IEA/H2/AR-00

IEA Agreement on the Production and Utilization of Hydrogen

2000 Annual Report

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NREL/TP-510-31287

Contents

Overview: International Energy Agency Hydrogen Implementing Agreement

The International Energy Agency

The International Energy Agency (IEA) was established in 1974, following the first oil crisis and is managed within the framework of the Organization for Economic Cooperation and Development (OECD). The mission of the IEA is to facilitate collaborations for the economic development, energy security, environmental protection and well-being of its members and of the world as a whole. The IEA is currently comprised of twenty-five member countries, ten of which are participants in the program focused on the Utilization and Production of Hydrogen.

The Hydrogen Program, or Implementing Agreement, has been in existence for more than twenty years for the purpose of advancing hydrogen technologies and accelerating hydrogen=s acceptance and widespread utilization. Past collaborations have been in the areas of Thermochemical Production, High Temperature Reactors, Electroloysis, Storage, Safety, and Markets.

The following countries/organizations participate in the Hydrogen Implementing Agreement: Canada, European Commission, Japan, Lithuania, the Netherlands, Norway, Spain, Sweden, Switzerland and the United States.

GUIDING PRINCIPLES OF THE HYDROGEN AGREEMENT

Today, hydrogen is primarily used as a chemical feedstock in the petrochemical, food, electronics, and metallurgical processing industries, but 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 decarbonization technologies, can reduce the climate impacts of continued fossil fuel utilization. The members of the IEA Hydrogen Program agree that energy related hydrogen technologies, thus, merit serious attention. The following are the guiding principles on which the scope of the Agreement is based:

Hydrogen--now mainly used as a chemical for up-grading fossil-based energy carriers--will in the future increasingly become an energy carrier itself. It is necessary to carry out the analysis, studies, research, development 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 due to anthropogenic carbon emissions, mobile source emissions such as CO, NOx, SOx, 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 utility 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 renewables 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). 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 technologies and hydrogen systems including progress in addressing hydrogen storage and safety concerns.

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 Hydrogen Agreement recognize that a long-term research and development effort is required to realize the significant technological potential of hydrogen energy. 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 is realized, it will contribute to the sustainable growth of the world economy by facilitating a stable supply of energy and by helping to reduce future emissions of carbon dioxide. Cooperative efforts among nations can help speed effective progress towards these goals. 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.

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 Hydrogen Program is to accelerate hydrogen implementation and widespread utilization.

IEA Hydrogen Strategy: Our strategy is to facilitate, coordinate and maintain innovative research, development and demonstration activities, through international cooperation and information exchange.

We will achieve this strategy by meeting the below listed objectives:

Technology Objective:
Promote acceptance of hydrogen as an energy carrier.
Actions:
$ Conduct research and development 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 analyze information on hydrogen technologies.
$ Develop direct hydrogen production technologies.

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 renewables 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.

Deployment Objective:
Promote 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.
$ Conduct case studies for hydrogen systems in developing countries.

Environmental Objective:
Exploit 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 decarbonization of fossil fuels.

Economic Objective:

Develop cost-effective hydrogen energy systems that can compete in global markets.

Actions:

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

Market Objective:

Identify and overcome 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.
$ Initiate safety-related educational and technology assessment activities.

Outreach Objective:

Advertise 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.
$ Increase cooperation to reach "critical mass" in research and development activities.

Summary

As we enter the new millennium, concerns about global 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, although, fossil fuel will likely remain a significant and transitional resource for many decades. Our 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 will implement our vision with advanced technologies including direct solar production systems and low-temperature metal hydrides and room-temperature carbon nanostructures for storage.

Current and Completed Annexes of the IEA Hydrogen Implementing Agreement

Annex 1	Thermochemical Production	1977-1988
Annex 2	High Temperature Reactors	1977-1979
Annex 3	Assessment of Potential Future Markets	1977-1980
Annex 4	Electrolytic Production	1979-1988
Annex 5	Solid Oxide Water Electrolysis	1979-1983
Annex 6	Photocatalytic Water Electrolysis	1979-1988
Annex 7	Storage, Conversion and Safety	1983-1992
Annex 8	Technical and Economic Assessment of Hydrogen	1986-1990
Annex 9	Hydrogen Production	1988-1993
Annex 10	Photoproduction of Hydrogen	1995-1998
Annex 11	Integrated Systems	1995-1998
Annex 12	Metal Hydrides for Hydrogen Storage	1995-2000
Annex 13	Design and Optimization of Integrated Systems	1999-2001
Annex 14	Photoelectrolytic Production of Hydrogen	1999-2001
Annex 15	Photobiological Production of Hydrogen	1999-2001

REPORT OF THE CHAIRMAN

Mr. Neil P. Rossmeissl
U.S. Department of Energy

INTRODUCTION

This will by my final report as Chairman of the IEA Hydrogen Agreement Executive Committee. My term as Chairman ends during 2001, at which time I will turn over the reins to one of our other Executive Committee members. As I reflect back on my two terms as Chairman, I am very pleased by our progress. We have had six extremely productive and successful tasks and have laid the groundwork for three new activities. Some very strong collaborations have been established with other IEA programs including SolarPACES, through our Tasks 10 and 14; Fuel Cells and Energy Storage, through our Tasks 11 and 13; and Greenhouse Gases and Bioenergy through our proposed Task 16. Much is still to be done and I will work with our new Chairman to continue and expand these inter-IEA collaborations.

The past several years have seen a great number of advancements in hydrogen technologies. Industry leaders like Norsk Hydro, Daimler, BMW, Ballard, Shell, BP and Air Products, among others, have shown themselves as hydrogen champions and are working towards bringing hydrogen technologies into the world market place. National hydrogen programs have grown in size and funding. Large demonstration projects are underway, proving the feasibility of hydrogen technologies and gaining the public=s acceptance for hydrogen-based energy systems.

It will still be some time before we realize our vision of a hydrogen future. However, a great deal of progress has been made. Efficiencies continue to improve for our renewable production routes. Decarbonization technologies have emerged that will not only minimize the global climate impacts of continued fossil fuel utilization, but will also facilitate infrastructure development. As hydrogen becomes utilized as a clean fuel for our future, growing demand will enable the transition to renewable-based hydrogen production.

MEMBERSHIP

We continue to focus on increasing the impact of our Agreement=s activities through expanding our membership. At our fall Executive Committee meeting, representative from China, Denmark, Hungary and Israel participated in our meeting and presented their respective national hydrogen activities. A presentation was also made on behalf of Mexico whose representative was unable to attend. Formal invitations to join our Agreement were made to all five countries. We hope that all of these countries accept our invitation and become official members during 2001.

Discussions have been underway with several other countries regarding membership in the Hydrogen Agreement. Australia, Iceland, New Zealand and the United Kingdom have all expressed interest in the Agreement=s activities. Representatives from these countries will be invited to meetings during 2001. We also continue to seek out other countries with interest in our collaborative activities.

STATUS OF TASKS

Task 12 - Hydrogen Storage in Metal Hydrides and Carbon

Task 12 officially ended in September. The accomplishments of this effort will be featured in a final report to be published in mid-2001. I wish to commend the Task 12 experts for the significant progress they made. Not only were they able to meet the original task target of 5 weight percent hydrogen storage at 150^{o}C, they exceeded it. As a result, the target was lowered to 5 wt% storage and 100^{o}C. Our experts nearly met this target as well. Twenty projects were undertaken over the duration of Task 12, sixteen on metal hydrides and four on carbon. Through these projects, much has been learned about hydrogen storage options.

Although we still have a great deal of progress to be made before practical on-board hydrogen storage is realized (with these materials), our collaborative efforts have brought us closer to this goal than most thought feasible. Again, none of this would have been possible without the dedication and expertise of our international experts and their teams. Finally, on behalf of our entire Executive Committee and our experts, I would like to thank our Operating Agent, Dr. Gary Sandrock, for his outstanding leadership and contributions. Dr. Sandrock was the driving force behind Task 12. His experience was key for bringing together experts and defining many of our most successful projects. We are very pleased that Dr. Sandrock has agreed to lead our new Task 17, Solid and Liquid State Hydrogen Storage (see below). Special acknowledgment also goes to Mr. William Hoagland, the original Operating Agent for Task 12, for helping us to launch this activity.

Task 13 - Design and Optimization of Integrated Systems

The first two years of this three-year effort are now complete and our experts have made a great deal of progress. The models developed under the previous Task 11 have been updated to the new modeling platform version and a stand-alone pressure swing absorption model has been added. Three hydrogen energy systems have been selected for evaluation. Cost guidelines have been set and data is being compiled. Finally, the life cycle assessment (LCA) of the conventional hydrogen system (steam methane reforming) has been completed and the LCAs of the renewable systems have begun. All of our Agreement Members are now participants in this Task, with the European Commission, Sweden and Switzerland having joined during 2000. This is testament to the importance and relevance of this effort. Special thanks go to the Operating Agent, Mrs. Catherine Gregoire Padró, and her experts for another extremely successful activity.

Task 14 - Photoelectrolytic Production of Hydrogen

We are at the halfway point of this three-year effort. Conversion efficiencies have now topped 16% with the gallium-based system and are approaching 8% with the lower-cost silicon-based systems. We are learning a great deal about system configurations and materials and have demonstrated that novel designs improvements can significantly lower efficiency losses and, ultimately, cost. Although much work must still be done we are nearing the point where a system can be selected for larger-scale engineering testing. During the coming year, we will be looking for a partner to help us with an engineering scale-up of a system selected by our experts. This engineering work would take place as part of a two-year extension of Task 14. At the same time, our experts would continue their fundamental development efforts, particularly material and catalytic improvements.

Task 15 - Photobiological Production of Hydrogen

This three-year effort is also at the halfway point. The goal is to achieve a light conversion of 3% into hydrogen gas. This fundamental effort has resulted in some very significant progress. Our experts have demonstrated sustainable photobiological production of molecular hydrogen using the green alga *Chlamydomonas reinhardtii*. Genetic modifications to various microalgae strains have progressed, resulting in improved oxygen tolerance and conversion efficiencies. This work is still in the very early development stage. However, our experts have already seen efficiencies around our 3% target. Our fermentation efforts are also progressing, with some very high carbohydrate conversion efficiencies being reported. Although not yet formalized, the Netherlands will be joining Task 15 and has already been participating on an unofficial basis. They will take over leadership of our subtask on bioreactor development and contribute to many of the other areas of work. We also continue to collaborate with other international groups, including the European Photobiological Network.

NEW INITIATIVES

Task 16 - Hydrogen from Carbon Containing Materials

The Task Development efforts for this new activity continue. Three subtasks have been defined: A) Large-Scale Hydrogen Production, B) Biomass to Hydrogen and C) Small Stationary Reformers. We will be collaborating with the Greenhouse Gases Agreement (GHG) on this Task and they will, in fact, lead Subtask A. Subtask B will collaborate very closely with the Gasification and Pyrolysis activities of the Bioenergy Agreement. A workshop will be held in early 2001 to define the Programme of Work for this Task. We expect formal Task approval sometime during 2001. I would like to thank Mr. Bjorn Gaudernack and Mrs. Elisabet Fjermestad Hagen for their hard work in bringing this effort together and for developing the collaboration with GHG.

Task 17 - Hydrogen Storage in Metal Hydrides and Carbon

As previously mentioned, great strides have been made in our hydrogen storage efforts, but much progress must still occur before we are at the point of having a material ready for practical on-board hydrogen storage. Safety, durability and cost still require a significant investigative effort. Likewise, material improvements are still needed to achieve the current storage target of 5 weight percent at temperatures below $100^{o}C$. Carbon adsorbents, such as carbon nanotubes, are being touted as having the greatest potential for meeting the hydrogen storage requirements. However, work in this area is still at the very fundamental stage. Our Operating Agent and experts have developed an excellent work plan for Task 17 and are now defining specific projects and formalizing participation levels. We expect that this Task will be authorized to begin work at our Spring 2001 Executive Committee meeting and that participants will include Canada, Japan, Lithuania, Norway, Sweden, Switzerland and the United States. China, Iceland, Israel, Mexico and the United Kingdom are also expected to join this effort upon formalization of their participation in the Hydrogen Agreement.

HIGHLIGHTS FROM THE 2000 EXECUTIVE COMMITTEE MEETINGS

43rd Meeting, San Ramon, California, USA, 14-17 May 2000

- Mr. David Haberman of DCH Technology participated as a guest in the meeting and presented an overview on the importance of planning hydrogen infrastructure safety. DCH is active in a number of international projects, including several underway in Iceland and Israel. Mr. Haberman is also a member of the Hydrogen Technical Advisory Panel to the U.S. Department of Energy.
- Final plans were made for IEA Hydrogen Day at the Hyforum 2000 meeting in Munich, Germany.
- The preliminary draft for the new Task 17, Solid and Liquid State Hydrogen Storage Materials, was approved. Dr. Gary Sandrock was accepted as the proposed Operating Agent for Task 17.

44th Meeting, Madrid, Spain, 24-27 October 2000

- Representatives from China, Denmark, Hungary and Israel participated in the meeting. Invitations were made to all four countries and to Mexico to join the IEA Hydrogen Agreement.
- Members gave overviews of their respective national hydrogen programs. Papers based on these presentations are included in this Annual Report.
- A follow-on activity to the Annex 11 Case Studies was approved. A minimum of 5 hydrogen demonstration projects will be critically reviewed. Dr. Thomas Schucan, the author of the Annex 11 Case Studies Report, will coordinate the activity.
- Dr. Antoon Kipperman of NOVEM, Netherlands, was unanimously elected to serve as Vice-Chairman of the Executive Committee.

HYFORUM

The HYFORUM 2000 meeting in Munich, Germany, was a great success. Dr. Winter and his team are to be commended for putting together an excellent meeting. Technical experts offered the latest developments in hydrogen production, storage and utilization technologies; international banking representatives discussed the implementation and financing of hydrogen/renewable energy technologies in today's world market; industry leaders gave their views on infrastructure needs and the transition to a hydrogen-based economy; and governments presented a diverse set of national approaches.

As part of the meeting, our Agreement was the proud sponsor of *IEA Hydrogen Day*. I would like to thank Mr. Hanns-Joachim Neef, Head of IEA Headquarters' Energy Technology Collaboration Division, for providing the opening remarks. I would also like to thank our Secretary, Ms. Carolyn Elam, for presenting the overview of our IEA Hydrogen Agreement activities and Mr. Trygve Riis, our ExCo Member from Norway, for presenting the overview of our Member Countries' National Hydrogen Programs. Finally, I would like to acknowledge our round table discussion participants for presenting their views on a "Sustainable Energy Industry: The International Challenge for Policy, Business and Technology." They were Mr. David Nahmias, Chair of the U.S. Hydrogen Technical Advisory Panel; Mr. Nick Beck, Natural Resources Canada; Mr. Yoshitaka Tokushita, New Energy and Industrial Technology

Development Organization (NEDO), Japan; Dr. Peter Lindblad, Uppsala University, representing the Swedish National Energy Administration; Dr. Antoon Kipperman, Netherlands Agency for Energy and the Environment (NOVEM), representing the European Hydrogen Association; and Mr. Angel Gutierrez, SDAD. de Gas de Euskadi, Spain. Special thanks go to Dr. Gerhard Schriber, our ExCo Member from Switzerland, for stepping in and facilitating our panel discussion. Our Agreement also had an exhibition booth throughout the conference. We had the opportunity to speak with a number of individuals and made some very good contacts.

The need for cost-competitive technologies, including safe hydrogen storage methods, infrastructure development, uniform codes and standards and financial opportunity were messages repeated throughout the meeting. Many asked the question of whether the advancement of hydrogen will drive the development of fuel cells or whether fuel cells are driving hydrogen technology development; approaches vary. Companies like BMW have taken the stand that hydrogen is necessary, particularly from an environmental concern, regardless of whether fuel cells make sense. At Hyforum, they displayed their fleet of dual-fuel luxury sedans that are powered by modified V-12 internal combustion engines and capable of running on either liquid hydrogen or standard hydrocarbon-based fuel. BMW plans on commercial sale of these vehicles within the next few years. Other companies are gearing their programs strictly towards fuel cells. Regardless, all agreed that hydrogen is a necessary ingredient in addressing environmental concerns and energy security.

OTHER ACTIVITIES

The Annex 11 Final Subtask Report, Case Studies of Integrated Hydrogen Energy Systems, remains in high demand. The experience gained from these demonstration projects is invaluable. Since the report was completed, a number of new demonstrations have been launched. Recognizing the importance of continuing to capture and evaluate the information gained from these types of projects, we have asked Dr. Thomas Schucan, the author of the Annex 11 Case Studies Report, to begin evaluating these new projects. A minimum of five integrated systems will be selected for review. Dr. Schucan will work with the demonstrators and the Annex 13 experts to prepare project reports. Again, emphasis will be placed on safety, permitting and lessons learned, as well as technical challenges.

We are closely following the Hydrogen Pipeline Forum development efforts underway in Japan. The general assessment of available information on and barriers to large-scale hydrogen transport via pipeline networks is applicable to a number of activities in our programs. Industry within our Member Countries are a great collective of this type of information, but, to the best of our knowledge, no one has attempted to compile all of this experience into a common database, until now. We will work with the Forum to help identify the applicable expertise in our countries and make available the tools developed through our Annex 11 and 13.

SUMMARY

Our Agreement is poised to make a significant impact on the future of hydrogen technologies. We will continue to advance our production and storage activities and support demonstration efforts with our integrated systems tools and expertise. We will launch our new Task 16, Hydrogen from Carbon Containing Materials, in the coming year. We have great hope that the near-term commercial opportunities of this Task will help increase hydrogen's share in the market place and decrease the world's carbon dioxide emissions. We will continue to build our base of data on international demonstration projects and help make this information available to developers and policy makers.

Development of uniform codes and standards will receive a great deal of our attention in the coming year. Many of the various national hydrogen associations have ongoing codes and standards activities. We will help share the results of these efforts and bring these organizations together for the common goal of accelerating hydrogen's introduction into the world energy market.

I would like to take this opportunity to thank all of the Executive Committee members for their support and for their faith in my leadership. I have learned a lot during my years as Chairman and I look forward to working with our next Chairman to continue our momentum. My sincere thanks go to Ms. Elam for all of her hard work and support. She has been an integral part of our success. Finally, I would like to acknowledge the leadership of our Operating Agents and the dedication and contributions of our Task experts. All have made my time as Chairman extremely rewarding.

National Programs of the IEA Member Countries

Carolyn C. Elam
Executive Secretary

Overview

In December 1994, the Executive Committee of the IEA Hydrogen Agreement prepared and published a report on the *Hydrogen Energy Activities in Eleven IEA Countries*. This comprehensive report was the result of a June 1994 workshop at which the Executive Committee members shared information on hydrogen technology research, development, demonstration and industrial activities in their respective countries. An update to this report was published in the *1996 Annual Report of the IEA Agreement on the Production and Utilization of Hydrogen*. We continue to track policy trends, technical progress, research needs, and technical and non-technical barriers, and to provide published updates on a periodic basis.

National Programs of the Member Countries

The national programs of the IEA Hydrogen Program Member Countries represent a diverse set of philosophies, policies, projects and budgets, brought together under the auspices of the IEA to accelerate hydrogen's acceptance and widespread utilization. These programs range from the hydrogen-dedicated North American and Japanese programs to those where hydrogen is but a player in various renewable and fossil programs. Budgets range from a few hundred thousand to more than twenty million U.S. dollars (USD) per year. Some large government programs have been reduced and transitioned to industry while others have continually grown and become more focused on hydrogen technologies. Regardless of size, the common theme among all of the members' programs is that hydrogen has many roles in the world's energy future, from reducing the climate impacts of fossil-based systems to facilitating the transition to renewables. It is a fuel for fuel cell vehicles and a storage medium for wind, photovoltaic, geothermal and hydroelectric energy. Hydrogen's versatility will solidify its niche in the world market and be a platform for achieving a sustainable energy future. It is truly a flexible energy carrier.

Currently, nine countries are active participants in the IEA Hydrogen Program: Canada, Japan, Lithuania, the Netherlands, Norway, Spain, Sweden, Switzerland and the United States. The European Commission is also a member, bringing with it a link to other European countries. With the growing awareness of global climate change, recent years have seen an increased number of international hydrogen-related projects.

The national programs of the nine member countries range from non-hydrogen specific programs, with hydrogen playing a role in multiple programs, to multi-million dollar (USD) hydrogen specific programs. Even in the cases where a country has a specific program focused on hydrogen research and development, hydrogen technologies are also found within programs dedicated to other activities, such as transportation or fossil technologies.

Following are brief overviews from our members on their respective national approaches and philosophies related to hydrogen energy technologies. It is difficult to track all areas within a country's research, development and demonstration portfolio where hydrogen benefits the overall technology. Thus, the papers focus only on the largest contributors.

CANADA

N. R. Beck and M. Hammerli
CANMET Energy Technology Centre
Natural Resources Canada

National Perspective

The Hydrogen and Fuel Cell R&D Program of Natural Resources Canada (NRCan) is focused on the development and/or evaluation of hydrogen systems and fuel cell technologies for transportation and stationary power, including off-grid applications. The program is managed by NRCan's CANMET Energy Technology Centre, with other federal government departments or agencies also contributing to hydrogen and fuel technology developments, such as the Department of National Defence and the National Research Council.

Program Structure

The Hydrogen and Fuel Cell R&D Program encourages innovation by facilitating R&D partnerships through cost-shared agreements with the private sector, frequently under multiple-partner arrangements. Program activities are oriented toward the development of technologies with short-to-medium term commercial potential.

The program has three components:

- Hydrogen Production - the objective is clean, efficient hydrogen production from water electrolysis using renewable or sustainable energy sources.
- Hydrogen Utilization - the objective is to develop the technologies and processes required for hydrogen to be a safe and effective energy carrier.
- Fuel Cells - the objective is to further develop Canadian fuel cell technologies to lower costs and move towards commercialization. In addition, other fuel cell technologies will be evaluated and adapted for use in Canada.

Funding

The NRCan budget, which does not include money spent by other departments/agencies or the provinces, is approximately $4 million per year (fiscal year 2000-2001). In contracting out R&D work, a key factor considered is cost sharing by the contractor.

Research, Development and Demonstration Activities

<u>Hydrogen Production</u>

Canada's R&D efforts in the area of hydrogen production focus mainly on improving Canadian water electrolysis technology and on how to supply hydrogen fuel to vehicles and other equipment in a sustainable and economical fashion. Research and development activities are underway that address new amorphous alloy electrocatalysts for water electrolysis; intermediate-sized advanced alkaline water electrolyzers; advanced water electrolyzer systems;

and production of hydrogen from hydrogen sulfide; as well as purifying hydrogen with the use of new ceramic materials.

Some of the Canadian companies involved in hydrogen production include:

Stuart Energy Systems is a world leader in the manufacture and development of Hydrogen Fueling Systems, which are the devices that supply hydrogen fuel to vehicles and other equipment. Users of Stuart's Fueling Systems and related components include the Montreal Urban Transit Authority, British Columbia Transit, Xcellsis, Ballard® Power Systems, Hydro-Québec, Gas Metropolitan, The South Coast Air Quality Management District and Xerox Corporation.

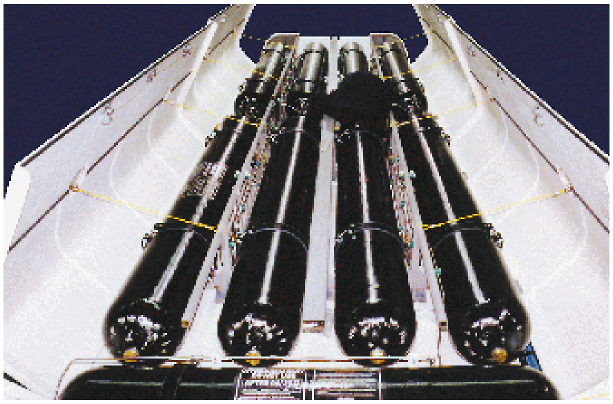
QuestAir Technologies Inc., deals with ultra-compact, pressure swing adsorption (PSA) based gas separators and purifiers. Questor's HyQuestor hydrogen purifiers have been in commercial operation since 1997.

