far that there are no significant gaps in the R&D programs but increased efforts are required to reduce hydrogen and fuel cell cost and performance. A list of emerging priorities has been identified, which include both R&D and policy issues:

R&D Priorities

- Reduce cost of producing CO_2-free hydrogen
- Reduce cost and improve life-time of fuel cells
- Improve hydrogen storage for FC vehicles
- Develop CO_2 C&S to extract H2 from fossil fuels
- Identify optimal strategies for R&D and deployment

Policy and Communication Priorities

- More Analysis on hydrogen/fuel-cell potential and transition phase
- Quantify infrastructure investment
- Identify early niche markets
- Set and harmonise international codes and standards
- Improve co-ordination with private sector
- Inform policy makers and the public with cautious optimism and realism

Preliminary conclusions of the HCG indicate that:

- Hydrogen and fuel cells are high-potential technologies - maybe the key to achieve near-zero emissions in transport;
- They implies however a development risk as technical breakthroughs are needed to reduce cost and achieve commercial maturity;
- Assuming significant technical improvements, hydrogen and fuel cell cost could be affordable in a fully-developed market, with hydrogen from fossil fuels and biomass being the most competitive options in the foreseeable future;
- The transition to hydrogen could take decades;
- More analysis is required on transition strategies, technology learning, investment, markets, etc.
- While many competing technologies exist for stationary applications, hydrogen and fuel cells are one of the few options to fuel transport with reduced or no emission.

Scope of the Analytical Policy Study

Overall objective of the proposed work is to provide a quantitative basis for the HCG conclusions The work will build on the analyses already done by the ETP project for other technologies (e.g., CO_2 sequestration) and for hydrogen itself.

Two basic analyses are proposed with focus on the transition phase to hydrogen & fuel cells, and on a fully developed market, respectively. Whilst the two analyses explore different time span - typically the next 2-3 decades for the transition and the subsequent 2-3 decades for the fully developed market - the results of the first analysis clearly influence the input for the second period analysis. Accordingly a larger emphasis will be given to the transition phase. To take into account the uncertainty on projected costs and performance of hydrogen and fuel cell technology each analysis will explore at least two scenarios broadly defined as pessimistic and optimistic view. Governmental policies and public/private investment strategy to support technology deployment in the transition phase will either be included in the two scenarios or result in additional scenarios to be defined during the work in co-operation with participating Members countries.

The program of work includes:

a. *Review of existing studies*

b. *Updating of the ETP model* - The model already includes basic hydrogen and fuel cell technologies. Further technology options will be incorporated such as hydrogen production from photo/biological process, high temperature thermo-chemical processes, fuel cell portable applications, etc.

c. *Collection and validation of basic input data* – This is a critical phase implying interactions with field experts, relevant Implementing Agreements, HCG, and the private sector. Technical meetings and workshops will be organised to discuss and agree basic input data. It is imperative to map the uncertainty that surrounds the input parameters.

d. *Technology learning analysis* - Strongly linked to the selection of the input data, this analysis is the key to evaluate future cost of the technologies. It requires assessing key technology R&D issues and prospects for improvements (R&D learning) as well as the effect of large scale production on final cost (learning by doing). Current methods for technology learning analysis will be adapted to hydrogen and fuel cell technology. The analysis should be carried out in parallel with the collection and selection of data and requires interactions with the private sector. Depending on the results obtained, the outcomes of the technology learning analysis could be reported in a separate publication.

e. *Analysis campaign and reporting* – At least six, non-independent variables may influence the market penetration of the hydrogen and fuel cell technologies:

- Technology breakthroughs and performance;
- Technology cost;
- Cost and performance of competing technologies;
- Government policies to mitigate CO_2 emissions;
- Government policies to improve energy diversification and security;
- Global and regional availability of energy resources.

