International Energy Agency

Agreement on the
Production and Utilization of Hydrogen

End-of-Term Report: 1999 - 2004

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and
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End-of-Term Report: 1999 - 2004

1. INTRODUCTION

The current term for the International Energy Agency (IEA) Agreement on the Production and Utilization of Hydrogen ends in June 2004. The Hydrogen Implementing Agreement (HIA) was initiated in 1977 to advance hydrogen production, storage and end-use technologies and to accelerate hydrogen's acceptance and widespread utilization. The most recent extension of the Agreement was approved in June 1999.

2. FRAMEWORK

Today, hydrogen is primarily used as a chemical feedstock in the petrochemical, food, agricultural, electronics, and metallurgical processing industries. Hydrogen, however, is rapidly emerging as a major component of clean sustainable energy systems. It is relevant to all of the energy sectors – transportation, buildings, utilities, and industry. Hydrogen can provide storage options for intermittent renewable technologies such as solar and wind, and, when combined with emerging decarbonisation technologies, can reduce the climate impacts of continued fossil fuel utilization. The members of the IEA-HIA agree that energy related hydrogen technologies, thus, merit serious attention. The following are the guiding principles on which the scope of the HIA is based:

- Hydrogen – now mainly used as a chemical feedstock – will in the future increasingly become an energy carrier itself. It is necessary to carry out the analyses, studies, research, development, demonstration and dissemination that will facilitate a significant role for hydrogen in the future;
- Significant use of hydrogen will contribute to the reduction of energy-linked environmental impacts, including global warming caused by anthropogenic carbon emissions, mobile source emissions such as CO, NO_x, SO_x, and NMHC (non-methane hydrocarbons), and particulates;
- Hydrogen can be used as a fuel for a wide variety of end-use applications including important uses in the transportation and energy services sectors;
- Hydrogen is currently used to up-grade lower quality, solid and liquid fossil fuels, such as coal and heavy oils. The use of hydrogen in such applications reduces harmful emissions through more efficient end-use conversion processes and extends the range of applicability. Ultimately, with the addition of hydrogen, carbon dioxide emissions can be used to produce useful chemicals and fuels;
- Hydrogen has the potential for short, medium and long-term applications and the steps to realize the potential for applications in appropriate time frames must be understood and implemented;
- All sustainable energy sources require conversion from their original form. Conversion to electricity and/or hydrogen will constitute two prominent, complimentary options in the future;
- Hydrogen can assist in the development of renewable and sustainable energy sources

by providing an effective means of storage, distribution and conversion; moreover, hydrogen can broaden the role of renewable energies in the supply of clean fuels for transportation and heating;

- Hydrogen can be produced as a storable, clean fuel from the world's sustainable non-fossil primary energy sources – solar, wind, hydro, biomass, geothermal, nuclear, or tidal. Hydrogen also has the unique feature that it can upgrade biomass to common liquid and gaseous hydrocarbons, thus providing a flexible, sustainable fuel;
- All countries possess some form of sustainable primary energy sources; hence, hydrogen energy technologies offer an important potential alternative to fossil fuel energy supply (in many instances to imported fuels) that is relevant to individual country conditions and goals. Utilization of hydrogen technologies can contribute to energy security, diversity and flexibility;
- Barriers, both technical and non-technical, to the introduction of hydrogen are being reduced through advances in renewable energy and hydrogen technologies as well as systems including progress in addressing hydrogen storage and safety concerns; and
- Hydrogen energy systems have potential value for locations where a conventional energy supply infrastructure does not exist. The development of hydrogen technologies in niche applications will result in improvements and cost reductions that will lead to broader application in the future.

The members of the IEA HIA recognize that a long-term research, development and demonstration (RD&D) effort is required to realize the significant technological potential of hydrogen energy as well as its economic and environmental value. This effort can help create competitive hydrogen energy production and end-use technologies, and supports development of the infrastructure required for its use. Attention is to be given to the entire system, in particular all of the key elements should be covered either with new research or based on common knowledge.

If the technological potential of hydrogen as an energy carrier is realized, it will contribute to the sustainable growth of member economies as well as the world economy by facilitating a stable supply of energy and by helping to reduce future emissions of carbon dioxide. Cooperative efforts among nations responsive to their national priorities and IEA goals can help speed effective progress towards these outcomes. Inasmuch as hydrogen is in a pre-commercial phase, it is particularly suited to collaboration as there are fewer proprietary issues than in many energy technologies.

2.1. Vision, Mission and Approach

IEA Hydrogen Vision: Our vision for a hydrogen future is one based on clean sustainable energy supply of global proportions that plays a key role in all sectors of the economy.

IEA Hydrogen Mission: The mission of the IEA HIA is to accelerate hydrogen implementation and widespread utilization.

IEA Hydrogen Approach: Our approach is to facilitate, coordinate and maintain innovative research, development and demonstration (RD&D) activities, through international cooperation and information exchange.

2.2. Objectives

The IEA HIA will realize its vision and mission and implement its approach by meeting the seven objectives listed as follows.

2.2.1. Technology Objective

Foster the technical advancement and acceptance of hydrogen as a prime energy carrier.

Actions

- Conduct research and development activities to address important barriers to the acceptance of hydrogen technologies;
- Foster and maintain a balanced portfolio of hydrogen technologies;
- Develop safe, efficient, and cost-effective hydrogen storage systems;
- Demonstrate integrated hydrogen systems;
- Collect, disseminate, and analyse information on hydrogen technologies; and
- Develop direct hydrogen production technologies.

