Proceedings of the 2001 DOE Hydrogen Program Review
NREL/CP-570-30535

INTERNATIONAL ENERGY AGENCY AGREEMENT ON THE PRODUCTION AND UTILIZATION OF HYDROGEN

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Abstract

Although hydrogen systems are recognized as viable, sustainable options for meeting the world's energy requirements, technical and economical barriers must first be overcome before worldwide use of hydrogen is realized. Hydrogen is relevant to all of the energy sectors - transportation, buildings, utilities and industry. It 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. Yet advances must be made in hydrogen production, storage, transport and utilization technologies and in the integration of these components into complete energy systems for hydrogen to become a competitive energy carrier. To expedite the advancement of hydrogen technologies, nations have come together under the auspices of the International Energy Agency's (IEA) Hydrogen Program to collaborate and address the important barriers that impede hydrogen's penetration into the world energy market. Through well-structured, collaborative projects, experts from around the world address many of the technical challenges and long-term research needs that face the hydrogen community. These collaborations have already led to significant advances in renewable hydrogen production and solid storage materials and to the development of tools to evaluate and optimize integrated hydrogen energy systems.

Introduction

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. Currently, Canada, the European Commission, Japan, Lithuania, the Netherlands, Norway, Spain, Sweden, Switzerland, the United States are all active participants in the IEA Hydrogen Agreement.

The IEA Hydrogen Agreement

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. The following have been established as the guiding principles on which the IEA Hydrogen Program 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 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 energy, wind energy, hydropower, 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.

- Hydrogen can be used as a fuel for a wide variety of end-use applications including important uses in the transportation and utility sectors.

- 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 which will lead to broader application in the future.

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.

Technology Activities

The use of hydrogen as an energy carrier is considered a mid- to long-term goal. Hydrogen production from renewables will likely not be cost-competitive with fossil-based production, at least in the near-term. Likewise, infrastructure barriers, particularly in the storage area, hinder near-term application of hydrogen for transportation applications. Additionally, safety issues, both real and perceived, are concerns for acceptance of hydrogen by the general population. 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.

- 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. Much must still be learned about photobiological processes before we are able to understand the economic potential of this production technology. 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.

- On-board storage in vehicles is one of the major barriers to the acceptance of hydrogen powered vehicles. Metal hydrides and similar storage medium, such as 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 technology to meet the hydrogen storage percentages required for maintaining vehicle weights within a reasonable range.

- 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.

- 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 Hydrogen Agreement has developed a broad portfolio of collaborative research activities to address the aforementioned challenges for hydrogen penetration into the world energy marketplace.

Renewable Hydrogen Production

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 design and material considerations will likely limit conversion efficiencies to less than 16%. Four types of solar photochemical hydrogen systems were identified: photochemical, semiconductor, photobiological and hybrid 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 [1]. Based on this study, four systems were selected for collaborative research and development projects:

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

Photoelectrochemical production uses semiconductor technology in a one-step process of splitting water directly upon sunlight illumination by combining a photovoltaic-type cell and electrolysis into a single device. Research efforts are being focused on identifying structures and materials that will meet the high electron voltage (eV) requirements (the optimal absorption threshold for a single photoconverter is at 1.6 eV) 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 for such systems, due to their lower cost. These photovoltaic devices have achieved efficiencies of 7-8%. Photovoltaic devices using more expensive materials, have demonstrated efficiencies of over 16% [2]. Researchers are now working to combine the low cost materials and high conversion efficiency materials to achieve a practical application of this promising technology.

An alternative approach to common photovoltaics is to use a tandem device that achieves the direct cleavage of water into hydrogen and oxygen [3]. Such a device is based on the in-series connection of two photosystems. A thin film of nanocrystalline tungsten trioxide (WO_3) absorbs the blue portion of the solar spectrum. The valence band holes (h+) created by band gap excitation of the WO_3 serve to oxidize water to oxygen, while the conduction band electrons are fed into the second photosystem that consists of dye sensitized nanocrystalline TiO_2 film. The latter is placed directly behind the WO_3 film capturing the green and red portion of the solar spectrum that is transmitted through the top electrode. The photovoltage generated by the second photosystem enables the generation of hydrogen by the conduction band electrons. The overall reaction corresponds to the splitting of water by visible light. 5% overall AM-1.5 solar light to chemical conversion efficiencies have been achieved with this device.