The basic question is whether hydrogen and fuel cells may play a role in the future energy market. What level of cost and performance are required to become competitive with other technologies in the quickly evolving framework of the coming decades. Which governmental policies and measures for emission reductions and energy diversification (e.g., carbon tax, emission limits, incentives to diversification, and public infrastructure investment) might play a role to achieve the competitiveness. The following questions will be investigate:

Transition issues

- *Which policies & measures to speed up deployment*
- *Transition cost and infrastructure investment needs*
- *Potential penetration in different world regions*

Long-term perspectives

- *Prospects for H_2&FCs in future energy mix*
- *Impact on energy security in the mid-long term*
- *Impact and cost-effectiveness in reducing CO_2 emissions*

Strategy and technology issues

- *Which H_2? From gas, coal, biomass, renewable, nuclear, all?*
- *Are H_2 and FCs necessarily linked together?*
- *Is transport the most attractive market for H_2& FCs?*
- *Competition and synergy with other transport options (on-board methanol/DME reforming, hybrid vehicles)*
- *What's role for stationary applications (distributed generation, electricity storage, back-up power for intermittent sources)*

Time Planning, Deliverables and Resources

If financial support will be confirmed the activity would start in January 2005 and include three phases:

- 1st Phase (3-4 months): Collection and validation of input data; Model's updating, Workshop to agree input data (spring 2004).
- 2nd Phase (3-4 months): Analysis of model's sensitivity to input data; Definition of scenarios; Analysis campaign; Result analysis; Workshop to discuss results (summer 2004).
- 3rd Phase (3-4 months) - Further analysis (if necessary); reporting and publication; draft publication expected to be available in the last quarter of 2005.

Reporting includes

- A technical report on the scenarios' analysis to be published by the IEA
- A separate report on the technology learning analysis will be considered as appropriate.

The overall work plan requires:

- About 20 staff-months over a time period of 10-12 months with the involvement of senior technologists of the IEA Energy Technology Office.
- The organisation of two technical workshops to agree on basic input data, and to present the results at the end of the project

The incremental cost for the Secretariat to carry out the activity is € 210,000.

More details on the program of work and technical information are given in the Technical Annex.

THE ETP PROJECT

The IEA Secretariat has developed a technical-economic model of the global energy system to carry out energy technology scenario analysis and technology policy studies. The model is based on the Markal software for modelling global and regional energy systems developed by the

ETSAP Implementing Agreement (Energy Technology System Analysis Programme).

Markal (Market Allocation) is a linear-programming software that is particularly suitable for quantitative analysis to assist decision making for energy and technology strategies. Markal is widely used to investigate the impact of emerging energy technologies on the energy market and to analyse the effect of policy measures on their market penetration. It simulates the energy system and market through a set of equations. Based on a user-defined initial energy system, the model determines the optimal configuration of the system and its evolution over time taking into account introduction and transition to new technologies in a competitive marketplace, and policy measures designed to minimise cost, reduce emissions and improve supply security and diversification. This approach gives in the same result that would be achieved in a perfect market.

The model inputs consist of a detailed description of the initial energy system (demand and supply technologies, technical performance and emissions, installed capacity, investment and energy production cost, energy demand and trading,) and appropriate user-defined constraints to represent policy strategies and real-life boundary conditions (e.g., public incentives for introduction of new technologies, restrictions and taxes on GHG emissions, market penetration rate of new technologies, physical and technology limits to installed capacity, etc.)

The ETP model includes 15 world regions and accounts for international energy trading, introduction of new technologies, performance improvement over time, impact of technology learning on cost, life-cycle of energy carriers and technologies, and fuel substitution. The model investigates a typical time horizon of 50 years (2000-2050) and relies on a very detailed demand/supply technology data-base. The ETP model is regularly used to support the IEA World Energy Outlook and to carry out impact analysis (e.g., market penetration, economic/emission implications) of individual energy technologies and policies under different assumptions and scenarios. Amongst others, the model has been used for CCS analysis (IEA, 2004) and for renewables analysis (Gielen et al., 2004). The model contains a detailed transport sector description and characterisation that has been developed in co-operation with the World Business Council on Sustainable Development (WBCSD) and used to carry out scenario analysis for hydrogen. This analysis (WBCSD, 2004) showed the potential role of hydrogen in the transport sector, but it did not consider cost or optimal allocation of energy resources and emission reduction efforts across sectors.