2.2.2. Energy Security Objective

Contribute to global energy security.

Actions

- Facilitate the transition from fossil fuel energy systems to sustainable hydrogen-based energy systems;
- Provide resources for the conversion of intermittent and seasonal renewable energies to base-load, load-following or peak-load power supplies, and to transportation fuels; and
- Assist developing countries in evaluating sustainable, indigenous resources for hydrogen production.

2.2.3. Deployment Objective

Promote the deployment of hydrogen technologies with important local and global energy benefits.

Actions

- Provide design support for hydrogen demonstrations;
- Conduct cost-shared and task-shared deployment activities for hydrogen energy systems;
- Act as an information resource for on-going and proposed hydrogen demonstration activities, including performance analyses; and
- Conduct case studies for hydrogen systems in developing countries.

2.2.4. Environmental Objective

Exploit and promote the environmental benefits of hydrogen.

Actions

- Carry out research and development on renewable hydrogen production techniques;
- Promote hydrogen as a "clean" fuel;
- Perform life cycle assessments of hydrogen technologies and energy systems;
- Conduct research and development on technologies that lead to the decarbonisation of fossil fuels.

2.2.5. Economic Objective

Contribute to the development of cost-effective hydrogen energy systems that can compete in global markets.

Actions

- Encourage industry participation to obtain market-oriented input for the prioritisation of research, development and demonstration activities;
- Develop and utilize analysis tools to evaluate and optimise hydrogen systems;
- Increase involvement of industry in the Agreement’s activities;
- Foster clean system incentive policies; and
- Identify secondary benefits of hydrogen energy systems, such as demilitarisation.

2.2.6. Market Objective

Identify and overcome non-technoeconomic barriers for hydrogen’s penetration into the energy and fuel markets.

Actions

- Contribute to the scientific and technical basis for approved codes and standards;
- Promote hydrogen infrastructure for supply, maintenance and operation;
- Pursue technologies that will lead to increased market penetration for hydrogen; and
- Initiate safety-related educational and technology assessment activities.

2.2.7. Outreach Objective

Advertise and promote the benefits of hydrogen.

Actions:

- Increase involvement of private and public organizations in the Hydrogen Program;
- Utilize media tools to promote hydrogen education;
- Establish collaborative research and development projects that promote international networks;
- Collaborate with other IEA Agreements to increase the effectiveness of crosscutting research and development activities; and
- Increase cooperation to reach "critical mass" in research and development activities.

2.3. Trends

The major part of the IEA member countries now maintains hydrogen RD&D programs. Many non-member countries of the developed and developing nations also share an interest in hydrogen and have invested in hydrogen RD&D. Globally, concerns about climate change and energy security create the forum for mainstream market penetration of hydrogen. Ultimately, hydrogen and electricity, our two major energy carriers, will come from sustainable energy sources, most importantly from the sun (refer to Figure-1). Nevertheless, fossil fuels will likely remain a significant and transitional resource for many decades. Therefore, challenges pertaining to refinement and decarbonisation of fossil fuel based sources of hydrogen merit serious and in-depth consideration. Likewise, carbon-free nuclear production of hydrogen is an important HIA interest area.

Our long-term vision for a hydrogen future is one of clean sustainable energy supply of global proportions that plays a key role in all sectors of the economy. We plan to implement our vision with a focus on fostering advanced pre-commercial technologies, including emerging direct solar production systems, low-temperature metal hydrides as well as room-temperature carbon nanostructures for storage, and enabling components in hydrogen conversion and hydrogen system integration.

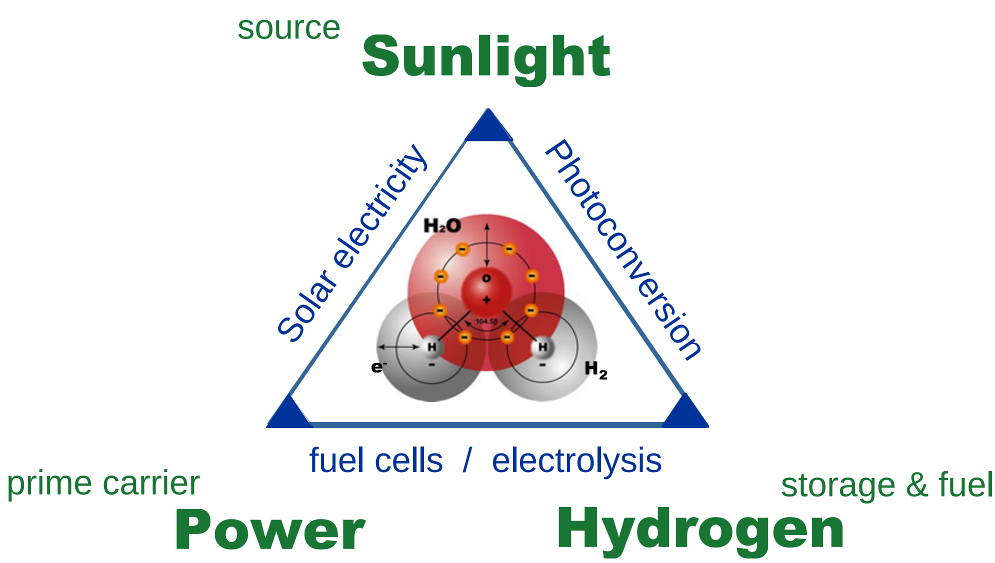

Figure-1: Solar-powered energy triangle of the post-fossil-fuel era, with electricity and hydrogen as main building blocks.

