Case Studies of Integrated Hydrogen Systems

International Energy Agency Hydrogen Implementing Agreement
Final Report for Subtask A of Task 11 – Integrated Systems

Thomas Schucan,
Paul Scherrer Institute
CH-5232 Villigen PSI Switzerland

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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^{TM}. 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^{TM} version, and a technical abstract of the model. (Major changes were made in the new release of ASPEN Plus^{TM}, 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^{TM} 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.

Chapter 1
SOLAR-WASSERSTOFF-BAYERN HYDROGEN DEMONSTRATION PROJECT AT NEUNBURG VORM WALD, GERMANY

1. PROJECT GOALS

The overriding aim of the Solar-Wasserstoff-Bayern (SWB) hydrogen project is to test, on an industrial demonstration scale, major technologies of the hydrogen cycle utilizing electric power generated without releasing carbon dioxide (in this instance, photovoltaic solar energy). Different technologies were compared and tested in interaction with other plant subsystems. Suppliers of the equipment were invited to collaborate in developing the test programs, with the intention of promoting interest on the part of industry and stimulating research and development efforts, since there is practically no market as yet for hydrogen systems concerned. Foremost among the aims of SWB and its shareholders is the acquisition of know-how for planning, realizing and operating (solar) hydrogen plants, sustained by evolving knowledge of internal system structures and actions (as distinct from pure black box operation). Another objective is to engage in realistic public relations work supported by first-hand information. This project will be terminated at the end of 1999, after successfully meeting the program goals.

2. GENERAL DESCRIPTION OF PROJECT

Major system components were installed on an industrial scale at a demonstration facility located in Neunburg vorm Wald, Germany for a potential future energy supply based on hydrogen generated by utilizing (solar) energy unaccompanied by release of carbon dioxide. Initial technical aspects of the stepwise transition from our present-day energy supply primarily aligned for fossil fuels were considered. Most of the plant subsystems are prototypes of innovative technologies. Among others, the facility includes photovoltaic solar generators, water electrolyzers, catalytic and advanced conventional heating boilers, a catalytically heated absorption-type refrigeration unit, fuel cell plants for stationary and mobile application, an automated liquid hydrogen (LH_2) filling station for test vehicles, and a gaseous hydrogen (GH_2) filling station.

Focal points of the investigations were performance of the plant subsystems and their interaction under practical operating conditions. Analysis of the work yielded a reliable database for updated assessment of the prospects and challenges of solar hydrogen technology.

Founded at the end of 1986, SWB is a joint venture with 70% of the shares held by Bayernwerk AG and 10% each by BMW AG, Linde AG (both through wholly owned subsidiaries) and Siemens AG. One of the original cofounders, Dasa, withdrew in 1994. The capital invested in the SWB project over the full run of 13 years is approximately DM 59 million (US$33 million, at an exchange rate of 1.80 DM/US$) in public funds, and DM 69 million (US$38 million) from SWB shareholders.

SWB has operated the aforementioned demonstration facility to develop an understanding of a possible future solar hydrogen energy supply scheme. The project was organized in two phases. Phase 1 was completed at the end of 1991, and Phase 2 is to be completed at the end of 1999.

3. DESCRIPTION OF COMPONENTS

An impression of the size and layout of the overall facility may be obtained from Picture 1.1. The aerial photograph shows the operating and multi-purpose building and the plant subsystems installed outdoors, including the south-oriented photovoltaic solar fields, $H_2/O_2/N_2$ storage vessels and the liquid hydrogen filling station. The main systems of the overall facility are mapped out in the block flow diagram of Figure 1.1 and discussed in the following subsections.

Picture 1.1: Aerial view of SWB solar hydrogen facility

3.1 Plant subsystems for hydrogen production and storage

- Nine fields of solar generators employing monocrystalline, polycrystalline and amorphous silicon technology with a total rated field capacity of 370 kW_p and efficiencies of 9-13% (crystalline) and 5% (amorphous) measured at standard test conditions, based on module surface area, and includes cable losses.

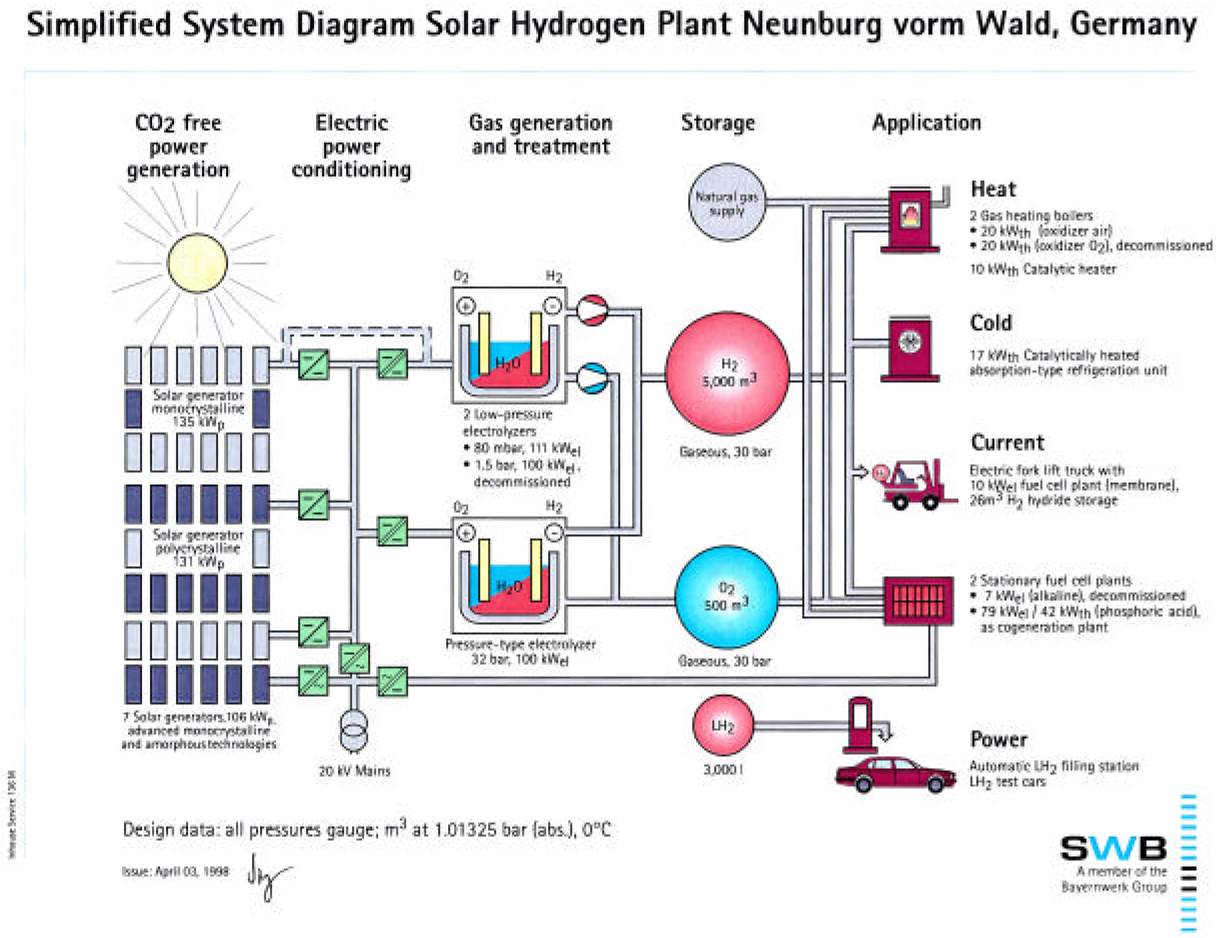


Figure 1.1: Simplified block diagram of SWB solar hydrogen facility

- Electric power conditioning units (DC-DC converters, DC busbar, electrolysis power supplies, converters, AC busbar, DC-AC converters).
- Two advanced low-pressure water electrolyzers employing different technologies, rated at 111 kW_{el} and 100 kW_{el} capacity, with a total maximum hydrogen output of 47 Nm^3/h.
- Alkaline pressure-type electrolyzer, 100 kW_{el}, working pressure 32 bar.

Hydrogen and oxygen gas systems for compression, purification, drying and storage of the electrolytically generated gases (purity 99.9 vol% H_2 and O_2 or better).

3.2 Plant subsystems for hydrogen utilization

- Two gas-fired heating boilers of calorific-value design working with different oxidizers (oxygen and air), capacity of each is 20 kW_{th}, burning natural gas/hydrogen fuel mixture percentages between 5-95 vol%, as well as natural gas alone.

- Catalytic heater of calorific-value design (10 kW_{th} boiler output) fueled with natural gas and mixtures of natural gas/hydrogen (90/10 vol% to 50/50 vol%) with air as oxidizer. This heater is integrated into the on-site building heating system.
- Catalytically heated absorption-type refrigeration unit (rated burner output 32.6 kW_{th}, rated refrigeration capacity 16.6 kW_{th}) with hydrogen as the fuel and air as the oxidizer. This unit supports the conventional chilled water circuit.
- Two fuel cell plants employing different technologies, alkaline type of 6.5 kW_{el}, phosphoric acid type of 79.3 kW_{el} and 42.2 kW_{th} (hydrogen fuel) or 13.3 kW_{th} (natural gas fuel) output.
- Fuel cell plant with proton-exchange membrane operating with air as the oxidizer, rated power output 10 kW_{el}, for mobile application in an electric forklift truck with hydrogen supply from metal hydride storage.
- Automated LH_2 filling station for testing automobile fueling systems, including comparison of two clean-break coupling systems of new design, operation of a cryogenic pump system, and testing of a vehicle fuel tank system without cryovalves.

4. INTEGRATION OF COMPONENTS

In describing integrated hydrogen systems, the emphasis is most often placed on the major components (PV panels, wind turbines, electrolyzers, compressors, fuel cells, etc). In fact, there are a number of essential subsystems, referred to as peripherals or balance-of-plant, that are vital to plant operation. These include utility and auxiliary subsystems (instrument/operating air supplies, nitrogen supply, demineralized water/KOH systems, ventilation, e.g.), process and safety control subsystems, and extensive test data acquisition subsystems. In addition, power conditioning (converters and inverters) play an important role in the operability and efficiency of the overall system. These subsystems are often overlooked in the process design and costing phases of projects. Cost overruns and operational delays can be avoided or reduced by paying proper attention to these important subsystems.

At SWB, particular attention was paid to the integration of the components and to the operability of the facility as an integrated plant, resulting in a well-integrated operating facility. Some of the coupling issues investigated in detail were:

- The electricity produced by the photovoltaic fields was distributed and/or transformed according to downstream needs. Surplus PV electricity was supplied to the grid, while electricity supply from the grid was used in other cases. Direct coupling of solar generators and electrolyzers was also possible.
- Generation, treatment and storage (G/T/S) of hydrogen and oxygen were adjusted to the downstream needs.
- Each of the various end use applications possible in the SWB facilities (i.e., production of heat, cold, or mechanical power) requires its own mixture of hydrogen, natural gas and oxygen and its own combination of G/T/S subsystems.

SWB did not select any optimum integrated system, but tested all possible varieties and many desirable combinations of applications, including different choices of solar generators or electrolyzers.

The process control system was supplied by the Power Generation Group (KWU) of Siemens AG. It consisted of a local control level by a programmable logic controller (PLC) for each subsystem, an open bus-system (Sinec-H1-Highspeed bus, Sinec-L2-Fibre Optical field bus) and a central control and monitoring system (5 computers PC-Pro M5 with operating system REAL 32). Some of its major characteristics are high availability by self-diagnostic, high transmission-safety via message protection, redundant archiving of data, and automatic reprints to guarantee updated documentation.

5. PERFORMANCE AND OPERATIONAL EXPERIENCE

Only a very compressed summary of the wealth of results obtained in test operation to date can be given here. In reviewing these it may be noted that the cumulative operating times logged for the various plant subsystems differ considerably according to the test programs run (i.e., alkaline low-pressure electrolyzer 6000 h, membrane electrolyzer 2000 h, catalytic heater 5200 h, PAFC fuel cell plant 3900 h, LH_2 filling station 900 h).

The first systems in operation were the solar generators at the beginning of 1990. The larger solar generators feed power through maximum power point (MPP)-controlled DC-DC converters to a common DC busbar interconnecting the solar generators, electrolyzers and AC power grid.

In the interests of better investigating the interaction of major plant subsystems, more flexible and accordingly more extensive electric power conditioning was provided than would have been necessary for operation exclusively in parallel with the AC power grid via DC-AC converters. Current feed to the electrolyzers is controlled by electrically isolating electrolysis power supply units. Direct or simulated direct coupling of the electrolyzers to a solar generator can also be made by appropriate electrical connection.

5.1 Solar generators and converters

The solar generators and associated converters installed during Phase 1 (the two major fields with 130 kW_p each) have been in operation for over seven years. Among the problems encountered in the photovoltaics to date were initially undetected damage incurred during installation and premature ageing of surge arresters. Both led to deterioration of insulation, resulting in the need for replacement of some modules and surge arresters. Changes were necessary in the method of measuring insulation level.

The monocrystalline field is operating well, but internal electrical defects have been found in a growing number of polycrystalline modules (30% thus far). This manifests itself in interruption of the series connectors of the cells. Experience with these faults has since led the manufacturer to introduce production improvements.

The defective modules have been dismantled. The number of modules sustaining glass breakage due to tension dating from the time of installation has stabilized. For a time, frequent failure of control cards was observed on the converters due to premature ageing, presumably caused by thermal stress. Energy harvest of the main solar fields is good, verifiably better than the figures reported by some other system operators in Central Europe.

In the winter of 1993/94, six new solar generators were installed. The efficiency of some crystalline technologies fell distinctly short of guarantee figures. In some cases, the necessary repairs or replacements undertaken by the suppliers proved successful. Efficiency of the two fields using amorphous technology met the guarantee levels. The degradation observed to date of 8-10%, depending on the technology, is in line with expectations.

Operation of most of the Phase 2 DC-DC and DC-AC converters also was not immediately satisfactory, which is only partly to be explained by the prototype nature of these units. Subsequent improvements, some of appreciable magnitude, were proved to be necessary.

5.2 Electrolyzers

5.2.1 Low pressure electrolyzers

The two low-pressure electrolyzers, installed in Phase 1, are advanced technology systems (zero gap geometry, absence of asbestos diaphragms, activated electrodes, increased current density) and exhibit significantly lower specific energy consumption than conventional designs (4.5 kWh/m^3 H_2 at rated current).

Problems occurring with the alkaline electrolyzer, notably inadequate purity of the product gases, were eliminated in August 1992 by installing polysulphone diaphragms reinforced on the cathode side to replace the previous plain type. Test results gathered over several years indicate that the alkaline low-pressure electrolyzer is working well. Test programs have largely been completed. Further work with this equipment will primarily add to experience with long-term operation. Cyclic recording of basic values (characteristics) is being made.

The membrane electrolyzer had to be shut down in June 1995 because of increasingly deficient product gas purities (above all, H_2 in product O_2). Up to the time it was decommissioned, the membrane unit also worked well even under conditions of greatly varying power input when directly coupled to a solar generator.

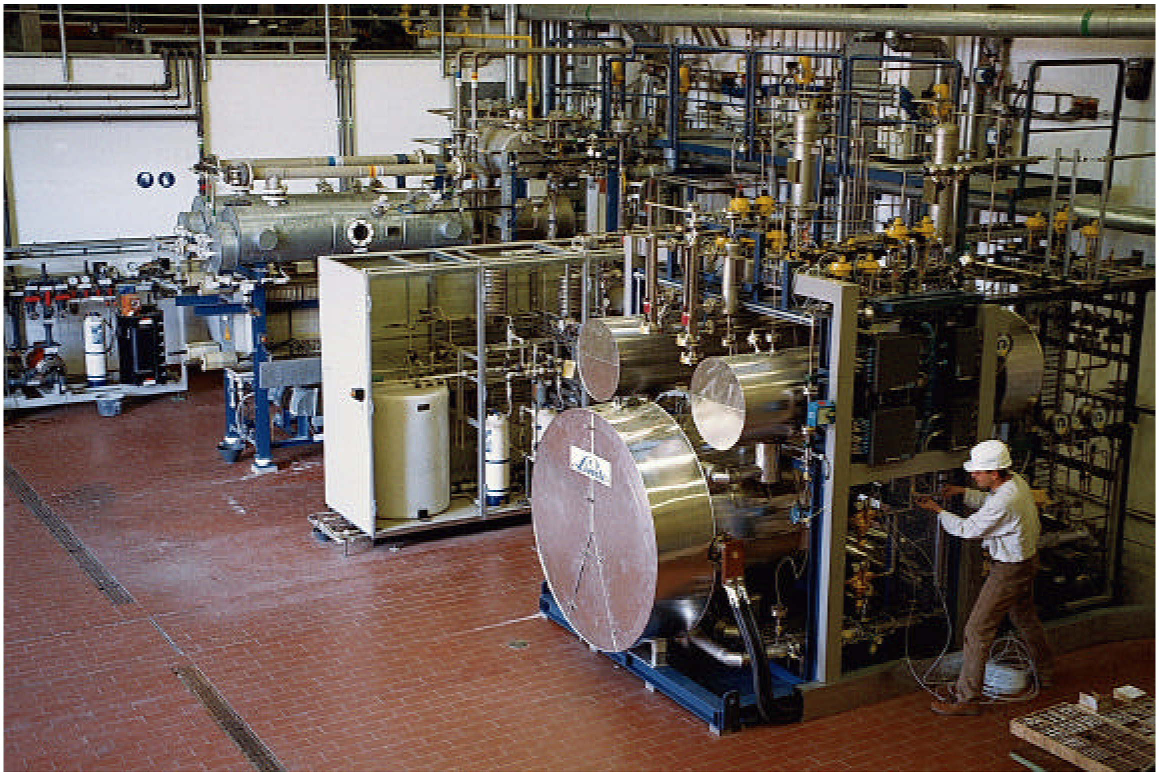
SWB's acquired know-how was available to the manufacturers for use in further development, but both have since abandoned this field of activity. Procurement of spare parts has become very difficult as a result, particularly affecting the membrane electrolyzer. After dismantling the cell stack in February 1996, the membranes were found to have deteriorated severely during the five years of test operation. The electrolyzer performed well over a long period, but had to be decommissioned owing to the lack of spare parts.

5.2.2 Pressurized electrolyzer

Advanced pressurized electrolyzers of the 100 kW$_{el}$ class working at about 30 bar were not available at the time the two low-pressure units were purchased. Placement of an order for an alkaline electrolyzer (with unitized EDE ceramic diaphragms and nickel electrodes) was delayed until November 1994. The guarantee test run for the unit took place in July 1996. Operating at 135°C, the specific energy consumption was about the same as for both low-pressure units, but no compression of the product gases was required in this case. The main characteristics of this unit are 30 bar pressure, operation with intermittent power sources, and quick response on load changes.

The first recording of basic data was interrupted at the end of 1996 when dismantling of the EDE cell stack became necessary, primarily due to rising O_2 impurity in the product H_2. Under the terms of guarantee, it was agreed that the supplier would install a cell stack of different makeup (polysulphone diaphragms with ceramics, chemically activated nickel electrodes, working temperature reduced to 105°C, new gasket design). A demister was inserted in the O_2 separator to reduce the KOH content of the O_2 product gas. SWB agreed to a one-year demonstration of this cell stack. However, although the specified characteristic values have been attained, a test run could not be performed due to a number of problems. After removing the demister and installing a third version of a cell stack (polysulphone diaphragms with ceramics, non-activated nickel electrodes) the test program resumed in May 1998. The electrolyzer was operating in more or less stable conditions until it had to be shut down again in August 1998 due to deficiencies in the cell voltage measuring lines.

With this third configuration of cell stack, at an operating temperature of 105°C, the specific energy consumption is 4.7 kWh/m^3 H_2, and the current density is 8.4 kA/m^2, at rated load. The three electrolyzers are shown in Picture 1.2.



Picture 1.2: Three electrolyzers (pressurized electrolyzer is right front)

5.2.3 Hydrogen and oxygen gas systems

Pressure storage of H_2 and O_2 generated by the two low-pressure electrolyzers requires subsequent compression of the product gases. Both gases are then cleaned of impurities (the other gas component) by catalytic combustion, dried in regenerated beds of alumina gel/molecular sieves, and finally stored in pressure vessels.

After correcting a number of defects (decentralized process control system, compressors, valve leaks caused by entrained particles of adsorbent, analyzer gas coolers), the H_2/O_2 gas systems are working satisfactorily. Occasional problems (including increased piston ring and cylinder wear) are still experienced with the hydrogen compressors, however, probably due in part to the test operation philosophy as practiced at Neunburg vorm Wald.

In addition to pressure storage of gas, liquid hydrogen (from an outside supplier) is stored in the liquid state for road transport utilization.

A special feature is the capability of operating some plant subsystems (gas-fired heating boiler, phosphoric acid fuel cell plant and catalytic heater) on either natural gas or hydrogen as well as partly on mixtures of natural gas and hydrogen.

In this way it is possible to demonstrate and investigate, at least at a preliminary level, the technical aspects of stepwise transition from contemporary energy supply based mainly on fossil fuels to a possible scenario where the energy medium employed is hydrogen generated without concomitant production of CO_2.

5.2.4 Heating boilers and refrigeration units

Although delivering reasonable test results in the past, the gas-fired heating boiler operating with oxygen as the fuel oxidizer was unable to reach an acceptable level of availability owing to problems (insufficient stability of the burner head) and the unit was decommissioned in May 1995. By contrast, the heating boiler operating with air as the oxidizer continues to work satisfactorily.

As expected, the efficiency was better when using oxygen instead of air with other conditions unchanged. Combustion of hydrogen with air resulted in slightly increased emissions of NO_x compared to combustion of natural gas. Significantly increasing the amount of excess air results in reduction of these emissions, but at the expense of efficiency.

Test programs for the gas-fired heating boiler with air as the fuel oxidizer have largely been completed. Further work with this equipment will primarily add to the experience of long-term operation. Cyclic recording of basic values (characteristics) is being made.

The calorific-value catalytic heater with a boiler capacity of 10 kW_{th}, designed to burn 100% natural gas or natural gas with a continuously variable mixture of 10-50 vol% H_2 was handled as a development project. Air was used as the fuel oxidizer, with external premixing of fuel gas and air. Owing to the reduction of combustion temperature below 900°C, NO_x emissions are less than 20 mg/kWh. Test operation of this unit started in December 1995.

Another development contract was placed for the catalytically heated absorption-type refrigeration unit fueled with hydrogen. A conventional absorption-type refrigeration unit for air conditioning service, fired with natural gas, was modified for this application.

Running air as the fuel oxidizer in the unit generates a refrigeration capacity of 16.6 kW_{th}. Heat is produced catalytically on diffusion burner structures (without premixing of fuel and oxidizer, which in principle eliminates backfiring). Due to the low burner working temperature of approximately 800°C, heat transfer in the high-pressure desorber is very efficient. Moreover, the possibility of corrosion problems is reduced by the coolant not being subject to overheating (≤160°C) in the desorber. NO_x emissions are less than one ppmv.

Several improvements had to be made to the refrigeration unit in the beginning, due to a number of problems with standard components; for example, the burner monitor and off-gas sampling piping. The unit is used to support the conventional chilled water circuit.

5.2.5 Stationary fuel cell plants

By the end of 1997, two fuel cell plants (alkaline and phosphoric acid) were tested by SWB. These two types are designed for different spheres of use.

Because it requires pure O_2 as the oxidizer and pure H_2 as the fuel, the alkaline fuel cell is more suitable for special niche applications (i.e., in space vehicles and submarines). These operate in conjunction with a so-called hybrid system – comprised of a DC-DC converter, battery buffer, converter and control unit. The alkaline fuel cell plant at SWB allowed reproducible simulation of electric vehicle running cycles under stationary conditions.

Following reversal of electrical polarity in individual cells, additional measures were adopted in the supply systems and monitoring of the feed gases. Several replacements of the fuel cell stack became necessary, leading to the decision in October 1994 to decommission this plant even though it had demonstrated good performance during periods of trouble-free operation. Electrical efficiency is related to gross calorific value and disregarding electrical utility consumption, and was measured at 53% at rated load. Current density was 4 kA/m^2 and random load transients were obtained within about 100 ms.

Experience with the alkaline fuel cell plant proved it to be too sensitive, due to its complexity. Above all, its usability is compromised by the risk of irreversible damage to the nickel anode. The manufacturer relinquished this field of activity some time ago in favor of the proton-exchange membrane fuel cell technology.

The phosphoric acid fuel cell plant (incorporating the possibility of heat decoupling) is regarded as an alternative to conventional heat-and-power cogeneration plants. The combination of hydrogen generation by steam reforming of natural gas including CO shift conversion and fuel cell technology is meaningful in view of pipeline supply of hydrogen not being available in quantities to meet energy supply requirements in the near future. By reason of the good overall efficiency of this type of fuel cell plant, CO_2 emissions are lower than with conventional systems.