TECHNICAL ANNEX

a) Review of existing studies

The study will build on existing analyses, which have been carried out in recent years, e.g., Australian Government, 2003; Bossel et al., 2003; NRC, 2004; IEA/WBCSD, in preparation. Further key studies and sources of information in IEA member countries will be identified. Goal of this step is to collect information and compile a comprehensive set of data. The HCG, IPHE, EUTP and the existing network of the IEA Hydrogen and Fuel Cells Implementing Agreements will be consulted.

The analysis will also build on conclusions from previous IEA analysis:

- Cost challenges for a hydrogen economy are in both the demand and supply side (IEA, 2003);
- For centralized production facilities, hydrogen transportation and distribution cost are of similar importance as hydrogen production cost (IEA, 2003);
- Electricity based hydrogen production (i.e., nuclear and most renewable-based electricity production) is generally much more expensive than direct production routes. However the cost of electrolyzers may decline significantly in the future. This is essential, or thermal and chemical conversion based production routes should be preferred (IEA, 2003);
- Hydrogen production from coal with electricity cogeneration and CO_2 storage could become an attractive option (IEA, 2004);
- Hydrogen is an expensive CO_2 emission reduction option. The feasibility of a hydrogen economy might strongly depend on supply security considerations (Difiglio and Gielen, 2003);
- Hydrogen appears to be an option for transport. Opportunities also exist for stationary applications but other technology options might be strong competitors (for both small and large scale applications).

b) Updating of the ETP model

Some prospective hydrogen production technologies are not yet included in the model, e.g.:

- Photo-electrolytic production
- Photo-biological production;
- Thermo-chemical processes using solar high-temperature heating (SI cycle);
- Solar methane steam reforming
- Hydrogen recovery from coke oven gas

On-board hydrogen storage for fuel cell vehicles is another issue to update. For the time being, high-pressure gaseous storage and cryogenic liquid storage are the only available alternatives. Credible, non-speculative solid storage alternatives to be included in the model must be carefully assessed. The same applies to all prospective technologies that are in a very early stage of development, for which credible evaluations of cost and performance are not yet available.

As hydrogen is one of the options to mitigate emissions, it is imperative to model competing emissions reduction options. Competing technologies in other sectors (e.g., carbon sequestration and renewable technologies in the electricity sector) are already modelled in detail (IEA, 2004). For the sake of this analysis special attention will be given to competing strategies for reducing emissions in transport, e.g., energy efficient vehicles, biofuels, and electric vehicles (Duleep, 2003). While the model contains data for such competing strategies, they need to be updated as well.

Hydrogen can also improve supply security. This will depend on the primary energy source for hydrogen production and the fuels that are replaced by hydrogen. Moreover, supply security needs a careful definition. For the sake of this study, global oil and gas use and the regional dependency on oil and gas imports will be used as indicators for supply security.
Apart from geo-political factors that can not be accounted for in the model, the energy security depends on future oil and gas supply and demand. If oil supply peaks in the coming decades there will be an increasing need for alternatives such as hydrogen, in particular in transport. The uncertainty regarding the remaining recoverable quantities of oil will be dealt with through scenario analysis**,** with oil production peaking at different periods in time.

Special attention will be given to competing options that can enhance the supply security such as DME from coal, biofuels, and energy efficiency.

The concept of hydrogen as energy storage medium needs further analysis. A diurnal, multi-day or even seasonal storage would be needed for intermittent renewable power sources, but also for base-load power plants. Hydrogen would be produced from base-load electricity (e.g., nuclear) during periods of low electricity demand (where the marginal cost of nuclear electricity is low). The analysis of hydrogen as energy storage medium requires an adequate representation of the regional electricity demand curves. Preliminary analysis suggests the demand curves for certain regions may need revision. Most ETP regions include in reality several separate electricity grids that may have different load curves. The model's load-curve should be a weighted average for these individual curves. Other options such as compressed air energy storage will be considered as a competing electricity storage options. Storage for varying periods of time must be assessed (diurnal, weekly, monthly, half-yearly).

In the hydrogen energy chain, the cost of single steps depends critically on the economy of scale. Cost estimates in chemical engineering commonly assume that investment cost increase with the scale of operations to the order 0.7. So, if the scale of operations is ten times as large, the cost double, and the cost per unit of capacity halve. Therefore, special attention will be given to assumptions regarding the economy of scale, which can have important consequences for the cost and feasibility of a hydrogen economy.