In pursuit of this vision, the IEA-HIA anticipates growth in membership and participation in its implementing agreement, together with the addition of increased management and administrative capacity.

3. PARTICIPATION

The IEA-HIA has 14 participating members at the end of the 5-year term from 1999 to 2004. Industry participation in the collaborative RD&D Tasks has been consistent, with a dominant effort in the two energy storage Tasks.

3.1. Member Countries

Table-1: List of the 14 participating HIA member countries and their contracting parties.

HIA Member Country	Contracting Party
Canada	Natural Resources Canada Stuart Energy Systems (formerly the Electrolyzer Corporation)
Denmark	Danish Gas Technology Center
European Commission	Joint Research Center
Iceland [1]	National Energy Authority
Italy	Ente per le Nouve Technologie, L'Energia E L'Ambiente (ENEA)
Japan	New Energy and Industrial Technology Development Organization (NEDO)
Lithuania [1]	Lithuanian Energy Institute
Netherlands	Netherlands Agency for Energy and the Environment (NOVEM)
Norway	Research Council of Norway
Spain	Ministry of Industry and Energy
Sweden	Swedish Energy Agency
Switzerland	Swiss Federal Office of Energy
United Kingdom	Department of Trade and Industry
United States	Department of Energy

[1] Non-IEA-member country participant

During the 5-year term, Italy returned to active status. The United Kingdom rejoined the HIA, this time with the Department of Trade and Industry as the Contracting Party. Non-IEA-member country participants were Lithuania, who joined the HIA in March 2002, and Iceland, who joined at the second part of 2003. Denmark was stated to join the HIA in early 2004. Turkey remains a signatory to the HIA, but is considered inactive.

Singapore has applied to the IEA for participation in the HIA as a non-IEA-member country. Australia, Austria, Finland, France, Korea and New Zealand have expressed strong interest to join the HIA, while Hungary and Mexico are still considering their membership.

3.2. Task Participation

Table-2: List of HIA Task participation by member country.

HIA Member Country	Task-13	Task-14	Task-15	Task-16	Task-17	Task-18
Canada	X		X		X	X
European Commission	X					X
Iceland [1]						X
Italy					X	X
Japan	X	X	X	X	X	X
Lithuania [1]	X				X	
Netherlands	X		X	X		
Norway	X		X	X	X	X
Spain	X			X	X	X
Sweden	X	X	X	X	X	X
Switzerland	X	X		X	X	
United Kingdom	X		X	X	X	X

HIA Member Country	Task-13	Task-14	Task-15	Task-16	Task-17	Task-18
United States	X	X	X	X	X	X

[1] Non-IEA-member country participant

3.3. Industry Involvement

Stuart Energy Systems (formerly the Electrolyzer Corporation), Canada, remains a signatory to the HIA and an active participant in the research tasks. Norsk Hydro, Norway, served as Operating Agent for Task-16 (Hydrogen from Carbon-Containing Materials). The Operating Agents for Tasks 12/17, 14 and 18, were/are from private consulting firms. Additionally, a number of industries participated in the collaborative Tasks (refer to Table-3). Such participation is predominantly in Task-16, with significant industry participation evolving in the newest task extension, Task-18 (Integrated Systems Evaluation). Several of the participating publicly funded research institutions have close connections to local private industries. These industries benefit from the IEA-HIA work as well. However, as indirect beneficiaries, they are not mentioned in the industry list below. The activities of all other Tasks are focusing largely on the conduct of collaborative, pre-commercial RD&D.

Table-3: List of industry participation in HIA Tasks.

Company	**Task-13** Design and Optimisation of Integrated Systems	**Task-14** Photo-electrolytic Production of Hydrogen	**Task-15** Photo-biological Production o f Hydrogen	**Task-16** Hydrogen from Carbon-Containing Materials	**Task-17** Solid and Liquid State Hydrogen Storage Materials	**Task-18** Integrated Systems Evaluation [1]
ABB						CH
Air Liquide						F
Air Products						USA
Associated Octel						UK
B9 Energy						UK
Biomass Technology Group				NL		
BOC						UK
BP-Amoco				USA		USA
Dynamotive				CAN		
ENI				ITA		
EniTechnology			USA			
Energetics						USA
Ergenics					USA	
ET Energie Technologie					GER	
Gas Natural				ESP		
Gastec				NL		
Gas Technology Institute				USA		
Gaz de France				FRA		

Company	**Task-13** Design and Optimisation of Integrated Systems	**Task-14** Photo-electrolytic Production of Hydrogen	**Task-15** Photo-biological Production o f Hydrogen	**Task-16** Hydrogen from Carbon-Containing Materials	**Task-17** Solid and Liquid State Hydrogen Storage Materials	**Task-18** Integrated Systems Evaluation [1]
General Hydrogen						CAN
Haldor Topsøe				NOR		
Harvest Energy Technologies						USA
HERA Hydrogen Storage Systems					CAN	
Hydrogen Solar Production Company		UK				
IGS Mahler				GER		
Ineos Chlor						UK
Intelligent Energy				UK		
London Hydrogen Partnership						UK
Longitude 122 West	USA					USA
Norsk Hydro				NOR	NOR	
NRG Technologies						USA
Nuvera						ITA
Osaka Gas				JAP		
PanCanadian				CAN		
Plug Power						USA
QuestAir Technologies						USA
Repsol				ESP		
Services Mij						CAN
Shell				NL		
Shell Hydrogen						UK
Sigen						USA
Sustainable Technologies International		AUS				
Statoil				NOR		
Stuart Energy Systems	CAN					CAN
SunaTech					USA	
Suncor				CAN		
Sycon	USA					
Sydkraft	SWE					SWE

Company	Task-13 Design and Optimisation of Integrated Systems	Task-14 Photo-electrolytic Production of Hydrogen	Task-15 Photo-biological Production o f Hydrogen	Task-16 Hydrogen from Carbon-Containing Materials	Task-17 Solid and Liquid State Hydrogen Storage Materials	Task-18 Integrated Systems Evaluation [1]
Tees Valley Hydrogen Partnership						UK
Texaco				USA		
Transport of London						UK
United Technologies					USA	
Wind-Hydrogen						UK
Würth Elektronik						GER

[1] Some of the listed industry participants are still being confirmed.