Testing of the previously mentioned transition scenario can be made at Neunburg vorm Wald by operating the phosphoric acid fuel cell plant (Pictures 1.3 and 1.4) either with natural gas from the public network or with hydrogen supplied direct from on-site gas storage. Ambient air is used as the oxidizer. To increase the fuel cell stack efficiency by up to 3 percentage points, the air may alternatively be enriched with oxygen to a maximum of 50 vol% O_2

Optimized for electric power output, the phosphoric acid fuel cell plant is designed to run in a variety of modes for test operation in a (solar) hydrogen demonstration facility. Heat is decoupled at 165°C and the operating temperature is 190°C. In other words, it is not designed as a commercial containerized standard unit.

Major problems occurred at the time of commissioning this plant, necessitating extensive repairs and changes, as well as considerable expense of time and labor for optimization in view of the high level of automation. The resulting delays caused substantial postponement of the guarantee test run. Most of the difficulties originated in the associate peripheral systems, with very few in the fuel cell stack itself.

The test program has proceeded at a good pace since March 1993. The first tests conducted in various modes for recording characteristics were run at the end of 1993. Load following and continuous operation (24 hours a day, 5 days a week) were investigated in 1994. In the summer of 1995 the plant was used in a simulation of the power requirements of a small hospital in an island-site operation.

Picture 1.3: PSA Unit

Picture 1.4: Phosphoric acid fuel cell plant

The starting and stopping behavior of the fuel cell plant was investigated more closely in the autumn of 1996 and measurements were made to check emission levels (CO and NO_x). Emissions are comparable with other commercially available phosphoric acid fuel cell plants, meaning that they are several orders of magnitude lower than the levels specified for gas engines (German TA Luft specifications).

Apart from these test periods, the phosphoric acid fuel cell plant was operated mainly at rated capacity (fuel cell at 610 A_{DC}). Output and load change response conformed to expectations. Note may be made of the electrical utility power consumption, which was unexpectedly high at the time (12 kW_{el} with hydrogen, 32 kW_{el} with natural gas), and the higher heat generation when using natural gas (20 kW_{th} instead of anticipated 13 kW_{th}).

Within the test runs, special attention was given to the behavior of the fuel cell plant under conditions of intermittent operation as practised at SWB and as would be expected in a (solar) hydrogen energy supply scheme.

Valuable knowledge related to long-term stability was acquired, under highly aggravated operating conditions. The approximately 450 starts and stops to date over a cumulative total of about 2600 h of test operation have thus far resulted in output of the fuel cell decreasing by about 20 kW_{el}.

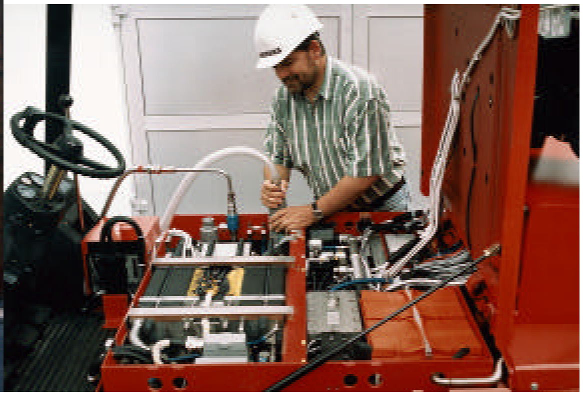
In December 1997, excessive H_2 concentrations occurred in the scavenging air of the fuel cell. The attempt to decrease the leakage caused by ageing of the seals by adjusting the tension in the cell stack, was unsuccessful. Remedy could be found by significantly increasing the scavenging airflow using the excess power of the cathode air compressor.

Test programs for the phosphoric acid fuel cell plant have largely been completed. Further work with this equipment will primarily add to experience of long-term operation. In addition to cyclic recording of basic values and characteristics, the main item of interest is further degradation of output.

5.2.6 Mobile fuel cell plant

The fuel cell plant with a proton exchange membrane, now on a trial run, was modified by the manufacturer for use of air (instead of oxygen) as the fuel oxidizer, which represents a new technology. It was constructed as a mobile system with a rated power output of 10 kW_{el} (operating temperature of 60°C, rated voltage of 52 V_{DC}), and serves as an electro-chemical power source to drive a standard electric forklift truck at the Neunburg vorm Wald site. The skid-mounted fuel cell plant was installed in the truck in place of the normal battery pack. Power for all electrical auxiliaries is supplied by the on-board system, using an external battery for start-up. In addition to its role as carrier of an experimental fuel cell demonstration plant for mobile and stationary tests of German PEM-technology, the forklift truck is also used for actual work, as shown in Picture 1.5. The fuel cell plant is shown in Picture 1.6.

Picture 1.5: Electric forklift truck at work



Picture 1.6: PEM fuel cell plant

The supplier was unable to meet the December 1996 acceptance date agreed at the time of ordering. Delay was caused by unforeseeable demands on the part of the licensing authorities. Among other things, provision of redundant system control and revision of the safety logic circuits were specified. The successful guarantee run was finally performed in December 1997. The agreed guarantees for effective electric power output of the fuel cell plant (≥9 kW net of electrical utility consumption), electrical efficiency of the fuel cell referred to net calorific value of hydrogen (≥50%), and total fuel cell plant efficiency (≥40%) were attained.

After overcoming initial deficiencies (problems with test data acquisition, unsuitable reaction water level indicators, defective pump motor for cooling water) during the trial runs starting in January 1998, the actual test operation proceeded satisfactorily, thus confirming the suitability of a membrane fuel cell plant in mobile operation. Due to the replacement of the normal battery pack for the membrane fuel cell plant, the weight conditions of the truck changed. Therefore, in July 1998, specific tests became necessary at the forklift truck maker to ensure safe operation again.

Metal hydride will be used for on-board hydrogen storage, which is advantageous in this special instance because of its weight. The effective hydrogen capacity is designed for 8 hours of forklift truck operation at average power requirement. The envisaged time for charging the hydride is about 10 min and the heat generated during the charging will be dissipated by an external cooling water circuit. This system gives SWB the opportunity to undertake practical testing and acquire corresponding experience with a third major hydrogen storage technology, complementing the pressurized gas and liquid hydrogen technologies already in use. The metal hydride is to be charged with hydrogen from onsite gas storage at pressures between 10 and 30 bar.

The entrance to the operating building on the west side has been converted as an access route for the electric forklift truck. The necessary hydrogen gas filling station is located in the operating building.

Conversions to the existing hybrid system (used in conjunction with testing of the alkaline fuel cell plant) have been completed, enabling its use for stationary testing of the membrane fuel cell plant to simulate vehicle drive cycles. As it now stands, the system can also be employed to verify any performance of the membrane fuel cell plant up to rated capacity. The air-oxidiser membrane fuel cell technology is well-suited for electric vehicles, in effect converting these to hydrogen gas fueling.

As an energy medium, hydrogen is environmentally friendly to a high degree on account of its chemical properties and thus is well-suited for use as a motor fuel, powering vehicles without locally producing noxious emissions.

5.2.7 Liquid hydrogen filling station

Work has been proceeding also on optimizing the liquid hydrogen fueling of test cars at Neunburg vorm Wald since 1991 with construction of a LH_2 filling station (Picture 1.7).

Through the pressure prevailing in the 3,000-liter site tank, liquid hydrogen is conditioned according to the vapor pressure curve and can be filled into the vehicle fuel tank either by the site tank pressure or by a LH_2 pump. The filling line is manually coupled to the vehicle whereas the actual filling operation takes place under program control.

Test results acquired to date by SWB have been evaluated to optimize the LH_2 filling station insofar as the time for a complete vehicle tank filling cycle has been shortened to approximately 5 minutes, while at the same time reducing the boil-off losses occurring during filling to less than 8% of the liquid volume transferred. Successive vehicle tank filling can be achieved within 3 minutes. This was mainly accomplished by using a new design of clean-break coupling systems for connection between the filling station and vehicle fuel tank. Beyond that, SWB ordered a 125 liter vehicle tank system without cryovalves, which was used during the second half of 1996 to achieve filling in about 3 min while eliminating return gas flow. Work on the task of automating operation of the Phase 1 LH_2 filling station has been completed. The filling station and the novel vehicle tank system remain on site for coupling demonstrations using the coaxial coupling system. At the same time, wearing behavior of components subject to stress remains under observation.

Picture 1.7: Test vehicle's liquid hydrogen filling station

6. SAFETY CONCEPT

6.1 Operation with limited attendance

As a rule, the solar hydrogen facility at Neunburg vorm Wald is manned by operating staff on workdays only, for one eight-hour shift from November-February, and two eight-hour shifts during the remainder of the year. When required for special test programs, the plant may be operated around the clock. As was to be expected, repeated starting and stopping of the plant has proved to slow down the test programs. On top of that, it causes heavier wear on the plant components. Under an arrangement with the licensing authorities, the gas production and utilization systems are shut down during the time the plant is unmanned.

A catalogue of measures was ultimately defined in cooperation with the licensing authorities as a prerequisite to temporary unsupervised operation of hydrogen systems (restricted to periods of 24 h). This involved adapting or utilizing the existing control systems for safety engineering duties, such as redundant monitoring of H_2/O_2 gas purities downstream of the alkaline low-pressure electrolysis and installation of pressure switches ahead of all mechanical safety valves in the H_2/O_2 gas route. Starting in September 1997, overnight unmanned running of some plant subsystems (alkaline low-pressure electrolyzer, H_2/O_2 gas systems, gas-fired heating boiler 2, catalytic heater, catalytically heated absorption-type refrigeration unit, and phosphoric acid fuel cell plant without oxygen-enriched air) became possible.

The permission to also operate the alkaline pressure-type electrolyzer according to this philosophy was granted by the licensing authority in August 1998, with operation expected to start in November 1998.

6.2 Basic elements of the safety concept

The operating concept described above is part of the safety-related requirements, as is of course observance of pertinent standard practice, occupational safety codes and explosion protection regulations for the chemical industry.

Experience gained by SWB shareholders from operating power stations, designing and operating chemical plants and cryogenic tank systems similarly entered into the planning of the safety measures, all of which were defined in collaboration with the licensing authorities.

The safety aspects for Neunburg vorm Wald reviewed here are those related to working with hydrogen. Structural and design provisions were made for the hazards associated with hydrogen during construction of the plant and buildings and were complemented by control and safety devices as well as operational measures. Other potentially hazardous fluids present in the plant (natural gas, oxygen, carbon monoxide, nitrogen, potassium hydroxide) are not considered in this report.

Generally, four types of safety measures may be defined:

Primary safety measures are directed at excluding sources of trouble, i.e., any formation of an ignitable mixture of hydrogen and air or oxygen. For that reason, the hydrogen was confined as safely as possible within the process equipment by appropriate engineering design and the use of approved materials of construction. Supporting measures include optimization of construction and layout, efficient ventilation systems, gas alarm systems and inertization of equipment with nitrogen.

Secondary safety measures concern the elimination of all possible ignition sources. Electrically or mechanically generated sparks are important ignition sources to be taken into account. Examples of the measures adopted are adherence to defined explosion proofing classifications and rules for maintaining safe distances around equipment and maintaining ground potential by connecting all electrically conducting equipment to a grounding system. It is obvious that smoking and open flames are prohibited throughout the fire and explosion hazard zones of the facility.

Tertiary safety measures have the purpose of minimizing the extent of damage in the event that both the primary and secondary measures should fail. At Neunburg vorm Wald these took the form of appropriate civil engineering and fire control procedures and action.

Additional precautions may be regarded as collective safety measures. Among these are the safety control system, uninterruptible power supplies for control systems and safety related electrical equipment, observance of safety notes contained in operating manuals and instructions, training courses and briefings, and routine inspection of equipment as directed by law or authorities.

It may be noted that no fundamentally new safety risks had to be considered when drafting and subsequently implementing the safety concept in force at the Neunburg vorm Wald solar hydrogen facility. It has been confirmed that, in industrial applications, the existing codes and regulations are adequate for safe working with hydrogen, a fluid that has been widely used in industry for decades both in gaseous and liquid form.

Long-term operating experience to date has given no cause to amend the concept for a still higher level of safety. Stipulations have been fulfilled that injury to persons present at the facility, damage to property and harm to the environment must be prevented.

The facility - largely constructed of prototype units as previously mentioned - has operated safely and without problems for about eight years now, not least of all thanks to the adequate safety engineering provided and the experience of the operating personnel. Except for a local cable fire in March 1991, which was put down by the operating crew with hand-held extinguishers, there have been no critical incidents.

Cooperation with the licensing authorities involved has proceeded on a decidedly positive note.

7. FUTURE POTENTIAL AND FUTURE PLANS

Assessing the work to which SWB has contributed, it is apparent that the beginnings of energy supply based on hydrogen as an energy medium are tied to prior expansion of electric power generation from renewable resources on a substantial scale. Storage of energy will only become meaningful when the electric power thus generated, concomitant with a shift away from fossil fuels, cannot be fully consumed as it is generated. Hydrogen and electric power are not competing alternatives.

One exception at the present time may be road transport, which will become reliant on a clean, readily storable motor fuel for control of source emissions in densely populated areas. Efforts are additionally being undertaken to make small-capacity cogeneration plants based on commercial phosphoric acid and molten carbonate fuel cell plants competitive with gas engines to exploit their better electrical and overall efficiency. Membrane and solid oxide fuel cell plants are also being investigated at the present time for small-capacity stationary applications. Realistic potentials for reducing the cost of individual plant subsystems should be explored further so as to successively narrow the gap to competing systems.

Even when regarded apart from the photovoltaic systems utilized at the site for electric power generation free of CO_2, the work undertaken in the field of hydrogen at Neunburg vorm Wald - this constituting the main focus of the project - furnishes valuable know-how for future hydrogen scenarios. It has, moreover, been shown that the process engineering and electrochemical attributes of these hydrogen systems make them more closely related to conventional plant engineering and construction than would appear to be conveyed by the term "solar technology", under which hydrogen is frequently classified in its capacity as an energy medium.

At the present time, any decision favoring long-term energy storage system based on hydrogen is still remote. Over time, however, the prospects for hydrogen could grow increasingly better. The appropriateness of a balanced energy mix will hold true for the future as well.

Over the past ten years of running the Neunburg vorm Wald demonstration project, SWB has acquired a wide range of know-how that is already utilized in accordance with the progress of experience. This covers conceptual design and possible realization of new (solar) hydrogen projects. Included among these are:

- WIBA, Co-ordination of Bavarian Hydrogen Initiative
- Munich Airport Hydrogen Project (preparatory project)
- Fuel Cell Propulsion for Municipal Buses and Trucks
- Munich New Exhibition Centre 1 MW Photovoltaic System (world's largest rooftop system).

The variety of experience gathered from the Neunburg vorm Wald project speaks strongly for the advisability, or rather need, to supplement basic research and development work by continuing technology-oriented demonstration and experimental projects on an industrial scale for practical test operation of prototypes.

Such use of hydrogen as an energy medium, with growing emphasis on economical viability of hydrogen utilization under operational conditions, will lend further support to its market introduction.

8. CONCLUSIONS

One aspect revealed in the course of running the SWB project in Neunburg vorm Wald is that hydrogen systems for energy conversion are for the most part only to be purchased at the present time as prototypes or individually engineered designs. In addition, their integration into a meaningful overall plant concept is often more difficult than commonly believed. For instance, the extent and complexity of the associate peripheral systems is often underestimated. The multitude of necessary utility and auxiliary systems required underscores the fact that large capacity hydrogen facilities are plant engineering and construction projects subject to individual planning.

Closely centralized generation and storage of the gas and its subsequent utilization as an energy medium is mandatory not only in the interests of cost reduction but also with a view to optimum attendance, service and safety installations. Beyond that, it is desirable that major plant subsystems for gas generation and utilization be constructed as outdoor installations, unlike the indoor configuration selected for the Neunburg vorm Wald facility. The decision there (based, in part, on the supplier’s conditions) to install the majority of prototypes in a common operating building for convenience of attendance and servicing, as well as for security considerations, necessitates extensive peripheral systems that would not otherwise be required. Frequently, the overall plant had to be shut down and the entire operating building inertized when work was required on individual systems. Since there is almost always work going on at some point in a test facility of this nature, and given the purposely planned complexity described above, the operating hours logged by some systems have been rather modest.

On the whole it can be stated that several of the systems installed at the solar hydrogen facility failed to work satisfactorily at the start. Throughout the operating period to date, SWB has, however, been able to adequately solve almost all of the problems occurring, and some recurring, both on individual subsystems and in interaction of the systems. In the course of so doing, several improvements have been devised, usually in collaboration with the system suppliers. Contributions to the inception of several new developments have likewise come out of the project. Examples of this, included in Figure 2, are certain solar cell technologies (e.g., AS hybrid, HE and BSF), the alkaline low-pressure electrolyzer, the two gas-fired heating boilers, the catalytic heater and absorption-type refrigeration unit with catalytically heated desorber, use of an alkaline pressure-type electrolyzer, the air-oxidizer membrane fuel cell plant, as well as the two advanced coupling systems and vehicle tank system without cryovalves for liquid hydrogen fueling of test vehicles. Stimulation of these developments is an important outcome of the project and wholly in keeping with SWB's objectives.

Chapter 2
SOLAR HYDROGEN PLANT ON THE MARKUS FRIEDLI RESIDENTIAL HOUSE

1. PROJECT GOALS

Integrated solar hydrogen production plants are rare and are generally being built and tested by public institutions (universities, national energy agencies) or by utilities with a major involvement of public funds. In contrast, the present report describes a private installation in Switzerland which was built by its owner (Markus Friedli, CH-3436 Zollbrück) for domestic use, mainly from commercial components and so far, without funding from the federal government. The aim of this project was to prove that it is technically possible to implement and operate such a facility on the every day level.

Involvement of academia therefore only started after completion of the installation, with the objective to analyze the overall performance of the system as well as of the individual subsystems and to suggest possible improvements. This task was undertaken by an expert group of energy system analysis of the Centre d'étude des problèmes de l'énergie together with researchers in the field of metal hydride storage of the Laboratoire de cristallographie (Université de Genève, Switzerland), without external funding.

2. GENERAL DESCRIPTION OF PROJECT

2.1 Overview

The system is integrated into a one-family house and consists mainly of commercial components. It is operational since 1991 and is located in a region of moderate climate (altitude 630 m, latitude 46.9°N, average sunshine 1,540 h/year, corresponding to 4,020 MJ/m^2/year). The system configuration (Figure 2.1) allows for the production and storage of hydrogen for both stationary (stove, laundry machine) and mobile applications (hydrogen or gasoline powered car); for PV electricity storage in a stock of lead acid batteries connected to the domestic grid; or for PV electricity feedback into public grid. Due to the manual control of the production mode, hydrogen production has actually been limited so far to demonstration purposes, so that the latter two storage modes still have priority.

Specific measurements combined with in-situ measurements, during operation on 3 typical summer days, allowed the characterization of individual subsystems and the determination of a disaggregated input/output diagram (instantaneous hydrogen production vs. solar radiation). Computer modeling based on later specifications and standard meteorological data enabled the determination of the yearly PV storage potential, under the hypothesis of hydrogen production having priority over the other storage modes.

2.2 System description

Solar radiation is transformed by PV panels into electric current which passes a control unit and a DC-DC converter before being transformed by an electrolyzer into chemical energy (hydrogen) or stored in batteries and/or injected into the grid. A small part of auxiliary energy is supplied by the electric grid for operation of the control unit, electrolyzer regulation, purification unit and hydrogen compressor. However, the electrolyzer can, in principle, also be operated from the public grid via an AC-DC converter. Water is needed as a feed, for cooling the electrolyzer, and for removing electrolyte from the hydrogen gas. Some hydrogen is consumed in the purification step, where any oxygen in the hydrogen stream is catalytically reacted with hydrogen. Hydrogen is transferred into an intermediate storage tank and then compressed for seasonal storage into a metal hydride storage tank. The latter is connected to house appliances such as a stove and a laundry machine (no longer in operation), and a second metal hydride storage tank is located in a minibus (which can alternatively also be fueled with gasoline). The household is exclusively powered by the battery stack via a DC-AC converter and is completely separated from the public grid.

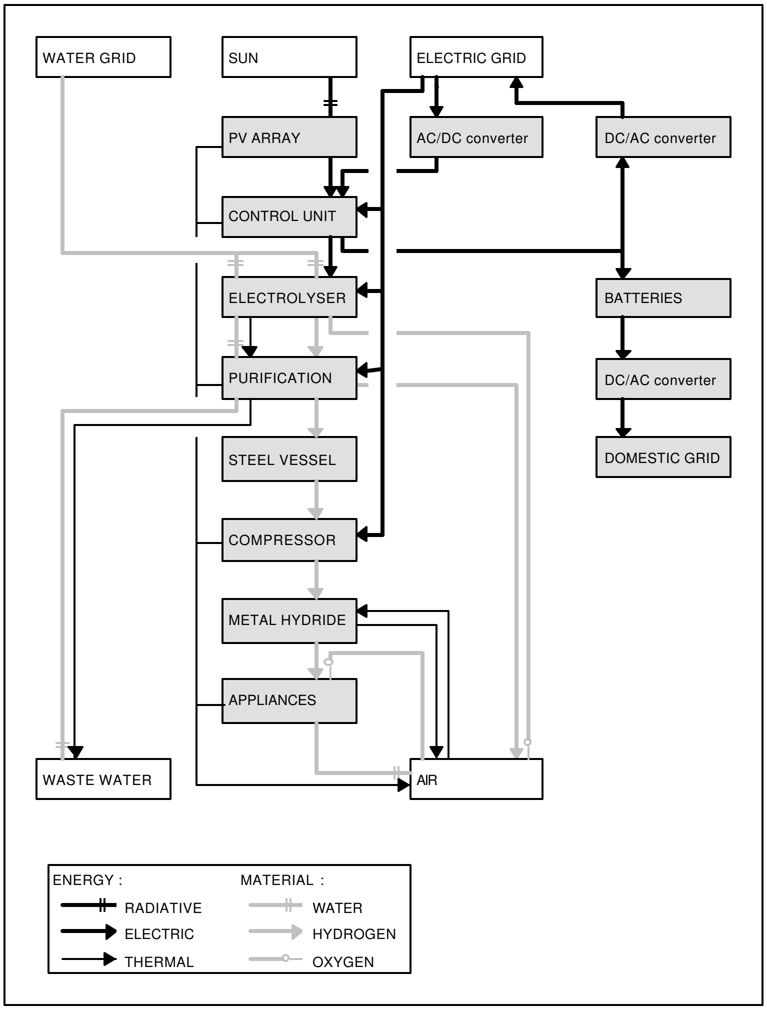


Figure 2.1: Schematic diagram of the system and energy/material flows.

3. DESCRIPTION OF COMPONENTS

3.1 Photovoltaic Field

The PV array consists of 162 solar panels, which are connected in series of 6 panels grouped into two subarrays (Picture 2.1). They cover a total surface of 65.2 m^2 (56.6 m^2 cell surface) and have a total nominal peak power of 7.4 kW_p (3.4 and 4 kW_p; for technical details see Table 2.1). The measured peak power during two sunny summer days (Figure 2.2) is much lower (4.5 kW_p), the discrepancy being mainly due to : 1) an overestimation of the panel performance by the supplier. The peak power as derived from U/I measurements and normalized for standard conditions, i.e. 1000 W/m^2 insolation and 25°C panel temperature, was found to be ~11% lower than the manufacturer rating; and 2) a loss of conversion efficiency due to the heating of the solar panels (up to 75°C at 1000 W/m^2 insolation).

Picture 2.1: PV-panels on house roof and minivan.

A quadratic regression on monitoring data for two summer days yields a PV base efficiency of 8.9% which decreases at a rate of 0.2% per 100 W/m^2 insolation. A more global estimation of the seasonal efficiencies was made by using the PV simulation computer program PVSYST (developed by A. Mermoud at the University of Geneva) and standard meteorological data available for that area. The values obtained vary between 9.7% (- 0.28% per 100 W/m^2) for the summer season and 10.4% (- 0.23% per 100W/m^2) for the winter season (see Table 2.1). The estimated yearly average panel efficiency is 8.4%.

3.2 Control unit and DC-DC converter

The unit consists of a regulator and a DC-DC converter developed and supplied by the Engineering School of Biel, Switzerland (Picture 2.2). Their main purpose is to maximize the hydrogen production by matching the characteristics of the PV array and the electrolyzer (power point tracking), and to increase the charging efficiency of the lead acid batteries. Technical details are summarized in Table 2.2.