Hydrogen Systems Inc., is a global hydrogen solutions supplier with operating units in North America, Europe and Asia. The company produces and distributes a new generation of alkaline membrane-based hydrogen generators. Hydrogen Systems' extensive range of Inorganic Membrane Electrolysis Technology® (IMET) generators replaces conventional hydrogen supply systems with on-site and on-demand hydrogen production.

Hydrogen Utilization

Storage system technologies provide solutions for safe storage and transportation of hydrogen. Canadian companies have been instrumental in developing safety standards that have been implemented worldwide. Activities are focused on developing advanced storage systems and materials including the use of metal hydrides and carbon nanotubes, as well as at ways of increasing operating pressures and lowering the weight and costs of hydrogen storage cylinders.

Some of the Canadian companies involved in hydrogen utilization include:



Cryo-nor specializes in high-tech containers for the transport, distribution and storage of liquid hydrogen worldwide.

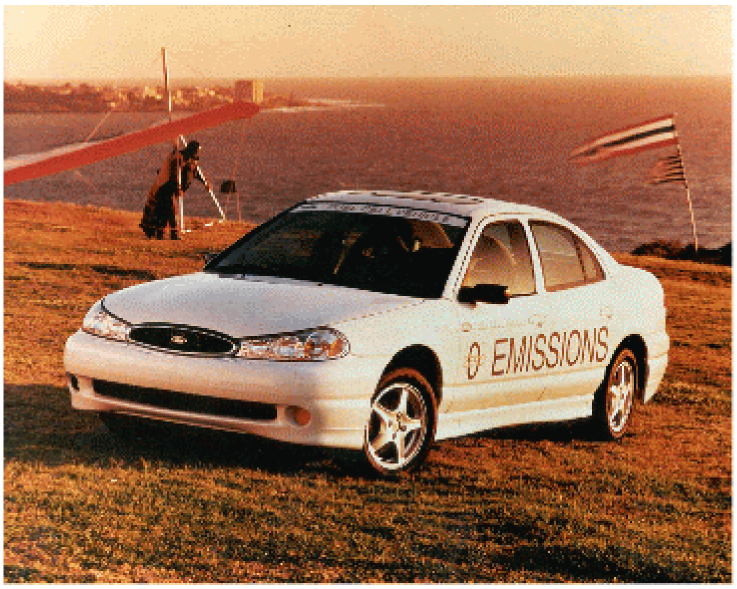
Powertech Labs has worked extensively with compressed gas cylinder technologies; including the testing and certification of cylinders and pressure components to various standards, worldwide.

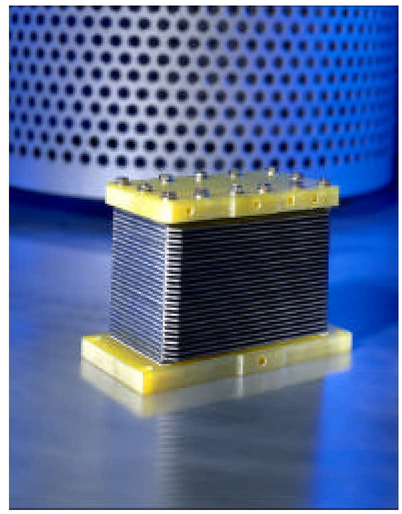
Dynetek Industries is the manufacturer of fuel storage systems for alternative fuels and fuel cell vehicles. Its DyneCell®, a lightweight composite cylinder, is the most advanced and lightest compressed hydrogen cylinder on the market. DyneCells have been used in transit buses in Chicago and Vancouver, and in low-floor airport buses in Munich, Germany.

Fuel Cells

Fuel cell technologies are becoming a viable option for clean power, both in transportation and stationary applications. The Canadian government and industry, by working together, have contributed to Canada being at the forefront of fuel cell technology. Projects are currently underway that address the use of Proton Exchange Membrane (PEM) Fuel Cells and Solid Oxide Fuel Cells for use in cars and buses, as well as in stationary applications to power industrial plants and buildings.

A Ford vehicle with a Ballard Fuel Cell





HPower Fuel Cell

Some of the Canadian companies involved in fuel cell technology include:

Global Thermoelectric is the world's leading supplier of thermoelectric generators and is presently developing advanced Solid Oxide Fuel Cell technology for various applications.

Ballard Power Systems is the world leader in the development and commercialization of proton exchange membrane (PEM) fuel cells. Ballard combines technology leadership in fuel cells and fuel cell systems with product engineering, manufacturing, marketing, distribution, and service capabilities.

Xcellsis develops fuel cell engines for passenger vehicles, buses and trucks. At the heart of each Xcellsis fuel cell engine is a Ballard PEM fuel cell.

Hydrogenics is a fuel cell systems integrator, that is currently working on fuel cells for residential applications and low temperature (-40^{o}C), remote sites. The company's first commercial line is an advanced series of test-stations for hydrogen fuel cells.

H Power Enterprises of Canada markets low power fuel cell systems (up to 1 kW) to power portable electrical devices and home products and also offers sub-kilowatt fuel cell systems for a variety of telecommunication and back-up power applications.

SIGNIFICANT ACHIEVEMENTS

In 1999, Canada opened its first Electrolytic Hydrogen Fueling Station in Port Coquitlam, B.C. The station, supplied by Stuart Energy Systems, provides hydrogen for three Fuel Cell Buses operated by the Coast Mountain Bus Company (formerly the BC Transit Authority) in its regular fare paying service in the Vancouver area.

Since the electricity used to generate the hydrogen fuel is renewable hydro-electricity, these transit buses are part of a clean fuel cycle. More recently, Stuart Energy Systems delivered a turnkey hydrogen fueling station to SunLine Transit in California.

OUTLOOK

Hydrogen and fuel cell technology in Canada is maturing at a rapid rate. Across Canada, research and development activities covering all aspects of hydrogen and fuel cell development are underway. In fact, a whole industry committed to providing cleaner transportation and stationary power systems is emerging and Canadian technologies are at the forefront of this new and exciting field.

With greenhouse gas reductions, energy efficiency and urban air quality being key drivers for fuel cell and hydrogen technologies, there will be many opportunities for fuel cell use in the coming years. Transportation is an obvious opportunity, with a zero emission fuel cycle as the goal. Other opportunities include remote and portable power, and fuel cells for residential and stationary power generation.

In the near-term, cost and size reduction is required in many hydrogen technologies. In the longer-term, cost reductions will continue to be an issue in some hydrogen technologies, including fuel cells. The changeover from the internal combustion engine to fuel cell engines will be gradual and will take several decades. However, a suitable hydrogen infrastructure is needed to enable fuel cell vehicles to be a viable commercial option. To this end, work is underway to evaluate and demonstrate various hydrogen fueling routes.

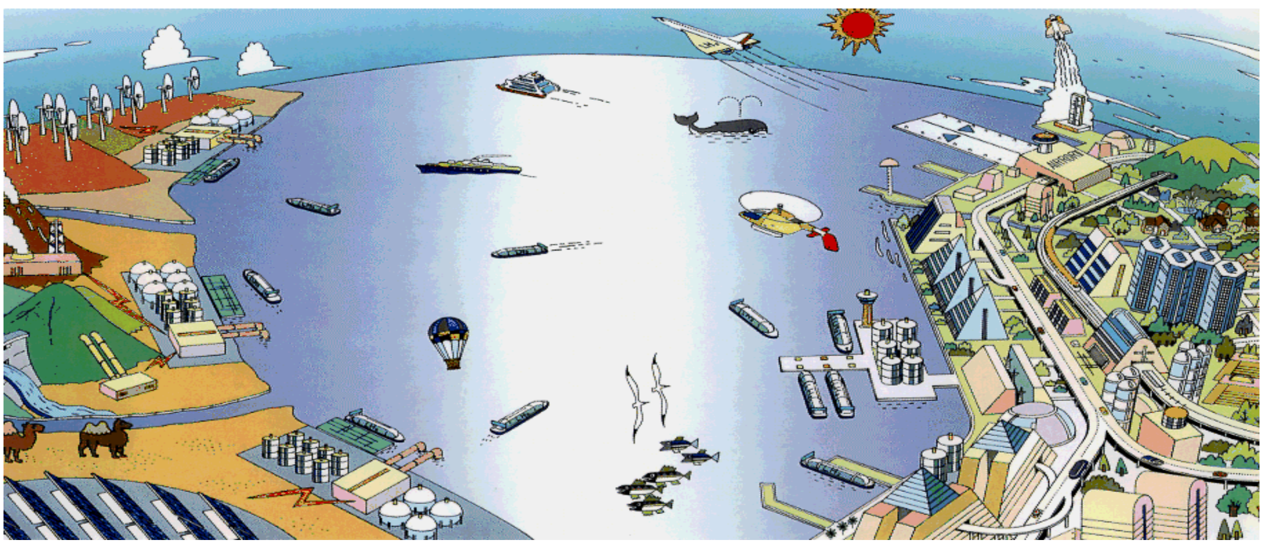

Government of Canada
Gouvernement du Canada
Canada
Hydrogen and Fuel Cell Activities
British Columbia
Alberta
Saskatchewan
Manitoba
Ontario
Quebec
Newfoundland

JAPAN

Plan/Overview of the WE-NET(World Energy Network) Project

Objectives of the WE-NET Project

The WE-NET project, which conducts the research and development on hydrogen energy, has been administered by the New Energy and Industrial Technology Development Organization (NEDO), under the Ministry of Economy, Trade and Industry (METI) of Japan, since 1993 . The project aims to provide a solution to the global dilemma of producing and utilizing energy while simultaneously preserving the environment. The project involves employing technologies for the production, transportation and storage of hydrogen on a large scale through the effective utilization of abundant renewable energy, such as hydropower and wind power. Implementation of the comprehensive conceptual design of a hydrogen energy system and the development of the elemental core technology are major milestones in this project.



Conceptual Diagram of WE-NET Includes: Hydrogen Aircraft, Hydrogen Rocket, Hydrogen Storage Tank, Energy Consumption Site, Hydrogen Bus, Hydrogen Combustion Power Generation, Hydrogen Tanker, Hydrogen Vehicle, Hydrogen Production Plant, Hydropower Station, Wind Power Station, Geothermal Power Station, Photovoltaic Power Station, and Rich Region in Renewable Energy

Overview of the WE-NET Project

The WE-NET project is being implemented as shown in Table 1. The research & development of Phase I (1993-1998) mainly involved ascertaining long-term goals. Phase I also emphasized analyzing the introduction of hydrogen energy into society. Phase II (1999-2003) proceeds with technical development leading to practical applications in the short- and mid-term. The duration of Phase III will be determined following formal evaluation of Phase II results.

Table 1. Overview of the WE-NET Project

Phase	Fiscal Year	R&D Overview
I	1993-1998	Conceptual examination of an international hydrogen energy network system was conducted along with the basic and leading elemental R&D, including production, transportation, storage and utilization.
II	1999-2003	Based on results from Phase I, distributed utilization technology development to promote the steady introduction of hydrogen energy into society is being carried out.
III	2004-	Verification of the system for the realization of distributed and concentrated utilization technology is planned. (Duration to be determined following formal evaluation of Phase II results.)

The details of the main activities and results of Phase I and II are as follows.

1) Phase I

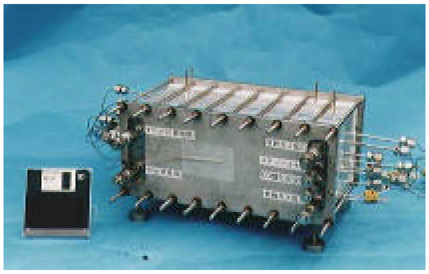
Significant knowledge was obtained on various subjects, including the energy balance evaluation of the hydrogen energy network system and the cost evaluation of hydrogen combustion power generation. In the case of the technical development of hydrogen production, an energy efficiency of more than 90% was achieved at an electric current density of $1A/cm^2$ employing solid polymer electrolyte water electrolysis. In the case of hydrogen combustion turbine power generation, the optimum cycle was designed under the conditions of a turbine inlet temperature of 1700°C with a thermal efficiency of 60%(HHV). Demonstrative tests of the hydrogen-oxygen combustor and the turbine-cooling blade were carried out under actual temperatures, verifying their capability. The R&D fruits of the WE-NET project were highly praised and the project received the1998 International Association for Hydrogen Energy “Rudolph Erren Award."

2) Phase II

Based on the accomplishments of Phase I, Phase II entails promoting the steady introduction of hydrogen energy into society. The establishment of distributed utilization technology is planned along with the demonstration of fuel systems for hydrogen vehicles, a hydrogen refueling station, a pure hydrogen-fueled solid polymer electrolyte membrane fuel cell, a hydrogen-diesel cogeneration system and so on. In developing the technology for distributed utilization, the areas comprising the components under research are simultaneously investigated in order to efficiently apply those results to the distributed utilization technology domain in parallel with development of the other research themes. For instance, the technical development of the solid polymer electrolyte water electrolysis for hydrogen production is applied to the hydrogen refueling station. The technical development of the new hydrogen-absorbing alloy is carried out with the objective of application to mobile and stationary hydrogen storage facilities. Table 2 displays the development schedule for each phase.

Home page address of the annual report: http://www.enaa.or.jp/WE-NET

5kW Class Methanol Reformer(Mitsubishi Electric)



	Value	Notes
Out Put	5kW	1ata,Uf=70%, 0.6V
Size	32(W) ×25(D) ×14(H)cm 11.2L	
Weight	20kg	
Power Density (kW/L)	0.446	
Power Density (kW/kg)	0.250	
Methanol Conversion	>98%	S/C=1.5
Combustion Efficiency	>99%	Air ratio 3.0
CO Concentration	<50ppm	

5kW Class PEFC Stack(Mitsubishi Electric)

	Value	Notes
Output	5kW	1ata, 0.62V 500mA/cm^2
Output (Max)	8.7kW	3ata, 0.60V 900mA/cm^2
Size	24(W)X37(D) X12(H)cm 10.7L	
Weight	19kg	
Power Density (kW/L)	0.47 (Rated), 0.81 (Max)	
Power Density (kW/kg)	0.26 (Rated), 0.46 (Max)	

Table 2. Schedule of the WE-NET Project

	Phase I	Phase II					Phase III
Fiscal Year	1993-1998	1999	2000	2001	2002	2003	2004-
System Evaluation Hydrogen Production Hydrogen Transportation and Storage Hydrogen Utilization (Concentrated) Hydrogen Combustion Turbine, etc.							
Hydrogen Utilization (Distributed)		[Hydrogen Diesel Cogeneration]					
Hydrogen Utilization (Distributed)		[Fuel System for Hydrogen Vehicles] [Hydrogen Refueling Station] [Pure Hydrogen-fueled PEFC]					
Hydrogen Transportation and Storage		[New Hydrogen Absorbing Alloy]					

LITHUANIA

J. Vilemas and A. Galdikas
Lithuanian Energy Institute

INTRODUCTION

Eleven years ago, Lithuania regained its independence. Sudden political upheaval followed, leading to deep changes in all sectors of the economy, including the energy sector. An abrupt price-rise for all primary energy resources and the loss of former Eastern markets were among the factors that led to a dramatic decline in industry and agriculture. Thus, energy demand and production have decreased considerably.

On 5 October 1999, the new National Energy Strategy, outlining the principal provisions of the Government on the reconstruction and development of the energy sector, was approved. This strategy will be in place until 2020. Included is the gradual decommissioning of the Ingnalina nuclear power plant (per the EU provisions), the reduction of fuel imports and optimal use of local energy resources via the following:

- Provide the economic, legal and organizational means to promote the use of wood, municipal and agriculture waste and other kinds of indigenous fuels.
- Increase the utilization of other energy resources (hydro, waste energy, biogas, municipal waste hydrogen, solar and geothermal energy), using the generalized experiences gained in the pilot projects, with support by the government, as well as foreign donors and investors.
- Expand the use of renewable resources, such that they provide ~12% of the energy requirements by 2020.

LITHUANIAN NATIONAL SOLAR PROGRAM

Lithuania has very limited fossil sources for energy, yet it has significant solar, wind, hydro, biomass and geothermal resources and the scientific, technological and industrial potential for renewable energy development. The development of renewable energy in Lithuania is guided by a National program targeted at increasing energy utilization effectiveness.

The Lithuanian National Commission of UNESCO, in conjunction with the Institute of Lithuanian Scientific Society (under support by UNESCO), carried out the *Participation Programme 1998-1999* and has developed the *Lithuanian National Solar Programme 2000-2005*. Efforts are underway to introduce this work into *the World Solar Program 1996-2005*. The Lithuanian National Solar Programme is closely correlated with the EU White Paper, “Energy for the Future: Renewable Sources of Energy (1997).” This paper will also serve as background for a Lithuanian State Programme for Renewable Sources of Energy.

The main goals of the Lithuanian National Solar Programme, as well as of the Word Solar Programme, remain research and development of technologies, construction of pilot power systems, establishment of education and information facilities, and implementation of legislation that promotes renewable energy.

Research on high temperature solid-state electrolyte fuel cells based on yttrium-stabilized ZrO_2 (YSZ) has been performed at the Lithuanian Energy Institute for more than ten years. Electrolysis and power production by fuel cells are both under consideration at the theoretical and experimental level. Both hydrogen and methane fuels are being investigated. The goals of the work include optimization of technological conditions; determination of relationships between process parameters; and development of a deep understanding, at the atomic level, of the physical and chemical processes in the solid electrolyte, electrode surfaces and fuel cell interfaces.

Two projects have been accepted by the Lithuanian Energy Institute for the term 2001-2003:

- **Investigation of the Formation of the Solid Electrolyte for Fuel Cells by Physical Film Deposition Methods**

The project leader is the Laboratory of Materials Investigation and Testing at the Lithuanian Energy Institute, with participants from the Physics Department of Kaunas University of Technology and the Faculty of Environment Sciences of Vytautas Magnus University, Kaunas. The project is sponsored by the Lithuanian Government.

The description of the project is presented in Figure 1.

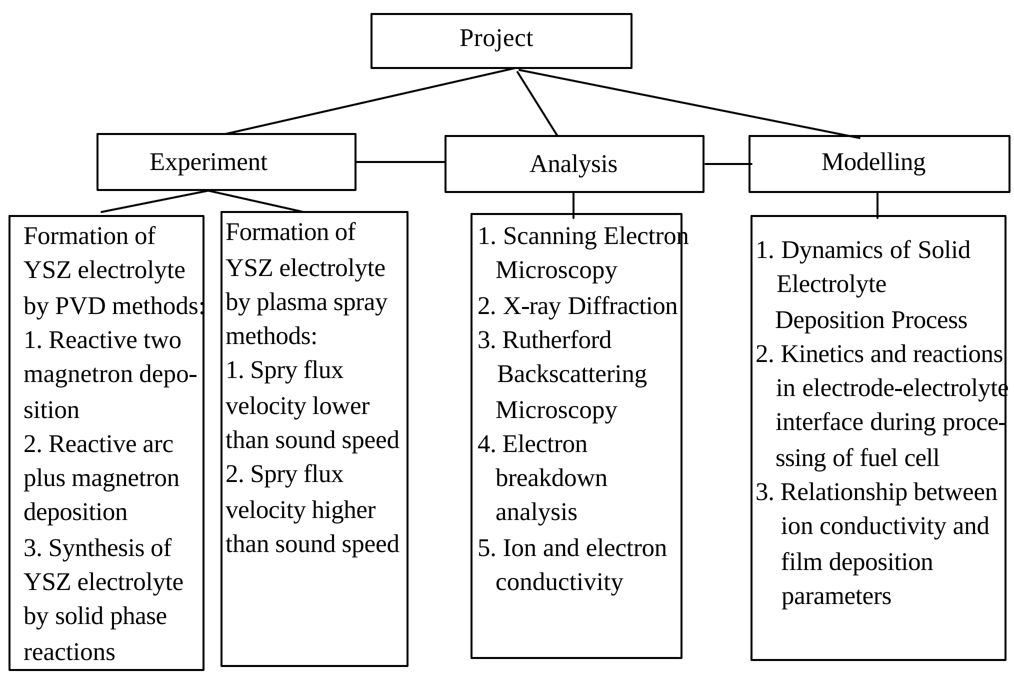


Fig. 1. Bock schematic for Film Deposition Project

- **Thin Protective Films on Interconnect Materials and their Interfaces Formed Towards Other SOFC Materials**

The project coordinators are the Laboratory of Materials Investigations and Testing at the Lithuanian Energy Institute and at the Materials Research Department at Risø National Laboratory, Denmark. The participants are the Faculty of Environment Sciences, Vytautas Magnus University, Lithuania, the Physics Department, Kaunas University of Technology and the Center for Materials Research at Oslo University, Norway.

The project is sponsored by the Nordic Energy Research Programme and the Lithuanian Government.

<u>Background</u>: Solid oxide fuel cells (SOFC) offer a highly efficient way of generating electrical energy from hydrogen, CO, reformed natural gas or even directly from methane. The waste heat from SOFC's, in the temperature range of 650-1000 °C, is so valuable that combinations of SOFC's with industrial processes or with electricity production using gas/steam turbines further increases the obtainable thermal efficiency.

If the operation temperature of SOFC's can be reduced, methanol may become the fuel of choice. Implementation of SOFC-technology in electrical vehicles or for domestic application will then be possible. Lowering of the operation temperature demands that thinner or better conducting electrolytes be made, leading to lower internal ohmic losses, and also that the electrocatalytic performance of the air and fuel electrodes can be improved.

The main center of expertise and activity for SOFC-technology in the Nordic countries is the Materials Research Department, Risø National Laboratory, which is strong in the technology of fuel cells fabrication and materials. The Center for Materials research at Oslo University is a worldwide leader in the characterization and understanding of the underlying defect chemistry of ionically and mixed ionically-electronic conducting oxides.

Both research groups have advanced electrical and electrochemical characterization methods.

<u>Scientific and Technological Goals</u>: In an SOFC stack, the layer sequence will be anode current collector/anode/solid electrolyte/cathode/cathode current collector/interconnect material/anode current collector. The present project focuses mainly on the above sequence. The interconnect component, as well as the solid electrolyte, must be gas tight, whereas the anode and cathode layers must be porous in order to maximize the so-called three-phase boundary area where the electrochemical reactions occur.

The electrical, mechanical and morphological properties of thin films of stabilized zirconia, primarily yttrium-doped ZrO_2, YSZ, can presumably be controlled by proper choice of the process parameters during deposition. The deposition technique may be reactive sputtering from Y and Zr targets, plasma spraying or other deposition techniques that are available at Kaunas University of Technology and Vytautus Magnus University, Kaunas.

The films to be investigated will typically be in the thickness range of 0.5-50 μm. Films may initially be deposited on gas-tight flat substrate materials and studied in this form. For a fruitful application and testing of the films in small SOFC's, it is essential that the thin films can be deposited as a gas-tight membrane on a porous electrode substrate. This is, on the technological side, the most challenging aspect of the project. The overall goal is to achieve gas tightness and mechanical stability of the film, stability during thermal cycling and absence of the formation of resistive phases at the interface with typical anode and cathode materials. The porous substrate materials will initially be delivered by Risø.

YSZ may also be used as a reduction/oxidation-stable coating on other types of oxygen ion conducting ceramics, such as those based on doped ceria. Ceria will expand upon exposure to reducing gases such as hydrogen or reformed natural gas. However, ceria has superior conductivity at lower temperature. It is the intention to study this protective action of YSZ on easily reducible oxides in the second half of the project.

The operation temperature will usually be higher than the deposition/fabrication temperature. It is, therefore, essential that the influence of the mechanical strain at the interdiffusion of cations be measured and, later on, predicted, both on the initial performance and the expected lifetime of the SOFC.