3.4. Withdrawals

There were no withdrawals during the 5-year period 1999 – 2004. Germany withdrew from the HIA just prior to the start of this period. Discussions continue with representatives from Germany to bring them back into the HIA.

4. PROGRAM OF WORK

The HIA considers the use of hydrogen as an energy carrier being a mid- (5 – 15 years) to long-term (beyond 15 years) goal, with economics remaining a key challenge to overcome. Likewise, infrastructure barriers, particularly in the storage area, seem to hinder the near-term (up to 5 years) application expectation of hydrogen as clean transport fuel. Additionally, safety issues, both real and perceived, are concerns for acceptance of hydrogen by the general population. Thus, the HIA has focused on pursuing collaborative RD&D efforts in technologies that will help overcome some of the infrastructure barriers and/or result in the reduced cost of hydrogen systems.

More specifically, the following key challenges are being addressed by the HIA:

- **Production**: To achieve the advantages of a "Hydrogen Economy” future, namely a reduction in carbon emissions, hydrogen must be able to be cost-effectively produced from, preferably, renewable energy sources or from nuclear energy and/or fossil fuels with carbon sequestration, most importantly natural gas and coal. Thus, the HIA has been pursuing collaborative RD&D in the areas of natural gas, biomass and, above all, solar hydrogen production, both biological and electrochemical. While natural gas reformation and biomass gasification are relatively well-advanced technology options, much must still be learned about photo-biological processes before one is able to understand the economic potential of this production technology. The same is true for the photo-electrochemical approach, most importantly as it is challenged by the fact that conventional PV technology is not yet cost competitive and promising new materials options still require extensive research programs. However, significant advances with lower-cost materials, dye-sensitisation, catalysis and novel system configurations that have been achieved during this 5-year collaborative RD&D period promise to bring the photo-electrochemical hydrogen production technology option much closer to potential commercial practicality.

- **Storage**: On-board storage in vehicles is one of the major barriers to the acceptance of hydrogen-powered vehicles. Metal hydrides and similar storage media, such as carbon, are thought to have the greatest long-term potential for the safe, on-board storage of hydrogen. Although current work has resulted in significant system performance advances, solid-state hydrogen storage technologies have not yet proven to be commercially attractive due to system costs and the inability of current technology to meet the hydrogen storage density required for maintaining vehicle weights within a reasonable range.
- **Safety**: With a cumulative world production of almost 600 billion Nm^3 of hydrogen gas in 2003, the use of hydrogen in the fertilizer, petroleum, chemical, metals, glass, food, electronics and space industries is well established. The range of uses has been constantly increasing, as has the consumption by specific application. Historically, hydrogen has had an excellent safety record. The many studies, RD&D efforts and experience base have contributed to the publication of regulations, standards, industrial data sheets and technical reports. Hydrogen safety is a totally integrated issue, covering all aspects from production to utilization. Safety continues to be of utmost importance, not only to those already working with hydrogen such as in research, system design, plant construction and operation, but also to the general public at large, including educational facilities, governments, local authorities, insurance agents, etc.
- **Systems**: Achieving the vast potential benefits of a hydrogen energy system requires careful integration of production, storage and end-use components with minimized cost and maximized efficiency, and a strong understanding of environmental impacts and opportunities. System models combined with detailed life cycle assessments provide the platform for standardized comparisons of energy systems for specific applications. Individual component models form the framework by which these system designs can be formulated and evaluated.

The HIA has developed a broad portfolio of collaborative RD&D activities to address the aforementioned challenges for the successful hydrogen penetration into the world energy marketplace. The portfolio of work includes task-shared basic as well as applied research, information exchange, and task-shared as well as cost-shared analyses of RD&D projects. Following are brief summaries of the five Task activities that have been undertaken during the five-year period 1999 – 2004 (note – Task participation is indicated in Table-2 as well as Table-3 above).

4.1. Task-13: Design and Optimisation of Integrated Systems (Jan/99 – Jun/02)

Integrated hydrogen energy systems have been proposed as a means to increase energy independence, improve domestic economies and reduce greenhouse gas as well as other harmful emissions from stationary and mobile sources. These systems, however, face technical and economic barriers that must be overcome before hydrogen can become a competitive energy carrier for the 21st century.

Comparison of different system configurations for a particular application requires a set of criteria on which the comparison can be made. This can include efficiency, environmental impacts, economic impact, capital and operating costs, and other measures of importance to the analyst. In all cases, these parameters can be reduced to a comparison of costs, when an appropriate scaling value is assigned to these criteria. It is important to develop consistent cost models for the various hydrogen components so that fair assessments can be made of alternative designs. This is particularly important when comparing dissimilar systems at very different levels of development and commercialisation.