Table 2.1: Data for PV panels and array

Panels	Supplier	Siemens
	Model	Arcosolar M73 and M75
	Number of cells	33/panel
	Surface/panel	4.023 m^2 (total), 3.494 m^2 (net)
	Nominal power	M73 : 41 W, M75 : 48 W
	Real power*	M73 : 37.8 W, M75 : 41.6 W
	Temperature	max. 75°C
Array	Connection	in series of 6, grouped in two modules
	module 1	42 M73, 48 M75
	module 2	72 M75
	total surface	65.2 m^2
	orientation	10°SSE azimuthal, inclination 35°
	power	7.4 kW (nominal*), 6.6 kW (real**), 4.5 - 5.0 kW (measured)
	efficiency	summer : 9.7% - 0.28% per 100W/m^2 insolation*** winter : 10.4% - 0.23% per 100W/m^2 insolation*** midseason : 10.1% - 0.28% per 100W/m^2 insolation*** yearly average : 8.4%

* for standard conditions (STC) of 1000W/m^2 insolation and panel temperature of 25°C.

** as derived from U/I measurements, normalized for STC by using the program PVSYST.

*** regression on hourly values as generated by program PVSYST with standard meteorological data.

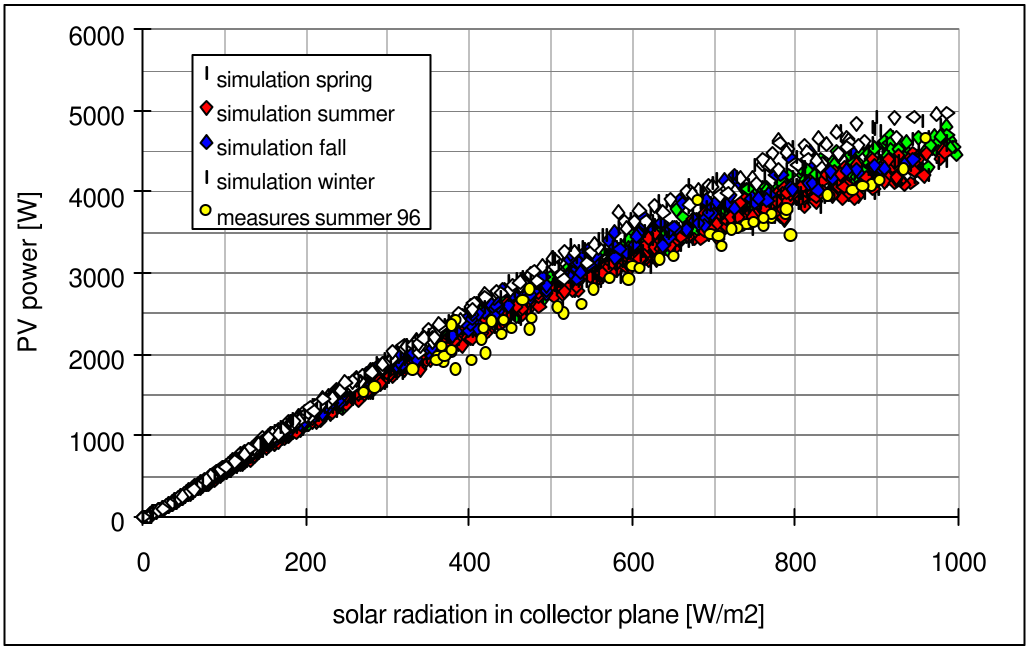


Figure 2.2: PV power versus solar radiation, measured over 2 summer days (5 min. step) and simulated over one year (hourly step).

Picture 2.2: DC-DC converter and integrated control unit

Table 2.2: Data for control unit and DC-DC converter

Supplier	Ecole d'ingénieurs de Bienne, CH-2501 Bienne	
Model	HMAX	
Voltage (V)	entry	70 - 150 DC
	exit electrolyzer	28 - 38 DC
	exit batteries	22 - 28.5 DC
Current (A)	entry	0 - 120 DC
	exit electrolyzer	30 - 300 DC
	exit batteries	0 - 300 DC
power (nominal)	11 kW (electrolyzer), 8.5 kW (batteries)	
auxiliary power	<30 W (950 MJ/year)	
dimensions	158x55x60 cm3	
efficiency	96% at 1.8 kW entry and greater	

The system needs less than 30 W auxiliary power. Its average efficiency exceeds 95% (Figure 2.3) at an incoming power greater than 1.8 kW. Various modes of operation, which are manually selected, are possible, such as hydrogen production from the two PV modules connected in parallel; charging the batteries from the PV modules and optional hydrogen production from the grid; charging the batteries from the 4 kW module and injection of electricity from the 3.4 kW module into the grid with optional hydrogen production from the grid; and hydrogen production from the 4 kW module with injection of electricity from the 3.4 kW module into the grid. The installation of the DC-DC converter and the suppression of the initially installed DC-AC ondulator coupled to the AC-DC converter in the electrolyzer decreased the losses by about 20%.

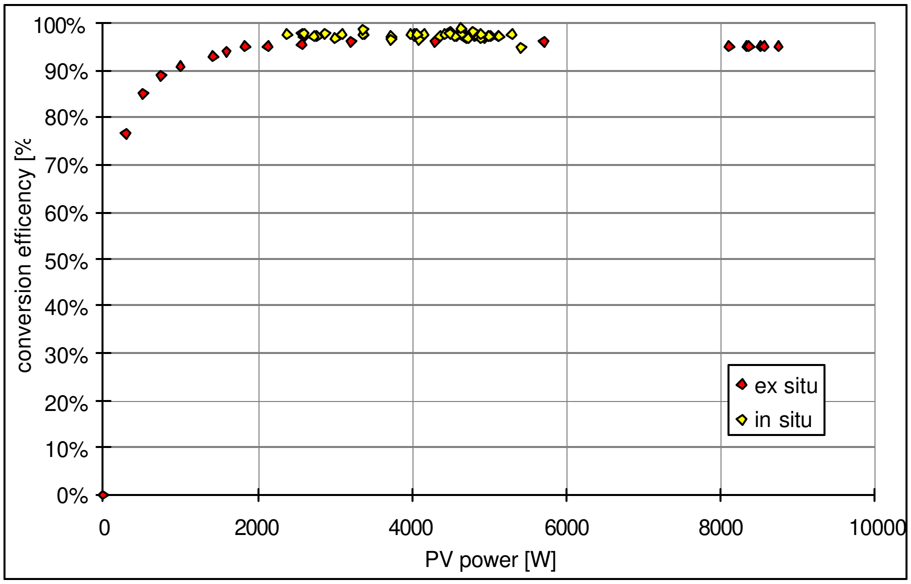


Figure 2.3: Measure of conversion efficiency at construction of unit (ex-situ) and during operation on a summer day (in-situ).

3.3 Electrolyzer

The commercial alkaline (KOH) type membrane model (Picture 2.3) was originally designed for continuous hydrogen production from the AC grid (for technical details see Table 2.3). It had a maximum power of 10 kW and yielded about 2 Nm^3 hydrogen gas per hour at a pressure of 2 bar and a purity of 99.8%. For the present intermittent operation from PV power, the original AC-DC rectifier in the electrolyzer was replaced by a DC-DC converter and the operating power was limited to a lower threshold of 1.4 kW (1.8 kW at start-up) for reasons of safety, and to an upper threshold of 4.6 kW to minimize wear. These correspond to current limitations between 45 A (55 A at startup) and 130 A, and a hydrogen production between 0.32 Nm^3 per hour (0.40 Nm^3 per hour at startup) and 0.95 Nm^3 per hour.

This unit also hosts an electronic regulation and display system which controls the electrolyzer as well as tracking the subsystems, basing on data like load, system pressure, purification temperature and storage capacity of metal hydrides. This regulation can be linked to a computer for on-line visualization of system operation and data acquisition.

Current versus tension characteristics at different operating temperatures (normal operating temperature being 45°C) were established by ex-situ measurements while bypassing the control unit and were compared to in-situ measurement in 5 minute steps on 3 typical operation days (Figure 2.4). Systematically higher voltage values at low current densities correspond to the start-up periods at the beginning of the day when the set-point temperature was not yet reached (see also Figure 2.6). The data shows the exponential rise of the cathodic and anodic overvoltages below 90 A, followed by a linear rise of the ohmic overvoltage. Correspondingly, electrolyzer voltage efficiency (defined by the ratio of the lower heating value of hydrogen and the electric power used) decreases with increasing load, passing from 66% (65% at startup) at lower threshold to 60% at upper threshold. Resulting yearly average electrolyzer efficiency is 62%.

Picture 2.3: Electrolyzer and regulation display

Table 2.3: Data for electrolyzer

General data	supplier / model	VCST Hydrogen Systems (Belgium)/IMET 2	
	cell number	16	
	cell surface	600 cm^2	
	temperature	45°C (average), 50°C (setpoint)	
	pressure	2 bar	
	electrolyte	KOH (30 wt%, density 1.27 g/cm^3)	
	dimensions	0.60 x 0.80 x 1.79 m^3	
	maximum power	9.5 kW (37 V, 250 A), 2Nm^3/h hydrogen	
Requirements	water	electrolysis	3 liter/Nm^3
		cooling of H_2 gas	7.5 l/hour
		cooling of cells	40 liter/Nm^3
	regulation power	22 W (690 MJ/year)	
limitations for PV operation	power	1400 W (1800 W at start-up) - 4600 W	
	current	45 (55) - 130 A	
	hydrogen yield	0.32 (0.40) - 0.95 Nm^3/hour	
	efficiency*	66 (65) - 60%, average 62% (LHV)	

* for standard conditions of 1000 W/m^2 insolation and panel temperature of 25°C.

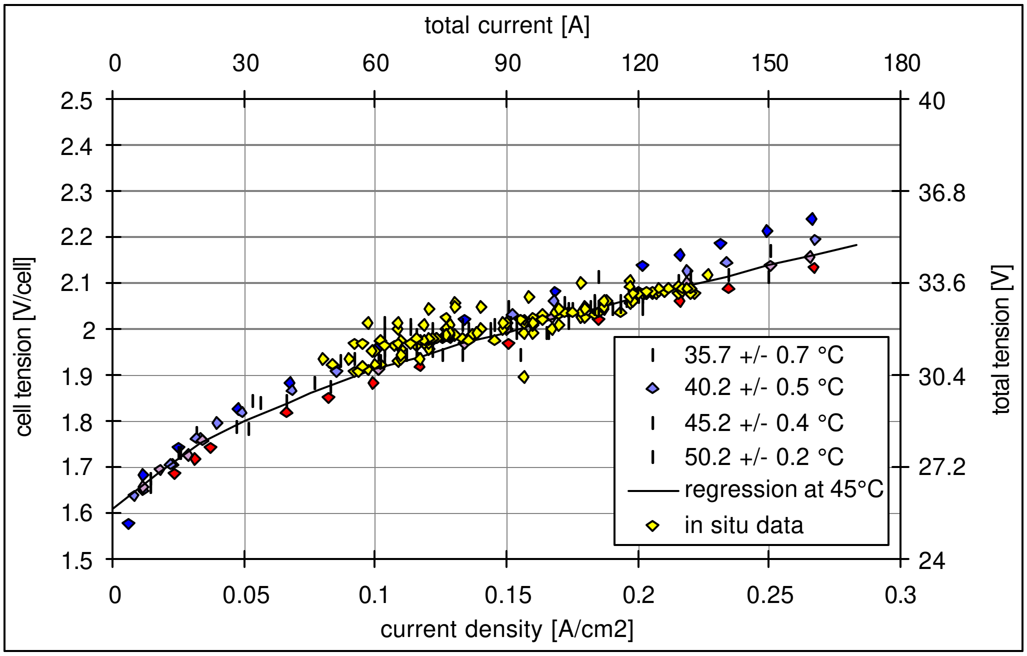


Figure 2.4: Electrolyzer current versus tension at different temperatures (triangles and squares), regression on the average operating temperature (solid line), and in-situ data in 5-min. steps over 3 operating days (crosses).

Some 22 W of electricity (from the grid) are needed for regulation, and up to 3 liters of demineralized water per hour for electrolysis. At full operation the total water consumption is about 40 liter/h, which includes about 30 liter/h for cooling.

3.4 Purification, intermediate storage and compression

The purification unit (Picture 2.4) is needed so as to enhance hydrogen purity to a level proper for storage in metal hydrides. It consists of a water bath, a condenser and a drying unit running on the grid. The bath removes traces of the KOH electrolyte and uses water from the cooling circuit of the electrolyzer. The condenser is filled with a noble metal catalyst that removes traces of oxygen. The drying unit consists of two molecular filters that remove water and are used in alternation. Originally designed to run under a constant hydrogen flow of 2 Nm^3/h, they are now controlled by the electrolyzer regulation. They are capable of treating about 2 Nm^3 wet hydrogen gas each and have to be regenerated by heating under a hydrogen flux. This requires rather high amounts of both electric energy (200 W during 45 min for heating to 85°C, and 60 W in equilibrium, corresponding to about 0.13 kWh/Nm^3 hydrogen gas) and hydrogen gas (0.2 Nm^3/hour). This represents an average loss of up to 8% of the total hydrogen generated by PV power.

Picture 2.4: Purification unit (on wall) and metal hydride storage tank (on ground).

The purified hydrogen gas is stored in an intermediate, cylindrically shaped steel vessel (Picture 2.5) of about 450 liter capacity in the pressure range between 1.9 bar (upper setting to start the compressor charging the metal hydride tank) and 0.6 bar (lower setting to stop the compressor). The corresponding useful capacity of the vessel per compressor cycle is about 0.59 Nm^3 hydrogen gas. In order to meet the operating conditions of the metal-hydride storage tank the gas is then compressed to about 29 bar by the compressor (for technical details see Table 2.4). This requires a few minutes time and some 0.125 kWh grid power per compressor cycle (0.763 MJ/Nm^3, corresponding to 7.6% of the lower heating value of hydrogen). The estimated yearly average energy consumption is 810 MJ.

3.5 Metal hydride storage tank

The metal hydride storage unit is situated at the floor of the electrolyzer control room (Picture 2.5) and consists of a stack of metal cylinders which are filled with a hydrogen absorbing alloy (multi-substituted derivative of $TiMn_2$). They are embedded in a cooling circuit operating on tap water which speeds up thermalization during absorption (exothermic reaction) and desorption (endothermic reaction). The circuit was switched on only for testing of the performance of the storage tank, but is not used during normal operation of the system. The total tank volume and weight is 91 liters and 235 kg, respectively, including 15 liters and 100 kg, respectively, of the alloy (for technical data see Table 2.5).

Picture 2.5: Compressor and intermediate storage vessel (partial view on side of picture).

Table 2.4: Data for purification, intermediate storage and compression

Hydrogen purification unit	Dimensions	70 x 20 x 105 cm^3
	Temperature setting	85°C
	start-up heating time	45 min (from 25 to 85°C)
	heating power	60 W (200 W during start-up)
	estimated yearly average	510 MJ (0.13 kWh/Nm^3)
	hydrogen requirement	0.2 m^3/hour
	pressure	2 bar
Storage vessel	supplier	Brand Anlagebau (CH)
	volume	454(+/-13) liter
	pressure	1.9 - 0.6 bar
	height	195 cm (total), 180 cm (vessel)
	diameter	60 cm
	H_2-capacity	0.59 Nm^3 (between 0.6 and 1.9 bar)
Compressor	Supplier	Corken (USA)
	Model	D191 AM4FBAB
	Power	3.2 kW, estimated yearly average 810 MJ
	Pressure	29 bar
	time/cycle	150 s
	power/cycle	0.125 kWh/0.59 Nm^3 (0.763 MJ/Nm^3)

Table 2.5: Data for metal hydride storage tank (in-house)

Supplier	Japan Metals & Chemicals
Pressure range	1.2 - 29 bar
Capacity	19 Nm^3 (nominal at 20°C, 30 bar)
Volume	15.2 Nm^3 (measured at 5.3°C, between 1.2 and 27 bar) 91 l (total), 15 l (metal hydride)
Weight	235 kg
Alloy composition	$Ti_{0.98}Zr_{0.02}V_{0.43}Fe_{0.09}Cr_{0.05}Mn_{1.5}$
Storage efficiency	1.8 wt% (alloy, total), 1.3 wt% (alloy, reversible) 0.54 wt% (tank, reversible)
Heat of absorbtion/desorption	14.4 MJ for 14 Nm^3

The storage characteristics of the metal hydride tank during absorption and desorption were measured during the winter season by using the thermalizing circuit of circulating tap water at 5.3°C (Figure 2.5). The total reversible hydrogen capacity as measured between 1.2 and 27 bar was 15.2 Nm^3 (14 Nm^3 in alloy, 1.2 Nm^3 of compressed hydrogen in free volume). This quantity is similar to that of other metal hydride based PV hydrogen storage systems, but falls short by about 20% from the total capacity of 19 Nm^3 as stated by the supplier. Likely reasons for this discrepancy are the difference between total and reversible storage capacity, aging, and the partial passivation of the metal hydride alloy due to contamination by impurities in the hydrogen gas during the past four years of operation. As expected, the failure to use the thermalizing circuit during normal operation reduced the actual storage capacity of the metal hydride tank further.

The tank is connected to a hydrogen-powered stove for cooking and a laundry machine (no longer in operation), and can be used to charge a mobile metal hydride storage tank in a minibus (Picture 2.6) having similar nominal characteristics (16 Nm^3 capacity at room temperature and 40 bar pressure, 3 bar desorption pressure at -20°C). This application has not been analyzed to date.

4. INTEGRATION OF COMPONENTS

According to the owner and the engineer who set up the interconnection of the distinct units and the regulation, significant effort was expended for component integration and regulation adapted to dynamic solar production including:

- Construction of a specific DC-DC maximum power point tracker for coupling of PV field with electrolyzer or batteries and short cutting of initially integrated AC-DC converter in electrolyzer.
- Adaptation of purification unit to intermittent hydrogen production.
- Design of an electronic regulator for the electrolyzer and downstream units, compatible with variations in solar insolation.

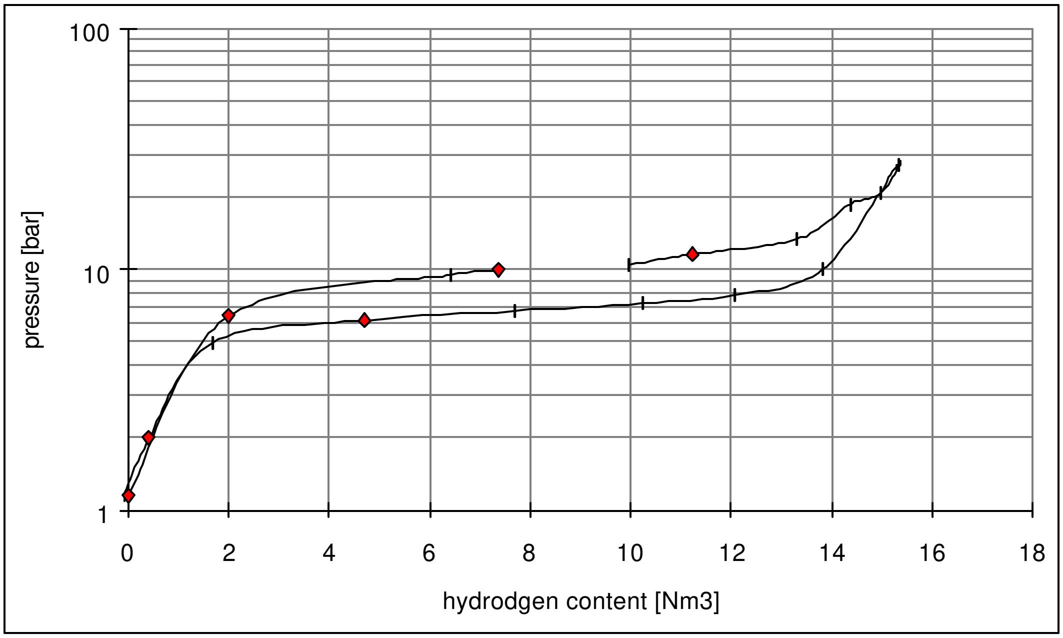
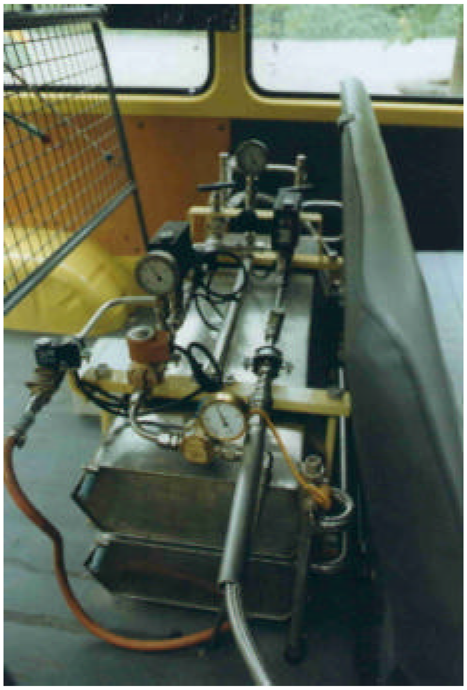


Figure 2.5: Pressure-composition isotherms of in-house metal hydride tank during absorption (upper curve) and desorption (lower curve) at 5.3 °C.



Picture 2.6: Metal hydride storage tank in minivan.

5. OPERATIONAL EXPERIENCE AND PERFORMANCE

5.1 Daily performance

The performance of the system was evaluated by in-situ measurements during 3 summer days in 1996. Relevant data for one day (July 26) are presented in Figures 2.6 and 2.7.

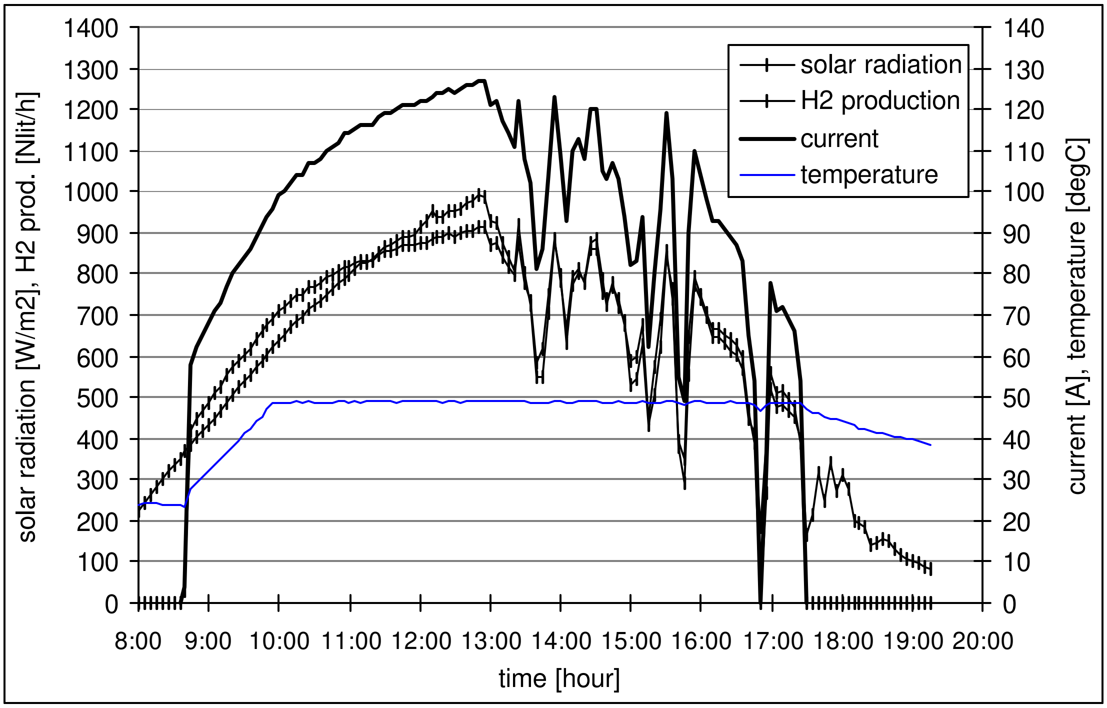


Figure 2.6: Hydrogen production on July 26th 1996.

Figure 2.6 shows the evolution of the insolation, hydrogen production, PV current and electrolyte temperature as a function of time. The weather conditions were sunny in the morning and cloudy in the afternoon. The measurements started at 08:00. The hydrogen production started at about 08:45 when the threshold setting of the electrolyzer (55 A, ~380 W/m^2 solar radiation) was met, and increased continuously as a function of time and insolation until noon. Note that the gross hydrogen production by the electrolyzer shown here was not actually measured, but calculated from the electrolyzer current, unlike the net hydrogen production after purification, which was measured by pressure differential in the intermediate storage tank. The electrolyzer temperature increased for about 1¼ hours until it stabilized at about 50°C at 10:00. The first clouds appeared around 13:00 and lead to strong variations in the electrolyzer current, including a complete switch-off of the electrolyzer shortly before 17:00, followed by an almost immediate switch-on, with the final switch-off around 17:30.

