INTERNATIONAL ENERGY AGENCY AGREEMENT ON THE PRODUCTION AND UTILIZATION OF HYDROGEN

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Introduction

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 baseload (geothermal), seasonal (hydroelectric) and intermittent (PV and wind) renewable resources, and, when combined with emerging decarbonization technologies, can reduce the climate impacts of continued fossil fuel utilization. Hydrogen is truly the flexible energy carrier for our sustainable energy future.

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. As part of this effort, the IEA launched the Production and Utilization of Hydrogen Program, known as the Hydrogen Agreement, in 1977 to advance hydrogen production, storage and end-use technologies and to accelerate hydrogen's acceptance and widespread utilization.

The use of hydrogen as an energy carrier is considered a mid- to long-term goal. This is due to infrastructure barriers, particularly in the storage area. Likewise, safety issues, both real and perceived, are concerns for acceptance of hydrogen by the general population. Finally, hydrogen production from renewables will likely not be cost-competitive with fossil-based production, at least in the near-term. Thus, the Hydrogen Agreement is focused on pursuing technologies that will help overcome some of the infrastructure barriers and/or result in the reduced cost of hydrogen systems.

- On-board storage in vehicles is one of the major barriers to the acceptance of hydrogen powered vehicles. Metal hydrides and similar storage medium, like carbon, are thought to have the greatest potential for the safe, on-board storage of hydrogen. However, work-to-date has not proven cost effective due to the inability of current hydride technology to meet the hydrogen storage percentages required for maintaining vehicle weights within a reasonable range.

- To achieve the advantages of a "hydrogen future," namely a reduction in carbon emissions, hydrogen must be able to be cost-effectively produced from renewables. Thus, the Hydrogen Agreement has been pursuing R&D in the solar production area, both biological and electrochemical. The electrochemical approach is, of course, hindered by the fact that photovoltaic technology is not yet cost-effective. Thus, it cannot compete with existing technology, except possibly in small niche markets. Much must still be learned about photobiological processes before we are able to understand the economic potential of this production technology.

- Achieving the vast potential benefits of a hydrogen system requires careful integration of production, storage and end-use components with minimized cost and maximized efficiency, and a strong understanding of environmental impacts and opportunities. System models combined with detailed life cycle assessments provide the platform for standardized comparisons of energy systems for specific applications. Individual component models form the framework by which these system designs can be formulated and evaluated.

- The use of hydrogen in the metals, chemicals, glass, food, electronics, fertilizer, petroleum and space industries is well established. The range of uses has been increasing as has the consumption by specific application. Historically, hydrogen has had an excellent safety record. The many studies, R&D efforts, and experience base have contributed to the publication of regulations, standards, industrial data sheets and technical reports. Hydrogen safety is an issue of every aspect from production to utilization and continues to be of the utmost importance; not only to those researching, designing and working with it; but to the general public, local authorities, insurance agents, etc., as well.

Technology Activities

Integrated Systems

Through the IEA Integrated Systems activities, twenty-four component models were developed to model hydrogen production, storage, distribution and utilization (see Table 1). Guidelines for a standardized modeling platform were defined to ensure that the component models could be linked to simulate fully integrated systems. Using the component models, two integrated systems were evaluated for grid-independent remote village applications: PV-electrolysis-metal hydride-PEM fuel cell system and wind-electrolysis-compressed gas-internal combustion engine generator set. Using resource data for the region and a demand profile for a similar-sized village, the system components were designed to provide constant power to the villagers. For the location used in this study, the PV system required about 1/6th of the storage of the wind system, even though the PV resource exhibited significant seasonal variation compared to the wind resource. Similarly, a comparative study of hydrogen storage technologies for a remote renewable energy system examined relative costs of compressed hydrogen gas, low-temperature metal hydride and high temperature metal hydride storage systems for a grid-independent system supporting a village of 100 homes in Central America. The analysis showed that, while the compressed gas storage system had the lowest capital cost, the low-temperature metal hydride system was the easiest to operate and maintain, and was therefore the overall lowest cost system. [1-8]