The objective of Task-13 was to provide a balanced means by which hydrogen energy systems can be compared to conventional energy systems. In order to meet this objective, existing, planned, and conceptual hydrogen demonstration systems were designed, optimised and/or evaluated using the tools developed under a previous effort (Task-11). Emphasis was placed on comparative analysis of these integrated systems. The activities focused on near- and mid-term applications (3-10 years), with consideration of the transition to sustainable hydrogen energy systems.

The three major activity subtasks included:

- A Cost Model was developed based on standard engineering procedures while allowing variations specific to each application. It uses multiple data sheets such as Components, Local Conditions, Investments, Operations, Cost Model and Cash Flows. The User is guided through each sheet and is asked to provide data where appropriate. Default values are included in the Cost Model. The "Components" section of the Cost Model provides information on the required system hardware. The "Local Conditions" sheet compiles data relative to the costs of various inputs in each country as well as prevailing economic conditions characterizing local business acceptability. The "Investment" section of the model details the required initial investment in each system as well as the future investment at the end of the life of the project. The "Operations" section compiles data relative to operating conditions of the system while the "Scaling" section adjusts the data to the size of the component for the project selected. Finally, the "Cash Flow" section determines the project's business acceptability in the selected country.
- Experts canvassed potential hydrogen demonstration project leaders to identify candidate configurations for analysis. This activity included designs for conceptual hydrogen demonstrations. Potential demonstrations were evaluated and recommendations made as to optimum design and operation of the facility to meet the needs of the project. Three studies were conducted: Residential Systems; Remote Applications; and Infrastructure.
- The value of hydrogen energy systems is often linked to environmental improvements (greenhouse gas reductions, and CO, NO_x, and SO_x reductions, etc.) or other intangible benefits (job creation, energy independence, health, environmental benefits, etc). Quantification of some of these benefits can be made using Life Cycle Assessment (LCA) comparisons. In this activity, the scope of an LCA for hydrogen systems was defined, based on established (published) LCA methodologies. The measures considered include comparison of CO_2 and other gaseous emissions, and determination of net energy ratio (amount of energy produced per unit of fossil fuel input). Assessments of the Residential Systems and Remote Applications were completed. A number of studies covering aspects of the Infrastructure case were also completed.

Results from these studies were presented at several international meetings and published in both annual and technical reports. Task-13 has been redefined and extended as new

Task-18.

4.2. <u>Task-14</u>: Photoelectrolytic Production of Hydrogen (Jul/99 – Mar/04)

Photoelectrolysis of water is the process whereby light is used to directly split water into hydrogen and oxygen. This can be achieved by placing a photoelectrochemical (PEC), semiconducting material or device similar to a photovoltaic (PV) cell into an electrolyte such as water. Upon irradiation with sunlight, electron-hole pairs are being generated at the catalytic PEC–electrolyte interface, driving chemical hydrogen and oxygen evolution reactions. Herewith, the optical solar energy is directly converted into chemical energy rather than into electrical energy as with solid-state or electrochemical PV cells. Such PEC water splitting systems eliminate the need for two separate systems regarding power generation and electrolysis, and hence offer great potential for cost reduction of electrolytically produced hydrogen compared with conventional two-step technologies.

RD&D programs on photoelectrolysis of water have been in place in IEA member countries such as the United States, Japan, Sweden, and Switzerland for many years with encouraging early scientific and laboratory trial device results. However, significant fundamental as well as applied science and engineering efforts are required for the development of practical demonstration systems through a collaborative RD&D program managed by the HIA. Addressing materials and systems studies, the main target areas for RD&D during this 5-year period included:

- Practical system efficiency;
- Device lifetime and costs;
- Semiconductor materials, structures and preparations;
- Light sensitisation using photosensitive dyes;
- Integrated PV/electrolysis systems; and
- Novel single- and dual-bed reactor arrangements.

Following a well-structured 5-year RD&D program, some of the main progress can be summarized as follows:

- Demonstration of a net solar-to-hydrogen PEC device conversion efficiency of 16% - the highest reported efficiency to date – and using a tandem PEC cell. The semiconductor materials used in this cell (gallium indium phosphide ($GaInP_2$) / gallium arsenide (GaAs), however, are still too costly for this to become an economically competitive technology in the near term. Successful alternative system designs using more abundant material combinations included amorphous silicon (a-Si) and tungsten trioxide (WO_3), the latter one in tandem with a dye-sensitised TiO_2 (“Graetzel”) solar cell. Their demonstrated solar-to-hydrogen PEC device efficiency has been 7.8% and 4.5% respectively;
- Identification of new low-cost material as well as production options have been identified. These include, among others, nano-structured, thin-film semiconductor photoelectrode materials based on iron oxide (Fe_2O_3), zinc oxide (ZnO) and titanium oxide (TiO_2);
- Establishment of equipment for fast-screening methods of electrochemical materials (combinatorial chemistry) to study and identify optimum material combinations and to develop comprehensive material data libraries for electrochemical applications
- Development of world-first powder photocatalysts for water splitting using apart from the

ultraviolet also the visible spectrum of sunlight;

- Analysis of the techno-economic potential of PEC devices, indicating that hydrogen production costs of the order of US$ 30 per GJ of hydrogen gas can be achieved with reliable PEC systems in a mid-term time horizon;
- Identification of promising economics when PEC hydrogen production is performed in conjunction with photodegradation of organic waste-water. Twofold efficiency gains seen with organic pollutants rather than water as reducing medium, combined with the cost/benefit of combining degradation of organic pollutants with hydrogen production, show great promise for commercial application;
- Definition of standards for measuring and reporting solar efficiencies. These standards are essential for making realistic comparisons between various photo-based systems for hydrogen production; and
- Participation of pioneering industry partners and venture capital groups confirm the great promise for sustainable commercial applications of PEC for solar water splitting.