Relevant data for storage are presented in Figure 2.7. When the pressure in the intermediate storage tank reached 1.9 bar, the compressor switched on and the hydrogen was transferred into the metal hydride storage tank. At the upper pressure limit of the hydride tank, hydrogen was vented into the air.

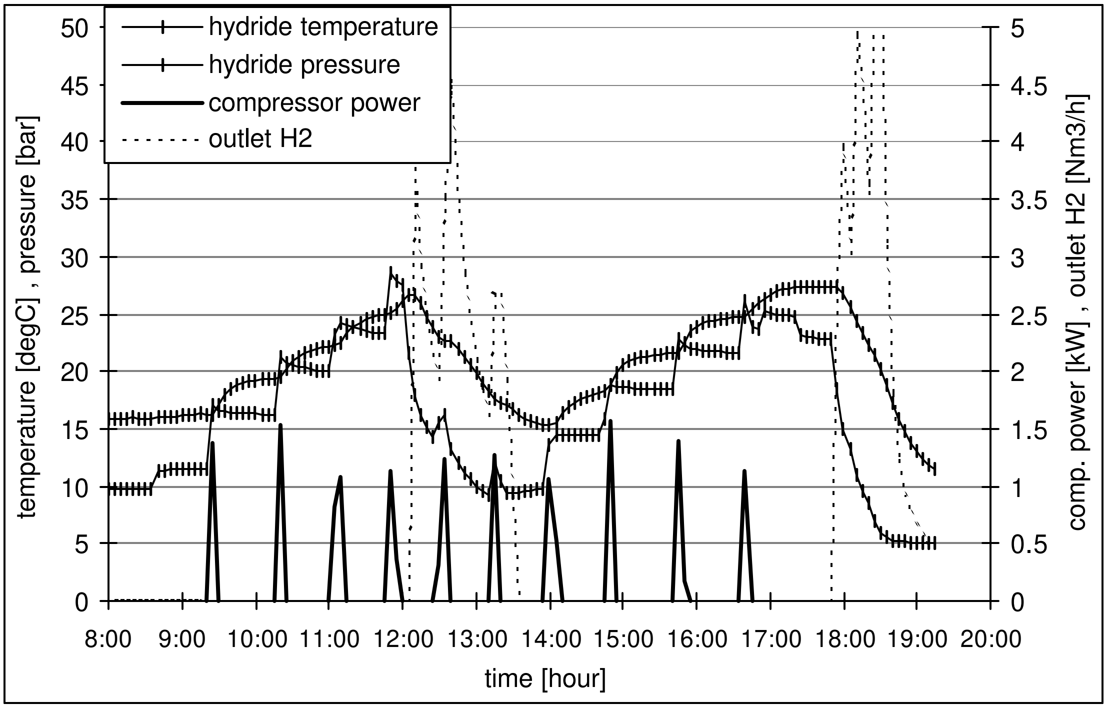


Figure 2.7: Hydrogen storage on July 26th 1996.

The graphs show the temperature and pressure in the hydride storage tank, the compressor power, and the rate of hydrogen venting as a function of time. During that day, the compressor switched on 10 times, corresponding to a total hydrogen production of about 6 Nm³. The temperature of the hydride bed increased from 15°C in the morning to 28°C at noon, while the pressure increased in intervals of about 1 hour stepwise from 10 to 30 bar, thus requiring a first venting of hydrogen at noon. A similar evolution was observed in the afternoon, requiring a second hydrogen venting in the evening. The total amount of vented hydrogen was 7.3 Nm³ (including H_2 production from the preceding day), which is largely below the measured total capacity of the metal hydride tank (15 Nm³). The failure to store the daily total production of hydrogen is due to the incomplete desorption of the metal hydride bed at the beginning of the measurements, and the inertia of heat transfer during absorption and desorption due to the failure to use the thermalizing circuit during operation. A summary of the system performance on that day and a comparison with the performance on two other summer days are shown in Table 2.6.

Table 2.6: Daily performance on 3 consecutive summer days.

Date	period of production	insolation total	insolation during production	Photovoltaic Gross[1]	Photovoltaic net [2]	Hydrogen Gross [3]	Hydrogen net [4]
	[hours]	[kWh/m^2]	[kWh/m^2]	[kWh]	[kWh]	[Nm^3]	[Nm^3]
26.07.96	8.8	6.6	6.1	(missing)	27.8	6.2	5.9
27.07.96	3.4	3.3	1.6	7.2	6.4	1.5	1.4
28.07.96	5.2	3.9	3	13.1	11.4	2.7	2.5

1) before DC-DC converter ; 2) after DC-DC converter ; 3) before purification ; 4) after purification

5.2 Disaggregation of instantaneous production

Measured efficiencies of the various system components allow for construction of a synthetic input/output diagram of hydrogen production as a function of solar radiation. Results are shown in Figure 2.8. For summer the resulting model is:

- Gross PV efficiency (before control unit) has a basis value of 9.7% with a decrease of 0.28% per 100 W/m^2 insolation, due to heating of cells.
- Net PV power is reduced by 4% due to energy losses in the control unit.
- Due to increase of ohmic losses with electrical power (see also electrolyzer U/I curve in Figure 2.4), gross hydrogen production efficiency falls from 66% at start-up threshold to 60% at maximum power. Yearly average is 62%.
- Net hydrogen production is reduced by 8% for regeneration of the hydrogen purification unit.

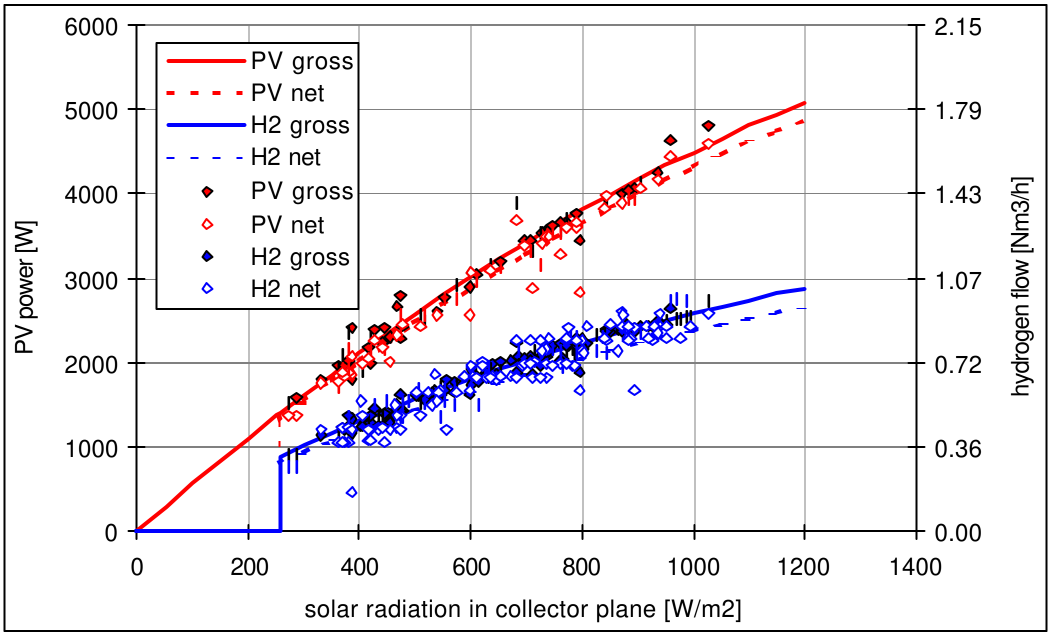


Figure 2.8: Summer input/output diagram (PV power and hydrogen production rate versus radiation in collector plane) and synthetic comparison between in-situ measurements in 5-minute steps (data points) and regressions (lines)

5.3 Simulation of yearly production and storage potential

Yearly hydrogen production potential was simulated using standard hourly meteorological data (temperature, incident solar energy) from a nearby meteorological station (Bern, 25 km away). Gross PV is derived using the computer program PVSYST as a more precise alternative to the mean seasonal efficiencies, while the other variables (PVnet, H_2gross, H_2net) are calculated in the same manner, as discussed earlier. The auxiliary power needed from the grid is evaluated by adding the steady power requirements of the control unit and the electrolyzer, the variable requirements of the purification unit during heating and at equilibrium, and the cyclic requirements of the compressor. Results are summarized in Table 2.7.

With a yearly total incident energy of 293 GJ and 65 m^2 PV panels (i.e. 4020 MJ/m^2/year, corresponding to 1540 hours of sunshine with a direct incident radiation greater than 200W/m^2), some 24.5 GJ of gross electric energy (23.4 GJ of net energy after the DC-DC transformer) are left for subsequent uses, corresponding to an average PV efficiency of 8.4%. Of the gross electrical energy available, only 18.6 GJ are powerful enough to drive the electrolyzer, while the rest (4.9 GJ) are stored in batteries and/or injected into the grid to compensate the auxiliary power (3 GJ) needed to operate the various components. From the 18.6 GJ used for water splitting, some 1148 Nm^3 (11.5 GJ) hydrogen gas are obtained per year (average electrolyzer efficiency of 62%), of which 1056 Nm^3 (10.6 GJ) remain after hydrogen purification and regeneration. This corresponds to an energy equivalence of about 300 liters of fuel and a hydrogen production potential of about 16 Nm^3/m^2 of PV panels per year.

Table 2.7: Yearly hydrogen production potential

	Energy		Hydrogen	
	[GJ/yr]	[MJ/m^2/yr]	[Nm^3/yr]	[Nm^3/m^2/yr]
solar power:				
solar radiation	292.7	4491	29134	447.1
PV gross (after panels)	24.5	393	2546	39.1
PV net (after DC-DC converter)				
to electrolyzer	18.6	286	1854	28.4
to batteries/grid	4.9	75	489	7.5
Total	23.5	361	2343	35.9
Hydrogengross (after electrolyzer)	11.5	177	1148	17.6
Hydrogen net (after purification)	10.6	163	1056	16.2
auxiliary power:				
DC-DC transformer	0.95	15	95	1.45
Electrolyzer	0.69	11	69	1.05
Dryer	0.51	8	51	0.78
Compressor	0.81	12	80	1.23
Total	3	45	294	4.5

The fraction of PV power stored in the form of chemical energy (hydrogen) thus amounts to 43%, while the net storage in the batteries and/or injection into the grid amounts to 8%, for an overall efficiency of 51% (electricity to storage energy). The total losses are 49%, comprised of 12% injected into the grid to compensate auxiliary energy use, 4% for DC-DC conversion, 29% for electrolysis, and 4% for purification. Thus the early average efficiency of the system for converting solar energy into chemical energy for seasonal storage is 3.6% (0.43 x 0.084), which is about 30 times bigger than that of photosynthesis.

As preceding analysis shows, performance of the present installation compares quite well with that of other PV hydrogen production plants.

Although operated only intermittently, hydrogen production has been running without major problems over some 7 years now. The sole major accident, at the beginning of the project, was due to carelessness during refilling of KOH into electrolyzer, which induced a short circuit that damaged the cell stack. Major shut down periods were only necessary for development and integration of the electronic regulation system of the hydrogen production and storage process.

The system nevertheless still lacks some minor, but nevertheless essential, optimization for long-term hydrogen production and storage:

- Installation of an automatic control unit, dependent on storage capacity: replacing the actual manual selection of the storage mode (hydrogen/batteries/injection into grid) would allow operation of the installation in absence of house inhabitants and thus increase efficiency.
- Increase of the hydrogen storage capacity: the estimated amount for seasonal hydrogen storage (~ 200 Nm^3 hydrogen gas, assuming a uniform consumption over the year) requires storage capacity that is ten times bigger.

Although not essential for long-term storage, replacement of the hydrogen purification unit by one that does not consume hydrogen would also significantly contribute to an increase in the net hydrogen production.

6. SAFETY

Safety measures were implemented at the following levels:

System layout:

> Subsystems containing significant amounts of gaseous hydrogen are located in a light shelter separated from the production and final hydride storage room.

Production control:

> Regulation cuts hydrogen production when certain parameters exceed minimum/maximum thresholds. These include pressure in the production system (electrolyzer, purification) and the intermediate and final storage units, water level in the electrolyzer H_2/O_2 columns, and purity of H_2 production.

Alarm:

> When sensors near the production system and appliances detect hydrogen concentrations in air exceeding 0.1%, the alarm flashes and sounds an audible signal. Production is halted.

A manually operated alarm button allows evacuation of the hydrogen from the production and intermediate storage units.

7. ENVIRONMENTAL ASPECTS

An investigation of environmental implications of hydrogen-gasoline propulsion in the minivan was conducted in collaboration with the Swiss federal laboratories for materials testing and research (EMPA, Dübendorf) and will soon be presented in the frame of a diploma thesis at the Université de Genève.

8. FUTURE PLANS

From the point of view of practical application, integration of the plant into a one family house makes this facility particularly interesting. Interconnection with battery storage for household appliances furthermore optimizes rational use of photovoltaic electricity, which can also be used when PV power is below the electrolyzer threshold. With the experience gained, institutions involved in energy issues are now being approached for funding of the necessary optimization still to be done, as well as for monitoring and analysis of long term operation.

Parallel to this real scale work on a demonstration facility, a techno-economical analysis of the photovoltaic hydrogen production path on an industrial scale has been initiated by an interdisciplinary group of the Université de Genève.

Chapter 3

ALEXANDER T. STUART RENEWABLE ENERGY TEST SITE

1. PROJECT GOALS

The goal of the project was to develop a workable photovoltaic (PV) hydrogen generator suitable for use in alternative energy systems, research systems, and meteorological systems. The first phase of the project, started in May 1991, was to demonstrate a PV-hydrogen generator using Stuart Energy's ***UNICELL-CLUSTER***™ concept. ***UNICELL-CLUSTER***™, a trademark of Stuart Energy Systems Inc., refers to direct coupling of the electrolyser cells to the photovoltaic power source wherein the "current sink" current-voltage characteristic of the electrolyser is matched with the "current source" current-voltage characteristic of the photovoltaic array. The site also tested the general system design and controls needed for intermittent operation. The unit is located on the roof of Stuart Energy's manufacturing plant in Toronto, Canada (Picture 3.1) and has been operating under the full range of climatic conditions experienced at this location, where the typical annual temperature range is –25° to 35°C. The site has been used as the basis for design of scaled up versions of the system including a similar demonstration system at the University of Florida Solar Centre Cocoa Beach, Florida, USA (1993); a 3-kW photovoltaic hydrogen vehicle refueling station at the University of California Riverside, USA (1994); a 40-kW solar hydrogen plant as part of the Clean Air Now! solar hydrogen project in El Segundo, California, USA (1996); and a 5-kW solar-wind powered generator supplied to Desert Research Institute in Reno, Nevada, USA (1998). Over the past seven years, the project has also served as a test bed for various components.

Picture 3.1: Photovoltaic Array of the Renewable Energy Test Site

2. GENERAL DESCRIPTION OF PROJECT

The A.T. Stuart Renewable Energy Test Site (RETS) located at Stuart Energy Systems (SES) Inc. in Toronto has been operating since May 1991. Located on the roof of the SES factory, the system was built to demonstrate a simple low cost renewable hydrogen system (Picture 3.2). In its current configuration, a 2.45 kW (peak) PV flat panel array provides 12 V_{DC} (nominal) to an electrolyser consisting of a cell bank of six “meteorological” type electrolysis cells. The oxygen produced by the electrolysis process is vented and the hydrogen gas fills a gas holder, which supplies a small single stage air-cooled compressor. The hydrogen is compressed to 7 bar and stored in a small tank. A separate PV array charges batteries, which provide power to the control system and the compressor motor.

Picture 3.2: The Alexander T. Stuart Renewable Energy Test Site

The initial installation of the equipment was performed by the Energy Projects Group of The Electrolyser Corporation Limited, the parent company of Stuart Energy Systems Inc. The cost of the project was shared between The Electrolyser Corporation Ltd., and the Ontario Ministry of Energy under contract 600186. Funding from Natural Resources Canada under SCC Contract No. 23440-5-143/001/SQ, provided operating support for the plant over the period of 1996-1998.

3. DESCRIPTION OF THE COMPONENTS

3.1 Photovoltaic Array

The photovoltaic array is made up of fixed orientation Siemens Type M54 panels in six skids of 8 panels configured to give an output of 11.7 V at 220 A (2.5 kW). The orientation is due south at an inclination angle of 45 degrees. The latitude of the test site location is approximately 44 degrees N. Blocking diodes were removed from the panels to reduce unnecessary voltage drops. Connection to the electrolyser was made using copper bus bar.

A second PV array (420 W at 24 V) is used to a charge a bank of lead acid batteries. The battery bank is used to power the compressor and controls.

3.2 The Electrolyzer

The electrolyser, supplied by The Electrolyser Corporation Ltd., consists of 6 SM-4 meteorological cells connected in series. The peak current rating of the cells is 250 A. The cells are two-plate unipolar design with a capacity of 19 liters of electrolyte per cell.

A water seal, operating in the range of 2-8“ WC (water column), is used to maintain equal pressures in the two cells. There are no electrical controls on the electrolyzer. The cells are batch fed from a head tank located above the cells.

3.3 Gas Storage Systems

Oxygen is vented to atmosphere at the water seal. The hydrogen is collected and fed to a gas holder. The gas holder acts as an accumulator. When the gasholder fills, a trip switch turns on a single stage air-cooled oil lubricated compressor. The capacity of the compressor is 0.03 m^3/min at 0.2 kW. Power to the compressor and the controls is provided by a separate PV array. Hydrogen is stored in a tank having a capacity of 17 Nm^3 at 7 bar.

4. INTEGRATION OF COMPONENTS

4.1 Matching Components

Ideally, in matching the two systems, the voltage variation of the electrolyzer which depends on the insolation should coincide with the peak power curve of the photovoltaic power source. By adding or taking away an electrolysis cell, the coupling of electrolyzer to PV array was studied. Both under-coupled modes and over-coupled modes were investigated. In the “under-coupled“ case, the electrolyzer is current limited by the current that the array can produce for any given level of insolation. In this case, the voltage/current of the system lies to the left of the PV-array maximum power point operating curve (Figure 3.1). In the case of over-coupling, the electrolyzer is “voltage limited,“ the voltage-current curve is to the right of the maximum power point operating curve. Based on the operating experience, the highest production occurred in the over-coupled state. This is primarily due to the improved cell efficiency of the system. An over-coupled system would increase the number of cells and reduce the current density, thereby raising cell efficiency.

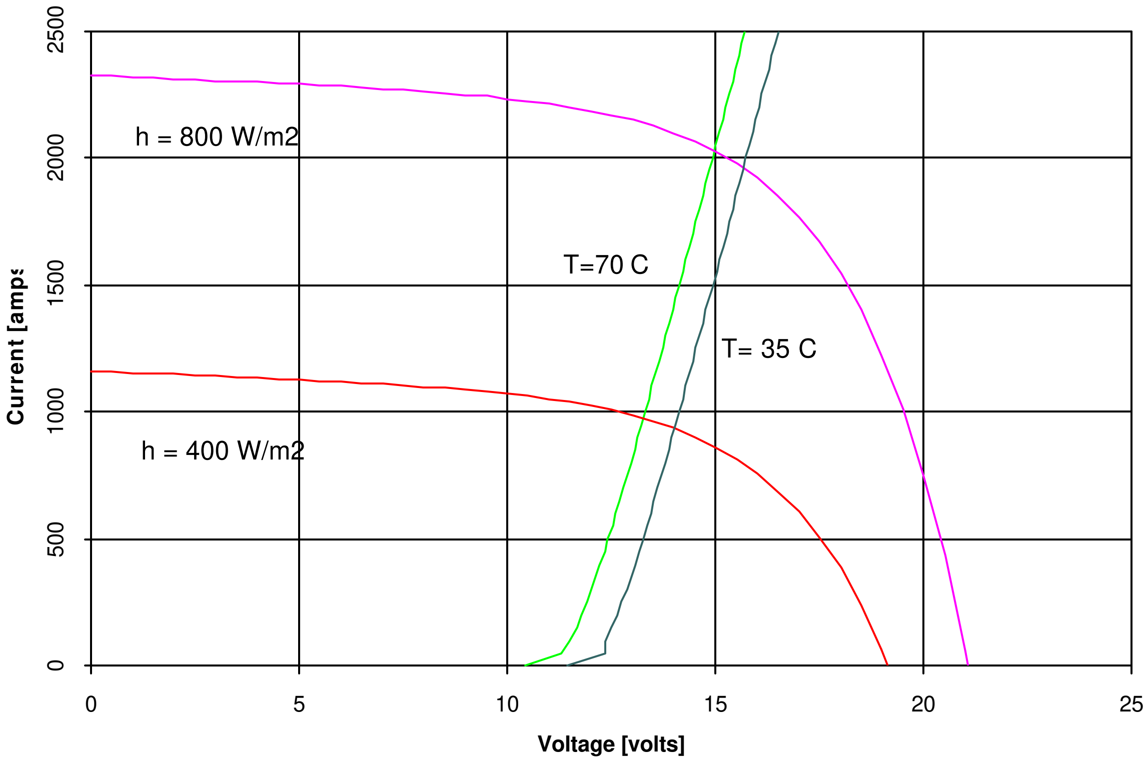


Figure 3.1: I-V Curves for PV-electrolysis integration at two values of insolation for two temperatures of the electrolyzer

4.2 Basic Schemes of Plant

The basic process elements and process flow are described in the attached drawings (Figures 3.2 and 3.3) for the gas generator and hydrogen compression system.

4.3 Plant Control

The controls of the electrolyzer are relatively straightforward and largely rely on mechanical systems. Water level control in the cells is manual, the cells having sufficient headspace to operate seven days without refilling during sunny periods. Because water additions are made directly to the cell and the concentration of KOH in the electrolyte is around 30%, the cells can operate over the temperature range experienced in Toronto, as low as –25°C.

Pressure is balanced using a water seal, which can vary between 2 and 8“ WC. The oxygen stream is vented and the hydrogen stream fills a gas holder that floats on a water bath. Limit switches on the gas bell control operation of the compressor. A check valve on the discharge of the compressor maintains a small back pressure on the compressor. When the storage tank is filled a high pressure switch stops the compressor, and the system vents through the water seal. A low-pressure switch at the inlet to the compressor insures that the pressure is positive at the suction of the compressor. The storage tank is fitted with a relief valve.