Table 1. Component Models Developed for Production, Storage, Distribution and Utilization

Technology	Team Lead
Production	
PV-Electrolysis	Spain
Wind-Electrolysis	USA
Grid-Electrolysis	USA
Steam Methane Reforming	USA
Biomass Gasification	USA
Biomass Pyrolysis	USA
Coal Gasification	Netherlands
Storage	
Low/High Pressure Gas	Canada
Metal Hydrides	USA
Liquefaction	Japan
Chemical Storage	Netherlands
Chemical Hydrides	Switzerland
Distribution	
Transport Tanker	Japan
High Pressure Pipeline	USA
Low Pressure Pipeline	USA
Tank Truck	Japan
Methanol Transport	Netherlands
Utilization	
PEM Fuel Cell	Canada
Phosphoric Acid Fuel Cell	Spain
Solid Oxide Fuel Cell	USA
Molten Carbonate Fuel Cell	USA
Gas Turbine	USA
Internal Combustion Engine	USA
Refueling Station	USA

In support of the Integrated Systems activities, fourteen international hydrogen demonstration projects were critically evaluated and compared, with system performance measurement as the central focus. Safety and regulatory issues were also considered. Representatives of these demonstration projects provided technical data and participated in the review workshops. Additionally, the international participants were able to visit a number of the demonstration sites to see the facilities and meet with the project engineers. The list of the projects that were reviewed is shown in Table 2.

Table 2. Hydrogen Demonstration Projects

Project	**Lead**
Solar H_2 Production Facility	Electrolyser
Demonstration Plant for H_2 Production and Use in Fuel Cell	ATEL
Solar H_2 Pilot Plant with 3 Storage Systems	INTA
Stand Alone PV-H_2 Small Scale Power System (SAPHYS)	ENEA
Alkaline Bipolar Electrolyser	ENEA
Off Peak Storage System	Kogakuin University
CO_2 Fixation and Utilization in Catalytic Hydrogenation Reactor	RITE
H_2 Vehicle	Mazda
H_2 Rotary Engine Cogeneration System	Mazda
H_2 Production Utilizing Solar Energy	Kansai Electric Power Co., Mitzubishi
Development of Solar H_2 Processes	Helsinki University of Technology
Solar H_2 Fueled Truck Fleet and Refueling Station	Clean Air Now, Xerox
Genesis Ten Passenger PEMFC Vehicle	Energy Partners
Schatz Solar H_2 Project	Humboldt State University
City of Palm Desert Renewable H_2 Transportation	Humboldt State University

Photoproduction of Hydrogen

As part of the IEA activities, the concept of using solar energy to drive the conversion of water into hydrogen and oxygen has been examined from the standpoints of potential and ideal efficiencies, measurement of solar hydrogen production efficiencies, surveys of the state-of-the-art, and technological assessments of various solar hydrogen options. The analysis demonstrated that the ideal limit of the conversion efficiency for 1 sun irradiance is ~31% for a single photosystem scheme and ~42% for a dual photosystem scheme. However, practical considerations indicate that real efficiencies will not likely exceed ~10% and ~16% for single and dual photosystem schemes, respectively. Four types of solar photochemical hydrogen systems were identified: photochemical systems, semiconductor systems, photobiological systems and hybrid and other systems. A survey of the state-of-the-art of these four types was performed and each system (and their respective subsystems) was examined as to efficiency, potential for improvement and long-term functionality. The following four solar hydrogen systems were identified as showing sufficient promise for further research and development: [10]

- Photovoltaic cells plus an electrolyzer
- Photoelectrochemical cells with one or more semiconductor electrodes
- Photobiological systems
- Photodegradation systems

Most photobiological systems use bacteria and green algae to produce hydrogen. These systems hold great promise for long term sustainable hydrogen production, but face two major barriers for meeting the cost limitations. These barriers are the fairly low solar conversion efficiencies of these systems of around 5-6%, and the fact that nearly all enzymes that evolve hydrogen from water are inhibited in their hydrogen production by the presence of oxygen. Research efforts are focusing on overcoming this oxygen intolerance by developing strains of the green algae, Chlamydomonas, which contain oxygen-evolving enzymes, and thus can produce oxygen and hydrogen simultaneously. Genetic alterations of Chlamydomonas are being investigated in attempts to improve the solar conversion efficiencies. These new genetic forms are predicted to reach efficiencies on the order of 10%.