Various physical deposition techniques will be studied: Electron microscopy, EDX, microprobe, XPS, TEM, AFM, AC- and DC-resistance methods, 2,3 and 4 electrode variants, Fuel cell testing, I-V characteristics, etc.

Two Ph.D. students will spend, on average, 3 months per year in selected Nordic research institutions - among these the two research groups mentioned above. The prime purpose of such stays abroad is for the student to become familiar with measurement and/or characterization techniques that are not available at the student's home institution. In the second and third year of the study, several electrical methods for characterizing bulk and interface properties will, hopefully, have been established at the student's home institution. Since true fuel cell testing is rather demanding with regard to equipment and know-how, this part can be done by the student entirely at Risø, if needed.

OTHER RESEARCH IN LITHUANIA IN THE FIELD OF HYDROGEN ENERGY

Solid Oxide Fuel Cells

The following investigations are performed in the Laboratory of Solid State Ionics at Vilnius University:

- Investigation of fast ionic transport for SOFC and mixed electronic-ionic conductors for SOFC electrodes.
- Measurement of the ionic conductivity of SOE, their dielectric properties in the frequency range of 1 Hz to 10 GHz and temperature range of 300-1200 K, the role of impurities, and stoichiometry on ionic and electronic conductivities of SOE.
- Determination of resistances of SOFC interfaces between the cathode/SOE/anode and possibilities for minimizing these resistances.
- Development of a technology for fabrication of ceramics samples and the thick layers of SOE, and the thick layers, thin films of electrodes for SOFC.
- Doping of the electrolyte by multivalent transition metals to enhance the cathodic reaction rate via the electronic conductivity of the electrolyte. (The redox properties of electroactive defect centers created in the interface region by doping with multivalent metals cause a mixed electronic-ionic conductivity of the electrolyte and allow the charge transfer reaction to take place over the entire interface.)

- Reduction of the cathodic overpotential by use of modified cobaltites, especially LSCN, as cathode materials. (A very simple preparation of uniform thin films of perovskite-type oxides by precursor solution has been successfully demonstrated.)

<u>Anaerobic Digester Gas for Fuel Cells</u>

The goals of this study are:

- Construction and operation of a biogas power plant demonstration at the agricultural company Vycia, Kaunas
- Investigation of biogas production and utilization for power purposes and environmental protection
- Analysis of a fuel cell power plant that accepts anaerobic digester gas
- Modeling of the physical-chemical processes taking place in an anaerobic digester gas fuel cell power plant system during processing

Rokai Pig Farm Demonstration Biogas Plant

Kaunas, Lithuania

Employment of Fuel Cells in Effective Hybrid Systems with Solar, Wind and Solar–Wind Electric Power Stations

After closing the Ignalina Nuclear Power Plant in Lithuania, which currently provides up to 80-90% of country's electric energy demands, one of the most favorable choices is to change nuclear power into ecologically clean electric energy from renewable sources. The main goal of this research is to develop the concept of optimal compatibility of fuel cells with solar and wind electric power stations. The work is performed at the Kaunas University of Technology.

Education in Renewable and Alternative Energy Conversion

The basis for studies and education (Kaunas University of Technology) in the field of renewable and alternative energy conversion is currently under development. The main purpose will be education, training and public information. The field will include technologies of renewable energy sources, fuel cells and other ecologically clean modern sources of energy. It will be realized in all levels: lectures, projects and laboratory research for students and postgraduate students and lectures and practical training for engineers working in industry and agriculture. This project will include 10-12 work places with blocs for structural realization and research of various renewable energy systems (solar, wind, fuel cells, hydrogen technologies, hybrid systems, and power electronics). Activity of this kind will be developed in the international program SOCRATES in cooperation with Stralsund Technical University (Germany).

CONCLUSIONS

The research (experimental and theoretical) in the field of hydrogen energy, including fuel cell investigations, solid electrolyte preparation methods, hydrogen storage and production is receiving growing interest from the scientists of Lithuania. Only a few years ago, the research in this field was performed only in the Lithuanian Energy Institute. Today, there are many institutions and scientific groups working in this field.

NETHERLANDS

Antoon H.M. Kipperman
Netherlands Agency for Energy and the Environment (NOVEM)

NATIONAL POLICY RELATED TO HYDROGEN

In the Netherlands, the national policy is such that hydrogen is considered an energy carrier, but with other features than hydrocarbons and coal. In cases where hydrogen projects can contribute to national targets, subsidies or tax reductions are applicable. The main targets are reduction of CO_2 and other emissions, and the increase in energy efficiency. Electricity from renewable sources, sun and wind, are not expected to reach the critical level of disturbing the grid performance within the next several years. Therefore, hydrogen is not yet considered necessary for solving this disturbance. National policy items on hydrogen are incorporated into the programs of the different ministries. As a consequence, there is no specific national program for hydrogen.

The Ministry of Economic Affairs (EZ) stimulates energy savings and CO_2 reduction through the introduction of hydrogen rich fuels, hydrogen and renewable sources (wind and solar). The ministry EZ no longer undertakes technology push activities, rather it facilitates market driven initiatives.

The Ministry of Housing, Spatial Planning and the Environment (VROM) stimulates the reduction of NO_x, SO_2 and CO_2 emissions, including promoting hydrogen as a solution to the environmental problem. VROM sets limits for the allowed emissions of polluting species and directs the market in the desired direction by doing so.

The Ministry of Education and Science (O&W) stimulates university research on energy related items and, in that framework, also hydrogen applications. Mainly, long-term objectives are studied such as hydrogen for fuel cells, hydrogen replacing natural gas and hydrogen as a storable energy for wind turbines and solar PV.

Apart from the individual programs of these ministries, joint program activities of EZ and VROM are:

- The *CO_2 reduction plan*
- *GAVE* - new gaseous and liquid energy carriers for a sustainable future
- *Clean Fossils* - less to zero CO_2 emission from fossil fuels (in preparation).

The three ministries, EZ + VROM + O&W, together stimulate research institutes and industry to set up joint projects for a sustainable future. (Program *EET* - energy, ecology and technology). Now, both EZ and VROM, with their specific areas of responsibility as a starting point, are studying the future energy supply and infrastructure development up to 2050. Hydrogen is very present in those studies, in particular, because a considerable degree of penetration of fuel cells in mobile and stationary applications is expected. Precise figures for the amounts of renewable energy from sun and wind are not yet settled for the year 2050.

PROGRAM STRUCTURE

Several programs have the opportunity to grant subsidies for R, D & D upon application for well-defined projects. Other stimulating measures applied are a reduction of taxes for more energy efficient, less polluting or renewable energy installations.

The New Energy Conversion Systems and Technologies (NECST) program, executed by the Netherlands Agency for Energy and the Environment (NOVEM), deals mainly with early technology innovations, with no restrictions to technology or energy carrier. The NECST program will run for many years and has looked at such issues as energy infrastructure development, in particular the implementation of hydrogen and renewable sources. A similar program, the Energy Saving through Innovation (EBDI) program, will begin in 2001 and will be executed by the Agency of the Ministry of Economic Affairs (SENTER).

A large program is running on Energy from Waste and Biomass (EWAB). EWAB was initially focused on electricity and heat. As a consequence of the upcoming fuel cell development, interest is growing for separation of hydrogen from gasification products. Bio-hydrogen research is now supported by a national platform for exchange of ideas and is organizing international collaborations, including within the IEA (start-up phase is part of NECST). Within NECST, NOVEM is exploring options for a national hydrogen platform in the Netherlands.

Joint programs like GAVE and EET have a tender system and a ranking of projects received in a particular period. The main agencies are NOVEM and SENTER. SENTER also carries out tax credit or tax reduction regulations.

FUNDING

The integration of hydrogen in other larger projects and programs only allows for a rough estimate of the ›hydrogen funding‑. Presently it is estimated that about 2 million Euro per year is targeted towards hydrogen technologies. It is projected that within a few years this funding level will increase to 5-10 million Euro per year.

RESEARCH, DEVELOPMENT, DEMONSTRATION AND COMMERCIAL ACTIVITIES

In the Netherlands, large amounts of hydrogen are produced as a feedstock for industrial purposes, partly produced and consumed at refineries for the production of fuels and part produced and transported for other industrial purposes. Therefore, a broad knowledge of hydrogen is at hand.

Hydrogen in the energy system has been studied both for particular applications with renewable sources and as an option for reducing CO_2-emissions at the individual consumers level by mixing some hydrogen into the natural gas grid.

Renewable hydrogen can be used in refineries for chemical upgrading and fuel production.

So far, only R & D projects exist for hydrogen as an energy carrier. Demonstrations are planned in the GAVE program - integral energy chain approach including industry and distribution. Fuel cell applications/demonstrations in the automotive sector are in preparation; the nature of the hydrogen supply is still under consideration. Some other demonstrations on hydrogen have been proposed during the last years, but they are still in the preparation phase.

The Universities of Delft and Eindhoven and the ECN research institute carry out research on energy infrastructure. They include, in particular, hydrogen in their long-term projections.

LEVEL OF INDUSTRY INVOLVEMENT

Several projects for energetic use of residual hydrogen-containing gasses have been considered in the past. A few of them were based on the use of fuel cells as energy conversion units. A typical example is a large co-operative project by industry, utility and NOVEM on producing several MW at a chemical factory through treating a residual stream of a varying mixture of hydrogen, methane and some higher hydrocarbons. Selective extraction of the hydrogen by phosphoric acid fuel cells (PAFC) with production of electricity, and, at the same time, purifying the gas up to a high caloric natural gas grade, made this concept attractive. Unfortunately, PAFC-producers showed such a strong reluctance to deliver anything other than their standard natural gas powered units that this project had to be cancelled. Finally, the residual gas could be used at much lower costs in a boiler provided a dedicated control unit with a very short response time to the varying hydrogen content was used.

Concerning energetic use of hydrogen, the activities of Shell Hydrogen can be mentioned. Energy supply companies, former electricity producers, and gas and electricity distribution companies enter the market with differently named ›green‹ electricity. In this same framework, they work on the introduction of hydrogen produced with wind power.

Recently, the steam reformer of a closed fertilizer production facility was reactivated to produce CO_2-neutral hydrogen. The CO_2 will be delivered to greenhouses and/or sequestrated underground. The hydrogen will go through a pipeline parallel to an existing one that is planned for CO_2 transport.

As illustrated, the market for hydrogen is still far from being fully developed, but some encouraging initiatives can be observed. It is, however, expected that in a national hydrogen platform more industrial parties could be involved.

Safety, Codes and Standards

The Netherlands Organisation for Standards (NEN) is organizing, along with NOVEM (NECST), a national symposium on "*Hydrogen as a fuel; codes for profitable and safe usage,"* 1 February 2001. Technology, experience with town gas, user requirements, insurance, fire risks, social acceptance, operation permits for public transport, international and national codes will be presented and discussed.

Outlook

Near-tem: A growing interest in hydrogen as an energy carrier can be observed. However, co-ordination of activities and more detailed information to relevant parties is needed.

Longer-term: Integration of hydrogen in the energy infrastructure will require dedicated investigations taking into account local features. Production for dedicated applications, such as a local gas grid, is supposed to be economically feasible. After installation of much more wind power (mainly offshore), the excess energy will stimulate the development of hydrogen applications.

A national hydrogen platform (i.e. Netherlands Hydrogen Association), once settled, will support more effective initiatives for hydrogen applications, research and demonstrations.

NORWAY

Trygve U. Riis
The Research Council of Norway

BACKGROUND

Norway is in quite a different energy position than most of the other European countries. With a small population of only 4.5 million people, Norway has the largest energy resources in Europe, next to Russia. Norway's yearly production is 200 million Sm^3 of oil, 50 million Sm^3 oil-equivalents natural gas (around 55 billion Sm^3 gas, to be increased to 70 billion, soon) and between 100 and 140 TWh electricity from hydropower. This means that Norway produces around 12-14 times its total energy consumption, and, at present, it is the world's 3rd largest oil exporter.

Norway=s electricity production is nearly 100% hydropower, a percentage that no other country in the world equals. Based on the traditional surplus of clean, renewable and rather cheap electricity, with rather low taxation, it is no wonder that out of Norway=s total energy spending, electricity makes up a very high percentage. Traditionally, heating houses with direct electricity has been considered a clean, cheap and practical solution.

The energy situation is, however, now changing for several reasons:

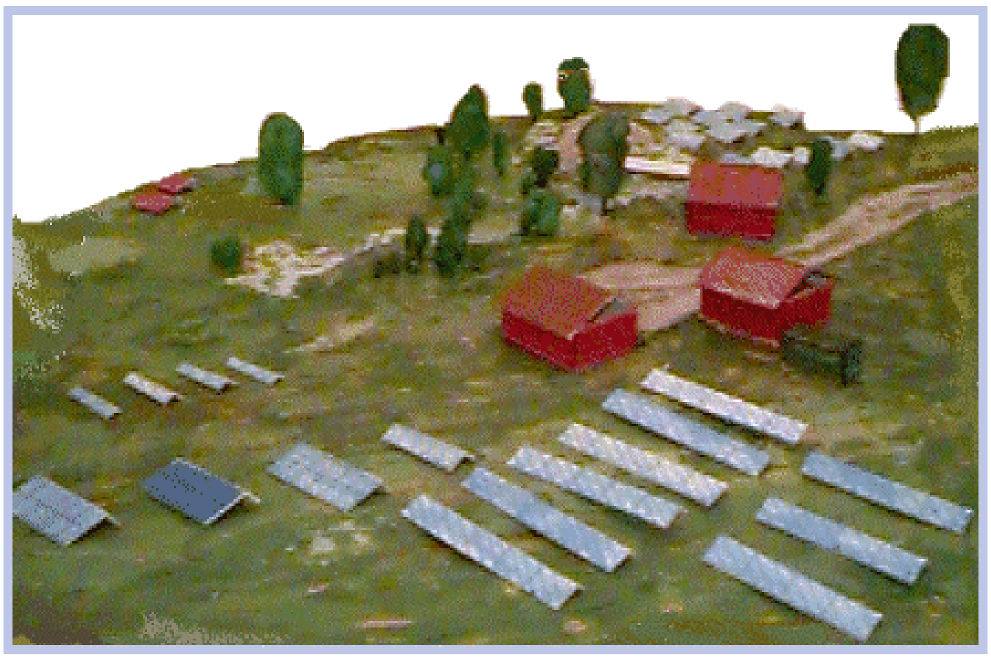
- There are rather few major waterfalls left to target and, due to environmental concerns, politicians in Norway have more or less terminated the construction of new, large hydropower units
- With constant growth in energy and electricity consumption, there is now a deficit in electricity in years with normal precipitation; import is, therefore, necessary.
- With the open marked for electricity in the Nordic countries (and further on into the rest of Europe), electricity is no longer considered a national resource, rather a good for trading.
- With increased focus on CO_2 and other climate gases, there are challenges to fulfilling the Kyoto agreement, as Norway has the starting point of no electricity-emitted CO_2. This means that the reductions must be taken from the transport sector, industry, heating oil, etc. With a growth in natural gas production - which is transported in pipelines to Germany and other European countries - Norway=s CO_2 emissions are increasing based on power production for gas compression.

Based on this background, it is hopefully understandable that the use of natural gas for power production in Norway is not an easy task, unless CO_2 can be taken care of by separation and, for example, underground or deep ocean deposition. This brings us closer to hydrogen.

NATIONAL POLICY RELATED TO HYDROGEN

Although the long-term solution for hydrogen, most likely, is to produce it from renewable sources, this is, at present, an expensive solution. Likewise, it will take a long time to build out the necessary energy production capacity from renewables. It is, therefore, considered a very interesting short- to medium-term solution to produce the hydrogen from fossil sources with deposition of CO_2. As described above and based on Norway=s huge natural gas resources, hydrogen production from natural gas with CO_2 deposition is now a high priority in Norway. In addition to the gas resources, Norway has access to huge areas suitable for CO_2 sequestration in the North Sea. As an oil producer, Norway also has the possibility of using CO_2 for enhanced oil recovery, which will give a value to the CO_2. However, just by deposition, it has been estimated that areas with saline aquifers suitable for CO_2 sequestration have the capacity to store all of the CO_2 from power production in the whole of Western Europe for at least 600 years. The extra cost of the separation and deposition adds around 1-1.5 cents (US) per kWh to the production cost of electricity. In other words, the whole of Europe can fulfill the Kyoto obligations in this way with the indicated incremental cost.

A lot has now been mentioned about hydrogen from fossil sources. However, it is important to stress that there is also increased interest in hydrogen from renewable sources. First of all, Norsk Hydro Electrolyzers must be mentioned. This is a company that is now one of the world's largest producers of and has a long experience in operating electrolyzers, even though their hydrogen production is currently based on reforming of natural gas. Hydrogen production by water electrolysis powered by wind energy, etc., is the subject of several projects (described later). There is also interest in biophotolytic hydrogen production.



Model of Energy Park at Agder College, Grimstad, Norway – 80 kW photovoltaic field supplies a 50 kW electrolyzer. Hydrogen supplies a 20kW fuel cell that is used to power facilities at the College.

PROGRAM STRUCTURE AND NORWEGIAN PLAYERS

Due to the limited size of the R&D budgets for a small country and to desired principles, Norway does not have very specified programs. Hydrogen activities have, so far, mainly been supported as part of the Efficient and Renewable Energy Technologies Program. Hydrogen has also been included under strategic programs, mainly supporting R&D in the Universities and R&D Institutes. Recently, hydrogen activities are also partly supported by the Natural Gas Program.

Norway has been a member of the IEA Hydrogen program since 1994. Several of the projects listed below are part of the IEA tasks.

The main driving force for the increased activities in Norway is the high focus on hydrogen from some major industrial companies in the last few years. Norsk Hydro is the leading company, but Statkraft, Statoil and others are now looking seriously into hydrogen for future business opportunities. Norsk Hydro has extensive experience in producing hydrogen as part of their ammonia production. Statoil also has experience in similar processes, as they are operating a world-scale methanol plant in Norway.

FUNDING

The funding for hydrogen-related R&D projects in 2000 was roughly 5 million NOK (600,000 USD) from the Research Council. Additional funding for demonstration projects by other governmental bodies, with support from industry, and projects run by industry, themselves, adds up to around 20 million NOK.

An increase in year 2001 is expected, but the exact numbers are not clear at present.

PROJECT EXAMPLES

A selected number of projects are listed below. Some projects closer to commercial applications are, of course, restricted. More details can be obtained from the author of the paper, or, preferably, from the companies listed.

The "Nebus" hydrogen-powered fuel cell bus was operated in Oslo for two weeks in August 1999. This was the first demonstration in regular service with a local driver.

Project title	*Support / participants*	*Comments*
Hydrogen Storage in Hydrides and C Materials	NFR[1] and industry / IFE[2] with Univ. of Oslo, etc.	Part of IEA task 17
Integrated System Studies	NFR and industry / IFE	Part of IEA task 13
Ammonia as Hydrogen Carrier	Hydro[3] and NFR / NTNU[4]	
Water Electrolysis with Polymer Electrolyte (PEM cells)	Hydro and NFR / NTNU	
Wind/Hydrogen Stand-Alone System at the Island of Utsira	NFR and Hydro / Hydro and others	Case study for IEA task 13
Wind/Hydrogen Stand-Alone System at the Island of Røst	NFR, Hydro and others / Hydro, etc.	Partly similar to Utsira, but partly different solutions
Ferry Boats with Hydrogen and Fuel Cells	NFR, Hydro / IFE, NTNU, MARINTEK	
City Buses with Hydrogen	EU, Hydro, OSL[5] / Hydro in coop. with many others	EU project
Fuel Cells		
CO_2 Capture Project (CCP)	Cooperation between 9 oil companies, Statoil and Hydro are among them	Big project aiming at power and H_2 production with very low CO_2 emissions
New IEA task: H_2 from Carbon Containing Materials	NFR, Hydro, etc.	Planning of a new IEA H_2 task.
Long-term H_2 Activities	NFR with industry / IFE, UiO, NTNU, SINTEF	Recently started long term R&D H_2 -cooperation

[1] The Research Council of Norway
[2] Institute for Energy Technology
[3] Norsk Hydro
[4] The Norwegian University of Science and Technology
[5] Oslo Municipal Transport

SPAIN

Antonio Garcia-Conde
Instituto Nacional Técnica Aeroespacial (INTA)

NATIONAL POLICY

Since 1988, INTA (the National Institute for Aerospace Technology in Spain) has been coordinating hydrogen energy activities through its own funds and subsidies from the regional government of Andalusia (south of Spain). At present, there is no specific program devoted to hydrogen energy in Spain; however, the Spanish Plan for Scientific Research, Technological Development and Innovation (2000-2003) contains strategic actions for "*alternative fuels*" and, specially, for the "*development of technologies for a safe and competitive use of hydrogen*." Additionally, there are strategic actions focused on A*more efficient and less polluting energy systems*@ and *"alternative propulsion systems for the transportation sector"* in which the development of fuel cell systems and components are considered.

PROGRAMME STRUCTURE

The Spanish Plan for Scientific Research, Technological Development and Innovation (2000-2003) is structured in sectorial areas and scientific-technological areas. Hydrogen activities are included in the sectorial area of Energy, which is supporting R&D projects, among others, in the following fields:

- More efficient and less polluting energy systems (renewables, fuel cells).
- Alternative propulsion systems and new fuels for the transport sector (alternative fuels, electric propulsion).

In addition, within the scientific-technological areas focused on Material Science and Chemical Processes, the development of materials and products for fuel cells receive preferential attention.

The main players in hydrogen and fuel cell R&D activities in Spain are the following:

<u>Public Research Institutions</u>:

INTA:	National Institute for Aerospace Technology	
CIEMAT:	Centre for Energy, Environmental & Technological Research	
CSIC:	High Council for Scientific Research	
ICP:		Institute for Catalysis and Petrochemistry
ICV:		Institute for Ceramics and Glass
ICTP:		Institute for Polymers Science and Technology
ITC/ITER:	Technological Institute of Canary Islands	
CIDAUT:	Centre for Automobile R&D	
Universities:		Alicante, Barcelona, Cantabria, La Laguna (Canary Islands), UPM (Politécnica Madrid), UCM (Complutense Madrid)

Industries:

Utilities:	GAS NATURAL, GAS de Euskadi, IBERDROLA and ENDESA
Vehicle Companies:	SEAT, IVECO/IRISBUS
Others:	ALCATEL Spain, ABENGOA, AIMPLAST, EXPERT, CLHORIDE-BOAR, URBASER, CASA and ACERALIA

At present, there is a big interest in hydrogen and fuel cell activities, and an important number of companies are involved in discussions with research institutions to become more informed and involved in relevant activities.