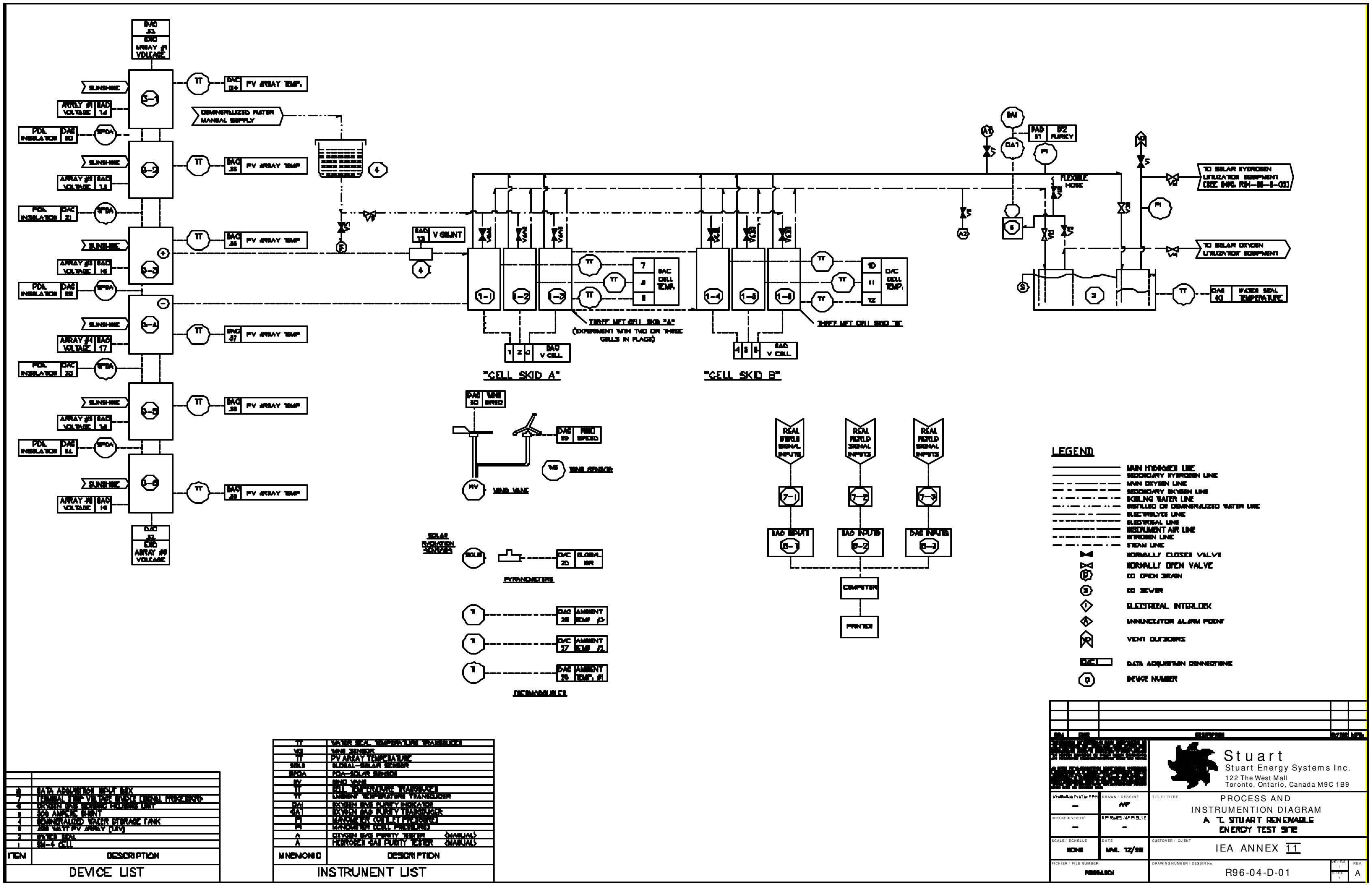


Figure 3.2: Process and Instrumentation Diagram for Hydrogen Generation Subsystem

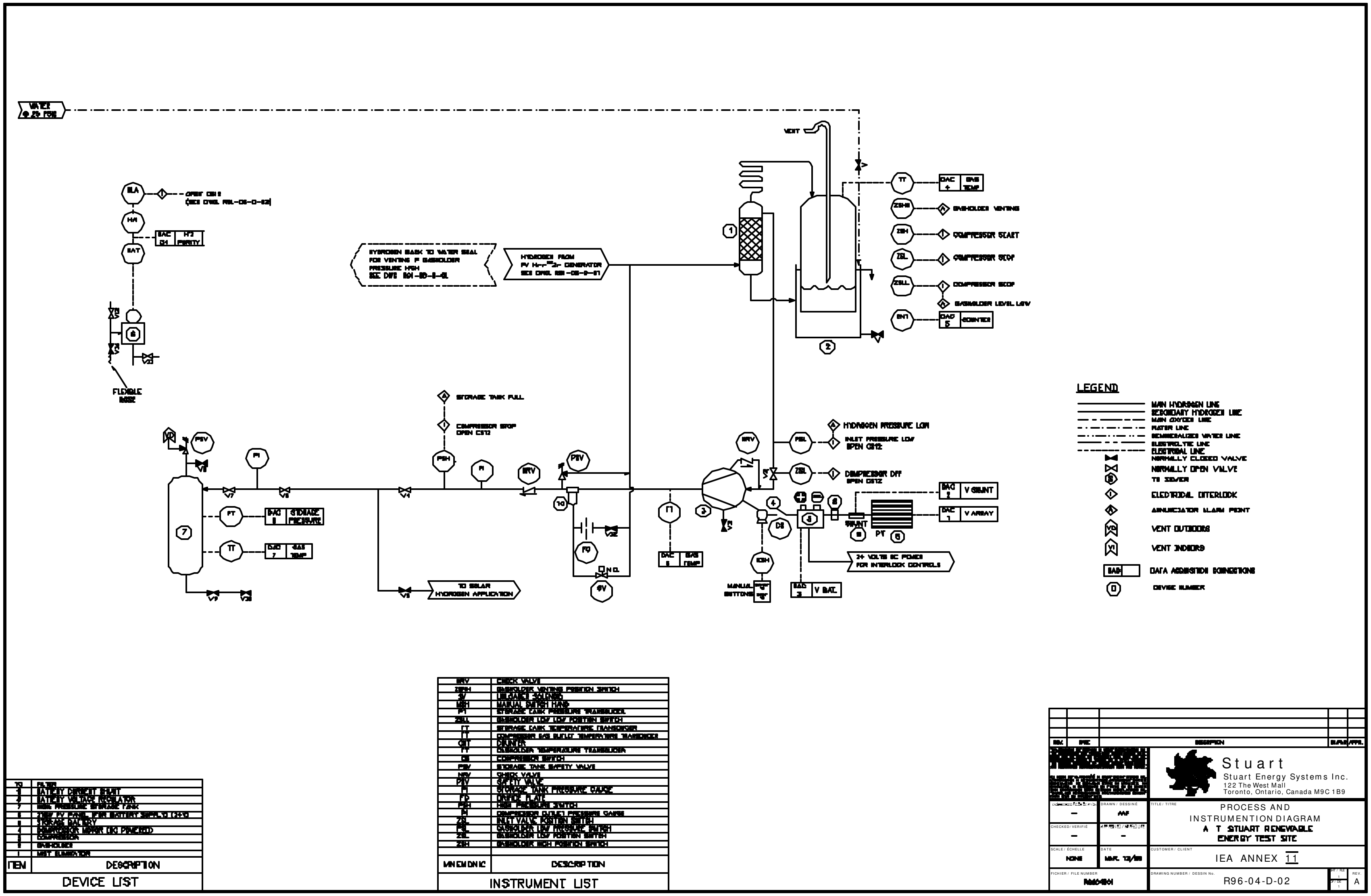


Figure 3.3: Process and Instrumentation Diagram for Hydrogen Compression and Storage

Gas purity is checked manually, once per month, using a catalyst-type gas purity sensor designed and supplied by The Electrolyser Corporation Ltd.

5. OPERATIONAL EXPERIENCE AND PERFORMANCE

Although intended to run unattended, some maintenance of RETS is required. Regular maintenance includes filling of cells with de-ionized feedwater, ensuring the water seal and gas holder are filled with water, checking for leaks, checking that the control system is operating, monitoring the pressure level at storage, and periodic checking of electrolyte concentration and gas purity.

In addition unscheduled maintenance has been required. Work performed over the period of Annex 11 (1996-1998) included:

- cleaning corrosion from the copper bus bar connecting the PV array to the electrolysis cells
- restoring electrolyte concentration in the cells
- replacing the compressor
- replacing the hydrogen inlet low pressure switch
- replacing batteries with traction type 6V.

The RETS plant is partially shut down during the winter since the compression system is not designed to operate in freezing conditions. Data were collected on all parameters even though hydrogen was not being compressed and delivered to the storage tank.

The performance of the RETS is described in various reports. A typical power/insolation curve for a summer day is shown in Figure 3.4. The power absorbed by cells (P_{cells}) follows the insolation as expected. The power discharged by batteries (P_{batt}) shows three spikes corresponding to operation of the compressor at three discrete intervals. The system efficiency from solar energy to hydrogen gas is around 7% (LHV).

6. DATA ACQUISITION

A computer controlled data acquisition system collects key operating data from RETS and displays it on a computer screen as well as stores it permanently on computer disk. The data can be imported into an Excel spreadsheet for analysis. The following parameters are measured:

- plane of array insolation
- main bus bar voltage loss
- array bus bar voltage loss
- wind speed
- single electrolyser cell voltage
- electrolyser cell bank voltage
- array current
- charging array voltage
- battery voltage
- battery current

- ambient temperature
- cell temperature
- array temperature
- compressor outlet temperature.

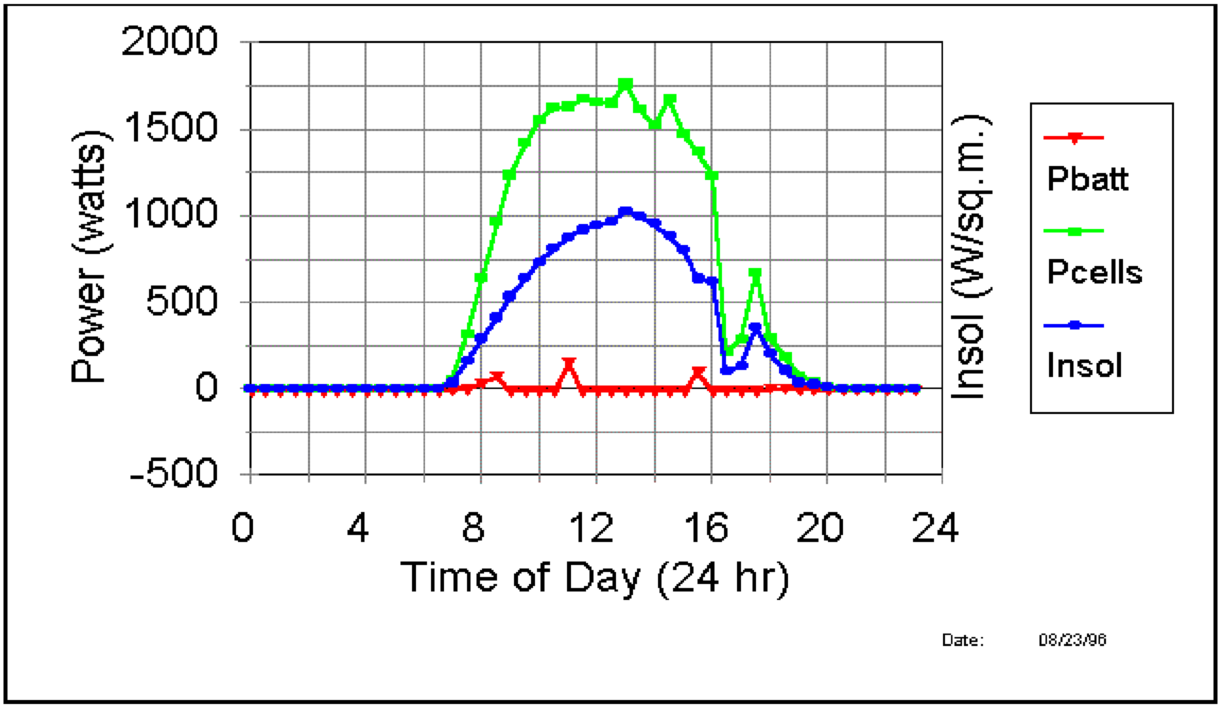


Figure 3.4: Power and Insolation Curves at RETS

The data are recorded every 10 min. Spreadsheet programs provide data analysis and presentation capabilities (see Figures 3.5 and 3.6).

7. SIMULATION

The performance of the cells and compressor were modeled with the equations in Annex 11 Subtask B. A comprehensive simulation of the entire system has not been performed.

8. ENVIRONMENTAL ISSUES

No environmental issues have arisen during this project; the only emissions are oxygen and water vapor. Essentially the unit operates as a “zero-emission“ hydrogen generator. Trace amounts of oil carryover from the compressor are collected in the storage tank and passed on to downstream applications.

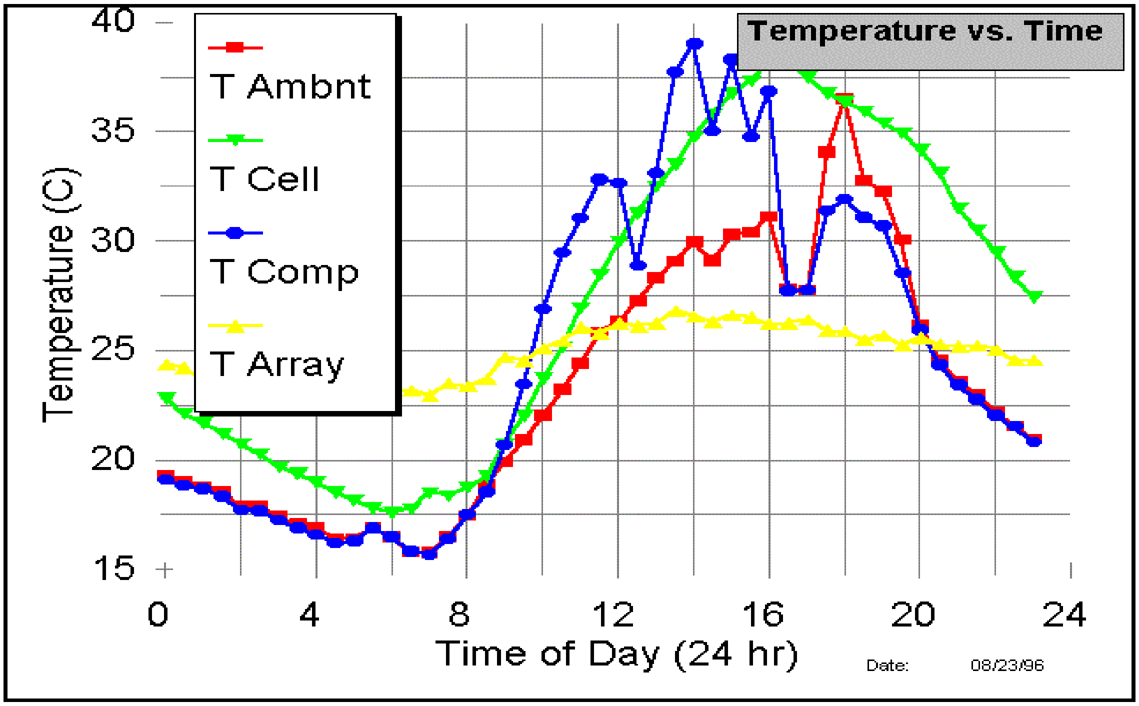


Figure 3.5: RETS Temperature Data

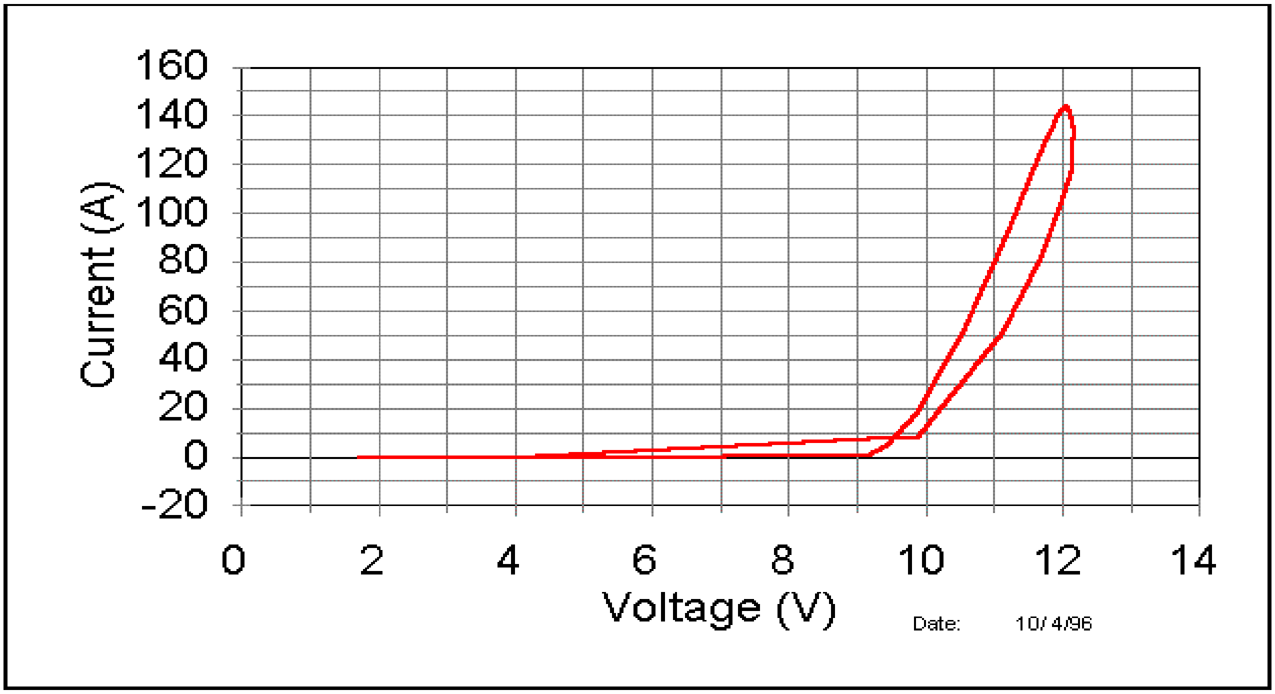


Figure 3.6: PV Array Current vs. Voltage

9. PUBLIC ACCEPTANCE AND SAFETY ISSUES

The system has been well-accepted by neighbors and is appreciated by visitors to the site. The operation of the site was approved by the Fire Branch of the Ministry of Commercial and Consumer Relations of the Province of Ontario, Canada. There have been no safety incidences reported during the seven-year period the plant has operated. Sensors for monitoring the site are not required because of the outdoor location of the equipment and the relatively small inventories of gas in the system. In general, the plant meets sound design principles for hydrogen plants: a positive pressure is maintained throughout the system, no ignition sources are permitted in areas where hydrogen may be released, and control systems prevent mixing of hydrogen and oxygen in the process.

10. OTHER EXPERIENCES

The construction and operation of this plant has provided a basis for a number of projects:

- ***UNICELL-CLUSTER***™ system at the Florida Solar Center. Similar in design to RETS.
- Riverside Solar Hydrogen Vehicle Filling station. Similar to RETS except using a four stage compressor to raise storage pressure to 345 bar.
- Clean Air Now! Solar Hydrogen Vehicle Filling Station. Using larger 5-plate Stuart cells (rated up to 4,000 A) with 15 Nm^3/h capacity, this system also uses a four-stage air-cooled compressor to compress gas to 4,200 psi.
- Solar-wind generator using a 5 kW power source. Based on the meteorological cell technology it uses a novel gas holder and water seal, which also acts as a feed water tank increasing the time interval between fills.

11. FUTURE PLANS

The current plans are to pursue the technology using the new CST (Compact Stuart) cell technology. A small wind-solar prototype is currently being tested at Stuart's Caledon Hills Test site, north of Toronto (Picture 3.3).

In pursuing commercial applications for this technology, Stuart Energy Systems is involved in a number of techno-economic studies which are examining the economic feasibility of hydrogen for energy storage to provide a continuous supply of renewable energy to small communities (Figure 3.7).

12. CONCLUSIONS

The test site has been successful in demonstrating the idea of a PV-electrolysis plant and over its seven years of operation has tested a number of different component designs. The operation of the system continues as a long-term test investigating cell life under intermittent conditions. Stuart is continuing its development of the CST cell technology and hopes to participate in the demonstration of a renewable hydrogen village energy system within the next five years.

Picture 3.3: Caledon Hills Renewable Energy Test Site

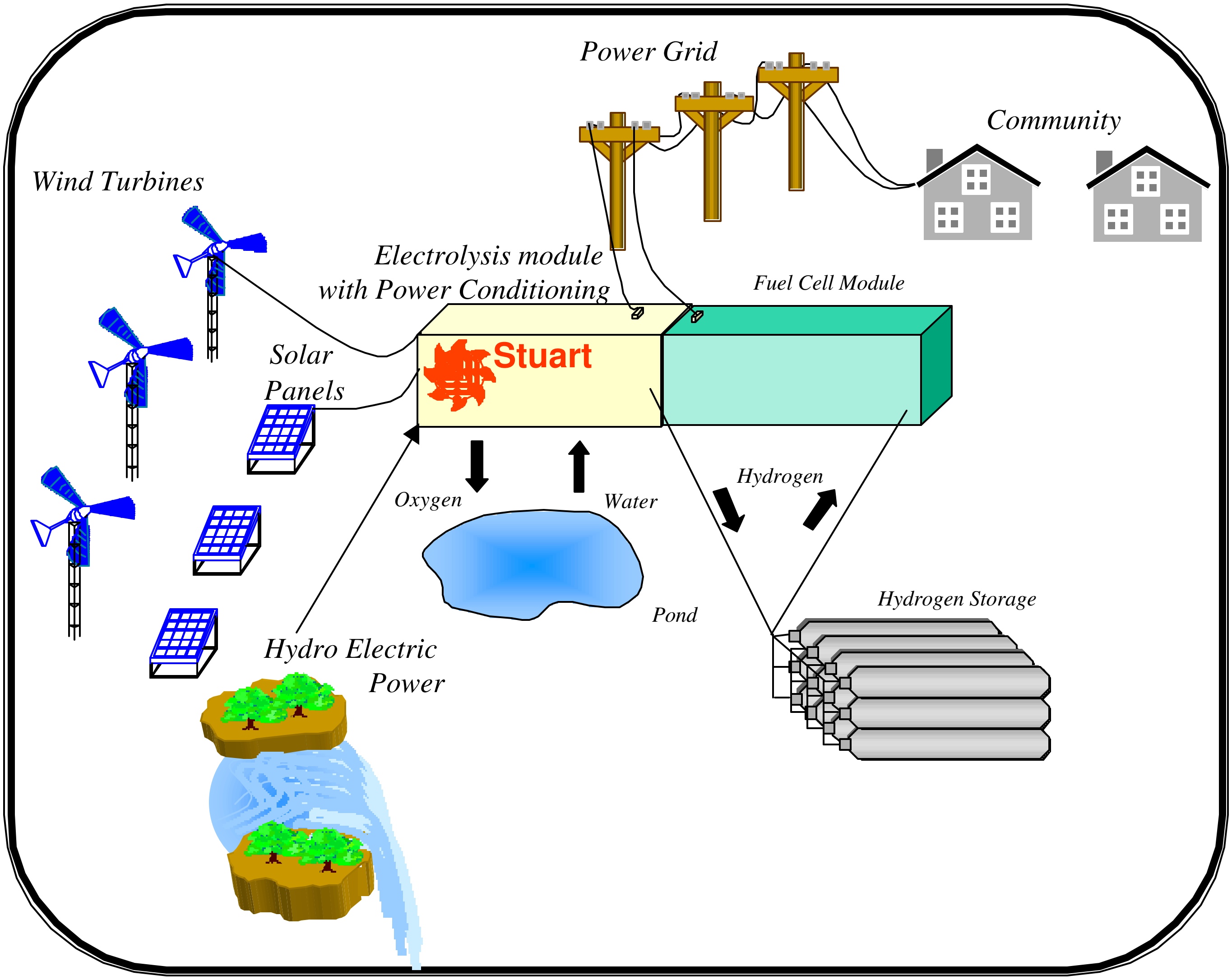


Figure 3.7: The Hydrogen Village Energy System

Chapter 4
PHOEBUS JÜLICH DEMONSTRATION PLANT

1. PROJECT GOALS

Due to the greatly varying availability and demand, future energy supply systems based on renewables will require energy storage. At present, the public grid can be used to store intermittent renewables, as long as the load penetration is low. If, therefore, larger supply contributions are to be provided from renewables, concepts of energy storage must be established for the short and long term as important system components of a regenerative energy supply. Appropriate measures for their realisation must be initiated now.

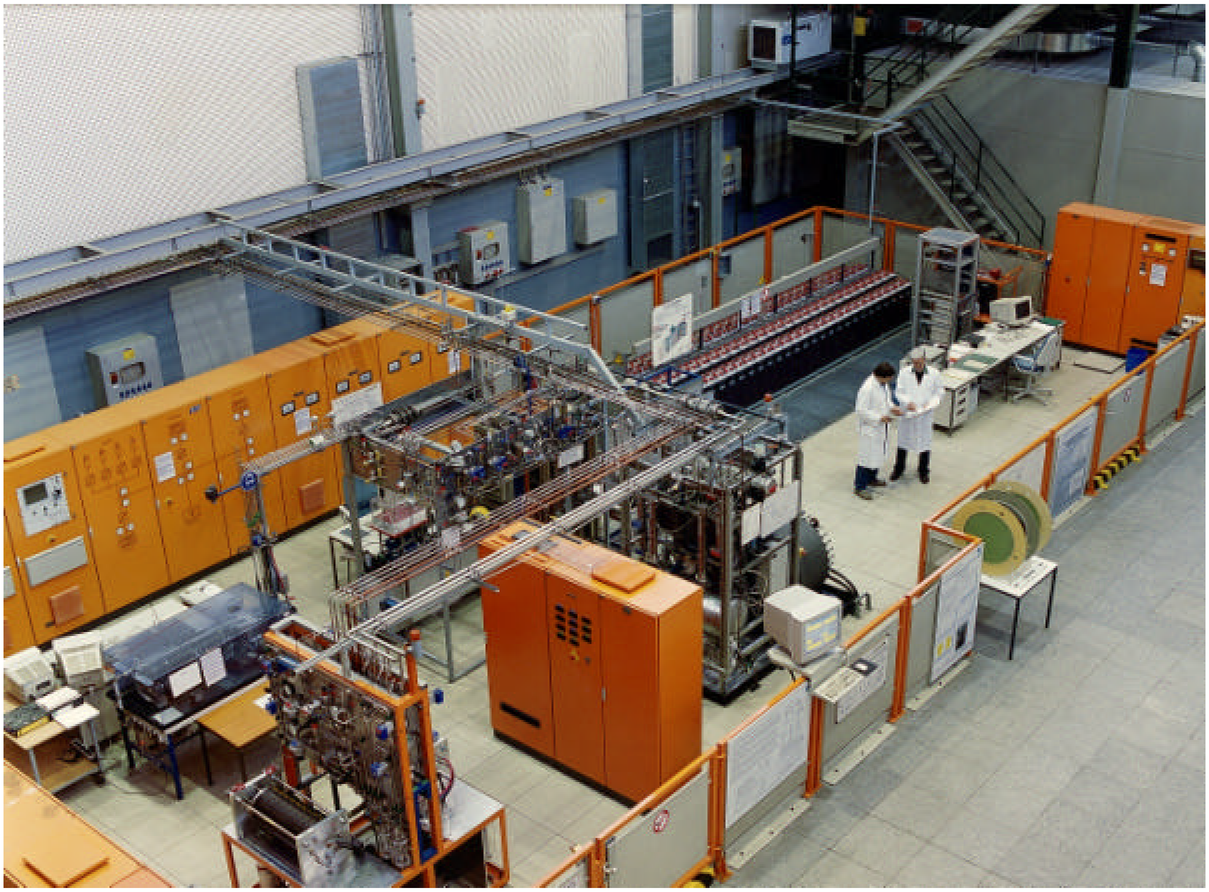
The overriding objective of the PHOEBUS project is therefore the development and testing of a solar energy supply system in combination with energy storage. The task is centered on demonstrating the supply under real solar- and consumption-specific conditions.