The broadening RD&D scope regarding materials, systems and applications, combined with the onset of commercial interest for PEC solar water splitting, encouraged the HIA to design and conduct a new follow-on Task for the period Jul/04 – Jun/07.

4.3. <u>Task-15</u>: Photobiological Production of Hydrogen (Jun/99 – present)

Biological hydrogen production, the production of hydrogen by micro-organisms such as green algae and cyanobacteria, has been an active field of basic and applied research for many years. The governments of Japan and the United States, for example, support significant, long-term applied RD&D programs in this field. These and a growing number of other countries also support related basic research. Given the fact that photosynthetic solar "collector systems" have very low capital cost requirements, realization of practical processes for photobiological hydrogen production from water using solar energy could result in a major, new source of sustainable clean energy, without greenhouse gas emissions or environmental pollution.

Collaborative RD&D activities on "biophotolysis" (the biological production of hydrogen from water and sunlight using microalgae photosynthesis) have been carried out under the HIA umbrella with the following specific research focus:

- Light-driven hydrogen production by microalgae
- Maximization of photosynthetic efficiencies
- Hydrogen fermentations
- Photobioreactor system improvements for hydrogen production

The main progress over the past 5-year period can be summarized as follows:

- Tests of various process-development-scale photo-bioreactor systems, demonstrating sustainable hydrogen evolution and improved oxygen tolerance;
- Review of system analyses and process economics for hydrogen production using hydrogenase-based bioreactor systems;
- Establishment and maintenance of a world-unique, comprehensive database on hydrogen-producing microorganisms (mainly green algae and cyanobacteria); and

- Provision of sponsorship of, and key collaboration with, the world's leading BioHydrogen Symposia and RD&D programs. The recent technological advances in (photo)-biological hydrogen production has generated a focus area for new academic, industrial and governmental collaboration, most importantly addressing the fundamental science and engineering questions of biological processes, photosynthetic bacteria, cyanobacteria, green algae, fermentations, mixed-hybrid systems and photobioreactors.

In light of the significant activities worldwide in biological hydrogen production, the progress made on fundamental and applied science in this area, the global relevance of the subject, and the recognised promising research directions for the future, the HIA is now actively pursuing the development of a 3-year follow-on Task.

4.4. Task-16: Hydrogen from Carbon-Containing Materials (Apr/02 – Mar/05)

Approximately 95% of the hydrogen produced today comes from carbon-containing raw material, primarily fossil in origin. Most of the conventional processes convert the carbon in the fossil fuels to carbon dioxide, which is discharged to the atmosphere. The growing awareness of the impact of greenhouse gas emissions on global climate change has necessitated a reassessment of the conventional approach. Integrating carbon dioxide sequestration with conventional steam reforming of hydrocarbon fuels will go a long way toward achieving "clean" hydrogen production from fossil fuels. Likewise, improving the robustness of pyrolytic cracking technologies for converting hydrocarbons to hydrogen and solid carbon should not only improve the process economics, but also its applicability to a variety of feedstock. Furthermore, the thermal processing of biomass can yield an economic and carbon-neutral source of hydrogen. These efforts are conducted with strong industry involvement and in collaboration with the IEA Greenhouse Gas and the Bioenergy Implementing Agreements. The specific research and development areas include:

- Efficient carbon dioxide separation and sequestration;
- Advanced thermal processing of biomass; and
- Small-scale, distributed systems for hydrogen production.

The main Task progress made so far includes:

- Evaluation of technology options for the decarbonisation of natural gas;
- In a collaborative program with the IEA Greenhouse Gas Office, completion of the first concept study phase of a large-scale integrated hydrogen production project for power production with precombustion decarbonisation has been completed. The second study phase, a detailed feasibility study of the preferred technology concept, is being undertaken;
- Preparation of (a) a comprehensive study about the status and RD&D challenges of hydrogen production options from biomass, and (b) a specialty report on biomass gasification (under the leadership of the IEA Bioenergy Gasification Task). A resource, technology and market analysis for biomass feedstock in IEA member countries is underway; and
- A detailed review of small-scale, stationary reformers for hydrogen production from fossil fuels has been undertaken, with a very recent update provided by industry participants involved in the provision of hydrogen fuel to the CUTE (Clean Urban Transport Europe) fuel cell bus project.

Reports have been published on the state of the art of biomass-to-hydrogen technologies and on distributed technologies for hydrogen from natural gas via small-scale reformers.

4.5. <u>Task-17</u>: Solid & Liquid State Hydrogen Storage Materials (Jun/01 – present)

On-board hydrogen storage remains an undisputed challenge for hydrogen-fueled vehicles. Although recent progress in metal hydride batteries has been significant, little progress has been made in advancing the room-temperature hydrogen storage capacity of traditional hydrides. This is particularly true for PEM fuel-cell vehicle applications, where a high gravimetric hydrogen storage density is required and where hydrogen must be liberated at temperatures compatible with the waste heat of the fuel-cell (<100°C). Alternatives to solid-state vehicular hydrogen storage exist, such as high-pressure gas, cryogenic liquids and on-board reforming of conventional liquid hydrocarbon fuels. But well-known disadvantages can be cited for each. Thus, the development of non-traditional hydrides and carbon materials (nanotubes, graphite fibres, etc.) has received a great deal of RD&D attention and support worldwide.