Previous IEA analysis (IEA, 2003) suggests that the bulk of the investment cost for a large-scale hydrogen economy will be on the demand side. Especially fuel cell vehicles (FCVs) can represent an important cost component. While it is clear that important cost reductions can be achieved for FCVs, it is unclear to what extent the cost gap between fuel cells and internal combustion engines (ICEs) can be closed. The comparison is further complicated by unclear evaluations regarding: life span perspectives of fuel cells; their energy efficiency depending on drive-cycle characteristics; annual mileage that differs widely over vehicle categories; and also unclear car buyer investment criteria. Defining "credible and consistent comparative options" will be of key importance. In the case of cars, this implies cars with similar emission levels for SO_2, NO_x and particulate as for hydrogen fuel cell vehicles. Additional costs for filters and catalysts should be taken into account.

c) Collection and validation of basic input data

Given the complexity of the analysis and the huge amount of data required, discussions on input data with selected experts should focus on key uncertainties regarding hydrogen and fuel cells. This includes for instance:

- Cost and cost reduction potentials for fuel cell vehicles;
- Efficiency, cost and cost reduction potentials for electrolysers;
- Cost and feasibility of advanced hydrogen production technologies;
- Key policies and measures in members countries or emerging international policies
- …. ….

Note that the bulk of the modeling work is in the selection of credible and consistent input data. Special attention will be paid to the uncertainty surrounding key model input parameters.

In order to map the uncertainty a typical range of figures will be identified for each topic including a low estimate, an average estimate, and a high estimate.

A workshop will be organised in spring 2005 to discuss and agree a proposed, consistent set of input data. Preliminary results based on these data will be presented as well. Invited experts will have the opportunity to measure the sensitivity of input data on final results. A close co-operation is envisaged with the participants of the Cascade-Mints and HyWays EU projects, as well as other groups involved in similar evaluations.

d) Technology Learning analysis

Strongly linked to the selection of the input data, this analysis is the key to evaluate cost reductions that are needed for market penetration. It requires assessing key technology issues and prospects for improvements coming from research efforts (called learning by R&D, or innovation) as well as the effect of large scale production on final cost (called learning-by-doing).

So far, a proper analytical basis to separate the two effects is not available. An effort will be made to improve the basic understanding of technology learning. This includes an analysis of current price levels, current cost levels, historical learning rates, evaluation of cost reduction potential and ultimate least-cost levels based on physical energy and materials inputs. The analysis should be carried out in parallel with the collection and selection of data and also requires interactions with the private sector. This work will build on ongoing analysis for renewable energy at the IEA ETO office.

e) Analysis campaign

The basic hypothesis is that “hydrogen can play a key role in a future, sustainable energy system. For this to happen technology breakthroughs are required to reduce cost and improve performance of hydrogen and fuel cells technologies. However, unless hydrogen and fuel cells will become significantly more convenient than other options in terms of cost and performance, even a marginal economic competitiveness could not be enough for consumers to switch to hydrogen. Public/private investment in infrastructure (e.g., hydrogen production, storage and distribution facilities) and governmental policies to reduce emissions and improve energy security might play a key role for market introduction and deployment. The question is to identify under which combinations of assumptions on:

- Technical improvements,
- Cost reduction,
- Infrastructure investments,
- Governments’ policies, and
- Resource availability (oil & gas peak, access to oil and gas reserves, etc., …)

Hydrogen and fuel cells might achieve a significant share in a competitive marketplace. The overall cost of the system (economics), the total emissions (environment), the global oil and gas demand (energy security) should then be evaluated and compared to scenarios with no hydrogen.