2. GENERAL DESCRIPTION OF PROJECT

The PHOEBUS demonstration plant has been designed to provide an autonomous solar electricity supply to the central library building of the Research Centre Jülich with an installed capacity of 38 kW_{el}. The major components of the plant in its first phase of operation are:

- A photovoltaic field with four facade and rooftop integrated generators consisting of monocrystalline modules with an active area of 312 m^2, peak power output of 43 kW_p, and an electrical energy output of 29 MWh/yr;
- A pair of DC/DC-converters (5 kW each) for each photovoltaic field, adjusting the voltage to the level given by the DC-grid which has the actual voltage level of the battery system;
- A system of 110 lead batteries of the OPzS OCSM type with electrolyte recirculation, designed for a DC-grid voltage of 220 V (200-260 V), and a capacity of 304 kWh, 1380 Ah over 10 hours;
- A bipolar 21 cell electrolyzer with an active cell area of 2500 cm^2, a current of 750 A, a current density of 3 kA/m^2, with 30% KOH solution, 80°C operating temperature, an operating pressure of 0.7 MPa and 90% efficiency in design load operation at a design power rating of 26 kW; maximum hydrogen production is 6.5 Nm^3/h and maximum oxygen production is 3.25 Nm^3/h;
- A storage system for the product gases, hydrogen (6.5 Nm^3/h) and oxygen (3.25 Nm^3/h), leaving the electrolyzer at 0.7 MPa. The hydrogen is compressed to 12 MPa and stored in 18 pressure bottles of 1.4 m^3 each with a total geometrical volume of 25 m^3 for H_2 (3,000 Nm^3 H_2). The oxygen is compressed to 7 MPa and stored in one high pressure storage unit of 20 m^3, sufficient for the whole seasonal storage requirements;
- An alkaline fuel cell system consisting of KOH gas diffusion electrode fuel cell of the Siemens BZA 4-2 type with a design power output of 6.5 kW at 48 V and 135 A, with a system efficiency at design load of 63% (LHV of H_2) and 70% at 30% partial load.

An overview of the experimental hall with fuel cell, alkaline electrolyzer, gas treatment unit, high-pressure electrolyzer (added in phase 2), battery system (from left to right) and all other subsystems (except the gas storage vessels), is shown in Picture 4.1.



Picture 4.1: Overview of the experimental hall

The central task of this project is to test the required storage system using hydrogen as the energy carrier. Combining an electrolyzer and a fuel cell with all essential system steps of a solar electricity supply, the objective is to match the system components and optimise the overall plant so that energy losses are as low as possible and high system reliability is achieved. In considering the energy flows and their conversion in the individual plant components it is important to maximise the energy yield and adapt power supply as efficiently as possible to the supply task. This requires high system engineering demands on the utilization rates as well as on the regulation and control of the individual components in a wide power range. On the whole, the tasks to be fulfilled involve a complex system composed of interlinked components of energy converters and energy stores integrated between a greatly varying solar radiation input and a consumer with load fluctuations. Moreover, account must be taken of various requirements to be met by the electrochemical components with respect to service life, operational reliability (H_2/O_2 gases), start-up and shutdown processes as well as exclusion of specific operating conditions (e.g. low-load ranges diminishing the utilisation rate, avoidance of exhaustive discharge and gassing charge of the battery, abruptly changing load).

An intelligent strategy must therefore be developed which, at any time of the day and year, distributes the energy flows to the individual paths and takes account of the boundary conditions of each system component with respect to its efficiency characteristics and its control and regulation dynamics.

It can be seen from the above requirements that entirely new standards must be applied to the system management of such a stand-alone plant, which can only be coped with by a computer-assisted energy management (EM).

The overall system development of energy storage technology relies on plant and systems engineering as well as open-loop and closed-loop control technology.

3. PERFORMANCE AND OPERATIONAL EXPERIENCE

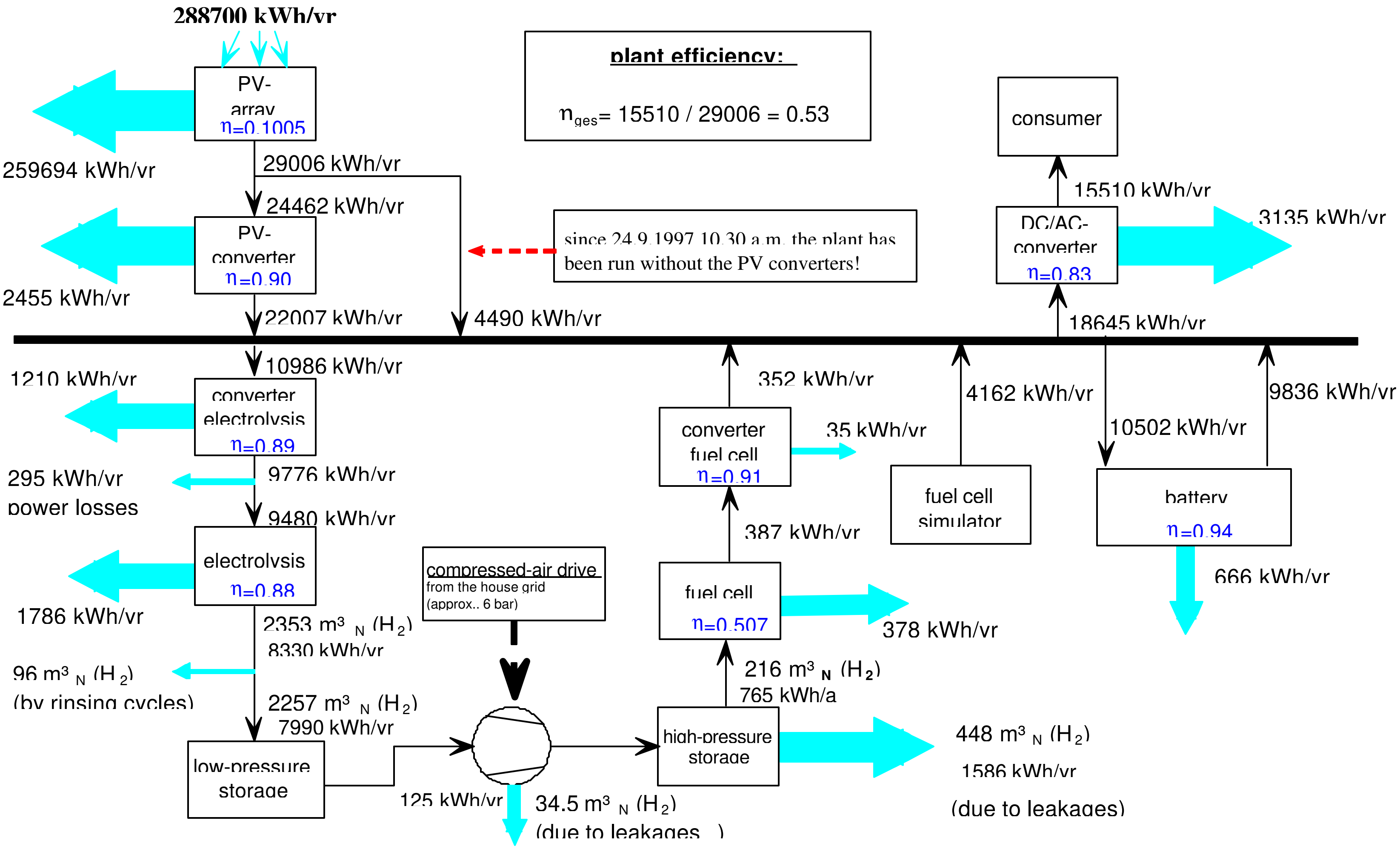
The general aim was to determine design strengths and weaknesses from the operating experience, and with the measurement data obtained, verify the models used in simulation programs, to energetically optimize the plant, to check the operational reliability and to propose and implement cost-reducing and advanced system modifications.

3.1 Results of a twelve-month operation

The energy balance for an annual scenario (1997) of PHOEBUS is shown in Figure 4.1. The energy flows and efficiencies measured were entered as annual sums or average annual efficiencies. The measurement result obtained is basically in agreement with the autonomy conditions calculated by simulation. It should be noted, however, that the energy driving the two pneumatic H_2/O_2 compressors was provided by the compressed-air grid and was not taken into account energetically, except for the leakage.

Since September 24, 1997, PHOEBUS has operated without the PV converters, i.e. the PV generators are directly coupled with the busbar and battery, and maximum power point (MPP) tracking by the converters is omitted. The results show that this step provides a positive balance compared to previous operation. Although the solar-electric energy yield decreases by 3 - 4% due to the floating power point (without MPP tracking), the conversion losses of the converter amount to 9% and the converter investment costs are eliminated. An increase of the battery voltage by 18 V (9 cells) would even further improve the performance.

A weak point in the storage system continues to be the fuel cell. The operation of the alkaline fuel cell (AFC) suffered from failures which were inherent in the system: failure of the electrolyte pumps, disturbances in the control electronics caused by failure of sensors measuring temperature, current and voltage, and leakages in the gap evaporator led to increased electrolyte concentrations in the cooling water and required a frequent supply of additional potassium hydroxide. The stored H_2 and O_2 gases could thus only be used to a minor extent. In order not to disturb plant operation by the failure of the fuel cell, the so-called "fuel cell simulator" switches itself on in this case. This is an AC-DC converter, which takes over the function of the fuel cell in conformity with power requirements so that autonomous operation continues to be ensured. On the whole, the fuel cell produced an electric energy of 387 kWh in the period under investigation. With an average power of 4 kW the fuel cell was thus in operation for 97 hours. This low availability was compensated by the "fuel cell simulator" supplying an amount of energy of 4162 kWh from the grid. In terms of control technology, there was no difference between the fuel cell and simulator.



plant efficiency:

η_{ges} = 15510 / 29006 = 0.53

since 24.9.1997 10.30 a.m. the plant has been run without the PV converters!

Figure 4.1: Measured energy balance of PHOEBUS Jülich plant in 1997

The balancing of plant operation was effected by the acquisition and storage of more than 200 data monitoring points measured by the sensors at intervals of one second. This includes checking of the data for plausibility with several computer programs, reducing them, forming the corresponding mean and summation values and considering data dropouts. The data are used to determine and balance the material and electrical energy flows, and power levels and efficiencies on all paths of the system from solar radiation input up to the consumer. The data are displayed graphically as time-variation curves or cumulative distributions for arbitrary periods of time.

An example of the comparison between measured values and simulation results for the efficiency of the total photovoltaic system (summed over all 4 fields) is given in Figure 4.2.

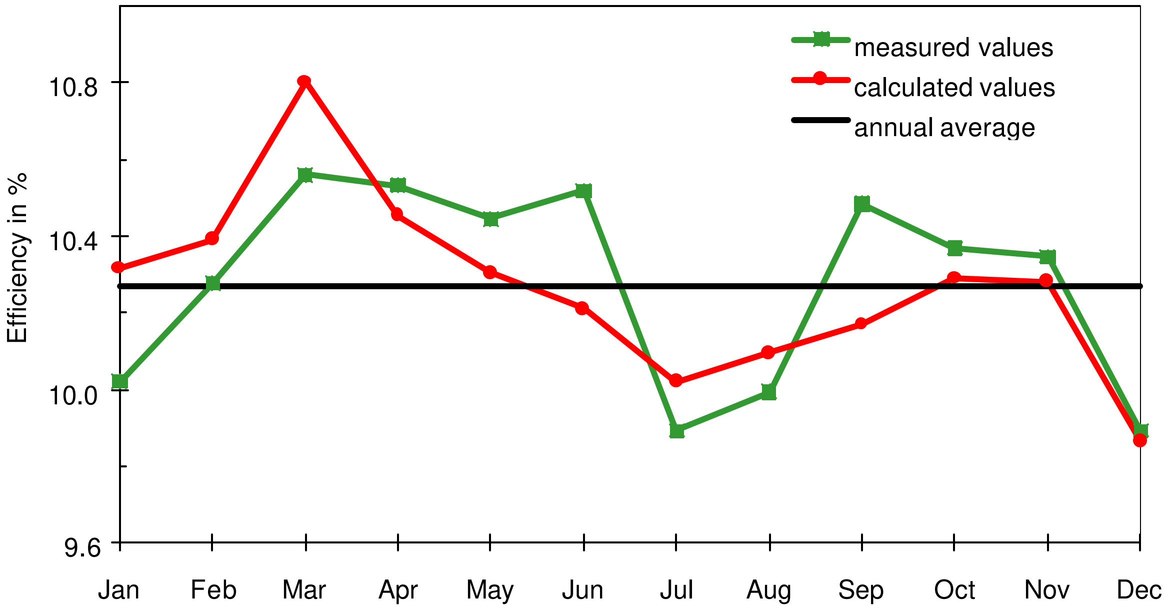


Figure 4.2: Efficiency of the photovoltaic system

3.2 Development of new system components

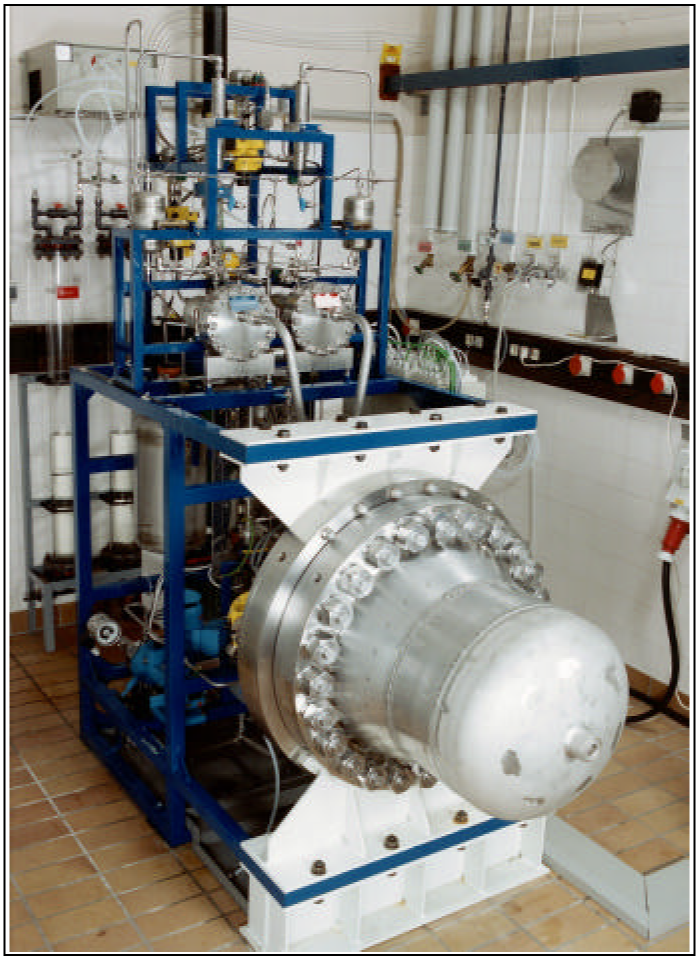
A priority task was the joint development of a fuel cell based on the proton-exchange membrane technology (PEMFC) for use in PHOEBUS with Sammer, USA. Work for the development, construction and testing of two 2.5 kW units was largely completed and the units were incorporated into the PHOEBUS plant. The peripherals (gas supply, cooling, measurement, electrical installation, control, and power converters) of the two fuel cell stacks were installed. Initial operation was not satisfactory and further improvements were required which did not lead to success until the end of the period under investigation. Problems encountered included membrane ruptures, water management, and channel dimensions. This dashed the hope of being able to use the new PEMFC for the first time in the winter 1997/98.

The gas storage system for H_2 and O_2 was operated for the first time without failure. Thanks to the high operational reliability of the electrolyzer it was possible to fill the gas storage tank for the first time at the end of the season (2257 m^3), so that the gas quantities required for autonomous operation were available. The leakage rate (approximately 1 m^3/day) was high in the hydrogen storage tanks at high pressure levels. A total of 19% of the annual production was thus lost. It was possible to reduce leakage by improving the flange construction. The two compressors continue to be a weak point of the storage system. Although it was possible to significantly increase the lifetimes by a new coating procedure for the cylinder bearing surfaces (approximately 300 h), this means two replacements during one season!

In cooperation with the Central Department of Technology (ZAT) and the Central Electronics Laboratory (ZEL) of Research Centre Jülich (FZJ), the high-pressure electrolyzer (5 kW, 120 bar) and the two-stage solar thermal metal-hydride compressor (120 bar) were developed as an alternative to mechanical compression.

The high-pressure electrolyzer is shown in Picture 4.2. It is currently being tested. The metal-hydride compressor was subjected to a thorough practical test within the framework of a doctoral thesis (K. Bonhoff). This test has been successfully completed.

In summary, the aim of an autonomous supply in automated operation has been achieved. An efficient control system has been developed by means of well-devised energy management with battery charge as the control parameter and electrolysis and fuel cell performance as the variables.



Picture 4.2: High pressure electrolyzer in testing stand

4. SIMULATION AND SYSTEM INTEGRATION

The efficiency, control strategy, and optimum size and configuration of autonomous PHOEBUS plants are governed by many factors (load structure of electricity and heat requirements, storage concept, control, costs, site etc.), and they can ultimately only be treated by means of simulation techniques proven in practical application. Optimization analyses for plant operation (energy management) and system studies with different plant configurations were carried out with the aid of simulation programs validated by measurements in PHOEBUS. This has led to simplified and more efficient PHOEBUS concepts incorporating reduced expenditure on electrical power conditioning (omission of the three power converters) and omission of mechanical compression by the use of a high-pressure electrolyzer.

The stability and controllability of direct coupling of the PV generator with the battery, electrolyzer, and fuel cell have been thoroughly investigated and feasibility was demonstrated by simulation. The efficiency of the overall plant can be improved from 54% to 65% and an appreciable reduction in construction costs may also be expected by the omission of the converters.

The aim of a further investigation of different system concepts is to explore the possibilities of integrating regenerative energy converters in a combined heat and power package of decentralised energy supply plants and to present corresponding systems.

Initial results have shown that a number of promising system variants based on the PHOEBUS concept and using the simulation tools are conceivable. These utilize the hydrogen storage system (electrolyzer/fuel cell) presented in order to either realize a purely electrical or an electrical and thermal energy supply. It is very advantageous to use another renewable source of energy (ambient heat) and incorporate it in the PHOEBUS system with the aid of an electric-motor-operated heat pump circuit for heating or cooling purposes.

On the input side of the energy supply system, wind energy also offers itself as an alternative to or can be used in combination with PV energy. Depending on the site, a hybrid operation of both energy sources leads to a homogenization of the annual variation in energy generation. This generally leads to a reduction in storage requirements compared to operation with a single source, and long-time storage becomes entirely superfluous if energy surpluses are abandoned. Such hybrid systems also offer the possibility of adapting oneself more or less to the consumption time-variation curve by selectively choosing the nominal power of each plant with its outputs. This will then require, for example, a correspondingly higher wind generator power for covering the electric and heating energy requirements or a higher PV generator power for meeting the electric and cooling energy requirements in the case of a strictly demand-oriented heat-power/coolant coupling.

5. FUTURE PLANS

With the aid of largely validated simulation programs, optimization analyses for plant operation and plant configuration were carried out and two advanced concepts, PHOEBUS-2 and PHOEBUS-3, developed.

The PHOEBUS-2 concept involves a greatly reduced system expenditure and thus a cost reduction of the entire PHOEBUS plant. This can be mainly achieved by directly coupling the PV generator with the battery, electrolyzer, and fuel cell. In this way, the expenditure and plant losses can be reduced by omitting the power converters. The use of a high-pressure electrolyzer makes the mechanical compression of the H_2 and O_2 product gases superfluous. This leads to a further reduction of the losses on the storage path so that the overall plant efficiency can be reduced by 10% to 15% compared to the present-day plant. Initial successes in the practical application of new or extended systems seem to be achievable with this procedure.

PHOEBUS-3 was conceived within the framework of a doctoral thesis (Ch. Meurer). It has been investigated whether and how an electrical and thermal supply in conformity with demand and purely based on renewable energy can be achieved with a modified system technology. It was shown in simulation calculations that the use of ambient heat (installation of heat pumps) makes it possible not only to uncouple energy supply (PV and/or wind energy) from energy demand in terms of time and power, but also to uncouple the electrical from the thermal energy requirements (heating) in terms of time using the same storage system (electrolyzer-H_2-fuel cell). Wind and photovoltaic generators in hybrid operation prove to be particularly advantageous due to their complementary annual variation. The storage requirements are considerably reduced due to the relatively uniform annual energy production.

6. CONCLUSIONS

PHOEBUS Jülich demonstrates that an electrical energy supply with purely renewable energy without connection to the public grid is basically possible. Plant operation is fully automated. The control strategy of the plant has been constantly improved so that a developed energy management system is now available as system software. The control system optimally distributes the energy flows and completely ensures the functionality of the plant by means of monitoring systems.

It has been possible to identify weak points of the plant by simulation and measured data evaluation: The optimum system management strategies were determined for individual components using sensitivity analyses.

The weak point of the storage system continues to be the fuel cell. Despite great efforts in developing the PEM fuel cell, it has not been possible to ensure operational reliability over prolonged periods. Worldwide efforts at making these fuel cells marketable in terms of technology and costs would also mean a breakthrough for the hydrogen (or fuel) storage system and its multiple application possibilities.

As stated above, the long-term hydrogen storage system proves to be the central unit of every system variant to decouple energy supply and demand in terms of time and power, but also to decouple electric and thermal energy requirements in terms of time using the same storage system. This is above all a clear advantage compared to conventional CHP plants. Current investigations are also aimed at finding cost-optimized systems in addition to those technically optimized. This will primarily be achievable by minimizing the storage system.

The know-how required for the above tasks can be utilized in further system studies and in the conceptual design and qualified handling of new tasks and projects.

The experience of PHOEBUS, including the measurement evaluation of the plant and the results of system engineering studies obtained for the conceptual design of renewable energy supply systems, can open up new paths for the development or improvement of equipment and systems technology (PEM fuel cell, pressure-type electrolyzer, metal-hydride compressor, metal-hydride storage, H_2 safety technology, H_2/O_2 gas treatment, system modelling, energy management, control and regulation technology).

Plant costs can be further decreased with standardized system-engineering solutions and with the market introduction of electrochemical energy converters (electrolyzer or fuel cell). The opportunities for near-term market introduction are: wherever a connection to the public grid is not economically efficient (due to extremely long distances or insufficient load compatibility); where decentralised CHP plants can uncouple power and heat; reduced emissions; lower fuel costs (including transport and storage); or a specific peak load in the grid must be accommodated.

Chapter 5
SCHATZ SOLAR HYDROGEN PROJECT

1. PROJECT GOALS

The Schatz Solar Hydrogen Project began in the fall of 1989. It is a stand-alone photovoltaic energy system that uses hydrogen as the storage medium and a fuel cell as the regeneration technology. Its goal is to demonstrate that hydrogen is a practical storage medium for solar energy and that solar hydrogen is a reliable and abundant energy source for our society.

A schematic for the system is shown in Figure 5.1. It is installed at the Humboldt State University Telonicher Marine Laboratory (124.15°W, 41.06°N) and the Lab's air compressor system, used to aerate aquaria, is the load. When PV power is available, it is used directly to supply the load. Any excess power is supplied to the electrolyzer to produce hydrogen gas. When the array cannot provide electricity, the stored hydrogen serves as fuel for the fuel cell, providing uninterrupted power. If the storage is depleted, the system returns to utility power supplied by the grid.

