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HYDROGEN IMPLEMENTING AGREEMENT
TASK 11: INTEGRATED SYSTEMS

Final report of Subtask A:
Case Studies of
Integrated Hydrogen Energy Systems

Executive Summary

T. Schucan
Paul Scherrer Institute
Switzerland

International Energy Agency Hydrogen Implementing Agreement
Final Report for Task 11 - Integrated Systems

Executive Summary

Hydrogen plays a significant role in the world's energy economy, but this role is almost exclusively as a chemical - hydrogen is rarely used as a fuel. The use of hydrogen as a fuel in the utility and transportation sectors faces hurdles that need to be overcome in order to transition to a hydrogen energy economy.

The existing hydrogen industry has resulted in a significant database of experience and knowledge about hydrogen, primarily as a chemical feedstock, but more recently as an alternative fuel:

- $ Natural gas, oil and coal are the most common fossil fuels used in large-scale hydrogen production processes, with approximately 400-500 billion Nm^3 of hydrogen produced yearly for use in the petroleum, food, and chemicals industries.
- $ Compressed hydrogen is transported safely in dedicated pipelines in Europe and North America, and in liquid tanker trucks over highways throughout the world.
- $ NASA uses hydrogen as a launch fuel and to power orbiting manned spacecraft.
- $ Fuel cells are used commercially to generate power and have recently found their way into transit buses in several cities around the world.

With this experience and knowledge base, it is logical to expect that an accelerated demonstration program could provide the needed stimulus to bridge the gap from hydrogen as an industrial chemical to hydrogen as an energy carrier for the transportation and utility sectors. However, technical issues, market forces and societal concerns continue to suppress this transition.

A structured approach was developed to minimize the perceived and real risks associated with the introduction of hydrogen as an energy carrier. Within the framework of the International Energy Agency Hydrogen Implementing Agreement, Task 11 was undertaken to develop tools to assist in the design and evaluation of existing and potential hydrogen demonstration projects. Emphasis was placed on integrated systems, from input energy to hydrogen end use. The activities were focused on near- and mid-term applications, with consideration of the transition from fossil-based systems to sustainable hydrogen energy systems. The participating countries were Canada, Italy, Japan, the Netherlands, Spain, Switzerland and the United States.

In order for hydrogen to become a competitive energy carrier, experience and operating data need to be generated and collected through demonstration projects. A framework of scientific principles, technical expertise, and analytical evaluation and assessment needed to be developed to aid in the design and optimization of hydrogen demonstration projects to promote implementation. The task participants undertook research within the framework of three highly coordinated subtasks that focused on the collection and critical evaluation of data from existing demonstration projects around the world, the development and testing of computer models of hydrogen components and integrated systems, and the evaluation and comparison of hydrogen systems.

Subtask A: Case Studies

Hydrogen energy systems were critically evaluated and compared, with system performance measurement as the central focus. Project descriptions of existing hydrogen demonstration projects were collected and assembled including the project goals, a description of the main components, a representative set of experimental results, and discussion of lessons learned.

The projects described in the Subtask A report were selected according to the following criteria:

- The projects were required to be integrated systems, with two or more of subsystems (production, storage, transport/distribution and end use) included in a relevant connection.

- The selection was primarily restricted to projects located in one of the countries participating in the IEA Hydrogen Implementing Agreement (to ensure access to data and other relevant information).
- Active cooperation of the project leaders was required.

A comparative overview of the selected integrated systems indicated that the sun is the primary source of energy for many of the hydrogen demonstration projects. Accordingly, the operation of electrolysers with intermittent sources of power (solar and wind) and the various possibilities for matching photovoltaic current with the characteristics of the electrolyser was one of the recurrent design issues in all such projects. Most of the electrolysers were of the alkaline type and operated at low pressure. Two projects used solid polymer electrolysers, and three projects operated the electroyser at higher pressures. While the storage technologies were restricted to the use of compressed gas and metal hydrides, a great variety of utilisation technologies and applications were included. In most of the projects, hydrogen is used in a fuel cell, with a wide variety of fuel cell types included. Transportation applications included two projects in which vehicles were fitted with polymer exchange fuel cells, and one in which trucks were fuelled with compressed hydrogen generated from a PV-electrolysis system, fed to a modified internal combustion engines.