The analysis will be structured as follows. A mapping scenario with favourable yet reasonable assumptions for hydrogen and fuel cells will be built to identify key opportunities and technologies of the hydrogen economy. Based on the mapping scenario, a sensitivity analysis will be carried out to identify key parameters, e.g.: Emission and diversification policies; Technology performance and costs (fuel cells, H_2 supply, storage, distribution); Competing *supply and demand* side technologies (CO_2 sequestration, renewable and nuclear technologies, enhanced ICEs, hybrid vehicles, residential and industrial end use technologies, etc.); Competing fuels and energy carriers (ethanol, synfuels, DME, etc.); Oil & gas supply peaking; GDP growth trends; Economic parameters (discount rates, etc.). Based on the sensitivity analysis, consistent sets of optimistic and the pessimistic input data will be defined. They will be used in the two analyses of the *Transition to Hydrogen*, and the *Fully Developed Market*. Other scenarios may be defined according to the main dimensions that can affect the future role of hydrogen.

Among the key parameters, government policies and measures need to be specified in more detail (e.g., penalty levels, taxation, emission limits and caps, incentives to diversification, emission trading, regional scope, sector specific targets, introduction path etc.). Member countries may want to propose specific policies and measures to take into account.

Reasonable assumptions and evaluations will be considered for technology cost and performance, taking into account that all technology options for hydrogen production, storage and transport need to be proven on a commercial scale.

Future oil supply potential, possible peaking and time to develop unconventional reserves also deserve attention. While it is clear that we are not “running out of oil”, the increasing demand can create a market for oil substitutes in transport. In addition, even if the resources base is sufficient, satisfying the increasing demand could be difficult for the production, and the increasing dependency on the Middle East can result in supply problems and/or high price. Possible oil production peak should be accounted for.

The following questions will be addressed in the course of the study:

1) **Transition issues**
   - *Which policies & measures to speed up introduction (specific policy measures may be suggested by Member countries)*
   - *Transition cost and infrastructure investment needs*
   - *What is a realistic time path for hydrogen introduction?*
   - *Is transportation the most attractive market for the transition to hydrogen?*
   - *Which regions will become early hydrogen adopters? Which economics, emission, and security benefits? What's the cost of the transition?*

2) **Long-term perspectives**
   - *Is hydrogen the best mid/long term option to mitigate CO_2 emissions in both transport and other sectors ?*
   - *Is hydrogen the best mid/long term option to mitigate oil supply security problems?*
   - *What are the global and regional costs of a hydrogen economy?*
   - *What's the long term cost of hydrogen supply chains in a fully developed market?*
   - *Are there regional differences in terms of hydrogen need/potential?*

3) **Technology and Strategic issues**
   - *Which H_2? From gas, coal, biomass, wind, solar, nuclear, ... all primary energy sources?*
   - *What hydrogen technologies deserve special attention?*
   - *How is the hydrogen attractiveness affected by regional energy demand and natural resource endowment?*
   - *What's the attractiveness of hydrogen in various segments of the transport sector?*
   - *Are H_2 and FCs necessarily linked together? What about hydrogen ICEs?*
   - *How do hydrogen fuel cell vehicles compare with methanol on-board reforming and DME in transport?*
   - *Can hydrogen hybrid vehicles become competitors for fuel cell vehicles?*
   - *Which fuel cell development targets should be met in order to make fuel cell vehicles a viable alternative?*
   - *What about innovative ideas such as using cars for distributed power supply and decentralised reformers to supply hydrogen for both stationary fuel cells and fuel cell vehicles?*
   - *What's the role for hydrogen in electricity storage for intermittent sources?*
   - *Can FutureGen-type electricity and co-generation plants reduce hydrogen supply cost?*

f) Reporting

The final goal of this effort is to produce an analytical report similar to the forthcoming report on CO_2 capture and storage (IEA, December 2004). For this purpose, a new IEA publications series "Energy Technology Analysis" has been created. The hydrogen report will follow a similar structure as the report on CO_2 sequestration, with three main sections on:

- Technology Status and prospects
    - Hydrogen production
    - Hydrogen transportation and distribution (with special emphasis on transition issues)
    - Hydrogen use for stationary and mobile applications (with emphasis on fuel cells and learning effects on fuel cell development)
- Analysis
    - BASE scenario, calibrated with WEO 2004 Reference Scenario
    - Mapping policy scenario and sensitivity analysis
    - Scenario analysis
- RD&D status compared to regional long-term perspectives
- Policies for a transition to hydrogen.

g) Time planning

The time required for the project is about 10 months. The study will start in January 2005.