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. To improve solar conversion efficiencies, methods for reducing light-harvesting pigments and antenna length are being developed. In the case of the water-splitting organisms, research efforts are focusing on overcoming oxygen intolerance by developing strains of the green algae, *Chlamydomonas*, which contain oxygen-uptake enzymes, and thus can produce oxygen and hydrogen simultaneously. 5-10% efficiencies have already been achieved with certain strains of the genetically modified water-splitting microorganisms. In the case of fermentative organisms, 60% conversion rates of biomass (acetic acid) to hydrogen, with 2.7% of the light energy absorbed stored as hydrogen, have been reported.

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 evidence that it can store significant quantities of hydrogen 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 [4].

Sixteen metal hydride and four carbon projects were undertaken by the international experts to develop materials with improved gravimetric capacity (5 weight %) and lower temperature (100-150^{o}C) release of hydrogen. Building on the developments from the Max Planck Institute für Kohlenforschung, Germany [5], the international experts undertook several projects to look at catalyzed sodium aluminum hydrides. Through their efforts, a formulation was found that is capable of 5 weight percent reversible hydrogen storage at 120^{o}C. In addition to this significant accomplishment, a great deal of knowledge has been gained on the effects of material formulations and treatments on hydrogen storage capability [6].

To build on the progress made by the completed metal hydride and carbon projects, twenty-two new projects have already been launched. These projects include fundamental investigations of new material formulations, mechanisms of chemical and physical hydrogen storage, and engineering considerations for practical on-board storage. Chemical hydrides will also be added to the array of materials being investigated.

Integrated Systems

Through the IEA Integrated Systems activities, twenty-seven component models have been developed to model hydrogen production, storage, distribution and utilization [7]. Guidelines for a standardized modeling platform have been defined to ensure that the component models can be linked to simulate fully integrated systems [8]. Using the component models, a number of integrated hydrogen energy systems were designed and evaluated [9-16]. Additionally, ten international hydrogen demonstration projects were critically evaluated and compared with regard to system design and performance and safety and regulatory issues [17].

Using the information, tools and methodologies that have been developed, experts are currently evaluating three potential demonstration projects. The first is a “greenfield” community that would be based in the Netherlands where there is an ambitious national plan to require 3% renewables in the power generation mix for new residential districts. Technologies under consideration include PEM and solid oxide fuel cells, heat pumps, and combined heat and power. The second system being evaluated is a hydrogen refueling station for a remote island community in Norway. For this case, a wind park will provide power for the community and for an electrolysis system to produce hydrogen for a public transportation system. The third case being evaluated is a transportation system. Under consideration are refueling alternatives (gaseous vs. liquid, delivery vs. on-site production), vehicle configuration, drive cycle implications, and cost variations (natural gas vs. electricity). Life cycle impacts and system cost will be key components for evaluating all three cases and their possible configurations.

Research and Development Needs/Future Activities

Many advances were made in the longer-term photoproduction area. 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 requires a great deal of effort.

Hydrogen use in non-energy processes, such as the chemical, metallurgical, and ceramics industries was 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.

Hydrogen energy system demonstrations continue to be undertaken throughout the world. The experiences gained from these projects need to be compiled and made available to future demonstrators. Public response must be captured and considered when planning any hydrogen demonstration. System efficiency and cost optimization will also remain paramount issues for developing competitive hydrogen-based systems. Thus, utilizing all available information and international expertise and continually refining and expanding modeling tools will be imperative.

Conclusions

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. The IEA Hydrogen Program has a vision for a hydrogen future that is one of clean sustainable energy supply of global proportions that plays a key role in all sectors of the economy. This vision will be implemented through 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.

Acknowledgments

None of the technical progress made in our IEA activities would be possible without the leadership and technical expertise of the Operating Agents (Task Leaders) and the efforts of the international experts and their research teams. The authors would also like to acknowledge the Executive Committee members of the IEA Hydrogen Program: Mr. Neil Rossmeissl, Chair, U.S. Department of Energy; Mr. Nick Beck, Natural Resources Canada; Dr. Giampiero Tartaglia, Joint Research Council, for the European Commission; Mr. Toshiaki Abe, NEDO, Japan; Dr. Jurgis Vilemas, Lithuanian Energy Institute; Dr. Antoon Kipperman, NOVEM, the Netherlands; Mr. Trygve Riss, Research Council of Norway; Dr. Antonio Garcia-Conde, INTA, Spain; Mrs. Karin von Kronhelm, Swedish National Energy Administration; and Dr. Gerhard Schriber, Swiss Federal Office of Energy.

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