RESEARCH, DEVELOPMENT, DEMONSTRATION AND COMMERCIAL ACTIVITIES

Hydrogen and fuel cells activities in Spain are carried out with support from national funds and/or European subsidies. The main Spanish national projects and European projects with Spanish participation are the following:

National Projects

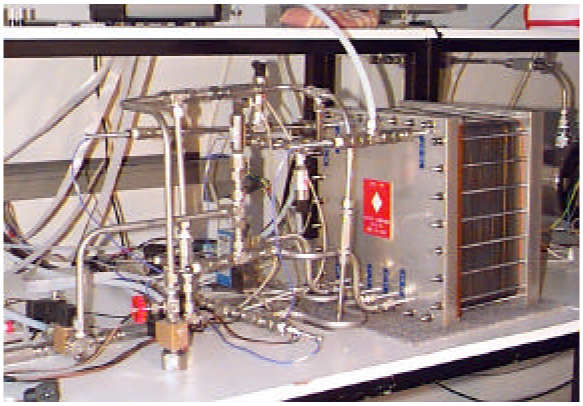
Solar Hydrogen and Fuel Cells at INTA:
Hydrogen production by photovoltaic-powered electrolysis and solar hydrogen utilization in phosphoric acid and proton exchange membrane fuel cells:

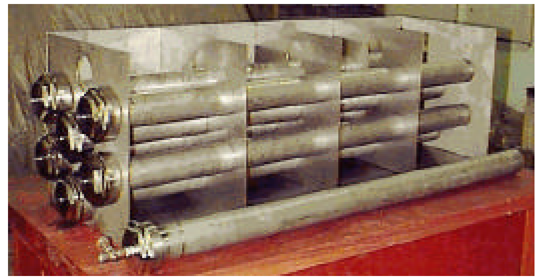
a) 7.5 kW_p Solar PV Field
b) 1 Nm^3H_2/h Alkaline Electrolyzer
c) H_2 Storage: 6 bar Buffer, Metallic Hydrides ($FeTiMn_2$), CGH_2
d) PAFC: 10 kW, 90 V, 112 A, Reformed Methanol or solar H_2 B Air
e) PEM Fuel Cells: 2.5 and 5 kW, 15 to 25 Vdc, 0 to 190 A

7.5 kW PV field (left)

Compressed hydrogen gas storage (below)

Alkaline Electrolyzer (right)





Metal Hydride Storage System for a PEM Fuel Cell Vehicle (above)

PEM Fuel Cell Test Bench (left)

Materials for Solid Oxide Fuel Cells (SOFC):
Several basic research projects in the field of material development for SOFC and Low Temperature SOFC are running at ICV-CSIC and Universidad de la Laguna.

PETRI - New materials development (cathodes and coatings) for Molton Carbonate Fuel Cell (MCFC) corrosion resistance:
CSIC, University Complutense de Madrid, INTA and PEP (Iberdrola, Endesa and Babcock & Wilcox Spain) ran a two-year project (1998-1999) to develop cathodes and coating materials for MCFC (budget: 0.25 MEuro).

DEMAPICO:
CSIC, INTA, IVECO, AIMPLAS and ARIES are conducting a two-year project (2000-2001) on the development of materials for PEMFC components: electrodes, bipolar plates and reformer catalysts (budget: 2 MEuro).

European Projects with Spanish Participation

The University of Alicante participated in two projects, coordinated by the University of Poitiers and the National Centre for Scientific Research (CNRS) in France, on the concept and realization of new catalytic anodes and cathodes for direct methanol fuel cells (1990-1994).

The University of Barcelona co-operated in one project, coordinated by Ansaldo Ricerche Srl, dealing with the development of a high efficiency methanol reformer for hydrogen production and SPFC feeding (1993-1995).

CSIC-ICV collaborated in one project, coordinated by the National Polytechnic Institute of Grenoble (France), concerning the synthesis and evaluation of electrode and electrolyte materials for SOFCs (1990-1994).

CSIC-ICP participated in a project, coordinated by the National Council of Research (CNR) in Italy, on theoretical and experimental studies for a compact hydrogen generator (1994-1996). They also participated in a project, coordinated by Advanced Technology R&D Srl in Italy, focused on the development of a heterogeneous catalytic reactor for methanol partial oxidation (1994-1996).

The Polytechnics University of Madrid participated in a project coordinated by the University of Pisa in Italy, to improve a model of turbulent hydrogen combustion and catalytic recombination for hydrogen mitigation (1996-1999).

DIREM - Development of Industrially Relevant MCFC Stacks: Ansaldo, ENEA and ITAE in Italy, along with Spanish partners Iberdrola, Endesa and Babcock & Wilcox Spain, completed a 100 kW MCFC Plant.

CSIC-ICP collaborated in the project entitled "Functional and structural studies of NiFe hydrogenases as a basis for the industrial production and utilization of hydrogen," coordinated by the Commissariat for Atomic Energy (France) (1998-2000).

FCMO - Fuel Cell with Methanol as a fuel Option: CIEMAT, CSIC and SEAT in Spain, with the participation of KTH (Sweden) and UTAD (Portugal), are developing a 1 kW reformed methanol fuel cell (1998-2001).

EIHP - European Integrated Hydrogen Project: INTA is participating in the project to develop a regulation concerning the use of hydrogen in vehicles. The regulation proposal will be presented at the United Nations during 2001.

Budget: 2,55 MEuro (Phase I) + 5 MEuro (Phase II)
Duration: 2 years (1998 B 2000) (Phase I) + 3 years (2001 B 2004) (Phase II)

STEEL C - Application of New Fracture Mechanics Concepts to Hydrogen Damage Evolution: The Spanish company ACERALIA and the University of Cantabria are participating in this project, coordinated by IRSID B Group USINOR (France), to develop a suitable failure criterion, accounting for local stress and strain distribution, to be applied to the conventional methods of testing for resistance to hydrogen-assisted cracking and to service conditions.

Budget: 1.45 MEuro
Duration: 36 months (1998 B 2001)

CRIOPLANE - Liquid Hydrogen Fuelled Aircraft-System Analysis: A large consortium of companies, research institutions and universities of eleven European countries, coordinated by Daimler-Chrysler Aerospace Airbus GmbH, with CASA and the Polytechnics University of Madrid as the Spanish participants, are investigating the use of liquid hydrogen as an aviation fuel. The project objective considers liquid hydrogen as the only known suitable aviation fuel that can be produced from renewable energy sources and offer extremely low pollutant emissions. The project will assess all relevant aspects including configuration, architecture, engine concepts, airport infrastructure definition and transition scenarios.

Budget: 4.47 MEuro
Duration: 27 months (2000 B 2002)

FAME - Fuel cell Application for Mobile Equipment: Alcatel (France), together with FISE and FDS in Germany, Nuvera and CNR in Italy and INTA in Spain, is developing the application of direct methanol fuel cells for mobile phones.

Budget: 2.6 MEuro
Duration: 2.5 years (2001-2003)

FIRST - Fuel Cell Innovative Remote System for Telecommunication: INTA (as coordinator), CIEMAT and CSIC-ICP as Spanish partners, together with FISE and Würth in Germany, Air

Liquide in France and Nuvera in Italy, compose the consortium of this project, whose purpose is to increase the availability of telecommunication antennas located in remote areas. The yearly availability obtained by a conventional photovoltaic system will be compared with one provided by a PEM fuel cell system operating with solar hydrogen.

Budget: 3.4 MEuro
Duration: 3 years (2000 - 2003)

EFFECTIVE - Biogas integration and MCFC Technology: CIEMAT and URBASER are the Spanish participants in this project, coordinated by Profactor in Germany. The main objective is the combination of MCFC technology and Biogas. The expected endurance of MCFCs for Biogas is being confirmed with two test units, each comprising a 500 W fuel cell and a laboratory-sized gas-cleaning unit (2000-2004).

CITYCELL: The bus manufacturer IRISBUS is promoting the use of hydrogen and fuel cells for urban buses propulsion. A project proposal has been sent to the European Commission to demonstrate operation of three buses to be driven in real service conditions in the cities of Torino (Italy), Madrid (Spain) and Paris (France).

Spanish participation: IRISBUS, IVECO, INTA, EMT (Bus operator Madrid city), TUDOR, Air Liquide (Spain).

Other European partners: ANSALDO, ALTRA, ENEA, ATM (Torino bus operator) and SAPIO in Italy and Renault VI, ALSTOM, INRETS and RATP (Paris bus operator) in France.

LEVEL OF INDUSTRY INVOLVEMENT

Spanish industries are participating in a number of European hydrogen and fuel cell projects. Regarding industry funding, the most relevant contribution has been the development of a 100 kW MCFC stack. The test facility built by Iberdrola, Endesa and Babcock Wilcox in San Agustín de Guadalix (near Madrid) is unique in Europe. Today, the level of involvement of Spanish car industries is also clearly increasing.

OUTLOOK

Near Term:

- An increase in R&D works on Hydrogen and Fuel cells is expected.
- An important number of companies are in contact with research institutions to become more informed and involved in relevant activities.
- A Spanish Hydrogen association could be set up.

Long term:

- Increase in renewable energy utilization will improve the use of hydrogen and fuel cell systems.
- Increasing concern of authorities for pollution in the cities will promote the use of hydrogen in urban transport.

SWEDEN

Peter Lindblad
Swedish National Energy Administration (STEM, Energimyndigheten)

NATIONAL POLICY

There is no national or official hydrogen program in Sweden. Minimizing the environmental impacts of fossil fuel utilization and, ultimately, a transition from fossil to renewable energy sources are important drivers in the country's overall research and development strategy. The current hydrogen R&D policy in Sweden can be characterized as active, world-wide monitoring of technology development. The implementation of this policy is accomplished by funding a limited number of high-quality research projects and case-studies within the field and by participation in international co-operation. The International Energy Agency Agreement on the Production and Utilization of Hydrogen is considered to be important; currently Sweden participates in four Tasks of this international co-operation. In addition to the hydrogen activities, there are also a number of national fuel cell projects.

CURRENT ACTIVITIES

The Swedish National Energy Administration (STEM) currently funds the following hydrogen related projects (MSEK = Million SEK):

- Stationary fuel cells/applied; 16 MSEK (6 MSEK from STEM)/3 years
- Stationary fuel cells/fundamental; 15 MSEK (100% from STEM)/3 years
- Fuel cell systems in vehicles (Volvo Technical Development); 26 MSEK (13 MSEK from STEM) & several smaller projects aimed at either increasing the efficiency of the fuel cell or of a reformer
- Artificial Photosynthesis with the ultimate goal of producing molecular hydrogen from solar energy and water; 29.4 MSEK (20.4 from STEM)/4 years
- Through Svensk Gastekniskt Center AB (SGC), 51 MSEK (15 MSEK from STEM)/3 years is spent on R&D of "energy gases," which includes hydrogen.
- Demonstration of stationary fuels cells in apartment houses, budget 18 MSEK (excluding the fuel cells)
- Minor hydrogen related activities of 5 MSEK/year and participation in all current tasks of the IEA Hydrogen Agreement are also funded by STEM:

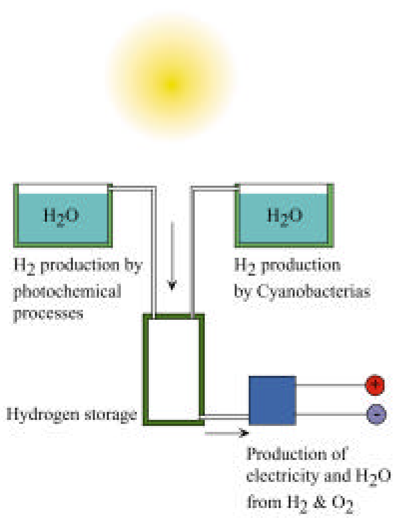
Annex 12/17	National Expert:	Noreœs, Stockholm University
Annex 13	National Expert:	Sjunnesson, Sydkraft AB
Annex 14	National Expert:	Lindquist, Uppsala University
Annex 15	National Expert:	Lindblad (Operating agent), Uppsala University

- The Swedish Foundation for Strategic Environmental Research (MISTRA) currently funds *Batteries and Fuel Cells for a Better Environment*; MSEK 54 (1997-2001).

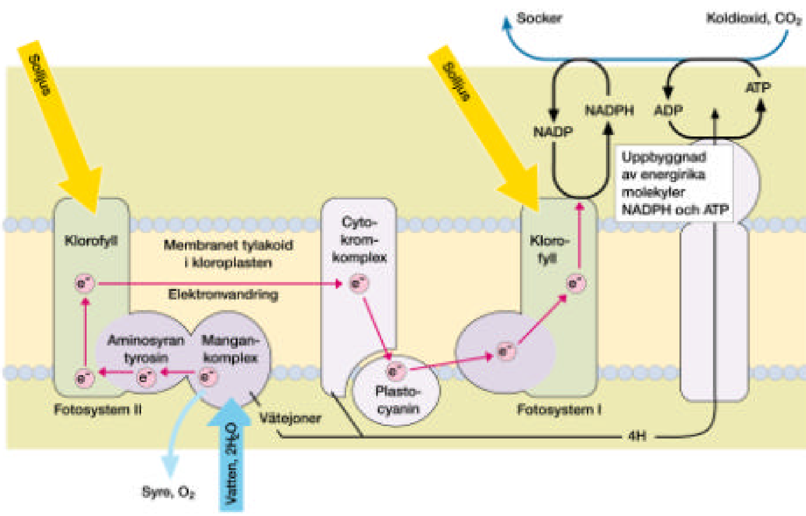
- The Swedish Agency for Innovation Systems (Vinnova) participates in the fuel cell bus demonstration project in Iceland with "evaluation" being the main responsibility.

- The Swedish Defence Research Agency participates in CRYOPLANE, a European project lead by EADS Airbus - 35 participants, in eleven countries are performing a system analysis of liquid hydrogen fueled aircrafts, including a detailed study of the infrastructure and logistics for Arlanda/Stockholm airport.

- A consortium consisting of private industries and city and governmental agencies has been established for the implementation of the European CUTE project in Sweden. Three fuel cell/compressed hydrogen buses will be tested and the performances evaluated when used in public transportation in the city of Stockholm.



Sustainable Energy Conversion with Hydrogen as a Storage Medium - goal is to investigate the feasibility of hydrogen production as a step in a sustainable energy conversion system.



Artificial Photosynthesis for the Conversion of Solar Energy into Fuel - goal is to synthesize and study Supramolecular Systems.

During 2000, Sweden changed from being an observer to an active partner in the International standardization of hydrogen energy, ISO/TC 197, and a national committee (SMS 9302) was established.

During 2000/2001, initiatives with the overall aim of increasing activities and funding have been coordinated by STEM including internal and external seminars and, in May 2001, a Public hearing about Hydrogen.

Commercial Activities

At present, there are very limited commercial activities in Sweden within the field of hydrogen as an energy carrier or fuel cells. Companies like AGA AB/Linde have the competence to produce, handle, store and distribute molecular hydrogen. Opcon Autorotor AB develops and produces twin-screw compressors for different applications and has one of the best twin-screw compressors worldwide for supercharging internal combustion engines and fuel cells. Opcon Autorotor AB has, since 1992, delivered compressors to most of the ongoing fuel cell projects and is engaged in most of the known projects with the world leading car manufacturers. Several fuel cell based start-up companies are currently being established.

Outlook

Sweden will continue to support basic research projects on the production, storage and utilization of hydrogen and the Swedish Research Council will continue to fund hydrogen-related projects based on their own priorities. Major programs are being discussed. The use of fuel cells in both stationary and transportation applications are targets for larger R&D and demonstration projects.

The level of activities and funding will increase and it is predicted that more companies, agencies and researchers will be actively involved in hydrogen energy activities in Sweden in the near future.

SWITZERLAND

Gerhard Schriber and Armin Reller
Swiss Federal Office of Energy

NATIONAL POLICY

In the Swiss National Energy Research and Development Program, hydrogen is considered an important future secondary energy carrier as well as an economically important chemical commodity. Consequently, the concerned Swiss authorities support R & D activities for the sustainable production, safe storage and efficient utilization of hydrogen. The main goals of the Swiss program are the regional regenerative production, i.e. the conversion of solar radiation into hydrogen by different processes, substitution of fossil fuels by hydrogen and utilization pathways. Simultaneously produced by-products are considered important incentives for the promotion of hydrogen technology. Owing to the fact that the implementation of hydrogen technology is often hampered by engineering, handling and safety challenges, considerable efforts are directed towards new functional materials and materials science as key disciplines for efficient development of hydrogen technology. Consequently, a paramount task consists of identifying and promoting niche uses, where hydrogen technology can be implemented in an economically and strategically reasonable way. These niches include the utilization of hydrogen as a chemical commodity, i.e. as a reducing agent in technical processes, and also as a fuel for high-temperature processes, where any trace of carbon or carbon oxides would change or even deteriorate the process or the properties of the products.

Research activities, including novel hydrogen production and storage technologies, are carried out by closely interacting teams of public research institutes and industry. The projects are subject to a short-, mid-, and long-term perspective. This is very important with respect to the financial and economic constellations governing the technical or industrial implementation of any process.

The Swiss research and development activities are clearly coordinated with international programs, above all with the IEA activities and the research and development programs of the European Commission. The present and future policy aims at identifying and realizing strongholds of activities, rather than supporting too large a spectrum of widespread and dispersed projects.

PROGRAM STRUCTURE

Research and development activities in the field of Hydrogen Energy and Technology are financially supported and logistically coordinated by the Swiss Federal Office of Energy. Federal and cantonal research institutes, as well as private institutions and industries, guarantee additional financial support. Since autumn 2000, the development and establishment of a Swiss Hydrogen Competence Center, HYDROPOLE®, has been launched. This center coordinates the ongoing R&D projects, compiles documentation and promotes the formation of new alliances between institutional and industrial partners. It is intended to create an optimum structure ranging from fundamental research to technical realization, including process engineering.

As is shown in the table of projects, the research activities are carried out at the Paul-Scherrer-Institute, within an alliance of three research teams located at the Universities of Bern, Lausanne and Geneva, as well as within an alliance of two research teams located at the Universities of Fribourg and Geneva. The Hydrogen Energy Program is divided into four segments:

- Hydrogen production based on regenerative energy sources, in particular solar energy and hydropower;
- Hydrogen storage and transportation technologies;
- Hydrogen utilization as a fuel and chemical commodity; and
- Supporting activities, such as development of functional materials and devices and practical demonstrations of technical and economic feasibility of hydrogen technologies, as well as educational activities.

FUNDING

The total public funding for Solar Chemistry and Hydrogen Technology is about 12 million Swiss Francs per year (about 7.5 million US$). Around half of this sum is dedicated to activities on hydrogen technology: 25% is funded by the Swiss Federal Office of Energy, 30% by the Board of the Swiss Federal Institute of Technology, 20% by the Swiss National Foundation and 25% by the Cantonal Universities. Private funding is less than half a million SFr per year. Any individual researchers or entrepreneurs can submit proposals for research or development projects. Projects may also be acquired or delegated by the program manager. Funding is expected to remain relatively constant for the coming years. There is, however, a strong need for national and international networking in order to optimize the rather limited means.

RESEARCH, DEVELOPMENT AND DEMONSTRATION ACTIVITIES

A list of projects benefiting through partial funding by the Swiss Federal Office of Energy is presented in Table 1. Fuel cell activities (about 4 million Swiss Francs) are not part of this program, but are closely coordinated.

Table 1: Main Hydrogen Energy Projects and Contractors

PRODUCTION	
Photolysis of water by use of solar energy	University of Berne University of Geneva EPF Lausanne
Chemical cycles based on metal oxides for hydrogen production using concentrated solar energy	Paul-Scherrer-Institute
Production of hydrogen from woody biomass	Paul-Scherrer-Institute
Electrolysis of water using regenerative sources, i.e. hydro and wind power	Various Industries

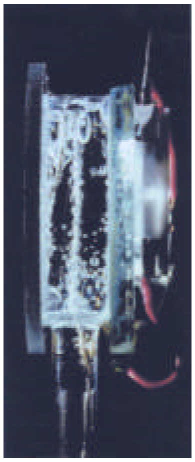
STORAGE AND TRANSPORTATION	
Synthesis and function of new hydrides	University of Geneva
Hydrogen storage in metals, alloys and nanotubes	University of Fribourg
Fast filling and storage of gaseous hydrogen in carbon fiber composite cylinders at high pressure	I. Cyphelly, Les Brenets
UTILIZATION	
Hydrogenation of CO_2 to alcohols and further chemical commodities under supercritical conditions	ETH Zürich
Reduction of metal ores and other novel processes	University of Augsburg Paul-Scherrer-Institute
SUPPORTING ACTIVITIES	
Materials science and process engineering for hydrogen technology	Paul-Scherrer-Institute University of Augsburg University of Basel EMPA, Dübendorf
Advanced education for hydrogen technology and systems analysis, organization of national and international symposia and conferences	Swiss Office of Energy HYDROPOLE® University of Augsburg

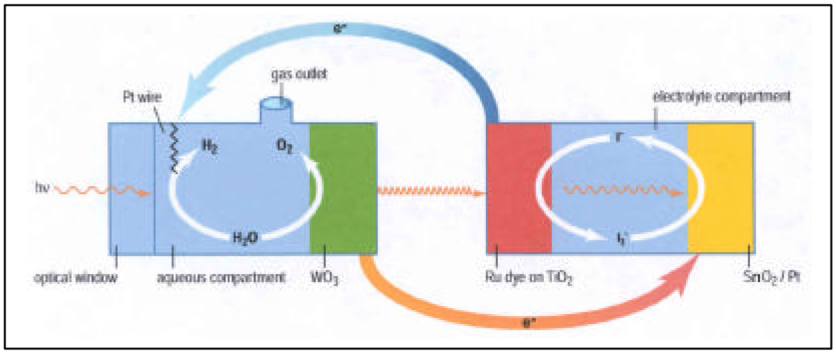
SIGNIFICANT ACHIEVEMENTS

Hydrogen Production

Promising results have been achieved in the field of photolytic cleavage of water into hydrogen and oxygen. Significant progress has been achieved by Prof. G. Calzaferri and his team (University of Berne), as well as by the teams of Prof. M. Grätzel (EPFL Lausanne) and Prof. J. Augustynski (University of Geneva). The cooperation between these three groups aims at the realization of a technically feasible and economically competitive cleavage of water into hydrogen and oxygen. The catalyzed photo-electrochemical process is driven by direct solar radiation. The generation of efficient photo-electrode materials has to be mentioned as a major achievement - in the reversible redox cycle developed and optimized for the tandem photo-electrode system that consists of a dye-sensitized titania electrode coupled to a platinum electrode (see figures), hydrogen can be produced with reasonable efficiencies. As an efficient photo-electrode for the production of oxygen, transparent nanocrystalline tungsten oxide is used. As an alternative, improvements have been made to the silver chloride/zeolite system. The recycling step of the formed silver, which is the decisive process (i.e. the re-oxidation of nanoscopic metallic silver to the initial silver cation), could be realized.

On a technical and industrial level, some industries produce substantial amounts of hydrogen as by-products of their processes (e.g. the production of chlorine). Due to economic reasons, these potentials are usually not utilized, merely burnt off.





Circuit diagram of the tandem cell for water cleavage by visible light (scheme by Michael Grätzel et al.)

Photograph showing the decomposition of water visible by a tandem cell consisting of a mesoporous WO_3, film an a mesoporous dye sensitzed TiO_2 which are superimposed

Storage Technologies

The search for technically suitable and cheap metal hydrides has been pursued by two research teams at the Universities of Geneva and Fribourg. Many new attractive metal hydrides have been synthesized and characterized with respect to composition, crystallographic structure, hydrogen storage capacity and charge/discharge cycles. Experimental research has been focussed on carbon nanotubes at the Universities of Fribourg and Augsburg.

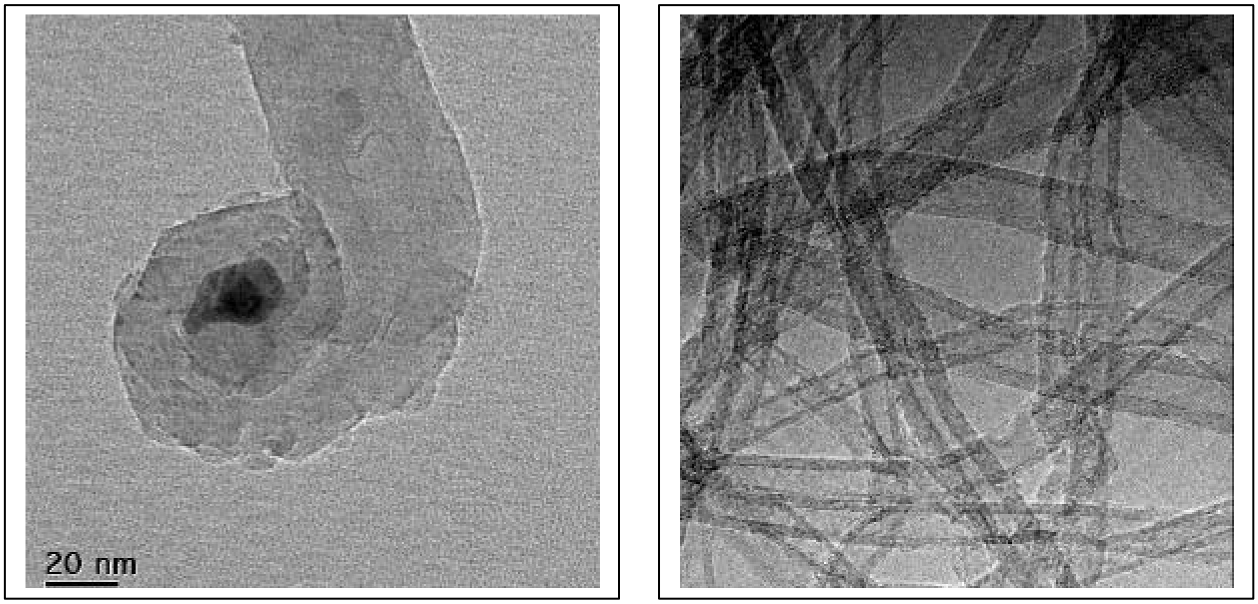
The technology of storing hydrogen in liquid organic commodities, i.e. the methylcyclohexane toluene-cycle, has been under development. Further advancement of this storage technology, i.e. the practical proof of its technical and economic feasibility, is still pending. Whether an industrial partner can be identified who supports the manufacturing and testing of a prototype is not yet certain.