1st Phase (3-4 months) - Data will be collected through literature search and contacting parties mentioned above; Data will be documented, so that they can be evaluated by other experts; The model structure will be completed and preliminary data will be included; A workshop will be organised to discuss and fix input data (spring 2004);

2nd Phase (3-4 months) - The key model sensitivities will be identified; Based on the outcome of this sensitivity analysis, scenarios will be defined; The scenario results will be analysed; A workshop will be organised to discuss the results (summer 2004); If necessary, further model runs will be done;

3rd Phase (3 months) - Reporting and publication; The draft publication is expected to be available in last quarter of 2005.

Model characterization

The ETP model is based on the MARKAL modelling paradigm (Rath-Nagel and Stocks, 1982). In a reference case, the model calculates the least-cost system configuration, which satisfies a certain demand. In an alternative analysis approach, the producer/consumer surplus is maximised by taking into account the shadow prices and demand elasticity for various demand categories[2]. The model covers the period 2000-2050 in 5-year intervals. The world is divided into 15 regions.

A summary schematic of the current model structure for hydrogen is shown in figure A1. It includes hydrogen production (from fossil fuels with and w/o CCS, biomass, electricity from various sources, and co-generation), transport/distribution, and end-use technologies for transport, industry and residential applications.

An example of model's input data and technology characterisation is given below with the reference to the ETP transportation fuel supply module.

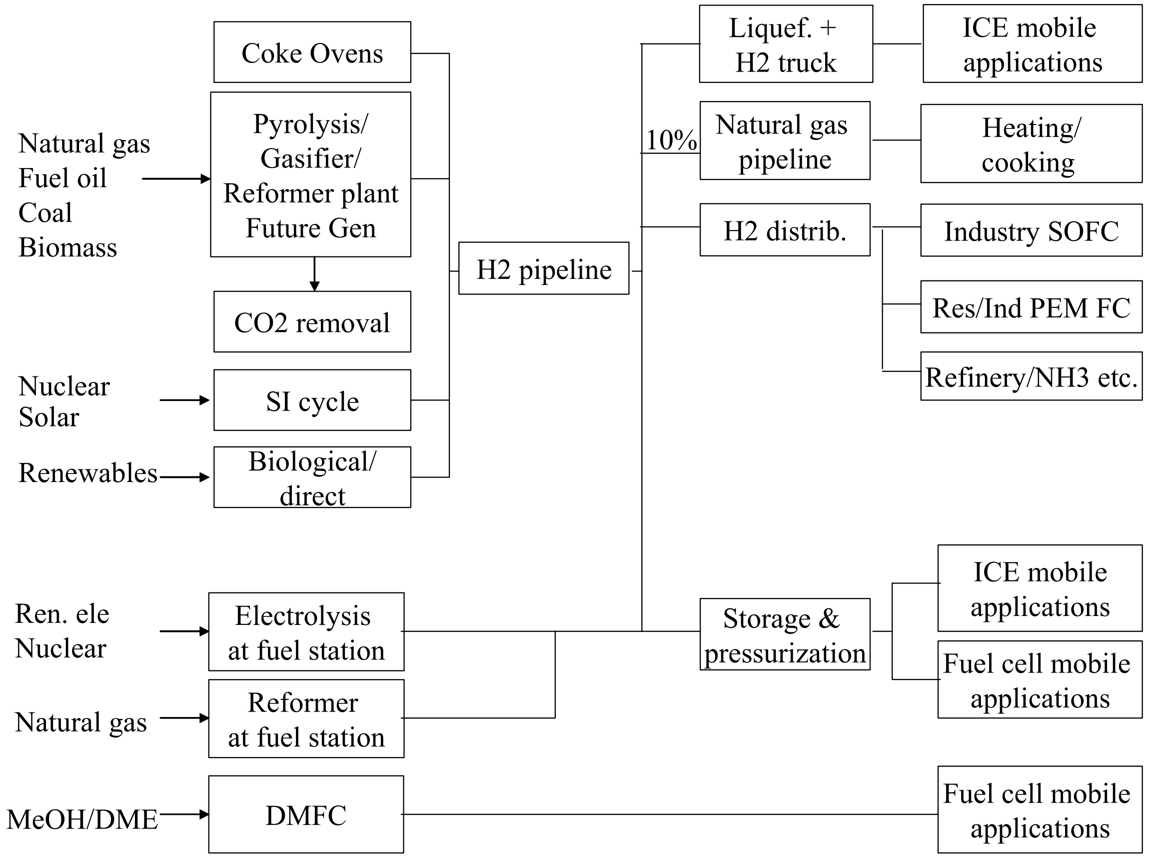


Figure A1: *ETP model structure for hydrogen*

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[2] The model runs that are discussed in this study are still based on common MARKAL, without demand elasticities.