Photoelectrochemical production uses semiconductor technology in a one-step process of splitting water directly upon sunlight illumination by combining a photovoltaic cell and electrolysis into a single device. Research efforts are being focused on identifying structures and materials that will meet the high voltage requirements to dissociate water, not be susceptible to the corrosiveness of the aqueous electrolytes used in the electrolytic process, and are cost-effective. Amorphous silicon devices are one of the types most favored, due to their lower cost. These photovoltaic devices have achieved efficiencies of 7-8%. Photovoltaic devices using more expensive materials, have demonstrated efficiencies of 12.4%. [9] Researchers are now working to combine the low cost materials and high conversion efficiency materials to achieve a practical application of this promising technology.

Metal Hydrides and Carbon for Hydrogen Storage

The use of hydrogen as a vehicle fuel requires a storage means that has inherent safety and both volumetric and gravimetric efficiency. Metal hydrides offer alternatives to the storage of hydrogen in gaseous and liquid form. They store hydrogen in an essentially solid form and offer the potential for volume efficiency, high safety, low pressure containment and ambient temperature operation. Unfortunately, most known hydrides are either heavy in comparison to the hydrogen they carry or require high temperature for hydrogen release. In the past few years, carbon adsorbent materials have also gained attention as a possible, cost-effective storage medium for hydrogen. Whereas carbon was once considered only as a cryoadsorbent for hydrogen, there is growing belief it can be used at ambient temperature. However, much must still be learned about consistent and high-purity production of these materials and the nature and potential for hydrogen storage. [11]

Work has been progressing to develop a variety of hydride and carbon materials for on-board storage, working towards both improved gravimetric capacity (5 weight %) and lower temperature

(100-150°C) release of hydrogen. Building on the advances reported by the Max Planck Institute, Germany, [12] several international collaborations have been established to further develop the catalyzed sodium aluminum hydrides for hydrogen storage. The joint efforts of the experts has led to the identification of a material capable of 5 weight percent reversible hydrogen storage at 150°C, the necessary target for economic on-board hydrogen storage for vehicles. [11] The experts are now working to meet the new target of 5 weight percent at 100°C.

Research and Development Needs/Future Activities

Many advances were made in the longer-term photoproduction area. This includes identification of a semi-conductor-based hydrogen production system capable of 12.4% solar efficiencies and the construction of a process development scale bioreactor. However, this work is still at the early development stage. A variety of materials and organisms remain under investigation. System design is also an area that still requires a great deal of effort.

Hydrogen use in non-energy processes, such as the chemical, metallurgical, and ceramics industries was also identified as an area where a concentrated research effort could facilitate the increased utilization of hydrogen. Annually, these industries account for nearly 50 percent of the world's 500 billion Nm^3 hydrogen consumption. Process improvements and novel synthesis approaches could lead to overall efficiency improvements and reduced environmental impacts. Likewise, increased market share for hydrogen in these arenas should lead to expedited infrastructure development, a necessity for facilitating the advancement of the energy-related and renewable-based applications.

Approximately 95% of the hydrogen produced today comes from carbon containing raw material, primarily fossil in origin. The conventional processes convert the carbon to carbon dioxide, the majority of which is discharged to the atmosphere. The growing awareness of the impact of greenhouse gas emissions on global climate change has necessitated a reassessment of the conventional approach. Integrating carbon dioxide sequestration with conventional steam reforming will go a long way towards achieving "clean" hydrogen production. Likewise, improving the robustness of pyrolytic cracking technologies for the conversion of hydrocarbons to hydrogen and pure carbon should not only improve the process economics, but also its applicability to a variety of feeds. Finally, the thermal processing of biomass can yield an economic and carbon neutral source of hydrogen.

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. Hydrogen in the new millennium is synonymous with energy supply and security, climate stewardship, and sustainability.

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