Task-17 is a follow on to the very successful Task-12 (Metal Hydrides for Hydrogen Storage). Under Task-12, the collaborative RD&D efforts on catalysed sodium aluminium hydrides have led to the identification of a hydride material capable of 5%-wt reversible hydrogen storage at 120°C, being the necessary target for economic on-board hydrogen storage for vehicles. Under Task-17, emphasis has been placed on fundamental material formulation and treatment techniques, on understanding the mechanisms of hydrogen storage, on reproducibility of results, and on engineering aspects of using some of the more promising materials in a realistic on-board storage scenario. The two specific targets of the Task are:

- Development of a reversible hydrogen storage medium with at least 5-wt% hydrogen recoverable at < 80°C and 1 atm absolute pressure; and
- Development of the fundamental and engineering understanding of hydrogen storage by various storage media that have the capability of meeting the above storage target.

Carrying over from Task-12, the main Task-17 progress made so far includes:

- Completion of sixteen metal hydride and four carbon projects. Significant advances were made in understanding the effects of formulation and processing techniques on optimising for hydrogen storage;
- Maintenance and extension of an extensive worldwide database on metal hydride hydrogen storage materials and experiments; and
- Continuation of joint RD&D efforts on thirteen metal hydride, nine carbon and ten combined hydride/carbon projects, with a particular focus on the development of suitable on-board storage materials.

A large number of publications, presentations and patent applications resulted from the successful RD&D work coordinated by the IEA-HIA Task-17.

4.6. <u>Task-18</u>: Evaluation of Integrated Systems (Apr/04 – present)

Hydrogen as clean, versatile, abundant and indigenous energy carrier has been identified to be of high priority around the world. Many "Hydrogen Roadmaps" are being developed and high-level strategy groups are being formed in many countries. Demonstration systems are being implemented in all of the participating HIA countries. However, there are still many technical, economic, market and acceptance barriers that must be further addressed in order for hydrogen energy systems to become commercial reality.

Specific design and optimisation tools have been developed and used under previous Task-10 and Task-13. In order to facilitate the comparison of different system configurations for a particular application, criteria have been developed on which a comparison could be made, including efficiency, environmental impacts, economic impact, capital and operating costs, and other measures of importance to the analyst. In all cases, these parameters can be reduced to a comparison of costs, when an appropriate value is assigned to these criteria.

With these tools, it is now possible to evaluate existing and planned demonstration projects in detail and to provide alternative configurations and operating conditions to optimise efficiency and cost. Non-proprietary information will be provided to participating countries and parties to improve future demonstration project designs and operation. The overall goal of Task-18 is to provide information about hydrogen integration into society around the world. Two specific objectives are (a) to provide data and analysis to the hydrogen community in the form of inventory databases or compiled summaries, and (b) to use modeling and analysis tools to evaluate hydrogen demonstration projects, or to guide their design and assessment, and to validate models and assumptions.

The new Task-18 addresses the growing need for a comprehensive collection and assessment of information about issues related to the technology, policy and regulation barriers to implementation of hydrogen energy systems. The specific targets of the Task include:

- Compilation of lists of hydrogen component manufacturers and developers;
- Development of comprehensive overview of existing or potential infrastructure and hydrogen resources, optionally including maps and Geographic Information System (GIS) data layers;
- Assessment / characterization of current hydrogen support programs (levels of investments, commitments, and activities in hydrogen) by country or region;
- Review, comparison, analysis and summary of previous analyses, such as "well-to-wheels" studies; and
- Preparation of commercialisation roadmaps by country for comparison of end-uses.

Task-18 continues also to gather data on hydrogen projects and modeling as well as analysis capabilities in order to evaluate demonstration projects and/or to guide the design of them, in collaboration with industry. Intellectual Property (IP) matters are carefully managed.

5. ACCOMPLISHMENTS

Table-4 provides and overview of the key accomplishments of the HIA achieved during the 5-year period 1999 – 2004. These accomplishments are compared to the aforementioned seven objectives of the HIA.

<u>Objective-1</u>: Foster the technical advancement and acceptance of hydrogen as a prime energy carrier.

Objectives / Actions	Accomplishments Towards Objectives
• Conduct RD&D activities to address important barriers to hydrogen's acceptance. • Foster and maintain a balanced portfolio of hydrogen technologies. • Develop safe, efficient and cost-effective hydrogen storage systems. • Demonstrate integrated hydrogen systems. • Collect, disseminate and analyse information on hydrogen technologies. • Develop direct solar hydrogen production technologies.	• Collaborative Tasks were carried out on the conduct of longer-term, pre-commercial hydrogen RD&D to advance scientific knowledge and to improve the efficiency as well as lower the costs of direct solar hydrogen production technologies. ⇒ Solar-to-hydrogen conversion efficiencies have topped 16% with gallium-based, proof-of-concept photoelectrochemical (PEC) water-splitting cells. ⇒ Sustainable photobiological production of molecular hydrogen using the green alga Chlamydomonas Reinhardtii has been demonstrated. • A collaborative Task is underway to develop efficient, low-emission technologies for producing hydrogen from natural gas. ⇒ Technology options have been evaluated for pre-combustion decarbonisation of natural gas. ⇒ A detailed analysis report was published on technologies for distributed hydrogen production from natural gas. • A metal hydride material has been developed that surpasses 5 weight % (5-wt%) reversible hydrogen storage at 150°C. • Information on 22 international hydrogen demonstration projects has been collected, documented, edited and published, with a further 13 projects being prepared for analysis, editing and dissemination. • Through the integrated systems modeling efforts, a number of conceptual hydrogen energy systems worldwide have been evaluated. ⇒ Planning evaluation has been conducted for the remote island "UTSIRA" showcase wind-power / electrolysis project in Norway.