A cooperation between industrial partners and the University of Augsburg aims at modifying high pressure carbon fiber composite cylinders in such a manner that pressurized hydrogen (pressures up to at least 300 bar) may be stored and safely transported. These efforts are the subject of multiple patents, whose awards are still pending.

Utilization of Hydrogen

The catalytic reduction of carbon dioxide to alcohols and further commodities is studied at the ETH, Zürich. Major successes have been achieved by the catalytic synthesis of methanol and amines; some of the catalyst systems have been patented.

Aside from classical applications of hydrogen as an energy carrier for fuel cells, engines or chemical commodities for industrial reduction processes of organic compounds, some efforts have been spent at the University of Augsburg to identify and characterize processes relevant for the metal mining and refining industry, where hydrogen can replace carbon or carbon compounds. This approach does not only lead to a mitigation of carbon dioxide emissions, but also gives rise to new mining and metallurgy technologies.



***Carbon Nanotubes** are thought to be high capacity hydrogen storage systems. These high-resolution transmission electron micrographs show a single nanotube containing the nanoscopic metal catalyst (left) and a agglomerate of nanotubes (synthesis of the samples and images by Anke Weidenkaff, University of Augsburg).*

SUPPORTING ACTIVITIES

The results of the Swiss Hydrogen Energy research and development program are published in internationally renowned journals and in the (Swiss) National Energy Information Service (ENET), as well as presented at international congresses. An Annual Report describing the programs and summarizing the supported projects is issued by the Federal Office of Energy. Selected reports are submitted to the IEA International Energy Technology Data Exchange System (ETDE). Within the IEA, Swiss representatives coordinate some of the tasks and subtasks.

COMMERCIAL ACTIVITIES

Industries like HRAND DJEVAHIRDJIAN SA, Monthey (production of sapphire and other precious stones, large scale hydrogen production by a high pressure electrolyzer); PANGAS AG, Winterthur (hydrogen trader); LINDE CRYOTECH AG, Luzern (liquefaction of hydrogen) and AMMONIACASALE, Lugano (utilization of hydrogen in industrial plants for the production of ammonia and methanol) are all concerned with hydrogen technology. Economical reasons, however, limit the implementation of novel processes or the enhanced large-scale application of hydrogen as a fuel. At present, an overview on all the economic issues directly or indirectly related to hydrogen technology is compiled under the auspices of HYDROPOLE®.

OUTLOOK

The successful promotion of hydrogen energy and technology depends not only on the research and development progress, but also on the transfer of the results into technical and industrial applications. Therefore, efforts to identify new niches of applications, novel processes or products based on hydrogen technology will be intensified. Simultaneously, the fundamentals of hydrogen energy and technology will be perpetuated in order to enlarge the basic knowledge and also to encompass the spectrum of potential applications.

Hydrogen is believed to be one of the crucial corner pillars for a future sustainable global energy system. For Switzerland, it also represents a potential for industrial and technical advancement. Owing to the actual economical disadvantages and the ecological advantages of the use of hydrogen, progress will depend on improving the know-how and on finding small- and mid-scale applications that are commercially successful within reasonable periods. This task affords enhanced investigations in hydrogen materials science and hydrogen process engineering.

Hydrogen storage tanks at the sapphire production plant of Djévahirdjian SA, Monthey

UNITED STATES

Neil P. Rossmeissl
U.S. Department of Energy

NATIONAL POLICY

In the next 20 years, concerns about global climate change and energy security will create the platform for the penetration of hydrogen into initial commercial markets. Ultimately, hydrogen and electricity will come from sustainable renewable energy resources, but fossil fuels will be a significant transitional resource during this period. The growth of fuel cell technology will provide a base for introducing the hydrogen option into both transportation and electricity supply markets.

The U.S. Department of Energy Hydrogen Research and Development Program focuses its efforts on meeting the fundamental technical challenges industry faces for deploying hydrogen energy options and conducts research and validation efforts to provide technological solutions to impending infrastructure issues that affect the hydrogen industry across-the-board. This is being accomplished by:

- Supporting the introduction of safe and dependable hydrogen-based energy systems including the development of codes and standards for hydrogen technologies.
- Developing and lowering the cost of technologies to produce hydrogen directly from sunlight and water.
- Performing research projects that introduce renewable-based options for hydrogen production and that decrease the cost of producing hydrogen from natural gas.
- Developing a hydrogen-based, reversible fuel cell electricity concept that will enhance the use of distributed, renewable-based utility systems (i.e., wind and solar energy) by 2004.
- Demonstrating fueling systems and onboard storage for hydrogen vehicles in urban non-attainment areas and examining how the infrastructure needs of those vehicles will be met by 2004.
- Developing and validating fuel cell electricity and hydrogen storage systems for remote and residential applications by 2003.

PROGRAM STRUCTURE

The development of a fully integrated hydrogen energy economy will be a major societal accomplishment. Such an accomplishment will be the result of fundamental and applied scientific research, systems engineering, integration, validation, industry and public outreach, and careful planning and analysis. The U.S. Department of Energy (DOE), Hydrogen R&D Program, conducts activities in four primary thrust areas for the purpose of making hydrogen a cost-effective energy carrier for utility, buildings, and transportation applications:

- **Core R&D --** research and engineering development in the areas of hydrogen production, storage, and utilization. The Program maintains and constantly reviews a diversified R&D portfolio of near-, mid-, and long-term technologies;

- **Technology Validation –** integration of components of novel and advanced technology into test-bed energy systems to evaluate their potential.

- **Outreach and Education --** educate and inform the private sector on the benefits and technology advances and facilitate the exchange of technical information to schools and non-scientific audiences.

- **Planning and Systems Analysis –** assess the economic feasibility, technical viability and environmental impact of current and developing technologies.

CORE R&D ACTIVITIES

The research supported by the Hydrogen Program focuses on the exploration of process improvements to conventional technologies and on longer-term, higher-risk concepts that address future energy needs and offer an economic payoff. While production of hydrogen from fossil fuels and from renewable resources has been predominant in the portfolio, the program also recognizes storage/distribution/delivery as an important component of any hydrogen application, including transportation, utility and industrial applications. Efforts in the development of efficient end-use technologies include hydrogen burners, PEM fuel cells and reversible fuel cells. In support of all hydrogen systems, the Program also conducts research on the understanding of safety issues and development of reliable and cost-effective sensors and detectors. Table 1 summarizes the activities pursued in the Core R&D portion of the Program:

Table 1: The Core R&D Technology Portfolio

Goal	Component	Relevant Projects
Improve the efficiency and lower the cost of fossil-based and biomass-based hydrogen production processes to $6-8/MM Btu.	Production (fossil based)	• Sorption-Enhanced Reformer (SER) • Ion-Transport Membrane (ITM) • Plasma Reformer • Thermocatalytic Cracking
	Production (biomass)	• Biomass to Hydrogen via Fast Pyrolysis and Catalytic Steam Reforming • Hydrogen Production from High Moisture Biomass • Bacterial Water Gas Shift
Advance emission-free and renewable-based direct hydrogen production technologies towards commercial viability, with a target cost of $l0-$15/MM Btu.	Photolytic Production	• Photobiological Production of Hydrogen • New Materials and Approaches to Photocatalytic Systems • Photocatalytic Cleavage of Water • Photoelectrochemical-Based Direct Conversion Systems

Demonstrate safe and cost-effective storage systems for use in stationary, distributed and on-board applications with a target of greater than 5 wt% hydrogen storage and a cost of less than 50% of the value of the hydrogen.	Storage, Transport, and Delivery	• Pressurized containers • Insulated pressurized containers • Hydride development • Hydride/organic slurry • Polyhydride complexes • Fullerenes • Carbon nanotubes • Graphite nanofibers
Develop fuel cell and reversible fuel cell technologies as an efficient low-cost means of converting hydrogen into electric power.	Utilization	• Low-Cost Fuel Cells • Low-Cost Fiber-Optic Chemochromic Sensors • Hydrogen Detector • Low-Cost Thick Film Sensor

TECHNOLOGY VALIDATION

The Core R&D Program serves as the incubator for the development of key technologies that will successfully progress to become components in technology validation projects. This development approach can be defined as cyclic, where lessons learned along each stage of the technology validation process will provide important feedback in setting goals and priorities for future R&D activities. As R&D activities provide new results and advances, the Technology Validation Program will incorporate this knowledge into improving its projects. Key integrated system concepts require validation.

In carrying out its activities, the Technology Validation Program will perform the following:

Foster Industry Partnerships
Technology validation projects promote government/industry partnerships to integrate and prove systems that will promote fuel choice. Through cost shared (50/50) projects with industry, the program tests critical infrastructure-related concepts for hydrogen energy applications in transportation, distributed generation, village power and residential and commercial buildings.

Validate Integrated System Performance and Availability
Technology validation projects gauge the readiness of basic technology for further industry development and evaluate how these technologies will fit in a hydrogen energy system.

Provide Feedback to the Core R&D Program
Technology validation projects identify critical technology readiness and provide feedback to researchers involved in core R&D projects.

Promote Hydrogen Uses and Safety
Technology validation projects promote safe hydrogen use in communities and validate safety codes and standards approved by regulatory authorities.

The overall goal of the Program's technology validation efforts is to support industry in the development and demonstration of hydrogen systems in the utility, residential and transportation sectors. The culmination of significant core R&D results and the need for infrastructure and system integration to support massive industry investment have resulted in the need to validate the use of hydrogen energy systems in projects for stationary and transportation applications by 2004. To achieve this goal, the program operates under the following strategic objectives:

- Obtain industry participation through competitive solicitations for long-term development and proof-of-concept testing
- Integrate renewable energy resources with hydrogen storage in remote, distributed power scenarios
- Test the viability of hydrogen production, storage, and refueling stations within several clean clusters
- Evaluate remote and residential “total” energy PEM fuel cell systems
- Develop hydrogen-based operating experience acceptable to meet safety codes and standards.

Several areas have already been identified where hydrogen energy systems may prove successful in proof-of-concept, integrated prototype systems. Projects in these areas will seek to validate system performance data under specific user site conditions. The data generated from these projects, both technical and economic, will contribute to industry’s determination of the viability of these systems for deployment in specific markets. Niche market opportunities exist to accelerate and facilitate the advancement of cost-effective hydrogen systems. These identified market opportunities for hydrogen include:

- **Renewable Hydrogen Systems**

  Distributed renewable power generation using PEM fuel cells will be a viable application of hydrogen. PEM fuel cells are being built today and can be a reliable source of energy to provide stationary distributed power. Fuel cells have no moving parts, are nonpolluting and quiet, and produce water as the only byproduct.

  The restructuring of the electric utility industry has opened the door to many competitors as well as provided opportunities for distributed generation. The increase in consumer demand for renewable energy sources and green power under the new restructuring regime will also help the penetration of hydrogen energy technologies. In this area, the program has solicited projects to demonstrate renewable grid-connected hydrogen systems that provide distributed electrical power.

- **Hydrogen Infrastructure**

  The co-production of electricity and hydrogen, whether it provides commercial or residential power, can be the foundation of a hydrogen transportation infrastructure. Commercial facilities could use hydrogen to generate electricity with a fuel cell. By oversizing the reformer or producing hydrogen when electricity demand is low, the system can produce excess hydrogen, which is stored and used for hydrogen powered fleet vehicles. In residences, hydrogen could also be used to provide electricity and to power individual vehicles on a smaller scale.

  To prove this concept, the program anticipates supporting several projects in urban, non-attainment areas where electricity rates are high such as Nevada and Southern California.

Projects will use the following technologies:

- Hydrogen energy systems comprised of distributed steam reforming and renewable electrolysis to produce hydrogen
- Hydrogen storage in both conventional steel and advanced storage tanks
- Fleet vehicles using fuel cell electric propulsion and internal combustion engine operating with hydrogen blends.

- **Remote and Village Power**

Globally, more than 2 billion people are without access to electricity, a power source that could significantly improve the quality of their lives. Many of the efforts being made today to bring power to remote areas include fossil fuel-based systems run by diesel, which can be expensive. While living standards may improve in the near-term, this fossil fuel use will eventually cause local pollution problems. Using hydrogen technologies in combination with hybrid diesel systems to provide remote power could reduce the economic and environmental burdens experienced by these regions based on their current energy use.

FUNDING

Hydrogen's potential as an energy carrier has been recognized for decades. The DOE, Hydrogen R&D Program was first initiated in the mid-1970's in response to oil supply shocks that brought world awareness to the scarcity of fossil energy resources and our growing dependence on foreign supply. During the 1980s, while energy prices were essentially stabilized, steady advances were made in energy efficiency and renewable energy technologies. Hydrogen's potential as a future energy carrier grew with the idea of linking hydrogen to renewable technologies to bridge the intermittent nature of renewable energy supplies. Since the early 1990's, the growing public concern over greenhouse gas emissions has been a primary driver of the Hydrogen R&D Program. In addition, technological advancements from both industry and national laboratories, and actions from the Administration and Congress have provided further incentives for the Program's advance. Funding for the Hydrogen R&D Program has expanded significantly since the Program was functionally reorganized in 1992 (see Table 1).

Table 1: Historical Funding Profile

Year	Appropriations (MM$)
1992	1.40
1993	3.85
1994	10.00
1995	10.00
1996	14.50
1997	15.00
1998	16.25
1999	21.00
2000	24.59
2001	26.90

The funding resources for the 1999 fiscal year and their respective allocation to a specific program focus are illustrated in Figure 1. Core R&D and Technology Validation, serve as the foundation of this technology development effort and account for approximately 89% of the Hydrogen Program budget. Outreach, Education, Planning and Systems Analysis serve the overall effort by guiding program activities through technical analysis and support development by educating stakeholders, fostering industry partnerships and communicating Program goals and objectives to the private sector.

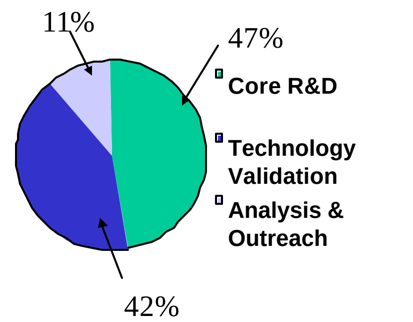


Figure 1: FY1999 Program Funding Chart, 22.25 MM$

SUMMARY

As we stand at the dawn of the twenty-first Century, it is becoming increasingly more apparent that the world faces major energy and environmental challenges. Reference case forecasts published in the U.S. Department of Energy, Energy Information Agency (DOE/EIA), *International Energy Outlook 1998*, indicate that world energy consumption in 2020 will exceed 1970 levels by a factor of three.

The demand for energy at these elevated levels indicates global society's desire for increased economic well-being. The Kyoto Climate Change Protocol Agreement (December 1997) illustrates that there is also a world demand for improved environmental well-being. While it is difficult to estimate the price thresholds at which energy and environmental demands can be appropriately met, the challenge is quite clear -- the world community needs reliable and affordable supplies of energy that minimizes the risk of global climate change,

The development of hydrogen energy technologies offer the opportunity to minimize energy security risks, reduce greenhouse gas emissions and create many new business opportunities in North America and abroad, but there remain significant technical and infrastructure challenges. The deployment of hydrogen energy options will require extensive research, development, and validation efforts, but these developments alone are not sufficient to assure that hydrogen technologies can compete in the marketplace. Estimates indicate that it could take several billion dollars to build the infrastructure needed to deliver, store and effectively utilize hydrogen in utility, buildings and transportation applications. The technical and infrastructure requirements for enabling hydrogen energy systems, the long-term high-risk nature of this endeavor, and the potential benefits warrant Federal leadership and support.

TASK 12 – METAL HYDRIDES AND CARBON FOR HYDROGEN STORAGE

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INTRODUCTION

The movement toward implementation of hydrogen as an alternate fuel has been an active goal among energy scientists and environmentalists since the 1973 "energy crisis". It is for this reason that the International Energy Agency (IEA) Agreement on the Production and Utilization of Hydrogen was established in 1974. After a quarter-century, the IEA Hydrogen Agreement continues to promote this same goal. In recent years, renewed support has come in the form of increasing interest from the industrial sector, in particular oil companies and automobile manufacturers. This trend seems to have at least three sources: (1) the technical successes of several new fuel-cell companies, (2) increasing movement toward efficient and clean vehicles, and (3) a growing scientific and political realization that the long suggested negative effects of greenhouse gases are likely real and pose very serious questions for our future. The renewed opportunity to participate in the practical implementation of "Hydrogen Energy" has been welcomed by all within the IEA Hydrogen Agreement family, but there are many technical and economic problems that remain. The IEA Hydrogen Agreement's Task 12, Hydrogen Storage in Metal Hydrides and Carbon, was specifically targeted towards addressing the problem of "solid-state" hydrogen storage.

On-board hydrogen storage remains an undisputed problem for hydrogen-fueled vehicles. Although recent progress in metal hydride batteries has been significant, little real progress has been made in efforts to advance the room-temperature hydrogen gas storage capacity of traditional hydrides over the last 30 years. At least this statement can be made relative to the present requirements for supplying PEM fuel-cell vehicles, where 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 onboard reforming of conventional liquid hydrocarbon fuels, but well-known disadvantages can be cited for each.

Something of a thermodynamic dilemma has evolved over the last 30 years when it comes to "conventional" metal hydride storage of hydrogen. Numerous hydrides with metallic bonding (e.g., those represented by $LaNi_5$ and TiFe) have been developed to reversibly store hydrogen at near-ambient temperatures, but they suffer from poor gravimetric capacity (typically no more than 2 wt.% H). At the other extreme, there are ionic- and covalent-bonded hydrides (e.g., Li- and Mg-based alloys, respectively) that have good gravimetric capacities (5-10 wt.% H), but require uncomfortably high temperatures (>250°C) to release the stored hydrogen at positive pressure. There are very few known hydrides between these two extremes.

The basic hydride problem was recognized by the IEA Hydrogen Agreement Executive Committee and led to the creation of Task 12 in 1995 to seek new and different storage possibilities. Thus, the Task focused new hydride storage R&D on non-traditional hydrides. In addition, carbon hydrogen-storage media were incorporated into the Task in response to reports of new promising results. This Final Report for Task 12 thoroughly summarizes the extensive solid-state hydrogen-storage R&D work completed on behalf of IEA during the period 1995-2000.

DURATION

Task 12 was formed October 1995, with William Hoagland (USA) as the charter Operating Agent. Gary Sandrock replaced Mr. Hoagland in late 1996. Originally, Task 12 was chartered for the period Oct. 1995 – Sept. 1998, but positive results led to its extension to Sept. 2000. Originally aimed solely at metal hydride R&D, carbon was added in 1998.
Targets

The Task took aims at the following two technical targets:

1. The identification of a formulation technique for a metal hydride or carbon material that is capable of 5 wt.% hydrogen capacity with a desorption temperature of less than 100°C and a desorption pressure of at least 1 atmosphere absolute.

2. The development of a metal hydride surface treatment such that high-efficiency, reversible electrochemical reactions can be accomplished over thousands of cycles.

Target 1 centered on the potential application of metal hydrides or carbon as hydrogen-storage media for PEM fuel cell vehicles, although other applications could also use such properties. Originally the temperature target was set at 150°C, but that was virtually met and superseded by a new target of 100°C during the course of the Task. Most of the Task activities were aimed toward Target 1. Target 2 concerned itself with electrochemical applications, for example electric storage batteries.

PARTICIPANTS

The countries that participated in Task 12 were: Canada, the European Commission (never formalized), Japan, Norway (first 3 years only), Sweden, Switzerland and the United States.

OFFICIAL EXPERTS AND INSTITUTIONS

The roster of Task participants and institutions (Table II) covers a large spectrum of experience, expertise, reputation and experimental capability in the field of metal hydrides and carbon-hydrogen interactions. Those skilled in the art will recognize most of the names and institutions listed in Table II. In addition to the designated Official Experts listed in Table II, there were many other staff members, graduate students and postdoctoral scientists involved in the work. The individuals are too numerous to be mentioned here; see the List of Publications and Presentations. Note that Bogdanovic' (Germany) and Verbetsky (Russia) participated unofficially because their countries were not formal participants in Task 12. However, they did have limited financial support from Sweden and Switzerland, respectively, as well as the IEA.

Table II
Participating Task 12 Experts and Institutions

Canada:	R. Chahine*, University of Quebec A. Zaluska*, McGill University
(European Commission*):	(P. Bernier*, University of Montpellier)
Japan:	E. Akiba, National Institute of Materials & Chemical Research S. Suda, Kogakuin University I. Uehara*, Osaka National Research Institute N. Kuriyama*, Osaka National Research Institute
Norway:	A. Maeland*, Institute for Energy Technology
Sweden:	D. Noréus, Stockholms University (B. Bogdanovic', Max-Planck-Institute für Kohlenforschung)
Switzerland:	L. Schlapbach, University of Fribourg K. Yvon, University of Geneva (V. Verbetsky, Moscow State University)
United States:	M. Heben*, National Renewable Energy Laboratory C. Jensen, University of Hawaii R. Loutfy*, MER Corporation F. Lynch*, Hydrogen Components Inc. R. Murphy*, Oak Ridge National Laboratory G. Sandrock, SunaTech, Inc. G. Thomas, Sandia National Laboratories

* indicates not involved for full 5 years; ( ) indicates unofficial

PROJECTS

Task 12 consisted of a series of R&D projects aimed at particular materials and approaches toward achieving one of the Task Targets. Table III lists the 20 projects (16 hydride and 4 carbon). Each Project had a Leader and was funded mainly by the Leader's country. However, most of the projects involved international collaborations beyond the Leader's home country or institution. All projects were experimental in nature except Project 7, which was a data compilation and public on-line database activity.

The projects listed in Table III are generally in order of initiation, with subdivision only as to hydride and carbon. It is useful though to group the projects into more specific categories to better explain their purposes:

Projects 5, 6, 10, 11, 14 and 15 can be collectively described as projects on complex hydrides involving mixtures of ionic species and covalently bonded complexes of hydrogen and non-transition or transition metals. Projects 5, 6, 10, 14 and 15 involve the family of non-transition metal complexes called the alanates, principally catalyzed $NaAlH_4$. The catalyzed alanates were brought into Task 12 as a result of the pioneering discovery of this new class of exciting materials by Prof. B. Bogdanovic' of Germany. Project 11 has searched for new transition metal complexes using high-pressure techniques. Project 16 can perhaps also be included in this category because it resulted in the discovery of a new class of hydrides based on the Zintl phase, a kind of hybrid among ionic, complex and metallic hydrides.