The ETP transportation fuel supply module

Table A1: Efficiency of transportation fuel supply options:

	Production of feedstock	Transp fuel production	Fuel compression/ liquefaction	Overall efficiency
Gasoline	0.98	0.90	1.00	0.88
Diesel	0.98	0.92	1.00	0.90
Hydrogen from nat. gas -CO2	0.95	0.78	0.81	0.60
H2 from coal -CO2	0.98	0.59	0.81	0.47
H2 from coal -CO2 "FutureGen"	0.98	0.60	0.81	0.47
H2 from biomass (gasfication)	0.98	0.59	0.81	0.47
H2 from onshore wind	1.00	0.80	0.81	0.65
H2 from offshore wind	1.00	0.80	0.81	0.65
H2 from solar thermal	1.00	0.80	0.81	0.65
H2 from PV	1.00	0.80	0.81	0.65
H2 from nuclear	0.33	0.80	0.81	0.21
H2 from HTGR cogeneration	0.64	0.80	0.81	0.41
FT Biomass	1.00	0.49	1.00	0.49
Lignocellulose ethanol	1.00	0.50	1.00	0.50
Lignocellulose DME	1.00	0.59	1.00	0.59

The ETP transport demand module

The transport sector module of the ETP model has been developed in cooperation with the World Business Council for Sustainable development (WBCSD, 2004). The transportation sector is split into fifteen demand categories:

- Inland aviation;
- International aviation;
- Buses;
- Minibuses;
- Three wheelers;
- Heavy trucks;
- Private SUVs and light trucks;
- Light and medium commercial trucks;
- Passenger cars;
- Two wheelers;
- Taxis;
- Rail freight;
- Rail passenger;
- Internal navigation;

- International navigation.

The relevance of certain demand categories is high in developing countries, but negligible in industrialized countries.

Within each category, a number of alternatives have been considered. This includes energy efficient ICEs, but also fuel substitutes. Ethanol has been split into 95% and pure ethanol for mixing with gasoline (which can be applied to any gasoline vehicle, not shown separately, modelled at the level of gasoline supply). A list of alternatives is provided in the annex. This representation of competition is complex, but it is still a simplification of the actual situation where the 90% interval for annual mileage may range from 5,000 kilometers to 50,000 kilometers. In the model, the annual mileage within one category is the same for all vehicles of a certain demand category.

The model has 15 regions. The vehicle mileage differs by region. Also the efficiency differs by region. Finally the demand split differs by region. This results in a different physical demand by region. As a consequence, the hydrogen potential at a given cost level will differ by region.

Also the discount rate differs by region, and regional cost multipliers are applied. As a consequence the choice between hydrogen and other options with will differ by region.

A correction is applied for the average regional vehicle mileage. This is important because in case of a longer distance driven per year, the investment cost per unit of transportation service will be lower.

Two types of corrections are applied for regional investment cost:

- a correction for regional vehicle production cost and retail prices
- a correction for regional vehicle use

The correction for production cost is a general one, applied to all energy technologies.

In the ETP model, the consumer time preference, the institutional barriers and the transaction cost factors are reflected in a so-called “hurdle rate”. The hurdle rate is the discount rate that is applied to future cost and benefits. It is a stylised way to reflect a wide range of barriers for investment in energy efficiency. This approach was chosen to represent various market distortions. For industrialized countries, the hurdle rate has been set at the real bond yield plus ten percent. For developing countries, twenty percent has been added. These adders should be considered as working assumptions. Finally the sluggish response to price changes is reflected via technology coefficients that limit capacity growth and decay.

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