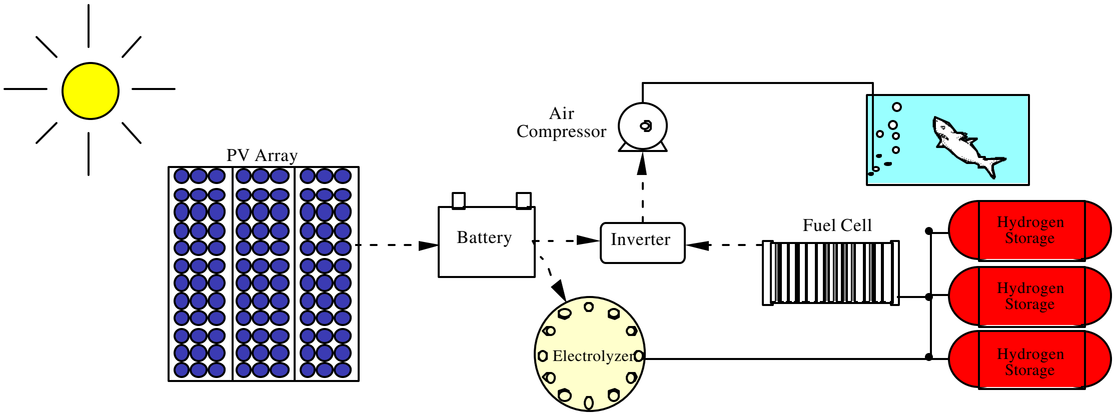


Figure 5.1: System Schematic

The objectives of the Schatz Project are:

- to assess the storage efficiency of hydrogen when used as a medium to store solar electricity
- to assess the use of a proton exchange membrane fuel cell as a means of regenerating electricity from stored hydrogen and oxygen
- to design, test, and utilize a computer based control system which will allow for efficient component integration and provide for reliable, unattended operation
- to monitor operating and environmental parameters to chronicle system performance and to allow development of a simulation model

2. GENERAL DESCRIPTION OF PROJECT

The impetus for this project came in the form of an intriguing offer from Mr. L. W. Schatz, the former president of General Plastics in Tacoma Washington. Mr. Schatz was, and still is, very interested in furthering the use of non-polluting hydrogen technology. He approached Dr. Peter Lehman in the spring of 1989 and proposed the arrangement that continues to this day wherein the Humboldt State University Engineering Department faculty and students formed the Schatz Energy Research Center (SERC). SERC's first project was to design, construct, and maintain the facility in Trinidad, California, USA. SERC has since grown into a research laboratory that employs 17 engineers, physicists, and students.

Design work began in the fall of 1989 and the PV array was installed in the summer of 1990. The building was contracted out to the McKinleyville High School Industrial Arts Class where it was designed and assembled before being installed on the site in Trinidad in the fall of 1990. The electrolyzer was installed shortly thereafter. A PEM fuel cell was obtained from Ergenics Power Systems in 1991 but a variety of problems prevented this unit from providing reliable power. Unfortunately, the company went out of business before a replacement unit could be obtained. This incident, coupled with a lack of available, affordable fuel cells induced us to manufacture our own stack.

In the fall of 1992, The Schatz Fuel Cell Laboratory was formed and began a collaborative effort with Texas A&M University to design and construct a 1.5 kW PEM cell using air as the oxidant. In December of 1994 the completed unit was installed in Trinidad. An overview of the plant is shown in Picture 5.1.

Picture 5.1: A fifth grade class visiting the Schatz Solar Hydrogen Project for an educational field trip

3. DESCRIPTION OF COMPONENTS

3.1 PV Array

The PV array consists of 192 Arco M75 modules configured into 12 independent sub-arrays. Each sub-array consists of 16 modules, wired in 8 series pairs for 24 V_{DC} operation. The sub-arrays are electrically isolated from each other by 60 A Schottky diodes. The sub-arrays are individually switchable to either the load or the electrolyzer. If not needed, the sub-arrays can be shorted; this also serves as the “safety off” configuration. The nominal power rating for the array is 9.2 kW.

3.2 Battery

The power supplied by this system must be consistent and reliable for the air compressor to function properly. Because PV modules depend entirely upon the vagaries of the weather, their output can vary substantially from second to second. For this reason we have included a small battery in the system to function as a buffer between the PV array and the inverter. This way, the battery can absorb or supplement momentary excesses or deficiencies of power from the array. This greatly reduces the need for frequent switching in and out of individual sub-arrays by the control system.

Initially, the system contained a 37 Ah nickel-cadmium (NiCd) battery. Unfortunately, this battery failed early on and had to be replaced. At this time our battery consists of four Exide GC-4, 6V, 220 Ah deep cycle golf cart batteries.

3.3 Electrolyzer

The electrolyzer is a medium pressure, bipolar, alkaline unit manufactured by Teledyne Brown Engineering. It consists of a 12 cell electrolysis module designed to deliver 20 standard liters per minute (slm) of H_2 gas at a current of 240 A at 24 V_{DC}. The module contains an electrolyte of 25% (by weight) potassium hydroxide.

It was chosen because it is the only commercial electrolyzer available in the correct size (7.2 kW maximum, 6.0 kW nominal) which supplies pressurized hydrogen, thus eliminating the need for supplementary compression.

3.4 Storage

The H_2 gas exits at 790 kPa and is stored in three steel tanks with a total capacity of 5.7 m^3. This provides approximately 133 kWh of storage at the higher heating value (HHV) for H_2 which will operate the load (600 W) for approximately 110 hours assuming a practical fuel cell efficiency of 50% (HHV). Three small tanks were selected as opposed to one large one due to local fire codes. Tanks larger than 500 gallons are subject to much more stringent set-backs from occupied structures.

3.5 Fuel Cell

A proton exchange membrane (PEM) fuel cell was chosen because of its passive operation, its high efficiency, and its ability to provide power quickly from a standby configuration. While the initial stack from Ergenics required pure oxygen at 250 kPa, the unit which we eventually developed utilizes low pressure (20 – 35 kPa) air as the oxidant. This eliminates the attendant problems and dangers associated with the use of pure oxygen.

The unit consists of 48 cells in series, each of which has an active area of 150 cm^2 , for a peak output of 1500 W. The membrane and electrode assemblies (MEA's) consist of DuPont Nafion™ 115 as the membrane and E-TEK solid polymer electrolyte electrodes with 1 mg/cm^2 platinum loading.

3.6 Inverter

We are using a Trace DR1524 inverter to convert our 24 V_{DC} (nominal) power to the 110 V_{AC} that the compressor requires to operate. This unit was selected due to Trace's reputation for reliability.

4. INTEGRATION OF COMPONENTS

4.1 Matching the PV Array and Electrolyzer

Various choices are possible in coupling the PV array and the electrolyzer. Significant work has been reported by the HYSOLAR project on the enhancement in performance that is achievable by tracking the maximum power point and then using DC to DC voltage conversion to match the electrolyzer voltage. Though enhancement is possible, its small magnitude plus the extra complexity and cost led us to choose direct coupling for our system.

Since the array and electrolyzer are directly coupled, it is crucial that there be a good match between the electrolyzer's operating points and the array's maximum power points. These will vary as conditions change but, in any circumstance, the electrolyzer must not be allowed to operate at a voltage much higher than the voltage at maximum power, V_{mp}. The steep decline in power beyond V_{mp} would be a serious loss.

The operating characteristics of the Altus 20 are temperature sensitive as can be readily seen from the various current-voltage (IV) curves shown in Figure 5.2.

According to Teledyne, the operating voltage of the module is expected to increase by 3.3 V over an operating life of approximately 25,000 hours. Additionally, as the temperature of PV modules increases, voltage output decreases. These, then, are the two main criteria for matching the array to the electrolyzer module.

The match between the array and electrolyzer can be shown by superimposing the possible range of electrolyzer operating voltages on the sub-array power curves. This is shown in Figure 5.3.

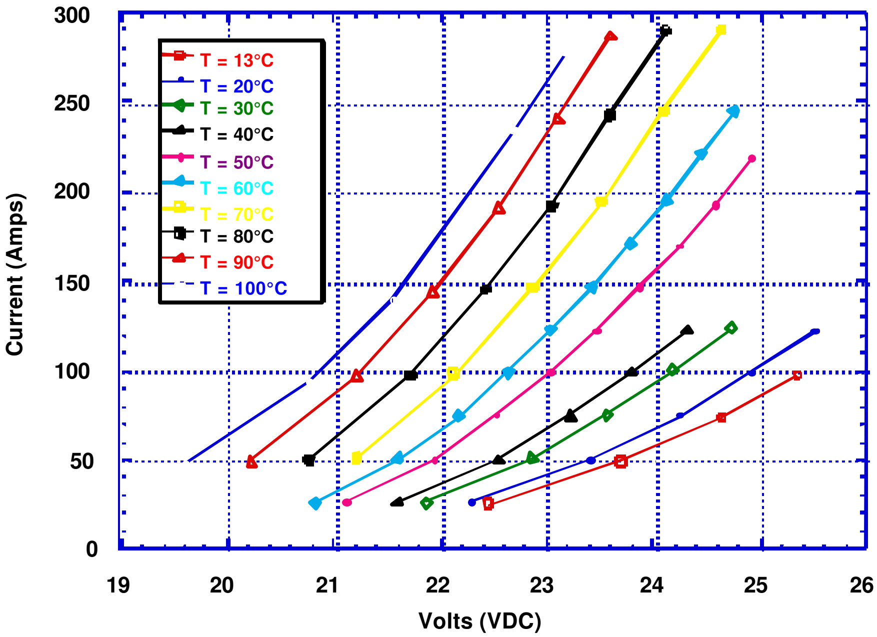


Figure 5.2: Electrolyzer I-V curves at varying temperatures

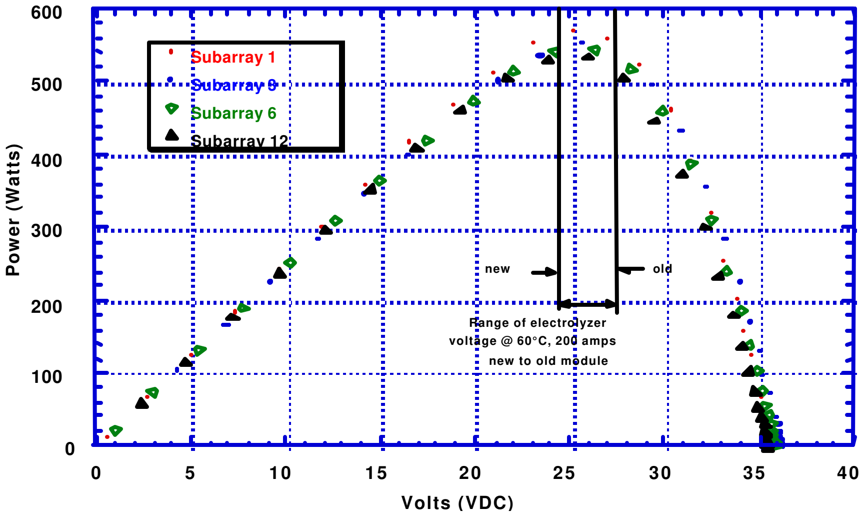


Figure 5.3: Sub-array power curves and electrolyzer operating range

At nominal operating conditions, the array and electrolyzer match very well. The worst of circumstances will occur with an old, cold electrolyzer and a warm array. Because of the cool, maritime climate, the array will never get much hotter than the 47°C. Even under these circumstances, the operating voltage would not exceed 29 V_{DC}. This would result in a power loss of approximately 10%, which would not be a serious loss.

4.2 System Control

The control system is designed to implement the basic logic and to do so automatically. In addition to regular operation, the system monitors various safety interlocks and provides for a shutdown if need arises. The system is configured so that input sensors can be calibrated and software parameters can be varied via on-screen commands to the control computer. Any or all of the subsystems can be run independently, with manual or automatic control, and a continuous graphic display provides constant updates on system configuration and operating parameters.

4.3 Control Hardware

A Macintosh SE microcomputer (SE) is used for the control system. The SE receives input parameters (both analog and digital) from a MacADIOS II SE data acquisition system via Analog Devices backplanes and Opto-22 digital backplanes.

Currents are measured with shunts, voltages directly, and temperature with a type T thermocouple, each with appropriate signal conditioning and amplification. The digital inputs are delivered to appropriate digital modules that provide a 0 or 5 V off-or-on signal.

The SE controls system operation by individually switching relays and solenoids. Output signals are sent by the computer through additional Opto-22 digital backplanes. 120 V_{AC} power for the coils of relays and solenoids is provided by optically isolated switching modules.

4.4 Control Algorithm

In the daytime the control algorithm, which allocates sub-arrays to the load or the electrolyzer, begins by determining the sub-array input currents and system configuration. A charging flag indicates whether the battery has been most recently charged or discharged. When the charging flag is on (recently discharged), the program determines the minimum number of sub-arrays which, when switched to the load, will provide enough PV current to exceed the current drawn by the inverter. It switches these to the load and excess current charges the battery. All other sub-arrays are connected to the electrolyzer.

When the charging flag is off, the program allocates the maximum number of sub-arrays which will not cause the PV current to exceed the inverter current. The deficit is provided by the battery. All other sub-arrays are again connected to the electrolyzer.

There are three circumstances that cause the program to limit the current to the electrolyzer and allocate fewer sub-arrays than are possible above. These are: 1) the electrolyzer can accept a maximum current of 275 A under any circumstances; 2) at low currents, the H_2 impurity in the O_2 line is too large so the program prevents operation below 20 A; and 3) at low temperatures, the electrolyzer can accept less than the maximum current. At 30°C and below, currents up to 125 A are allowable. At 60°C and above, a maximum current of 275 A is allowable. Between these two temperatures, the current limit increases linearly.

At night, or when there is insufficient insolation to provide PV power to the load, the control system starts up the fuel cell and, when its output stabilizes, transfers this power to the load. When the sun comes up, or the level of insolation increases sufficiently, the load is transferred back to the PV array.

4.5 Safety Interlocks

The system has several safety interlocks. The electrolyzer has its own programmable controller that monitors operation. If any of the monitored parameters is out of normal range, a signal is produced which, under normal circumstances, would shut down the electrolyzer's DC power supply. The SE monitors that signal and shuts down if it is activated. Power to the feedwater pump is also monitored. This serves as a safety backup to the feedwater level sensor. If the sensor fails in the full position, neither the pump nor a shutdown would be activated. This would cause loss of electrolyte water and electrolyzer module failure. If AC current does not flow to the pump after 50 Ah of operation (as it should), a safety shutdown is effected.

The electrolyzer is mounted within a sealed, ventilated hood. Bacharach combustible gas alarms are mounted in the laboratory room and inside the hood. If either indicates an alarm condition (set at 40% of the lower explosive limit), the system shuts down. The hood is also fitted with an air movement sensor. If ventilation in the hood fails, a shutdown occurs.

While the control computer is connected to an uninterruptable power supply (UPS) this unit is intended only to provide sufficient back-up power to safely shut down the system in the event that the local utility grid fails.

A fail-safe power transfer system has been incorporated to return the load to the local power grid in the event that the solar hydrogen system cannot supply power. This allows the system to run automatically and ensures that the air compressor will run at all times without the need for human intervention. The marine laboratory has always had an auxiliary generator system in place.

The control system microcomputer and the monitoring system microcomputer also exchange signals to show they are operating properly. If either computer fails or detects an abnormal condition, a shutdown occurs. This protects against the possibility that the control system SE would crash and leave the system in a dangerous configuration.

Finally, if the smoke detector or the emergency push button shows a positive signal, a shutdown also occurs.

5. OPERATIONAL EXPERIENCE AND PERFORMANCE

5.1 1995 Operating Data

The system first went on line late in 1992. At that time, the PV array and the electrolyzer were fully functional and the data collection system began operating. From that time through the end of July 1998, the system has been on line for 26010 hours, has powered the load for 7012 hours, and produced 4556 normal cubic meters (Nm^3) of hydrogen gas. Over this period, the electrolyzer has had a Faraday efficiency of 96.4%, an electrolyzer efficiency of 79.2%, and a voltage efficiency of 84.0%.

Our most complete set of operations data is from 1995. Over the course of this year, the system was operational for a total of 6326 hours, the load was powered by the PV array for 2272 hours, the fuel cell for 1490 hours, and the local utility for 2538 hours. During 1995, 208244 Ah of electricity were provided to the electrolyzer, which in turn generated 1096 Nm^3 of hydrogen gas.

A bar graph showing the daily sources of power to the load over the course of the year is shown in Figure 5.4.

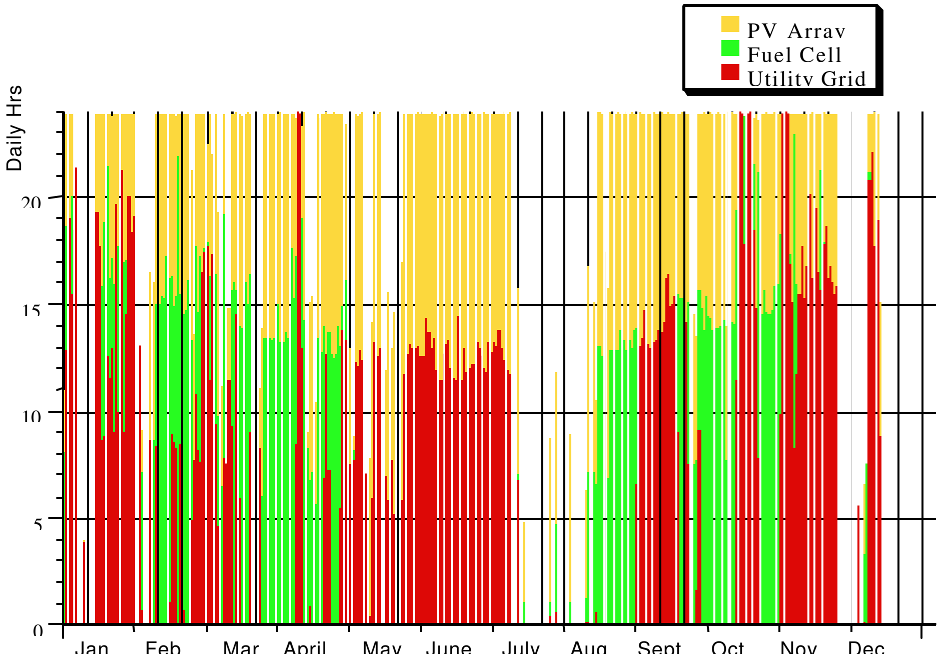


Figure 5.4: Daily totals of the source of power supplied to the load in 1995

As can be seen from Figure 5.4, there are large blocks of time in which the load is powered entirely by the PV array and the fuel cell. Areas where fuel cell operation are not represented are generally due to control software modification and debugging, or, as in the case of the period from May through July, a result of stack modification and damaged cell replacement.

5.2 Efficiency Definitions

The following definitions are used for the efficiency calculations:

Electrolyzer
$$\frac{\text{Hydrogen produced in watts}}{\text{DC power supplied to the electrolysis module}}$$

Faraday
$$\frac{\text{Actual amount of hydrogen produced}}{\text{Theoretical production of hydrogen for the current that passed}}$$

PV
$$\frac{\text{PV power used by the system}}{\text{Solar power incident on the array}}$$

System
$$\frac{\text{Hydrogen produced in watts + DC power to the load}}{\text{Solar power incident on the array}}$$

Voltage $$\frac{\text{Theoretical voltage required for hydrogen production}}{\text{Actual voltage necessary for hydrogen production}}$$

Fuel Cell $$\frac{\text{Power supplied by fuel cell in Watts}}{\text{Hydrogen consumed by fuel cell in Watts}}$$

There are a few noteworthy comments to make about these definitions. For the electrolyzer efficiency, the DC power supplied to the electrolysis module refers only to the power used for electrolysis; it does not include the auxiliary power requirements necessary for operating the electrolyzer, such as the control system, feedwater pump, and cooling system.

The area of the entire photovoltaic array (made of 12 sub-arrays) is used for the PV and system efficiencies. The photovoltaic system, load and electrolyzer have been carefully matched to maximize power production, efficiency, and utilization. However, under certain circumstances one or more sub-arrays is sometimes disabled from the system because the power output is either too low or too high for operating the load or electrolyzer. When these conditions occur, the PV and system efficiencies are depressed because part of the available solar power is not being utilized by the system (i.e., the value of the denominator increases while the numerator remains constant or decreases).

The second term of the system efficiency equation, "DC power to the load" refers to the photovoltaic array power delivered to the load and buffer battery in this circuit. However, when the load draws upon the buffer battery for extra power, this term refers only to the photovoltaic power being supplied to the load; it does not include the battery power, since this would be double counting the array power that was delivered to the battery during the charging period.

5.3 Efficiencies

Efficiencies were calculated according to the definitions presented above. These overall averages, as shown in Table 5.1, are based upon data that were averaged over short intervals (typically 2-3 minutes) before being recorded.

Table 5.1: Average Efficiencies for 1995 (%)

Faraday	Electrolyzer	Voltage	PV	System	Fuel Cell
97.6	80.1	83.5	6.7	5.7	43.1

As can be seen from Table 5.1, the various efficiencies related to the electrolyzer are all quite good. The PV and System efficiencies, on the other hand, are somewhat less than expected. Direct testing of individual sub-arrays at solar noon found efficiencies approaching 10%. Prior to the implementation of fully automatic operation, the average PV efficiency was in excess of 8%. Clearly there is some dynamic at work here that is driving the efficiency down.

Unfortunately, we have not been able to develop a method for determining the number of sub-arrays actually providing power to the system at any given time. As a result these particular efficiencies are calculated using the entire area of the PV array by default. As mentioned above, this can have a substantial effect upon the final value.

There are several sets of circumstances in which one or more sub-arrays cannot be utilized. For instance, during start-up periods when the electrolyzer is not yet up to operating temperature it can only run at half power. In addition, during periods of low insolation (which occur frequently in this coastal region), there is more power available than is required to run the load, yet not enough to provide the minimum 20 A to the electrolyzer that is necessary to prevent dangerous levels of hydrogen contamination in the oxygen stream. In this case, the power cannot be utilized. Lastly, we have observed periods of intense cloud focused sunlight when each individual sub-array is capable of producing in excess of 30 A of current, yet one or more must remain idle as the total power would considerably exceed the system's ability to absorb it.

Lastly, during the summer there were periods when the fuel cell could not use the hydrogen stored in the tanks at night as fast as the electrolyzer was producing it during the day. As a result, there were many occasions when the tanks would be full by midday and the electrolyzer would be forced to go into 'standby mode' in spite of an abundance of sunlight. This situation would leave eleven sub-arrays idle with the twelfth powering the load. For instance, on August 19, 1995 the PV grid ran the load for 11.06 hours, but the electrolyzer ran for only 5.35 hours. The resulting PV efficiency was only 5.0%.

As a result of all of these circumstances, there are significant periods of time in which all of the measured solar energy cannot be used, yet that total is used in calculating the PV and System efficiencies.

Prior to fully automatic operations we ran the system only when an operator was present. Typically this would have been during normal working hours. During this extended period we measured PV and System efficiencies that were, on average, more than 1 percentage point higher. The subsequent decrease in these efficiencies following the switch to automatic operation can be attributed to the much broader range of operating conditions that the system encountered due to 24-hour operation. A larger pool of data with a much higher percentage of marginal operating conditions, such as those that are found at sunrise and sunset, provide a more appropriate picture of 'real world' operations, as opposed to the previous data which was comprised largely of middle of the day measurements.

5.4 Electrical Storage Efficiency

One of our primary objectives with this project was to assess the efficiency of hydrogen for storing electrical energy from the sun. For purposes of this analysis, we considered this to be the electrical energy produced by the fuel cell divided by the electrical energy used by the electrolyzer to produce the same quantity of hydrogen.

To perform this calculation we took several blocks of time in which the entire system ran continuously for several days at a time during 1995. Over this 45-day accumulation of data, we measured the cumulative quantities of hydrogen gas and electrical energy produced and consumed by the system. As it turns out, the electrolyzer requires, on average, 4.17 Wh to produce a single standard liter of hydrogen, while the fuel cell produces an average of 1.42 Wh from one liter. The average electrical storage efficiency of this system is therefore 34%. This is slightly lower than we had hoped for, but typical of what can be expected for this storage cycle. Furthermore, the fuel cell did not perform as well as we had expected.

5.5 Shutdowns

As can be seen in Figure 5.4, there are quite a few periods of time in which the system was not operational. The total on-line period of 6,326 h accounts for 72% of a year, leaving the remaining 28% as non-operational.

This system is designed to function automatically with only the occasional need for an operator. In general, this works quite well with the control system routinely performing its tasks. However, when there is an emergency shutdown, for whatever reason, the system cannot be restarted without an operator. As a result, a fairly innocuous cause, such as a brief loss of utility grid power to the ancillary equipment, can result in a multi-day shutdown if an operator is unavailable to restart the system. Unfortunately, due to our location in a fairly remote coastal region, power outages and sags are not uncommon. Table 5.2 gives a complete listing of all the emergency shutdowns that occurred in 1995.