Projects 1, 2, 8, 9 and 12 all look at materials based on Mg_2NiH_4 or Mg_2NiH_4-containg alloys. Mg_2NiH_4 can also be classified as a transition metal complex and has been known as a classic Mg-based hydride since 1968. These projects have examined some new ways to improve Mg_2NiH_4 properties and understanding by thermomechanical means (1), mechanical milling (8, 9, and 12) or vapor-phase synthesis (2). Although Project 12 started out to improve the hydriding and dehydriding properties of the Mg_2NiH_4-Mg eutectic alloy by ball milling and fluorination, it evolved into a project examining the catalytic properties of the material on the hydrolysis-driven liberation of H_2 from $NaBH_4$ complex solutions.

Projects 4 and 13 studied the relatively unexplored area of Ca-based alloys and intermetallic compounds. Project 3 discovered a new AB_2 Laves-phase hydride.

Projects C-1, C-2, C-3 and C-4 widely addressed the newly active area of hydrogen in/on carbon. C-1 focused on single-wall nanotubes with an emphasis on optimizing synthesis and cutting for the purposes of hydrogen storage. C-3 and C-4 surveyed a range of available carbons relative to gaseous and electrochemical hydrogen storage, respectively. C-2 studied the potential of storing and liberating covalent-bonded hydrogen on fullerene carbons.

Table III
List of Task 12 Projects and Leaders

No.	Title	Lead Expert	Lead Country
1	Destabilized magnesium nickel hydride	D. Noréus	Sweden
2	Vapor phase synthesized Mg_2Ni	G. Thomas	USA
3	Fine-structured $RE(Mn,Al)_2$ alloys	L. Schlapbach	Switzerland
4	Laves phase $CaAl_{2-b}X_b$ alloys with substitutional and interstitial elements X	I. Uehara	Japan
5	Preparation and characterization of titanium-aluminum alloys as potential catalysts for reversible alkali metal-aluminum hydrides	A. Maeland	Norway
6	Structural investigations of intermediates and end products in the synthesis of Ti-doped alkali metal-aluminum hydrides	D. Noréus	Sweden
7	Comprehensive hydride review and associated IEA databases	G. Sandrock	USA
8	Mechanical destabilization of metal hydrides	A. Zaluska	Canada

No.	Title	Lead Expert	Lead Country
9	Ball milling under reactive atmosphere	E. Akiba	Japan
10	Application of polyhydride catalysts to Na-Al hydrides	C. Jensen	USA
11	High-pressure synthesis of new hydrogen storage materials	K. Yvon	Switzerland
12	Ball milling effects during fluorination of the eutectic alloy $Mg-Mg_2Ni$	S. Suda	Japan
13	Ca-based ternary alloys	N. Kuriyama	Japan
14	Catalytically-enhanced sodium aluminum hydride	C. Jensen	USA
15	Metal hydride safety testing	F. Lynch	USA
16	Synthesis and structural analysis of new ternary hydrides based on hydride-fluoride similarity	E. Akiba	Japan
C-1	Optimization of single-wall nanotube synthesis for H_2-storage	M. Heben	USA
C-2	Hydrogen storage in fullerene-related materials	R. Loutfy	USA
C-3	Assessment of hydrogen storage on different carbons	R. Chahine	Canada
C-4	Hydrogen-carbon, hydrogen-metals	L. Schlapbach	Switzerland

COMMUNICATIONS

The keys to a successful Task are interactions, collaborations and communications among the participants. For Task 12, this was accomplished in two ways. First, every two months or so, Project Leaders provided short progress reports that were then assembled and distributed by e-mail.

The second method of communication was in the form of Experts' Workshops that were held about twice per year, on the average. Table IV lists the official Experts' Workshops held throughout the duration of Task 12. The first three listings represent Planning Workshops held before the formal start of the Task. Often Workshops were held in conjunction with international meetings to minimize extra travel and maximize IEA participation. The Workshops usually covered two areas: (1) necessary information transfer and (2) technical reviews of all the projects by the Leaders or their representatives. Attendance at the Workshops was excellent. In almost all cases, good direct or proxy presentations were made and all Experts were encouraged to interact and provide advice and comments. International collaborations were reinforced or newly established. The spirit of the IEA Workshop was fulfilled in all cases.

Table IV
List of Experts' Workshops

Dates	Location
21 March 1994	Washington, D.C., USA
12 October 1994	Miami Beach, USA
17-18 July 1995	Henniker, USA
27-28 September 1995	Kjeller, Norway
27 August 1996	Les Diablerets, Switzerland
13 March 1997	Alexandria, USA
14 July 1997	Henniker, USA
26 January 1998	West Palm Beach, USA (carbon only)
9-10 March 1998	Davos, Switzerland
30 September – 1 October 1998	Tokyo, Japan
20-21 July 1999	Henniker, USA
2-3 March 2000	Davos, Switzerland
6-7 October 2000	Noosa, Australia

SUMMARY OF RESULTS ACHIEVED

The overall result of the Task was significant measurable progress toward Target 1, as well as general progress in the understanding of metal hydrides and carbon as hydrogen-storage media. This will be only a brief summary of the principal results, project by project. Each of these projects is presented in some detail later in the form of individual Project Reports, the main summary mechanism of this Final Task Report. In addition, Publications and Presentations resulting from each Project are listed in order for interested parties to pursue even more details.

The closest approach to achieving the 100°C, 5 wt.% hydrogen-storage target resulted from the sodium alanate (hydride complex) projects. Sequential Projects 10 and 14 studied the catalyzing of $NaAlH_4$ by mechanical (ball milling) methods using liquid and solid catalyst precursors. Preliminary determinations of engineering behavior and properties were made. By the end of the Task, 4-4.5 wt.% at 125°C was routinely demonstrated with reasonable hydriding and dehydriding rates. This is close to the target and represents a hydride capacity-temperature combination never achieved before. Related work showed the validity of the two-step $NaAlH_4$ reaction and determined the structure of the important intermediate phase Na_3AlH_6 (Project 6). The exact catalyst(s) influencing the alanate reactions have not been determined, but Project 5 examined the possible structural and reaction roles of Ti_3Al hydrides as catalysts. A much needed safety study of $NaAlH_4$ was started in Project 15, but, unfortunately, was not completed. As a measure of the progress made in the IEA alanate efforts, distinct interest has resulted from outside of the IEA, including commercial interest among automotive and fuel cell companies. An example of increased national interest can be seen by the fact that Japan's WE-NET project has begun the funding of independent alanate work by one of the IEA alanate Experts.

Project 16 discovered a new family of hydrides based on the Zintl-phases, e.g. $SrAl_2$ and $SrAl_2H_2$, both of which are Zintl-phases. These new hydrides have certain similarities to the mixed ionic-covalent alanates and may offer an exciting new “nonconventional” area for future catalyzed hydride R&D.

Project 11 opened the stage for extending the catalyzed alanate work to transition metal complexes. It reported the discovery of a number of new complex hydrides. One of the most promising for future attempts at catalyzing is Mg_3MnH_7.

Five projects revisited the old and classic complex hydride Mg_2NiH_4 with aims at destabilizing it, i.e., making hydrogen desorption easier at lower temperatures. Projects 1 and 2 showed it was possible to destabilize Mg_2NiH_4 by lower temperature synthesis (avoiding microtwinning), mechanical working and controlling phase impurities like Mg. It also identified for the first time color and electrical resistivity changes that may have practical applications. Project 2 was performed in close conjunction with Project 1 using a newly developed method of synthesizing single-phase Mg_2NiH_4 by a Mg-vapor process. Projects 8 and 9 studied the effects of ballmilling. Project 8 showed that the temperature of hydrogen desorption could be synergistically lowered by ball milling mixtures of Mg_2NiH_4 and MgH_2. Project 9 examined the ball milling of Mg_2Ni in an H_2 atmosphere (i.e., the formation of Mg_2NiH_4 while milling). Although finer products resulted, the hydride phase structure was similar to static hydriding. In summary, the four projects cited immediately above resulted in significant improvements in hydriding/dehydriding kinetics and modest increases of equilibrium plateau pressures. In general, hydrogen liberation temperatures above 200°C were still practically required, so the Task Target was not approached as nearly as the alanate work.

Project 12 was the only project in Task 12 that did not involve reversible hydriding and dehydriding. Instead it focused on the irreversible liberation of H_2 by the catalyzed hydrolysis of $NaBH_4$ solutions. It found ball milled and fluorinated Mg-Mg_2Ni eutectic alloy (and its hydrides) to be promising hydrolysis catalysts.

Projects 4 and 13 searched for new Ca-based alloys and intermetallic compounds. Although several were identified, they seem to be highly prone to disproportionation and unlikely to provide much practical hope of achieving the Task Target. Similarly, Project 3 reported on the discovery of a new AB_2 Laves-phase CeMnAl. It does not seem to offer practical hydrogen-storage properties, but may be useful as a hydrogen getter.

The four projects on carbon storage media provided mixed results. Projects C-3 and C-4 surveyed a number of commercially and experimentally available materials with regard to gaseous and electrochemical hydrogen storage, respectively. Although some hydrogen storage was measured, results of these two projects fell well short of confirming the high levels of hydrogen storage often noted in the literature. In distinct and credible contrast to this, Project C-1 showed promising levels of hydrogen storage in single-wall carbon nanotubes that had been properly synthesized, purified and cut by mechanical/chemical processing. Levels of around 6.5 wt.% H_2 were shown, with some of that hydrogen coming off room temperature and the rest in the 200-400°C range. Next to the alanate results, this project comes closest to meeting the technical Task Target of 5 wt.% H_2 at 100°C.

Project C-2 studied chemisorbed hydrogen on fullerenes, i.e., fullerene hydrides. Because of the relatively strong H=C bonding, fullerene hydrides are a thermodynamic challenge for practical hydrogen storage. However, like the catalyzed alanates, promising catalyst results were shown in the project, along with possibilities for metal atom substitution.

Finally, Project 7 (the only non-experimental project) resulted in an extensive series of on-line hydride databases (URL: http://hydpark.ca.sandia.gov). The hydride data are far more complete than any printed resource. It has become a widely used Internet resource by hydride scientists and engineers.

FUTURE WORK

The ExCo, Task 12 Experts and Operating Agent all agreed that the results of the Task 12 work were promising enough to construct a new and broader hydrogen storage task. The new proposed Task, Solid and Liquid State Hydrogen Storage Materials, has been approved and is being finalized for startup about May 2001. It will be broader in the sense that it will consider other solid and liquid storage media beyond nonconventional hydrides and carbon. It will also involve more than experimental projects, in particular theoretical, modeling and engineering activities. Additional countries, organizations and Experts will participate.

ACKNOWLEDGEMENTS

The strong support and encouragement of the ExCo members from both the participating and nonparticipating countries is greatly appreciated. Special thanks goes to participating ExCo members for their continued funding and guidance to their Experts and to the U.S. Department of Energy Hydrogen Program (Mr. Neil Rossmeissl) for providing the Operating Agent. Finally, acknowledgements and thanks go to Mr. William Hoagland for his efforts in starting Task 12.

TASK 13 - DESIGN AND OPTIMIZATION OF INTEGRATED SYSTEMS

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INTRODUCTION

Hydrogen energy systems have been proposed as a means to increase energy independence, improve domestic economies, and reduce greenhouse gas and 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. In an effort supported by the International Energy Agency Hydrogen Agreement (Annex 11 - Integrated Systems), design guidelines were developed for a large number of hydrogen-based and non-hydrogen-based components. These guidelines provide data on individual components to assist in the design of integrated energy systems. Included in the guidelines are measures of performance that provide relevant means to compare systems. In addition, a tool was developed to assist in the design of hydrogen energy systems. Computer models were developed for a large number of hydrogen production, storage, distribution, and end-use technologies, based on data collected from hydrogen demonstration projects throughout the world. These models can be linked through the use of a common integrating platform into integrated hydrogen systems. Renewable-based and fossil-based components are included in the component model library to assist in comparative analysis between advanced systems and commercial systems.

OBJECTIVE

The objective of Task 13 is to provide a means to increase energy independence, improve domestic economies, and reduce greenhouse gas and other harmful emissions from stationary and mobile sources. Emphasis is placed on comparison of systems with respect to efficiency, environmental impact, capital and operating costs and other measures of importance.

To accomplish this objective, work is performed within the framework of two coordinated Subtasks.

TASK DESCRIPTION AND PROGRESS

Subtask A: Model Development

Subtask A includes improvement to existing component models and development of additional component models (Activity A1), and the development cost models for each component model (Activity A2). The results of this Subtask support the analyses that are performed in Subtask B.

Activity A1: Component Model Development and Improvement

In the evaluation of existing and proposed hydrogen demonstration systems, it may become necessary to develop additional component models in order to perform technical and cost analyses. In this activity, data are collected and ASPEN-based models are developed and validated for additional components, as needed. In addition, several of the original models require modification, based on new or improved data. For example, a more robust pressure swing adsorption model that can operate as a stand-alone model (rather than as an integral part of several of the current models) was developed.

Documentation of the new or revised models follows the standard format established in Annex 11. The existing component library is updated as necessary.

Activity A2: Cost Model Development

The basis for the development of consistent cost models has been established and includes appropriate size ranges, scaling factors, installation factors, operating and maintenance costs, etc. This basis is used throughout this activity to insure consistency and fairness. Cost models based on existing non-proprietary data and standard engineering procedures will be developed for each component. This activity will include development of spreadsheet models and/or graphical representations. A range of sizes has been identified for the components, so that the cost models will be applicable for a range of integrated system sizes. These cost models will include non-proprietary projections for future costs based on cost-reduction parameters (such as mass production, market size, and technological advances) that will be defined as part of this activity (based on literature values to the largest extent possible).

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 commercialization.

In addition to developing traditional engineering cost models, this activity will also address the issue of externality costs in close collaboration with Activity B2 (Life Cycle Assessments). Specifically, a set of cost parameters will be developed for important greenhouse gas emissions, so that the benefits of renewable hydrogen production systems can be compared to fossil-based production systems. Some effort will also be directed to assigning value to other intangible benefits such as job creation, energy independence, etc.

 # Subtask B: Systems Analysis

Subtask B activities involve the identification of candidate configurations (in cooperation with Subtask A), design of the system using the design guidelines developed in Annex 11, modeling of the integrated systems using the tool developed in Annex 11, and evaluation of the performance, costs and environmental benefits of hydrogen energy systems.

Activity B1: Design and Optimization of Hydrogen Systems

Experts canvassed potential hydrogen demonstration project leaders in participant and non-participant countries to identify candidate configurations for analysis. Using information, tools, and methodologies developed in Annex 11, comparison of different system configurations for a particular application can be made. This requires a set of criteria on which the comparison can 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, given that appropriate value can be assigned to the individual criteria. Three case studies have been selected for evaluation.

Residential Systems

The development of "greenfield" communities is an important opportunity for hydrogen energy systems. In the Netherlands, new residential districts are being developed, with housing additions of 60,000 (1-2% of the total housing market of 6 million). There is an ambitious national plan to require the power generation mix to include 3% renewables (green energy) by 2010 and 10% renewables by 2020. The Dutch national energy policy includes price supports via an eco-tax of up to 30% on non-green energy. Given the requirement to integrate renewables in the national power mix, continued deregulation of utilities, and the desires by many communities to include "green" homes, hydrogen systems offer interesting opportunities for residential developments.

In a preliminary study, an integrated systems approach was used to design the energy system for a new community or district. Services required include heating, lighting, communications, etc. Technologies considered included PEM fuel cells, solid oxide fuel cells, heat pumps, combined heat and power (CHP), heat buffer, electric grid, natural gas grid, hydrogen grid, etc. Schematics of the four main configurations examined in the Residential Systems study are shown in Figure 1.

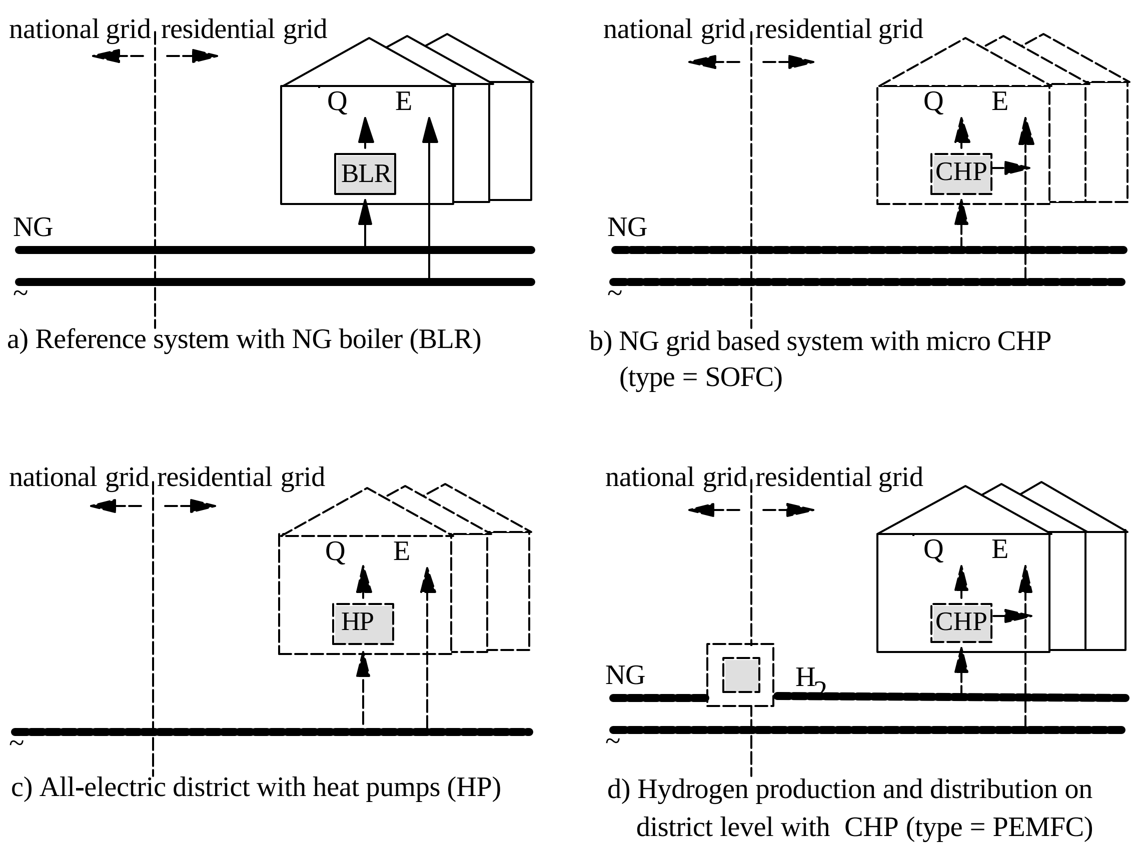

Figure 1 - Configurations for supplying heat and electricity to households in the Residential System study.

Using Matlab, systems were designed using cost, efficiency, and environmental impacts as Measures of Performance. The results of the simulations indicated that the size of the buffer was influenced by and also influenced the size of the components and the use of the grids (for storage and as an energy supplier).

Introducing hydrogen as an energy carrier requires a different infrastructure from the existing infrastructure. For stationary applications, the role of hydrogen will likely depend strongly on the introduction strategies for fuel cells. The first large-scale application of fuel cells may well be small-scale CHP systems. One interesting starting point for developing a hydrogen infrastructure is the use of hydrogen as a fuel for CHP units based on fuel cells. To fully realize the ultimate clean-energy benefits, hydrogen energy systems will use hydrogen from renewable sources. However, in the nearer term, hydrogen will most likely be produced from fossil fuels. The availability of appropriate technologies to support a hydrogen energy system based on fossil fuels is one important aspect of this early-introduction strategy.

Remote Communities

In Norway, more than 99% of the electricity demand is supplied by hydropower. During the last 10 years, however, public resistance, based on environmental issues, has virtually brought the development of the remainder of these resources to a standstill. Because of the increase in power demand and good wind resources along a sparsely populated coastline (a potential of around 10 TWh/year is recognised), the focus on wind energy plants has grown over the last years. It seems that the public resistance, especially in the early phase of the introduction of large-scale wind energy development, is smaller than is the case for further hydropower development. Over the last year (2000), the Norwegian government has approved several applications for building of wind parks, in total amounting to some 300 MW peak power.

The selected locations for Norwegian wind parks are remote areas, such as islands, where the best wind resources are found. The wind parks will produce power for the small communities in these areas, but also for the common electricity grid as a complement to the existing hydropower. In this study, the production and use of hydrogen in fuel cells in relation to such wind parks is discussed. A wind/electrolyser hydrogen refuelling station taking the base power from one of the large windmills in a wind park is modeled. The hydrogen produced is assumed to be used in buses operating the public transport on the remote location. At a later stage, hydrogen for operation of ferries would also be an attractive alternative. A schematic of the system is shown in Figure 2.

The existence of a low-voltage grid is assumed for this study. In practice, this enables testing under constant conditions during the commissioning period. In the modeling work, the assumption of a weak grid enables the identification of several cases of operation of the filling station. In addition to a grid-connected case, two cases where the power from the renewable energy source (wind) is used to run the filling station autonomously are identified and discussed.

A wind-hydrogen system for a remote location is being studied to determine the feasibility of producing hydrogen for transportation applications. This case study was initiated by STATKRAFT SF, Norway's largest producer of hydroelectric power and the second largest producer in the Nordic region. The modeling work is performed by the Institute for Energy Technology (IFE).

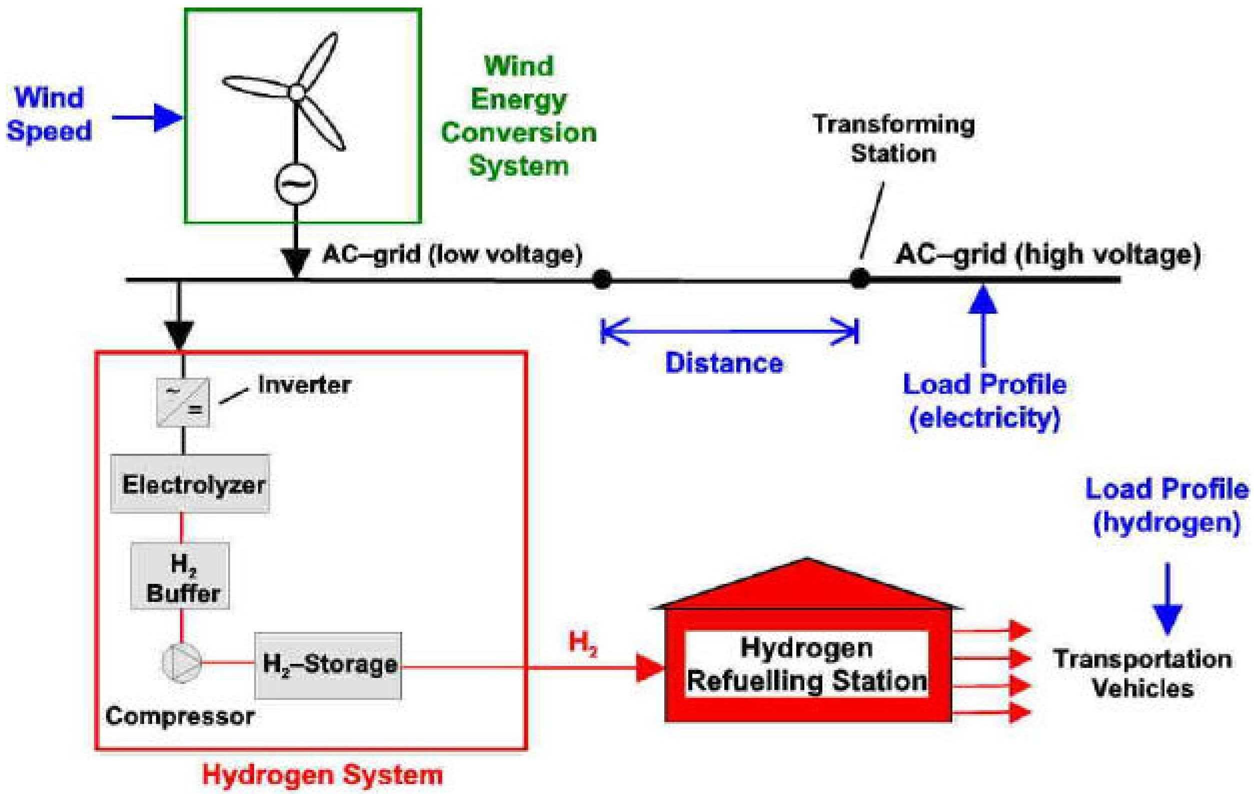

Figure 2 - Schematic of the Remote Communities system under study.