Ten projects were analysed and evaluated in detail. As appropriate, each project report includes sections on project goals, a general description of the project, descriptions of the components, simulation and system integration, performance and operational experience, data acquisition, a discussion of public acceptance and safety issues, environmental aspects, future plans, and conclusions. The detailed project descriptions included in the Subtask A report are:

Project Title	**Project Partners**
Solar Hydrogen Demonstration Project	Solar-Wasserstoff-Bayern, Bayernwerk, BMW, Linde, Siemens (Germany)
Solar Hydrogen Plant on Residential House	M. Friedli (Switzerland)
A.T. Stuart Renewable Energy Test Site	Stuart Energy Systems (Canada)
PHOEBUS Jülich Demonstration Plant	Research Centre Jülich (FZJ) (Germany)
Schatz Solar Hydrogen Project	Schatz Energy Research Centre, Humboldt State University (USA)
INTA Solar Hydrogen Facility	INTA (Spain)
Solar Hydrogen Fueled Trucks	Clean Air Now, Xerox (USA); Electrolyser (Canada)
SAPHYS: Stand-Alone Small Size Photovoltaic Hydrogen Energy System	ENEA (Italy); IET (Norway); FZJ (Germany)
Hydrogen Generation from Stand-Alone Wind-Powered Electrolysis Systems	RAL (United Kingdom); ENEA (Italy); DLR (Germany)
Palm Desert Renewable Hydrogen Transportation Project	Schatz Energy Research Centre, City of Palm Desert (USA)

Subtask B: Analysis Tools

As part of the effort to design and optimize hydrogen energy systems, computer models were developed and validated for hydrogen production, storage, transport/distribution, and end use components. The modeling platform selected for Task 11 was the process simulation package ASPEN Plus™. The models are available to interested users and the Task 11 experts can assist in the use of the models and in the interpretation of results.

The component models developed were:

- Production (8 component models)
- Storage (5)
- Transport/Distribution (5)
- End Use/Refueling (9)

The component models available are:

Technology	Team Lead	Technology	Team Lead
Production		**Transport/Distribution**	
PV-Electrolysis	Spain	Transport Tanker	Japan
Wind-Electrolysis	USA	High Pressure Pipeline	USA
Grid-Electrolysis	USA	Low Pressure Pipeline	USA
Steam Methane Reforming	USA	Tank Truck	Japan
Biomass Gasification (2)	USA	Methanol Transport	Netherlands
Biomass Pyrolysis	USA	**End Use/Refueling**	
Coal Gasification	Netherlands	PEM Fuel Cell	Canada
Storage		Phosphoric Acid Fuel Cell	Spain
Low/High Pressure Gas	Canada	Solid Oxide Fuel Cell	USA
Metal Hydrides	USA	Molten Carbonate Fuel Cell	USA
Liquefaction	Japan	Gas Turbine	USA
Chemical Storage	Netherlands	Internal Combustion Engine	USA
Chemical Hydrides	Switzerland	Refueling Station (3)	USA

Standardization of the component models was essential, since individual component models were to be used in combination with other component models to form integrated hydrogen energy systems. Documentation for each component model was developed to provide important information on the model series, flow sheet number, authors, date created, ASPEN Plus™ version, and a technical abstract of the model. (Major changes were made in the new release of ASPEN Plus™, rendering many of the original models virtually unuseable by most potential users. In order to permit use of the component models in the new version, all component models were converted to ASPEN Plus™ Version 10.1, although this version was released after the end date of Task 11).

The documentation also provides a detailed summary of the model including both a description and its implementation. In the description section, the flow sheet is described along with system inputs and outputs. The physical property set selected, along with descriptions of important design specifications and Fortran blocks, are provided in the implementation section. Each component model report concludes with a listing of the input and output streams (material, work and heat).