<u>Objective-2</u>: Contribute to global energy security.

Objectives/Actions	Accomplishments Towards Objectives
• Facilitate the transition from fossil fuel energy systems to sustainable hydrogen-based energy systems. • Provide resources for the conversion of intermittent and seasonal renewable energies to base-load, load-following or peak-load power supplies, and to transportation fuels. • Assist developing countries in evaluating sustainable, indigenous resources for hydrogen production.	• A research effort was launched on converting carbon-containing resources (fossil and biomass) to hydrogen. Successful implementation of these nearer-term options will establish necessary infrastructure. • The engineering modeling tools developed under the HIA over the past years have been successfully tested and are ready to be used to design and optimise renewable hydrogen systems worldwide.

Objective-3: Promote the deployment of hydrogen technologies with important local and global energy benefits.

Objectives/Actions	Accomplishments Towards Objectives
• Provide design support for hydrogen demonstrations. • Conduct cost-shared and task-shared deployment activities for hydrogen energy systems. • Act as an information resource for hydrogen demonstration activities, incl. performance analyses. • Conduct case studies for hydrogen systems in developing countries.	• The integrated system modeling tools have been used to design and optimise conceptual energy systems, including the remote island "UTSIRA" showcase wind-power / electrolysis project in Norway. ⇒ Under the new Task-18 (Evaluation of Integrated Systems), the modeling tools will be used to evaluate a broad range of existing demonstrations. • 22 detailed case studies of existing hydrogen demonstration projects have been completed, with a further 13 projects being evaluated ⇒ Lessons learned from these projects can be applied to future demonstration projects.

Objective-4: Exploit and promote the environmental benefits of hydrogen.

Objectives/Actions	Accomplishments Towards Objectives
• Carry out RD&D on renewable hydrogen production techniques. • Promote hydrogen as a "clean" fuel. • Perform Life Cycle Assessments (LCA) of hydrogen technologies and energy systems. • Conduct RD&D toward the decarbonisation of fossil fuels.	• Collaborative RD&D has been carried out on photobiological and photoelectrolytic water-splitting, and on biological and thermal routes to hydrogen. • Life Cycle Assessments (LCA) were conducted on renewable (wind and biomass) and on fossil-based systems (steam-methane-reforming and coal-gasification). ⇒ The results of these studies have been presented at international meetings. • A Front-End Engineering Design (FEED) has being jointly developed under Task-16 for the precombustion decarbonisation of natural gas.

Objective-5: Contribute to the development of cost-effective hydrogen energy systems that can compete in global markets.

Objectives/Actions	Accomplishments Towards Objectives
• Encourage industry participation in HIA to obtain market-oriented input for RD&D activity prioritisation. • Develop and utilize analysis tools for hydrogen systems. • Advocate incentive policies for clean energy systems. • Identify secondary benefits of hydrogen energy systems, ie demilitarisation.	• There has been significant industry involvement in several of the collaborative Tasks, most notably Task-16 (Hydrogen from Carbon-Containing Materials), Task-17 (Solid and Liquid State Hydrogen Storage Materials) and Task-13/18 (Integrated Hydrogen Systems) • The system modeling tools developed under the previous integrated systems Tasks are now being validated based on real-world demonstration projects.

Objective-6: Identify and overcome non-technoeconomic barriers for hydrogen's penetration into the energy and fuel markets.

Objectives/Actions	Accomplishments Towards Objectives
• Contribute to the scientific and technical basis for codes and standards. • Promote hydrogen infrastructure for supply, maintenance and operation. • Pursue technologies that will lead to increased market penetration for hydrogen. • Initiate safety-related educational and technology assessment activities.	• The Case Studies of international hydrogen demonstration projects highlights safety and permitting. ⇒ Reports published to the web to increase impact. ⇒ Operational and maintenance issues highlighted specifically. • Task-13 (Design and Optimisation of Integrated Systems), included an assessment of various cases for hydrogen supply to a hydrogen fueling station. ⇒ Results presented at multiple international meetings. ⇒ Included infrastructure costs, supply issues, and environmental impacts of various technologies.

Objective-7: Advertise and promote the benefits of hydrogen.

Objectives/Actions	Accomplishments Towards Objectives
• Increase involvement of private and public sector organizations in the HIA. • Use media tools to promote hydrogen education. • Establish collaborative RD&D projects that promote international networks. • Collaborate with other IEA Agreements to increase the effectiveness of crosscutting RD&D activities. • Increase cooperation to reach "critical mass" in RD&D activities.	• Presentations on the IEA-HIA and its activities were made at multiple international meetings and conferences, including the World Hydrogen Energy Conference, Hyforum 2000, the International Gas Conference, the World Energy Congress and the IEA Ministerial Meeting. • HIA web site has been redesigned to improve content and increase hits (from search engines). • Sponsored international meetings and conferences featuring the IEA efforts such as the IEA Hydrogen Day at Hyforum 2000 and BioHydrogen 2002 (including publishing support). • Task collaboration with other international networks: ⇒ Task-14 with IEA SolarPACES Task 2, Solar Chemistry ⇒ Task-15 with COST 8.41 Program ⇒ Task-16 with IEA Greenhouse Gases and IEA Bioenergy