Transportation System

The transportation analysis is not as geographically specific as the other two case studies. It is, however, based on current U.S. experience with hydrogen fueling infrastructure. It is meant to contribute to the ongoing discussion, both in the U.S. and internationally, on the preferred choice for fueling options and hydrogen distribution alternatives.

The overall scope of the transportation analysis is shown in Figure 3 and includes a comparison of hydrogen passenger vehicle fueling options, including:

- Refueling alternatives, primarily various sources of gaseous or liquid hydrogen
- Vehicle configuration alternatives, primarily storage and power plant
- Driving cycle implications
- Cost variations for electricity, natural gas and hydrogen.

The specific cases analyzed include:

- Bulk liquid hydrogen from an existing central reformer is transported to the refueling station by truck, stored as a cryogenic liquid and dispensed to the vehicle as a liquid.
- Bulk liquid hydrogen from an existing central reformer is transported to the refueling station by truck, stored as a cryogenic liquid and dispensed to the vehicle as a gas.
- Bulk gaseous hydrogen is transported to the refueling station by existing pipeline, stored as a compressed gas at 5000 psi and dispensed to the vehicle as a gas. This case is valid only where there is a nearby pipeline. (Pipeline construction costs were not considered.)

- Gaseous hydrogen is generated at the refueling station from natural gas by steam methane reforming, stored as a compressed gas at 5000 psi and dispensed to the vehicle as a gas.
- Gaseous hydrogen is generated at the refueling station from natural gas by a partial oxidation process, stored as a compressed gas and dispensed to the vehicle as a gas.
- Gaseous hydrogen is generated at the refueling station by electrolysis, stored as a compressed gas at 5000 psi and dispensed to the vehicle as a gas.

From the analysis done to date, capital cost of the on-site generation options was found to be generally greater than bulk delivery of hydrogen to the refueling station. The small steam methane reformer is the most costly option; it is also the most uncertain, as there is little commercial experience for this technology (although there is considerable development activity). When the station is underutilized, the delivered cost of hydrogen from all sources is always greater because the capital, O&M, and labor charges are independent of the utilization factor. For projected future costs of on-site generation technologies, the differences between on-site technologies and between on-site and bulk delivered hydrogen become less significant.

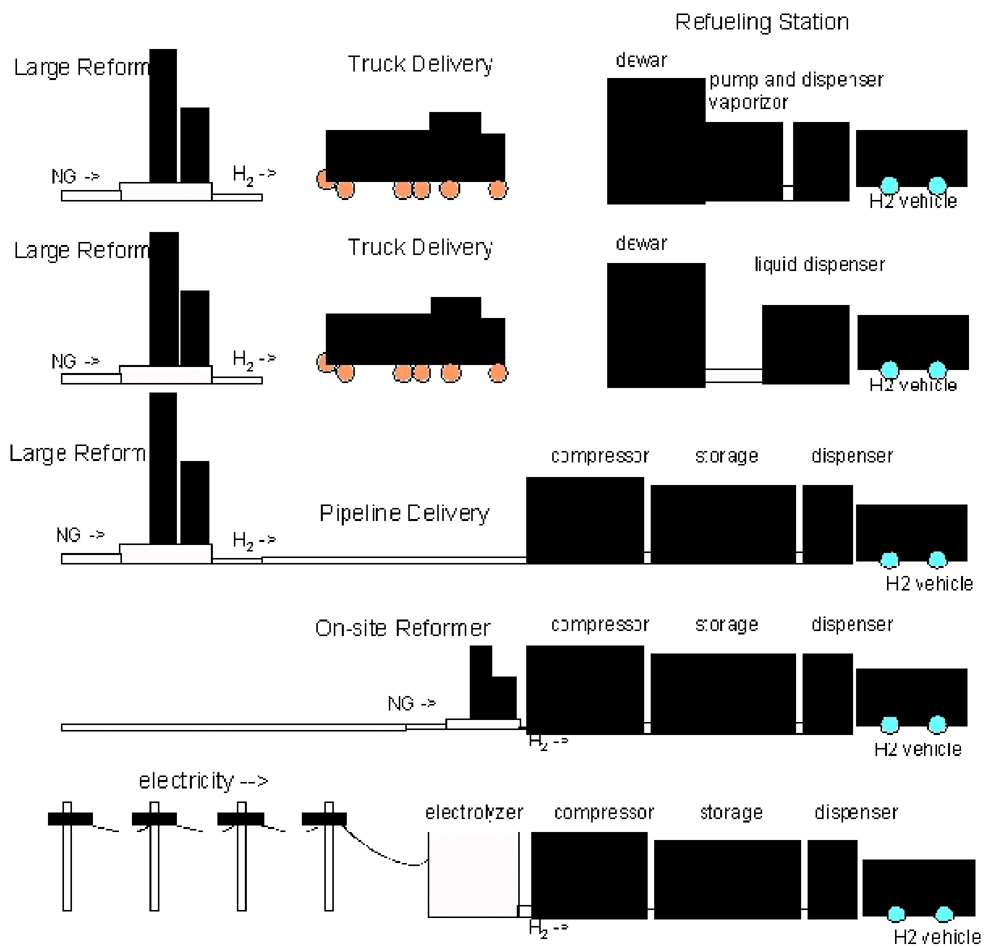

Figure 3 - Transportation Systems cases.

Activity B2: Life Cycle Assessments

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 security and independence, etc). Quantification of some of these benefits can be made using life cycle assessment (LCA) comparisons. LCA is a systematic analytical method to identify, evaluate, and help minimize the environmental impacts of a specific process or competing processes. Material and energy balances are used to quantify the emissions, resource depletion, and energy consumption of all processes between transformation of raw materials into useful products and the final disposal of all products and byproducts. The results are then used to evaluate the environmental impacts of the process so that efforts can be focused on mitigating possible effects.

The scope of an LCA for hydrogen systems is defined based on established (published) LCA methodologies. The measures to be 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).

A baseline LCA was performed to assess the environmental impacts of producing hydrogen via steam methane reforming. The study indicated that two-thirds of the global warming potential (GWP) is due to the CO_2 emissions from the reformer process, the remaining one-third of the GWP is due to natural gas losses during production and distribution. Although the emissions of methane are not high, the GWP of methane is 21 times that of CO_2. Therefore, small leaks can contribute significantly to the overall GWP of the process.

The Joint Research Center of the European Commission is active in the area of LCA. Current efforts include analysis of a cryoplane, with fuel cycle modeling. They have also conducted studies on the safety of infrastructure and performed policy assessments of the political and regulatory changes that may be required to institute a hydrogen energy system. They also have emission data on renewable systems that will be needed in future LCA studies.

PERSONNEL CHANGES/ADDITIONS

Dr. Ed Skolnik of Energetics in the Unites States, has been replaced by Dr. Susan Schoenung, who has extensive experience in renewable hydrogen systems and energy storage. Dr. Skolnik will continue to participate in other hydrogen activities for the U.S. Department of Energy.

Dr. Oystein Ulleberg, of IFE, has taken a post-doctoral position in Australia as of 01/01/01. He has been replaced as the representative of Norway by Dr. Ronny Glöckner, also of IFE. Dr. Glöcker has expertise in solid oxide fuel cells and has performed fuel chain analysis.

Dr. Denis Sarigiannis, of the JRC, has joined the group as a representative of the European Commission. He brings extensive experience in cost modeling and life cycle assessment, including impact assessment.

Mr. Bengt Ridell has joined the group as the alternative representative for Sweden. Mr. Ridell is active in a number of IEA activities, particularly fuel cells. Mr. Lars Sjunnesson remains the primary representative.

DURATION

The Task began on 1 January 1999 and is scheduled to be completed 31 December 2001.

PARTICIPATION

There are nine participants in Task 13: Canada, European Commission, Japan, Lithuania, the Netherlands, Norway, Spain, Sweden and the USA. Switzerland has expressed its intent to participate.

MEETINGS IN 2000

Spring 2000 Amsterdam, Netherlands
Fall 2000 Munich, Germany*

* In conjunction with Hyforum 2000

UPCOMING MEETINGS

Spring 2001 Ispra, Italy
Fall 2001 Oslo, Norway

PUBLICATIONS IN 2000

Spath, Pamela L. and Margaret K. Mann, "A Complete Look at the Overall Environmental Impacts of Hydrogen Production," HYFORUM 2000, The International Hydrogen Energy Forum 2000, September 11-15, 2000, Munich, Germany.

Spath, Pamela L and Margaret K. Mann, "Life Cycle Assessment of Hydrogen Production via Natural Gas Steam Reforming," National Renewable Energy Laboratory, Golden, CO, TP-570-27637.

TASK 14 - PHOTOELECTROLYTIC PRODUCTION OF HYDROGEN

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INTRODUCTION

Photoelectrolysis of water is the process whereby sunlight is used to split water into hydrogen and oxygen. This can be achieved by illuminating a photocatalytic semiconductor device or system either directly or via dye sensitization. Such systems eliminate the need for separate power generation (e.g. via photovoltaic solar cells or solar thermal power station) and electrolysis, and, hence, offer great potential for cost reduction of electrolytically produced hydrogen using solar energy. In addition to the splitting of water, hydrogen can also be photoelectrolytically produced by using organic matter as the electron donor.

TASK DESCRIPTION

The overall objective of Task 14 is to significantly advance the fundamental and applied science in the area of the photoelectrolysis of water. More specifically, it is aimed at establishing performance data on practical system efficiency, device lifetime and costs. From a scientific point of view, key investigations are focusing on semiconductor materials and structures, photo-sensitive dyes, integrated photovoltaic/electrolysis systems, and novel single- and dual-bed reactor arrangements.

The research efforts are undertaken in two highly-coordinated Subtasks:

- **Subtask A: Material Studies**

Subtask A concerns (a) improvement of the light absorption of wide-bandgap semiconductor materials by dye-sensitization and other techniques and (b) the development of catalytic and protective layers for photoelectrochemical (PEC) cells. The Subtask is aimed at demonstrating a system using dye-sensitized tandem cell devices that can achieve reliable water cleavage with a sunlight-to-hydrogen conversion efficiency of more than 5%.

- **Subtask B: System Studies**

Subtask B concerns (a) maximizing the efficiency of multi-junction water splitting systems and (b) assessing reactor system designs for the photoproduction of hydrogen. Multi-junction systems are being developed and studied with the aim of reaching a stabilized sunlight-to-hydrogen conversion efficiency of 10%.

DURATION

The Task was formally started on 1 July 1999 and is scheduled for an initial three-year period, with an option for a two-year extension.

PARTICIPATION

The following countries were official participants in Task 14 during 2000: Japan, Sweden, Switzerland and the United States.

ACTIVITIES & PROGRESS DURING 2000

During 2000, two expert meetings were held. The first was organized in Canberra, Australia (14-15 March 2000), the second in Lausanne, Switzerland (1-3 November 2000). Both meetings were well attended, including visitors from non-member countries. Photochemistry experts also gathered during the 13th International Conference on Photochemical Conversion and Storage of Solar Energy (IPS-2000) in Snowmass, Colorado, USA (30 July - 4 August).

The following research groups were active in Task 14 during 2000: The National Renewable Energy Laboratories (NREL), the Florida Solar Energy Centre (FSEC) and the Hawaii Natural Energy Institute (HNEI), United States; the University of Uppsala (UoU), Sweden; the University of Geneva (UniG), the University of Bern (UniB) and the Swiss Federal University of Technology (EPFL), Switzerland; and the National Institute of Materials and Chemistry Research (NIMC), Japan.

Collaborations included joint investigations and publications and exchange of researchers and materials. Efforts are underway to link new research teams into the current Program of Work. Particular interest has been expressed from countries such as Australia, China, France, Germany and Mexico.

- **Subtask A: Material Studies**

Photoelectrochemical (PEC) devices for water splitting are best designed with two cells in which oxygen and hydrogen evolution occur separately. Research efforts concerning light harvesting in semiconductors have continued to mature the more "common" photoanodes (in particular WO_3) and to investigate alternative semiconductors, as well as materials for the photoanode or photocathode (mainly Fe_2O_3, AgCl, dyes and organic pigments). The anodic oxidization of water to oxygen is generally the performance-limiting step in a two-cell PEC device. Figure 1 shows a schematic of the two-step electrochemical tandem-cell process for water splitting as demonstrated jointly by research teams at the EPFL and the UoG.

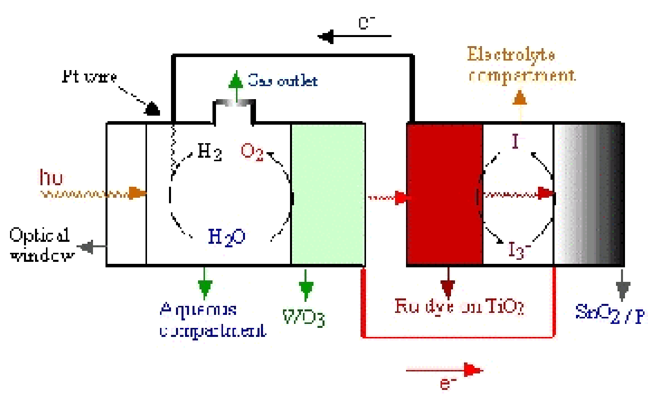

Figure 1: Schematic of a two-step photoelectrochemical cell for water splitting.

Tungsten trioxide (WO_3) - Nanostructured polycrystalline tungsten trioxide (WO_3) films, thus far, remain the best-performing anode for the PEC water splitting systems under investigation worldwide. It is still one of the few n-type semiconductors resistant against photocorrosion in a range of aqueous solutions (pH ~ 4-10). A broad variety of highly-reliable films and production techniques have been designed, characterized and patented by the Swiss (UoG), Swedes (UoU) and Japanese (NIMC) Task 14 groups [Santato et al., 2001; Wang et al., 2000].

Figure 2 shows a scanning electron microscopy (SEM) image of a close to 2-µm-thick film by UoG consisting of a network of plate-like WO_3 particles with diameters ranging from 20 to 50 nm. Due to its mesoporous structure, such a WO_3 film can be penetrated by the electrolyte down to the back contact to form high-surface-area semiconductor/liquid junctions. Using a 1-M_{aq} $HClO_4$ solution, UoG established an Incident Photon-to-Current Efficiency (IPCE) of up to 80% at close to 400 nm, or even a photocurrent-doubling when 0.01-M methanol is added. This compares with the IPCE registered by the UoU of up to 60% at 380 nm when using its WO_3 films in water.

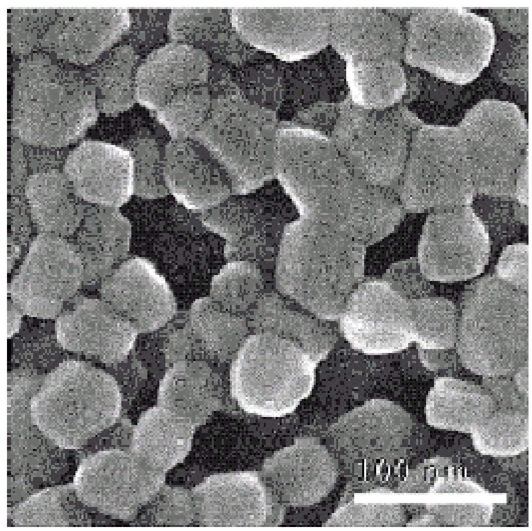

Figure 2: SEM image of a 2-µm-thick transparent anisotropic film consisting of a network of plate-like WO_3 particles with diameters ranging from 20 to 50 nm.

Light absorption of WO_3 thin films is noticeably limited to the blue portion of the sunlight (475 nm) and possibly also by the film thickness. Nevertheless, nanostructured WO_3 photoelectrodes are able to deliver significant photocurrents (e.g. up to 6 mA/cm^2), especially in the case of the oxidation of various organic molecules. The degradation of a variety of organic effluents is, therefore, possible whereby an extra voltage bias (provided by a suitable PV cell) of only about 0.8-1 V is necessary.

Hematite (α–Fe_2O_3) - Since the band-gap of WO_3 (~ 2.6 eV) is too high for optimal performance in a dye-sensitized tandem PEC cell for water splitting, α–Fe_2O_3 is being studied as a promising alternative. As major progress in 2000, the EPFL researchers managed to produce stable photocatalytic Fe_2O_3 layers deposited on conducting glass using a multi-layer spray pyrolysis method. With assistance from the University of Augsburg, Ti^{4+}-doping was found to result in a beneficial shift of the spectral response of the Fe_2O_3 films toward the visible light (red shift). A photocurrent of over 2 mA/cm^2, under simulated AM-1.5 sunlight, was reliably maintained using water as the electron source. Figure 3 shows photocurrent action spectra of doped and un-doped Fe_2O_3.

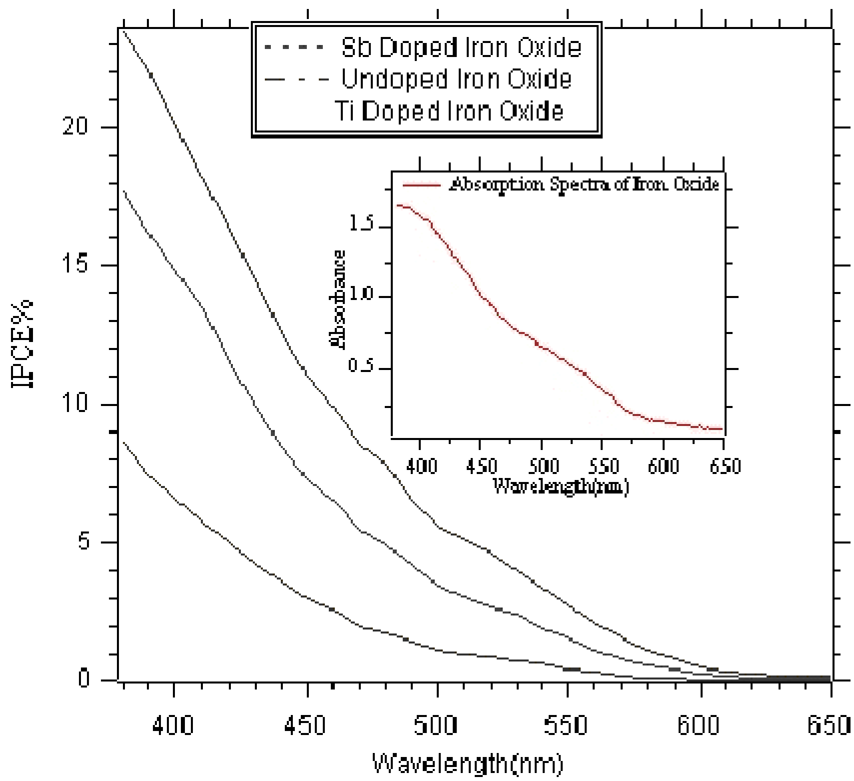

Figure 3: Photocurrent action spectra of doped and un-doped Fe_2O_3. Inset shows absorption spectra of Fe_2O_3.

At UoU, a new method for manufacturing nanostructured electrodes on plastic substrates has progressed. The method is adapted for fast on-line production of thin nanostructured films [Lindström et al., 2001]. For α-Fe_2O_3 films, the photocurrents in an iodine/iodide electrolyte have been found satisfactorily high (> 2 mA/cm^2); however, the photocurrents in water are, thus far, an order of magnitude lower [Lindgren et al., 2001]. Improvements are possible through the addition of minute amounts of ruthenium oxide at the electrode surface. These investigations into catalytic improvement remain on-going.

Additionally, researchers at NIMC and the Mexican Academy of Material Science (UNAM) are studying the effects of doping of various semiconductor thin-films including SiC, CdTe, CdSe, CdSexTe1-x, $CuInSe_2$, $Cu(In,Ga)Se_2$, WO_3, MoO_3, TiO_2, Fe_2O_3. This screening work is designed to provide insight into"tuning" the conduction and valence bands of the semiconductor materials of interest for PEC devices.

New oxide semiconductor catalysts - At NIMC, new families of oxide semiconductor photocatalysts with a comparably narrow band gap, typically between 2.5 eV and 2.7 eV, have been designed and characterized. Typical polycrystalline oxides include Bi_2MNbO_7 (M=Al,Ga,In), $InNbO_4$ and $InTaO_4$ [Zou et al., 2000], the latter ones loaded with 0.5%-wt NiO_x. H_2-evolution induced by visible light was observed when the photocatalysts were suspended in pure water, with O_2-evolution, so far, not observed. It is speculated that the oxygen was adsorbed over the photocatalysts.

Silver chloride (AgCl) - Quantum-sized silver, silver-chloride and silver-sulfide clusters (zeolite A composites) were synthesized and characterized at the UoB in 2000. Such clusters can be combined with a semiconductor photocathode (eg. Si, SiC, Cu_2O, CdS, Ag_2S or p-$GaInP_2$) to act as an antenna system for the oxygen evolution part in a water splitting PEC cell [Calzaferri et al., 2001]. The combination of silver-based zeolite A antenna systems with the TiO_2-based "Graetzel"-cell is envisaged to form a water splitting device. Figure 4 illustrates a van der Waals model of a generic zeolite cluster.

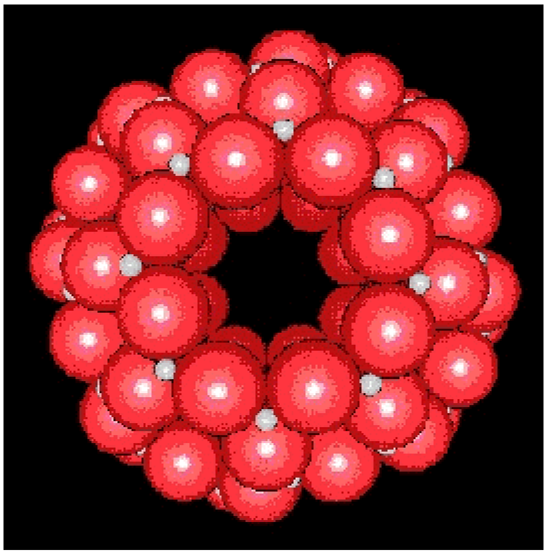

Figure 4: Van der Waals model of a generic zeolite cluster.

Pigments & dyes - Pigments and dyes can act as photo-catalytic agents in solar water-splitting schemes. At FSEC, various new organic pigments have been studied, whereby semi-empirical molecular orbital calculations based on voltammetry and PM3 were confirmed to accurately predict the oxidative water-splitting ability of pigment candidates [Slattery et al., 2001]. The best performing pigments (e.g. perylene) have been made into films containing 1.0%-wt Pt catalyst for illumination with Xenon lamps. The oxygen evolution was found to be significantly better than with TiO_2 samples, encouraging the further development of the dual-bed PEC reactor concept.

Advanced dye-sensitized zeolite-L sandwiches have also been synthesized at the UoB [Pauchard et al., 2000]. These nanocrystal-sized cylindrical structures act as artificial antenna systems for light harvesting, as well as transport. Using a three-dye antenna, light harvesting over the whole visible spectrum, with subsequent energy transport leading to fluorescence at the zeolite-L ends, has, for the first time, been demonstrated. Attempts are being made to use this system for the development of a novel thin-layer solar cell in which light absorption and the creation of an electron-hole pair are spatially separated.