Subtask C: Design Evaluation and System Comparison Guidelines

Guidelines for the evaluation and comparison of system designs were developed to aid in the optimization and selection of hydrogen systems. A design methodology was instituted to ensure unambiguous and optimal use of these guidelines. For this purpose, five design steps were defined. The guidelines consist of information that has been collected and formatted according to the data structure defined by the design methodology, and include indications for the use of data in the subsequent design steps. Systems can be compared to each other and to non-hydrogen systems and/or conventional systems using the measures of performance.

Distinguishing five different steps in the design of hydrogen energy systems is useful. These steps are:

- *Generation of process routes:* In the first step, the possible process routes or 'energy chains' that can fulfil the function that has been defined for the energy chain are generated;
- *Preselection of process routes:* The second step consists of selecting those process routes that seem most attractive, with the objective of reducing the number of systems that are to be studied in more detail;
- *Process integration:* This setup includes modeling an integrated system for the selected process routes, making use of or making available, respectively, the output streams (heat, work, mass) and the required input streams;
- *Determination of the measures of performance (MOP)*: In this step, predefined system characteristics (MOP) are calculated and used to compare different integrated systems. These characteristics are indicated as the measures of performance of the system;
- *System selection*: In the final step, a system is selected, for example, by comparing different systems that have been selected in the first phase or by comparing an integrated hydrogen system to conventional energy systems.

Using the guidelines, the experience acquired in existing and future integrated systems is made accessible for use in designing integrated systems. Guidelines for the design and optimization of future demonstration projects were based on data collection, demonstration case studies, component simulation, and integrated systems modeling. The guidelines have been formulated using the experience of the experts participating in Task 11, experiences from existing demonstration projects and other experiences of the participating experts.

The guidelines assist in making choices for the system configuration of future demonstration plants that meet operating and user requirements. Ultimately, the guidelines will facilitate the systematic integration of hydrogen into the world's energy system.

Integrated System Design and Optimization

In order to demonstrate the use of the tools developed in Task 11, several integrated hydrogen energy systems were designed and analyzed. The systems were designed following the guidelines established in Subtask C, and were modeled using the component models developed in Subtask B (using the data collected in Subtask A).

Four biomass-to-hydrogen thermal processing routes, in combination with gaseous and liquid hydrogen transport and storage, were examined to determine the most efficient method of decentralized renewable-based hydrogen production for a vehicle refueling operation. The tool was used to reduce the number of options to a manageable number, and simulations were conducted. Based on the results, it appears that gasification and pyrolysis production processes are essentially equivalent on an efficiency basis, although purity and storage issues can have a large effect on the overall efficiency (and cost-effectiveness) of the processes.

Intermittent renewable resources such as photovoltaics (PV) and wind were evaluated as elements of stand-alone renewable power systems for remote communities. In two case studies, the electricity produced by the PV or wind farm was first routed to the community to fulfill its power requirements, with any remaining power routed to the electrolysers to produce hydrogen. The hydrogen was then stored as a compressed gas or in metal hydrides. If the resource was insufficient to meet demand, the stored hydrogen was used to produce electricity in a fuel cell or generator set. The results of the case studies showed that intermittent renewables could provide reliable power to a remote community if the hydrogen generation and storage units are properly sized.

Detailed papers on these two studies were presented at the World Hydrogen Energy Conference in Argentina in June, 1998 and can be found in the proceedings.

Conclusions and Future Efforts

Task 11 successfully developed tools for the design and optimization of hydrogen energy systems. The use of these tools was demonstrated in a series of case studies that resulted in a number of important presentations and publications. The models continue to be improved as additional information becomes available.

Optimization efforts for Task 11 focused primarily on maximizing efficiency. In reality, cost is the most important parameter for optimization of commercial systems. In the follow-on activity to Task 11, efforts will be focused on the development of cost models for the individual components.

In addition, the recent increased awareness of the impact of greenhouse gas emissions on global climate change has increased interest in hydrogen technologies and their apparent environmental benefits. Life cycle assessments will also be included in future efforts, based on the tools developed here. The outcome of this new activity will be an enhanced tool that incorporates efficiency, environmental impact, and cost for the optimization of hydrogen energy systems.