A number of dye-sensitizers for tandem PEC cells, as introduced before in Figure 1, were designed and characterized at the EPFL in 2000. Novel ruthenium sensitizers containing functionalized hybrid tetradentate ligands (refer to Figure 5) were confirmed to have a markedly enhanced response in the near-IR portion of the solar spectrum [Nazeeruddin et al., 2000]. These novel trans-complexes render themselves as suitable dyes for dye-sensitized TiO_2 dioxide mesoporous electrodes.

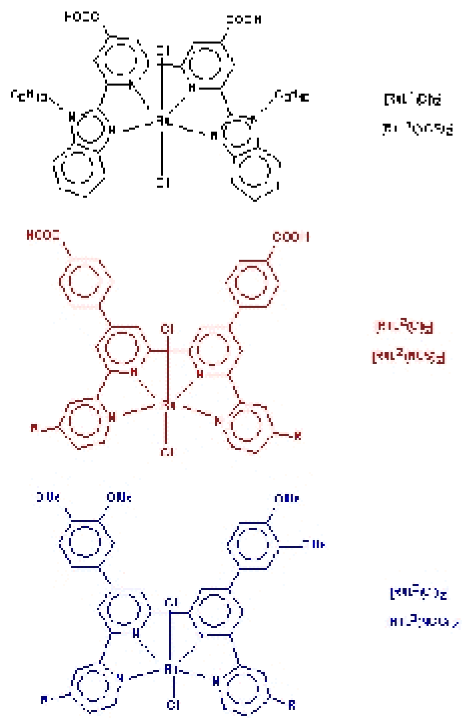

Figure 5: Structure of novel "black" ruthenium sensitizers in trans-arrangement with tetradentate ligands.

The optimal conversion efficiency of tandem PEC cells requires band gaps of 1.4 eV for the dye-sensitized solar cell and 1.8 eV for the photoanode. The spectral onset of this novel ruthenium "black" dye, when used in the dye-sensitized solar cell, corresponds perfectly to 1.4 eV. As mentioned before, the band gap of the current WO_3 photoanode, however, is at 2.6 eV, encouraging the search for alternative materials, such as Fe_2O_3.

At NIMC, dye-sensitized oxide semiconductor powder photocatalysts have been developed for a two-step water splitting system. Steady H_2-evolution from water on Eosin-Y fixed TiO_2 photocatalysts using a silane-coupling reagent has been observed under visible light irradiation [Abe et al., 2000].

- **Subtask B: System Studies**

In 2000, research and development on monolithic devices that combine single-gap or multi-junction photovoltaic (PV) cells with electrolysis systems has been progressing at NREL, HNEI and UNAM in Mexico. R&D on two-stage and dual-bed reactor systems that incorporate O_2- and H_2-evolving photocatalyst suspensions was continued at FSEC.

Multi-junction systems - With monolithic multi-junction PEC devices, the surface areas of the PV cell and the electrolyzer are identical. Tandem-junction $GaAs/GaInP_2$ and triple-junction amorphous silicon PV cells have been integrated with an alkaline (2-M KOH) electrolyzer [Khaselev et al., 2000]. Based on the short-circuit current, solar-to-hydrogen conversion efficiencies of over 16% were demonstrated with the gallium-based monolithic solar system, where as 7.8% was achieved with the low-cost silicon-based system.

While the $GaAs/GaInP_2$ PEC systems were found to be relatively stable in aqueous environments, the a-Si-based multi-junction system suffered from surface oxidation. This was markedly reduced through the use of single- and multi-layer a-Si/a-SiC systems studied at UNAM [Sebastian et al., 2001]. SiC possesses good stability in alkaline, as well as acidic solutions. A solar-to-hydrogen conversion efficiency on the order of 7% has been realized with such PEC cells. The major disadvantage of a-SiC, however, is its large band gap (> 3 eV), but this limitation may be overcome by sensitization of SiC with synthetic dyes, as well as narrow band gap semiconductors.

Dual-bed system - At FSEC, an electrochemical equivalent of perforated tandem dual-bed system using perforated printed circuit board and an interdigitated array of Ni wire has ben designed and implemented.

At NIMC, two-step water splitting systems have been designed using a combination of two narrow band gap semiconductor powders (eg. WO_3-Fe^{2+}-Fe^{3+}, CeO_2-Ce^{4+}, WO_3-Ce^{4+}-Ce^{3+}) and a redox pair in an aqueous solution by mimicking the Z-scheme in photosynthesis.

FUTURE ACTIVITIES

Major materials research accomplishments have occurred during the first two years of Annex 14. Future work will aim at achieving reliable performance of key materials. For tandem PEC devices, tungsten trioxide (WO_3) and hematite (α–Fe_2O_3 iron oxide) remain the most effective photo-anodes in combination with titania-based photo-cathode systems. In terms of monolithic multi-junction devices, amorphous silicon-based designs will be studied further for novel single- and multi-layer PEC systems. However, no materials preference has been identified for aqueous PEC systems (based on suspended photoactive semiconductor powders).

2001 will see the narrowing of materials and system research directions toward the definition of small-scale engineering proof-of-concept demonstration systems.

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TASK 15 - PHOTOBIOLOGICAL HYDROGEN PRODUCTION

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INTRODUCTION

Biological hydrogen production, the production of hydrogen by microorganisms, has been an active field of basic and applied research for over two decades, with significant applied R&D programs supported in Europe, Japan and the United States. Realization of practical processes for photobiological hydrogen production from water using solar energy would result in a major, novel biological source of sustainable and renewable energy, without greenhouse gas emissions or environmental pollution. However, development of such practical processes will require significant scientific and technological advances, and relatively long-term (>10 yr) basic and applied R&D. Photobiological hydrogen production was a component of the prior Task 10 of the IEA Hydrogen Agreement, and has evolved into the independent Task 15. This effort covers research areas and needs at the interface of basic and applied R&D that are of mutual interest to the countries and researchers participating in the IEA Hydrogen Agreement. Task 15 provides for the establishment of collaborative research projects among participating countries in a coordinated program.

TASK DESCRIPTION

Task 15 deals specifically with "biophotolysis", i.e. the biological production of hydrogen from water and sunlight using microalgal photosynthesis. The overall objective of Task 15 is to advance the basic and early-stage applied science in this area. This will allow an evaluation of the potential of such a technology to become a renewable energy source for the 21st Century. The biophotolysis process uses microalgae, either green algae or cyanobacteria, to fix CO_2 into carbohydrates that are used by the algae to generate hydrogen gas, first in the dark by fermentations and then in the light through photosynthesis-coupled reactions. The Task 15 goal is to achieve a light conversion of 3% into hydrogen gas.

The main objective of Task 15 is to develop hydrogen production by microalgae (both green algae and cyanobacteria) emphasizing early-stage applied research on biophotolysis processes with intermediate CO_2 fixation. This research will help to provide the advances required to achieve the practical efficiencies and cost goals of biological hydrogen production. The Task investigates microalgal hydrogen metabolism, both in the dark and in the light, as well as the mechanisms that would allow the photosynthetic processes and hydrogen evolution reactions to achieve their maximum possible efficiencies. In addition, subsidiary metabolic processes require investigation, such as the efficient accumulation of large amounts of carbohydrates, the regulation of the photosynthetic processes and the recycling of the algal cells after hydrogen evolution is completed. Complex underlying genetic mechanisms and biochemical pathways are involved in these physiological processes and require significant research efforts.

The work in Task 15 is divided into four Subtasks: (A) Light-driven Hydrogen Production by Microalgae; (B) Maximizing Photosynthetic Efficiencies; (C) Hydrogen Fermentations; and (D): Improve Photobioreactor Systems for Hydrogen Production.

DURATION

Task 15 began work on 1 July 1999 and is scheduled for a three-year period, with an option for a two-year extension.

PARTICIPATION

Present participants in Task 15 are Canada, Japan, Norway, Sweden, and the United States.

ACTIVITIES AND PROGRESS DURING 2000

(1) Two Experts meetings were held during 2000:

a) March 20-21, at the National Renewable Energy Laboratory (NREL), Colorado, U.S., with 15 participants (including observers from Hungary, Italy and the Netherlands).

b) August 11, at Potsdam, Germany, following the 6th International Conference on the Molecular Biology of Hydrogenases (Hydrogenases 2000; August 5-10, 2000), with 10 participants (including observers from the United Kingdom, Hungary, the Netherlands, Portugal and Italy).

(2) General Progress

a) Annex 15 has been presented and discussed at the following conferences:

(*i*) 10th Canadian Hydrogen Conference (Quebec; May 2000). Poster.

Lindblad, P., Asada, Y., Benemann, J., Hallenbeck, P., Melis, A., Miyake, J., Seibert, M. and Skulberg, O. 2000. IEA Hydrogen Agreement, Task 15: *Photobiological Hydrogen Production* - An International Collaboration. Proceedings 10th Canadian Hydrogen Conference. Pages: 731-733. Editors: Bose, T.K and Benard, P. ISBN 0-9696869-5-1.

(*ii*) 13th World Hydrogen Energy Conference (Beijing; June 2000). Oral Presentation.

Lindblad, P., Asada, Y., Benemann, J., Hallenbeck, P., Melis, A., Miyake, J., Seibert, M. and Skulberg, O. 2000. IEA Hydrogen Agreement, Task 15: *Photobiological Hydrogen Production* - An International Collaboration. Hydrogen Energy Progress XIII. Volume 1: 56-59. Editors: Mao, Z.Q. and Veziroglu, T.N.

(*iii*) 4th Asia-Pacific Conference on Algal Biotechnology (Hongkong; July 2000). Poster.

b) A national Biohydrogen feasibility study (BREEZE; Biological Recycling System of Energy and Organic Substances for Zero-emissions of CO_2) is being conducted in Japan. The following is the outline of report of the fiscal year 2000:

Chapter 1: Hydrogen production by degradation of organic wastes
1-1 by pure culture

1-2 by mixed culture

Chapter 2: Useful product from CO_2 by using hydrogen-utilizing bacteria

- 2-1 Analysis of CO_2-fixation in hydrogen-utilizing bacteria and production of useful materials
- 2-2 Ethylene production from organic wastes and CO_2
- 2-3 CO_2-utilization by using decarboxylasting enzymes
- 2-4 Useful materials from hydrogen and $CO_2$by using newly-isolated bacteria

Chapter 3: Analysis of structure and function of hydrogenase and its application

- 3-1 Structure and function of hydrogenases
- 3-2 Probability of stabilization of hydrogenase
- 3-3 Probable application of hydrogenases

Chapter 4: Construction of "Energy Metabolic Engineering"

- 4-1 Concept of "Energy Metabolic Engineering"
- 4-2 Analysis of hydrogen energy metabolism with genome informatics and construction of utility cassette
- 4-3 Use of electric power for biological reaction
- 4-4 Probable application of sulfur compounds for biological energy source
- 4-5 Chemical industries and CO_2 & energy problems
- 4-6 Environmental assessment of current biological technologies
- 4-7 Technology assessment of Energy Metabolic Engineering

c) Scientific exchange.

Marc Forestier (postdoc in the lab of Mike Seibert; NREL, U.S.) visited and worked in the lab of the Operating Agent (Uppsala University, Sweden) for a week proceeding the Hydrogenases 2000 and the Experts-meetings in Potsdam, Germany. The subject was green algae hydrogenases and, specifically, the identification and characterization of the molecular information needed to synthezise a functional hydrogenase. This scientific exchange was financially supported by the Swedish National Energy Administration.

d) New Members.

Observers from Hungary, Italy, U.K., Portugal and the Netherlands participated in the Experts Meetings with the aim of becoming official members during 2001.

e) BioHydrogen 2002.

An international conference, Biohydrogen 2002, held under the auspices of the IEA Hydrogen Implementing Agreement Annex 15, *Photobiological Hydrogen Production*, and the EU COST 8.41, *Biological and Biochemical Diversity of Hydrogen Metabolism*, has been discussed and planned.

The aims of Biohydrogen 2002 are to summarise the state-of-the-art of biological hydrogen production, evaluate current progress on early-stage applied science in this area of research and development, and to identify promising research directions for the future. Biohydrogen 2002 coincides with the end of the first 3 years of Annex 15 which will be extended for another two years.

Dates: April 21-24, 2002

Location: the Netherlands

A web-address has been established:

http://www.ftns.wau.nl/prock/Research/Rene/Biohydrogen%202002.htm

(3) Progress Related to Subtasks

a) Subtask A: Light-driven Hydrogen Production by Microalgae

Light-driven hydrogen evolution mediated by hydrogenase(s) was discovered in green algae over fifty years ago, and subjected to extensive investigations over the following decades. However, there are still many fundamental and applied issues that must be addressed before this type of reaction can be considered for practical applications.

Novel, sustainable photobiological production of molecular hydrogen upon a reversible inactivation of the oxygen evolution in the green alga *Chlamydomonas reinhardtii* has been demonstrated (Melis, et al, 2000). In this organism, a two-stage hydrogen production method circumvents the severe oxygen sensitivity of the reversible hydrogenase by temporally separating photosynthetic oxygen evolution and carbon accumulation (stage 1) from the consumption of cellular metabolites and concomitant hydrogen production (stage 2). A transition from stage 1 to stage 2 is accomplished by sulfur deprivation of the culture, which reversibly inactivates photosystem II (PSII) and oxygen evolution. Under these conditions, oxidative respiration by the cells in the light depletes oxygen and causes anaerobiosis in the culture, which is necessary and sufficient for the induction of a reversible hydrogenase. Subsequently, sustained cellular hydrogen gas production is observed in the light, but not in the dark. The use of green algae as a source of renewable hydrogen was also reveiewed (Ghirardi et al 2000), including different molecular methods to decrease the oxygen sensitivity of the green algal hydrogenase enzyme.

A heterologous expression of a clostridial hydrogenase has been achieved in the cyanobacterium *Synechococcus* PCC7942 (Asada et al 2000). The *Clostridium pasteurianum* hydrogenase I was expressed in the cyanobacterium Synechococcus PCC7942. The hydrogenase gene was cloned downstream of a strong promoter, previously isolated from *Synechococcus* PCC7942, with a cat gene as a reporter gene. Expression of clostridial hydrogenase was confirmed by Western and Northern blot analyses in both *Synechococcus* and *Escherichia coli*, whereas in vivo/in vitro measurements and activity staining of soluble proteins separated on non-denaturing polyacrylamide gels revealed functional expression of the clostridial hydrogenase in the cyanobacterial cells only.

The present knowledge about cyanobacterial hydrogenases and their potential as photobiological producers of molecular hydrogen has been reviewed (Lindblad and Tamagnini 2000). The diversity of cyanobacterial hydrogenases was examined using a molecular approach (Tamagnini et al 2000). Filamentous strains from a broad range of sources were screened for the presence of *hup* (uptake hydrogenase), *xisC* (recombinase responsible for the rearrangement within *hupL*), and *hox* (bidirectional hydrogenase) genes. As expected, an uptake hydrogenase seems to be present in all nitrogen-fixing cyanobacteria. On the other hand, no evidence was found for the presence of a conventional bidirectional enzyme in several strains. The natural molecular variation of hydrogenases in cyanobacteria is a field to explore, both to understand the physiological functions of the respective enzymes, and to identify a genetic background to be used when constructing a strain for photobiological hydrogen production in a bioreactor.

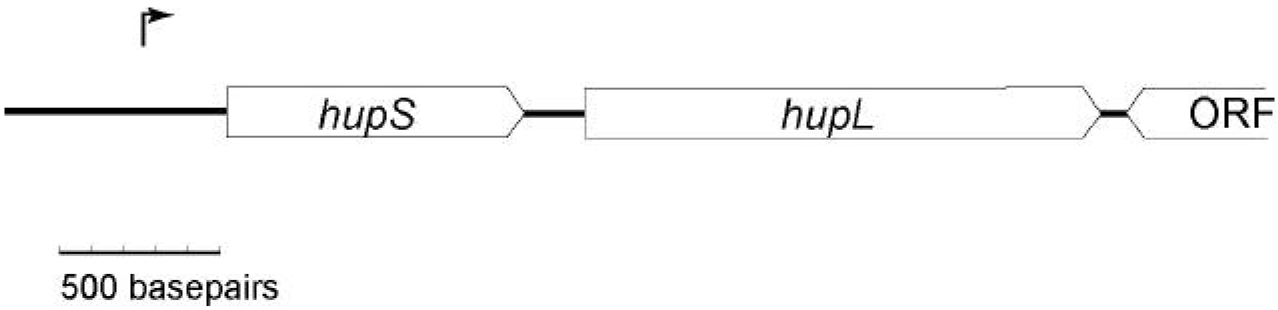


Figure - The genes encoding the uptake hydrogenase in the cyano-bacterium Nostoc PCC 73102. The uptake hydrogenase is a two-subunit enzyme and hupS and hupL encode the small and large subunit, respectively. The arrowheads show the direction of the genes. The ORF (open reading frame) is a putative gene downstream and in the opposite direction of hupL. The smaller arrow indicates the position of the transcription start site (Lindberg et al. 2000).

b) Subtask B: Maximizing Photosynthetic Efficiencies

Photosynthesis can achieve relatively high solar conversion efficiencies, but only at low light intensity. At full sunlight, efficiencies drastically decline. The reason is the large amounts of so-called light-harvesting pigments that capture more photons at full sunlight than the photosynthetic apparatus can actually handle. These excess photons are, thus, wasted, with their energy released as heat or fluorescence, even causing damage to the photosynthetic apparatus. Reducing antenna sizes is a method for increasing photosynthetic efficiencies and is a central R&D need in photobiological hydrogen production.

The dependence on carbon source of the photosynthetic apparatus organization and function in wild type and a Chl *b*-less mutant of the green algae *Chlamydomonas reinhardtii* has been examined (Polle et al 2000).

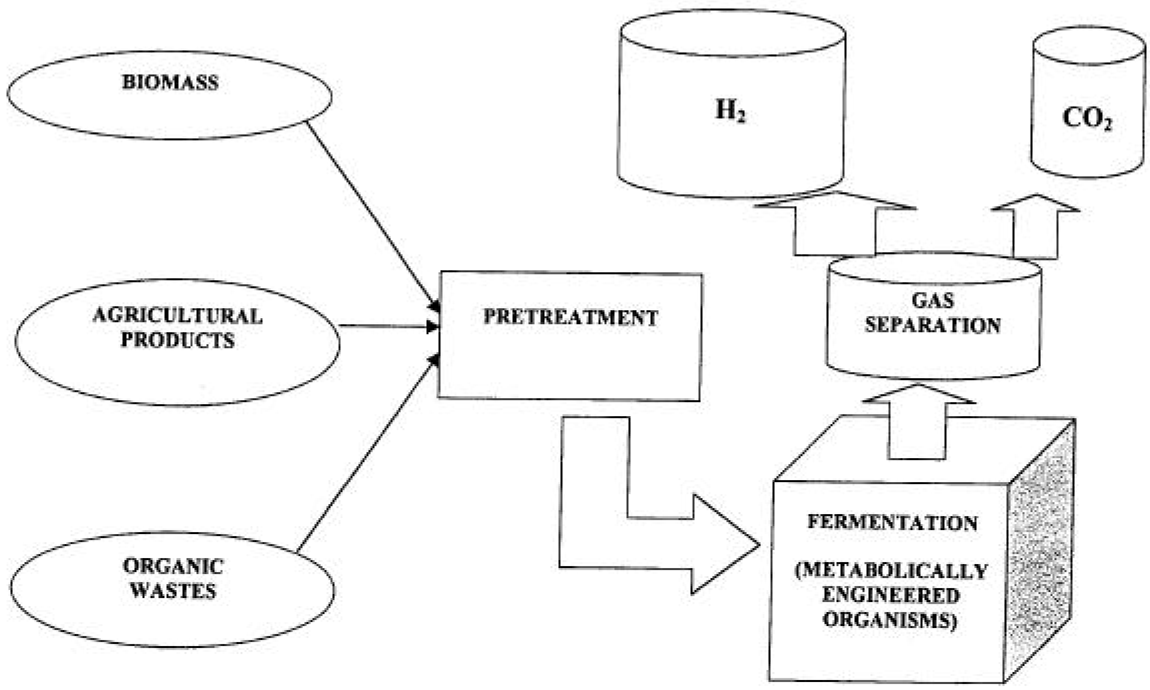
c) Subtask C: Hydrogen Fermentations

After accumulation of carbohydrates and activation of their inducible hydrogenase, a fermentation process is initiated in which storage carbohydrates are converted to hydrogen and a number of fermentation products, including acetate, glycerol, and other excreted substrates. Such fermentations have been reported in both green algae and cyanobacteria, but require further study. At present, typical hydrogen yields from storage carbohydrates in the algae are less than 10%, based on a stoichiometry of 12 H_2/mole glucose.

Although, in theory, the amount of hydrogen that could be generated from renewable sources of energy, such as cellulose (a polymer of glucose), is vast, only 16-24% of the maximum stoichiometric yield of hydrogen from glucose is typically achieved by biological methods. However, an amazing 11.6 mol of H_2 generated per mol of glucose-6-phosphate has been demonstrated using enzymes of the oxidative pentose phosphate cycle coupled to a hydrogenase purified from *Pyrococcus furiosus* (Woodward et al 2000).

Experiments focusing on electron transport processes and fermentative hydrogen production by enteric bacteria are presently being set up in Canada (Hallenbeck, unpublished).

The Netherlands (Observer) introduced their national project, *Biological Hydrogen Production,* with 10 partners and the participation in the EU project, *Hydrogen Production from Biomass, Waste Materials of Energy Crops,* with a total of 7 partners.



d) Subtask D: Improve Photobioreactor Systems for Hydrogen Production

A major objective of applied R&D in photobiological hydrogen production has been the development of suitable photobioreactor systems. Development of such systems will serve as an intermediate step in the scale-up of hydrogen production from the laboratory scale to the commercial sector. A large number of different concepts and designs have been proposed and tested. However, there is a lack of engineering research for practical devices.

During 2000, only limited progress has been made within this Subtask. Photobioreactors with both green algae and cyanobacteria are up and running and initial experiments have been performed examining hydrogen production and evolution, gas transfer coefficients, sunlight interception, solar conversion efficiencies and hydrogen losses. A small-scale photobioreactor has been set up to monitor the competition between wild-type and genetically modified cyanobacteria. Further progress will be made as soon as present observers are active participants.

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INVITED SEMINARS

AAAS Annual Meeting and Science Innovation Exposition. Washington, D.C., Session on Photosynthesis and the Production of Renewable Hydrogen. "Single-organism, two-stage biophotolysis and H_2 production in green algae" by Tasios Melis. February 2000.

American Hydrogen Association, Silicon Valley Chapter, Palo Alto. Featured Speaker. " Photosynthesis and the Production of Renewable Hydrogen" by Tasios Melis. March 2000.

10th Canadian Hydrogen Conference; Quebec City, Canada, "Cyanobacterial hydrogenases and biohydrogen: Present status & future potential" by Peter Lindblad. May 2000.

University of Bonn, Botanical Institute, Germany. "Photosynthesis and the production of hydrogen gas by green algae" by Tasios Melis. May 2000.

Howard Hughes Biology Fellows Program, UC Berkeley. "Hydrogen production in photosynthesis" by Tasios Melis. June 2000.

13th World Hydrogen Energy Conference; Beijing, China. "Cyanobacterial hydrogenases and biohydrogen: Present status & future potential" by Peter Lindblad. June 2000.

13th World Hydrogen Energy Conference; Beijing, China. "IEA Hydrogen Agreement, Task 15: *Photobiological Hydrogen Production* - An International Collaboration" by Peter Lindblad. June 2000.

2000 ASPP Annual Meeting, San Diego, CA. Minisymposium on Algal Physiology. "Two-stage photosynthesis and hydrogen production in green algae" by Tasios Melis. July 2000.

4th Asia-Pacific Algal Biotechnology Conference; Hongkong, China. "Cyanobacterial hydrogenases and biohydrogen: Present status & future potential" by Peter Lindblad. July 2000.

6th International Conference on the Molecular Biology of Hydrogenases; Potsdam, Germany. "Cyanobacterial Hydrogenases" by Peter Lindblad. July 2000.