Table 5.2: 1995 Shutdowns

Cause	Frequency
Hood exhaust fan sensor	5
Utility power outage	4
Monitoring computer not responding	3
Low electrolyzer current	3
Computer failure	2
Electrolyzer feedwater conductivity too high	2
Electrolyzer temperature too high	1

Some of the shutdowns, such as the hood exhaust fan error, occurred repeatedly until the source of the problem (a defective switch) was determined and corrected. The high electrolyzer temperature was caused by an inadvertently disconnected thermocouple.

Other shutdowns were the result of computer and software idiosyncrasies. For instance, the '*monitoring computer not responding*' error is the result of writing data files to a crowded folder on the hard drive. The bookkeeping necessary to create a new file in the presence of a large number of old files would delay the monitoring computer sufficiently, so that it could not respond in a timely fashion to the control computer's routine inquiries. Additionally, if the control computer happened to turn off the electrolyzer while the monitoring computer was measuring electrolyzer current, a transient reading would cause an erroneous shutdown for '*low electrolyzer current*'. Both of these problems were solved, the former by having the operator sort the data into monthly folders, and the later by requiring two consecutive readings for a shutdown to occur. Finally, the computer failures seemed to be related to transient problems with their power supplies, as nothing obvious was found, and they went away of their own accord.

5.6 Maintenance

In addition to unscheduled shutdowns, there were several occasions that required the system to be shut down for the installation or maintenance of equipment. The electrolyzer requires fairly extensive inspection and maintenance twice a year. This typically requires one to two days, depending upon what is found during the inspection. Other maintenance includes changing the deionization filters for the electrolyzer feedwater, testing the various safety interlocks, regenerating the desiccant in the Employ pyrometer, testing and recalibrating the various sensors, checking and topping off the electrolyte in the battery bank, and testing all the safety interlocks.

5.7 Equipment Failures

5.7.1 Battery

In late December 1993, we began experiencing occasional system shutdowns due to low battery voltages during overnight standby mode. These events tended to occur following periods of extremely low insolation and our initial thought was that the 20 cell, 37 Ah nickel-cadmium (NiCd) battery was simply not being charged sufficiently. However, continued problems led us to run discharge tests that revealed that its capacity had diminished to less than 10 Ah.

NiCd batteries are known for their ability to sustain thousands of deep discharge cycles without damage. Although this battery had been in place for nearly three years, the system was in full time operation for only five months at the time of the failure. We concluded from this that the manner in which the battery was being used rather than the length of service was the culprit.

For this system it is not unusual for charging current to approach 20 A on sunny days (the output of a single sub-array). This amounts to a C2 charge rate, wherein the battery is charged at a rate that would, if continued for an hour, equal one half its total capacity. The manufacturer recommended that this battery be charged at a C5 rate.

With all of this in mind we decided to replace the failed battery with a larger capacity unit in order to decrease the rate of charge. As the cost of a large NiCd unit was prohibitive, we obtained an Exide Commercial lead-acid battery. Although lead-acid batteries should not be discharged below 80% of their rated capacity, the substantial increase in absolute capacity more than compensates. At a 20% depth of discharge, the usable capacity of the lead-acid battery is 44 Ah. Further, the charge rate problem experienced with the NiCd is no longer an issue as a 20 A charging current is equivalent to a C11 charge rate.

We identified a further problem with the battery system. Any time that the system was shut down, the inverter would remain connected to the battery. Although this unit goes into a reduced power ‘standby mode’, it nevertheless draws about 0.5 A. This adds up to 12 Ah/day, a quantity sufficient to discharge the battery to dangerous levels if the system remains down for several days. We corrected this oversight by adding a relay to the control system to disconnect the battery from the inverter during shutdowns.

5.7.2 Fuel Cell

In May of 1995, after the fuel cell stack had been in operation for approximately 5 months, several individual cells showed signs of serious degradation, making it difficult for the unit to start up properly. The stack was removed from the system and disassembled. Serious corrosion was discovered internally in several regions of the threaded stainless steel rods which held the stack together. This corrosion had contaminated several of the cells, and was the likely cause of poor cell performance. The stainless steel rods were replaced with nylon rods and new MEAs were manufactured and installed. The stack was reinstalled on July 7, 1995.

In November 1995, we saw the first signs of a cross leak in one of the cells in the rebuilt fuel cell stack. Initially, the only real problem was in starting up the stack when cold. However, following a period of prolonged shutdown (6 weeks) due to the holidays, as well as a failure of the fuel cell control computer, performance declined precipitously. We speculate that this long period of non-operation allowed the Nafion membranes to dry out, turning a small perforation into a substantial tear. By February 20, 1996, the stack could no longer be started due to low cell voltage. As we were concerned that further attempts to operate the stack might result in dangerous mixing of hydrogen and air, we decided to remove this stack from further service pending future repairs. Since that time, our fuel cell efforts have largely been diverted into electric vehicle research, so this stack remains off-line.

5.7.3 HydroNet system

Prior to July 3, 1996, environmental data were collected from the PV array area via a HydroNet field data collection system. When this system failed, we discovered that parts are no longer available. A Dataforth SCM9B system with new thermistors was selected and obtained, but we were unable to install this equipment until June 1998. During the intervening period of time, the data on wind speed, insolation, air temperature, and PV module temperatures were not collected.

6. DATA ACQUISITION

A variety of data is measured and recorded whenever the system is running. These include the following:

• Temperature	Electrolyzer (various locations) Ambient air in the array field PV modules (3) Hydrogen storage tank
• Pressure	Hydrogen at the electrolyzer Hydrogen storage tank
• Gas Flow	Hydrogen from the electrolyzer Hydrogen to the fuel cell
• Voltage	Electrolyzer Battery Inverter
• Current	Electrolyzer Battery Inverter
• Miscellaneous	Wind speed Insolation

Most of these data are available on diskette in tabular form for any period in which the system was running. Note that, at times, various components of the system have been off-line and are not included in these files.

In addition to the daily operational data we also have data available for certain of the system components. For example, we have individual IV curves for each of the 192 PV panels in the array, as well as for the twelve sub-arrays. Electrolyzer data include the IV curves taken at various operating temperatures, as well as a range of steady state constant power runs using a DC power supply. Finally, we also have IV curves for the fuel cell prior to its demise.

7. SIMULATION

7.1 Hydrogen Production

Several mathematical models have been developed by SERC staff members to simulate the performance of the photovoltaic array and the electrolyzer in the system. These models were developed using a variety of computer software tools such as Language Systems FORTRAN for programming, Minitab for statistical analysis, and Kaleidagraph for graphing and statistical analysis.

We used these models to simulate our system and then made direct comparisons to measured performance over an eight-day period with highly variable weather. We ran the simulation for this period with a number of variations in order to compare different simulation configurations. The variations include running the simulation with two different electrolyzer temperature models: the Vanhanen Electrolyzer Temperature Model and the Jacobson Electrolyzer Temperature Model. We also made runs with each day broken into time intervals of different lengths: once with one-hour time intervals and once with three-minute time intervals. Finally, we ran the simulation once using the measured electrolyzer environmental temperature from a data file and another time setting this value equal to a constant 20°C. The hydrogen production results from these runs for the eight day period are presented in Table 5.3.

The results given in Table 5.3 show that the simulation's predicted values and the measured values are in close agreement for all of the different configurations. This is important in part because it establishes that the simulation does an excellent job of predicting hydrogen production and in part because it shows that the different configurations have almost no effect on the simulation performance.

The Jacobson electrolyzer temperature model is slightly better at predicting the electrolyzer temperature than the Vanhanen electrolyzer temperature model during the eight-day period but the two are not different in terms of predicting the hydrogen production. The Vanhanen model is much simpler than the Jacobson model, so we have chosen it as the preferred electrolyzer temperature model.

Data are recorded in three-minute time intervals at the SERC project. We used this time interval for much of the original work with the simulation. Weather files often use one-hour time intervals to report data. We were interested to see if the longer time interval would decrease the accuracy of the simulation. The results presented in Table 5.3 show that there is no significant difference in the prediction of hydrogen production between three-minute and one-hour time intervals. Trial runs with longer time intervals suggest that two- or four-hour intervals can be used without significant error.

A final run was done with the electrolyzer environmental air temperature set to a constant value of 20°C. This also did not result in a significant change in the predicted hydrogen production. This means that the user can set the electrolyzer environmental temperature to a constant value when reliable data for this temperature are not available.

Table 5.3: Hydrogen Production Comparisons

Model Configuration	Hydrogen Production (stand. liters)	Residual (Predicted – Measured)	Percent Error
Measured Value	53,550	n/a	n/a
Vanhanen, 1 h intervals, T_{amb} from Data[1]	55,400	1850	+3.5%
Vanhanen, 3 min intervals, T_{amb} from Data	55,350	1800	+3.4%
Vanhanen, 1 h intervals, T_{amb} = 20°C[2]	55,400	1850	+3.5%
Jacobson, 1 h intervals, T_{amb} from Data		1850	+3.5%
Jacobson, 3 min intervals, T_{amb} from Data	55,400	1850	+3.5%

[1] T_{amb} is the Electrolyzer Environmental Air Temperature; in this configuration the data were collected in the space that contains the electrolyzer.

[2] In this configuration the Electrolyzer Environmental Air Temperature was set equal to a constant 20°C.

7.2 PV Array Delivered Power Modeling

Perhaps the most interesting aspect of the modeling occurred when examining the power output of sub-array #1 and the power received by the electrolyzer. As demonstrated in Figure 5.5, the PV model very closely simulates the measured IV curve for this sub-array.

This is also the sub-array that is furthest from the electrolyzer, has the longest wire runs, and hence has the greatest resistive losses. When the system was designed, wire and cables were sized using the Table of Conductor Properties in the National Electric Code Handbook to limit voltage drop to 2%. Resistance measurements of the #2 AWG wire that runs from the sub-array to the junction block in the gas generation building revealed the actual value to be 24% higher than the values in the NEC table. Similar tests on the 4/0 cable running from the bus bar to the electrolyzer found a value that was 19% higher than the design value.

Plugging these values into the voltage loss to wire resistance portion of the model and including other resistive components such as the sub-array fuse disconnect, the blocking diode, and the relays, revealed that of a possible 656 peak Watts produced, nearly 60 W, or 9% of the total, were lost to these components.

To date we have not observed any increased voltage requirements for the electrolysis module as predicted by Teledyne. An analysis of electrolyzer data has shown that as the unit reaches operating temperature, only 22.5 V are required for electrolysis. This is 4 V below the maximum power point for this sub-array. This mismatch loss results in another 40 W loss for a total power loss from all sources of 15%. This is a substantial loss.

Possible remedies for these losses include the installation of larger wires, installation of higher capacity rated blocking diodes, or additional diodes could be paralleled to reduce power loss. Power loss from the sub-array disconnects is small in comparison to the other devices, but some reduction could be made by replacing one of the series fuses in each unit with a low resistance conductor. Finally, this analysis shows that substantial improvement in PV efficiency (and hydrogen production efficiency) can be made by adding two cells to the electrolyzer to enhance the electrolyzer-sub-array-voltage match.

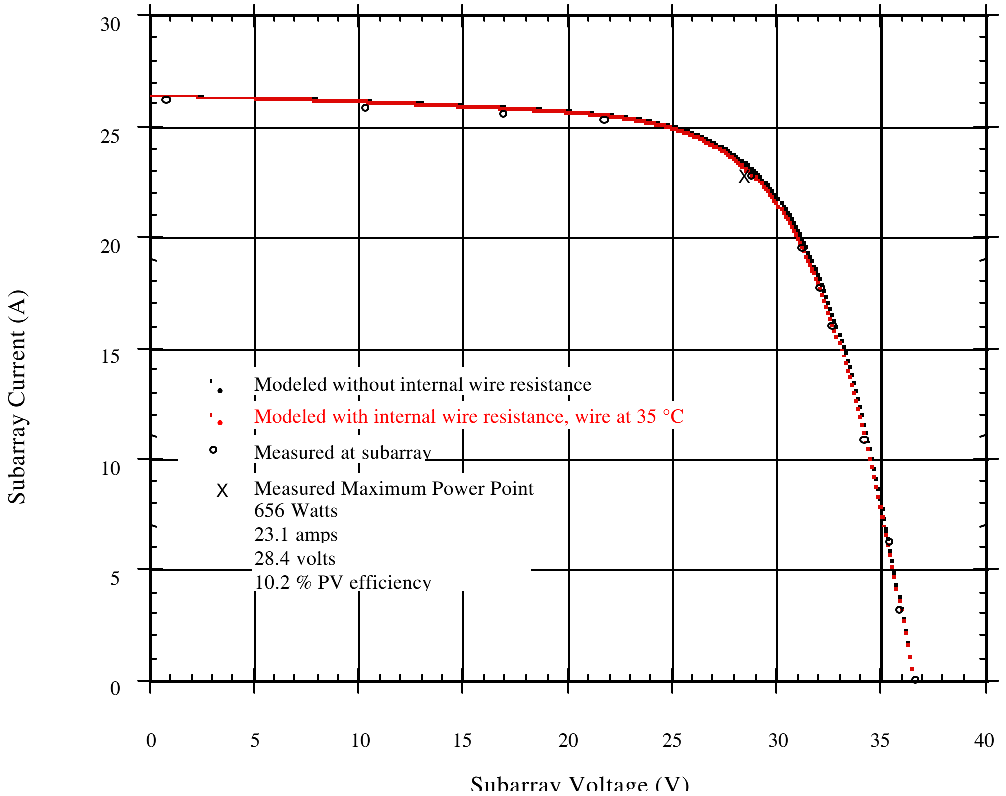


Figure 5.5: Subarray 1, predicted vs. measured IV curves

7.3 Future Modeling

These models are not limited to the specific components and configuration found in our system. By simply changing the input parameters, virtually any conceivable system can be modeled at any location for which solar data are available. We have used the National Renewable Energy Laboratory's Solar and Meteorological Surface Observation Network data to simulate similar systems in other parts of the country. Specifically, we are using these models in the design of the Palm Desert Solar Hydrogen Refueling Station, which is the subject of a separate report.

8. PUBLIC ACCEPTANCE AND SAFETY

The public has responded very well to this project. We have received very little negative feedback, and in general, people seem to be very taken with the idea of solar hydrogen as an energy source. We have not had any problems with inspectors or fire marshals. We attribute this to the fact that we have done substantial work addressing issues of safety and code compliance prior to construction. Through this, we were able to discuss the issues with the inspectors and to bring up specific safety issues ourselves that the inspectors had not considered.

8.1 Safety Interlocks

The various safety interlocks were enumerated earlier. In addition we also have mechanical excess flow valves on the hydrogen storage tanks. These isolate the tanks if a hydrogen gas line is damaged or disconnected.

8.2 Emergency Response Plan

During the spring and the summer of 1993, we developed an emergency response plan. This document includes general information about the hazards associated with hydrogen gas as well as an outline of procedures to follow in an emergency situation. It defines procedures for situations including hydrogen fires, chemical spills involving potassium hydroxide or hydrochloric acid, and earthquakes. In addition, it clearly describes a number of ways that the solar hydrogen system can be shut down in the event of an emergency.

While the emergency response plan was developed with our staff in mind, it also lays the groundwork for training the staff of the Telonicher Marine Lab. This lab lies adjacent to our facility and the air compressor used to aerate their fish tanks is powered by the solar hydrogen system. If the system is to operate in an unattended, continuous mode it is important to train members of the Marine Lab staff how to react in an emergency situation.

Thus while we are taking great pains to insure that our system is safe and reliable, we recognize that accidents can happen. With this plan, we are working to ensure that if an accident does occur, we will be able to respond quickly and efficiently to minimize the threat to human lives as well as potential damage to the system. Fortunately, no such accidents have occurred in our 8 years of operation.

8.3 Fault Tree Development and Testing

In order to develop and test the safety interlock system, we created a fault tree for our facility, and then tested those 'reasonable-to-perform' faults under actual operating conditions. For those fault tests that could not easily be simulated, such as an earthquake or a flood, we relied upon thought experiments and manufacturer's safety information to estimate the possible ramifications on the operation of the system and its equipment. When deficiencies were found, software and/or hardware modifications were made.

In order to cover the equipment that is in place, the fault tree is organized into three major sections: electrical, electrolyzer, and general. Each of these sections is built off a branched structure that lists the possible abnormal conditions with the affected components. A reader finds the possible fault conditions on the first branch, and then scans to the right for the equipment that might be affected with more specific faults conditions listed beneath each component.

The intended use of the fault tree is twofold. The first was to help Schatz personnel identify compromising or detrimental operating situations for the system, and then use this information to design the safety interlock system (and system control algorithms). The second purpose is to facilitate testing of the safety interlock system, both initially and in the future. Although the system contains many "off-the-shelf" components, the shared history of operation for these components in the setting of a solar hydrogen energy system is still very young. As a result, we intentionally made the fault tree general in nature, rather than attempting to specify every possible fault condition and component combination or interrelationship. In this way more variability is included so that the fault tree might better serve to uncover deficiencies in the safety interlock system.

8.4 Maintenance Schedule

To ensure safe and reliable operation of the system and related equipment, we developed a comprehensive maintenance schedule that includes regular weekly, monthly, biannual, and annual inspections. While most of the review intervals follow manufacturer's timetables, several have been made more frequent to ensure a margin of safety.

9. FUTURE PLANS

We intend to continue operating the Schatz Solar Hydrogen Project into the foreseeable future. When funding becomes available, we will construct a new fuel cell stack that incorporates the many design improvements that we have developed in our vehicle research. An improved fuel cell should increase the electrical storage efficiency by several percentage points.

10. CONCLUSIONS

We believe that the Schatz Solar Hydrogen Project has demonstrated that hydrogen is a viable medium for the storage of electrical energy derived from the sun. Over eight years of operation we have found the following efficiencies:

– Faraday	96.4%
– Electrolyzer	79.2%
– Voltage	84.0%
– Fuel cell	43.1%
– Overall electrical storage	34.0%

The use of solar hydrogen generation systems in regions that are rich in solar energy would enable the efficient long-term storage of this energy either for later use or for export to other locations.

Chapter 6
INTA SOLAR HYDROGEN FACILITY

1. PROJECT GOALS

Solar photovoltaic conversion for electricity production is well established in Spain at an industrial and commercial level. The combination of PV and electrolysis technologies to produce hydrogen, store it, and use it in fuel cells for times when the sun is not shining is a way to supply "solar energy" at night or on cloudy days.

With this idea in mind, and given the nature of INTA (Instituto Nacional de Técnica Aeroespacial; Huelva, Spain) as an aerospace-related institution, a program was started in 1990 with the following goals:

- Study the feasibility of solar hydrogen production
- Evaluate different component technologies
- Stimulate Spanish R&D in this field, looking towards component development
- Analyze the use of such concept for terrestrial applications.

Within this framework, INTA started a program, partially funded by the regional government of Andalucia. This program was divided into several subprograms, according to funds availability:

- Feasibility study of solar hydrogen as an alternative fuel
- Analysis of solar systems to produce hydrogen
- Definition, design, construction and start-up of a pilot plant for solar hydrogen production
- Characterization of components (PV field and electrolyzer)
- Annual operation of the system
- Definition, design, construction and start-up of a double storage system for the solar hydrogen production pilot plant
- Evaluation of the storage system
- Integration and evaluation of a phosphoric acid fuel cell (PAFC) into the Solar Hydrogen Production Facility.

2. GENERAL DESCRIPTION OF PROJECT

The INTA program on hydrogen technologies had two main objectives, as defined in 1989:

- The use of hydrogen as a storage medium for solar electricity
- The use of integrated systems: PV, electrolysis, hydrogen storage, and fuel cells for manned space missions.

The space related activities were abandoned on 1993. Since 1994, hydrogen activities were concentrated on the utilization of hydrogen in fuel cells in a non-centralized electricity generation services sector as well as a clean fuel for transportation.

The Solar Hydrogen Pilot Plant consisted of three phases. Figure 6.1 shows the general configuration of the facility. The pilot plant for solar hydrogen production (Phase I) was designed, constructed and evaluated during 1991-93. The storage system (Phase II) was defined and evaluated during 1993-95. Both systems were used during Phase III (1994-96) in conjunction with phosphoric acid (PAFC) and proton exchange membrane fuel cells (PEMFC).

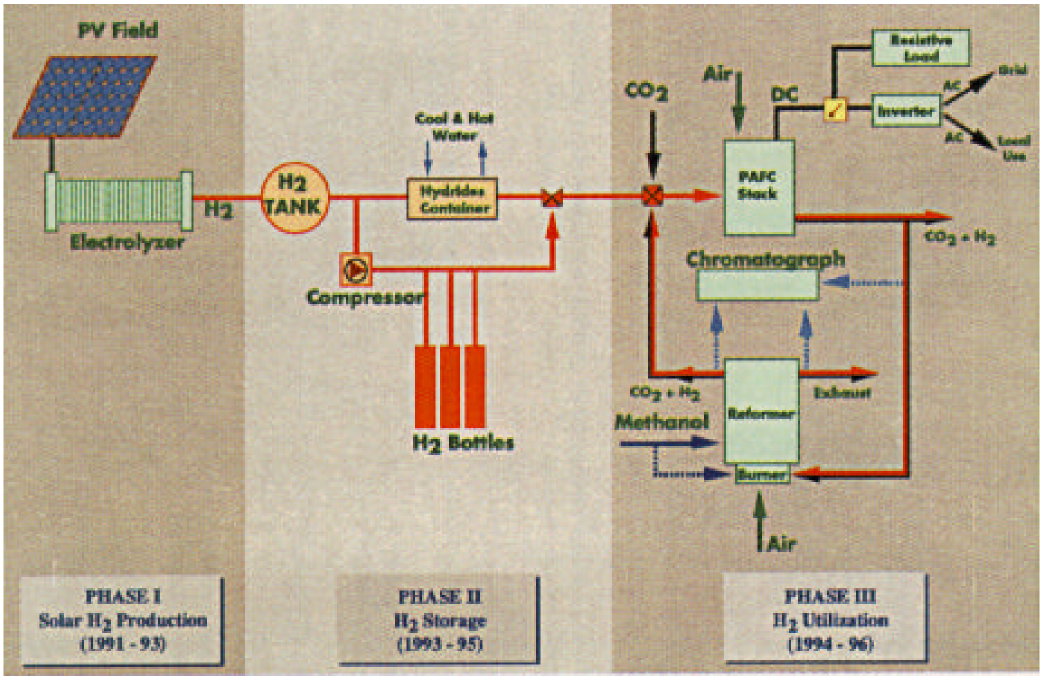


Figure 6.1: INTA Solar Hydrogen Facility: General Configuration

The main characteristics of the pilot plant are:

- 8.5 kW_p photovoltaic field
- 5.2 kW alkaline electrolyzer
- 24 m^3 metal hydride ($TiMn_2$) storage
- Conventional pressurized gas installation for bottles of 8.8 m^3 at 200 bar
- PAFC of 10 kW
- Two PEMFC stacks of 2.5 and 5 kW (hydrogen/air).

3. DESCRIPTION OF COMPONENTS

3.1 Phase I - Photovoltaic Field

Table 6.1 and Table 6.2 present the main characteristics of the Phase I facility. These characteristics, together with properties of the other components of the system will be presented in the subsequent sections.

Figure 6.2 shows an overview of main components associated with the solar hydrogen production section.

Table 6.1: Facility Arrangement for Phase I

- Power Generation System:
  - 8.5 kW solar photovoltaic field
  - 7.4 kVA AC-DC converter
  - AC-DC MPPT power conditioning
- Electrolysis System:
  - 5.2 kW alkaline electrolyzer
- Control System:
  - Process supervision
  - H_2 supervision
- Data Acquisition System (DAS)
  - External bus data logger
  - Distributed data acquisition cards
  - Host computer
- Auxiliary systems:
  - Water treatment
  - GN_2 supply
  - Fire protection
  - Uninterrupted power supply
  - Cooling water supply

Table 6.2: System Characteristics for Phase I

- Photovoltaic Field:
  - 8.5 kW_p at 1 kW/m^2
    - and 25°C cell temperature
  - 144 BP Solar modules (260S)
- Electrolyzer
  - Alkaline Electrolyzer (METKON)
  - 5.2 kW at nominal 108 A, 48 V
  - H_2 production: 1.2 Nm^3/h
  - H_2 purity : 99.7% ± 0.1% vv
  - Operational conditions:
    - 6 bars, 80 °C, 30% KOH
- Water treatment:
  - Activated carbon filter
  - Ionic exchange resins filter bed
- GN_2 supply:
  - Steel bottles type B50
  - 10 Nm^3 N_2, 200 bar
  - N_2 purity:100 ppm H_2O, 50 ppm O_2

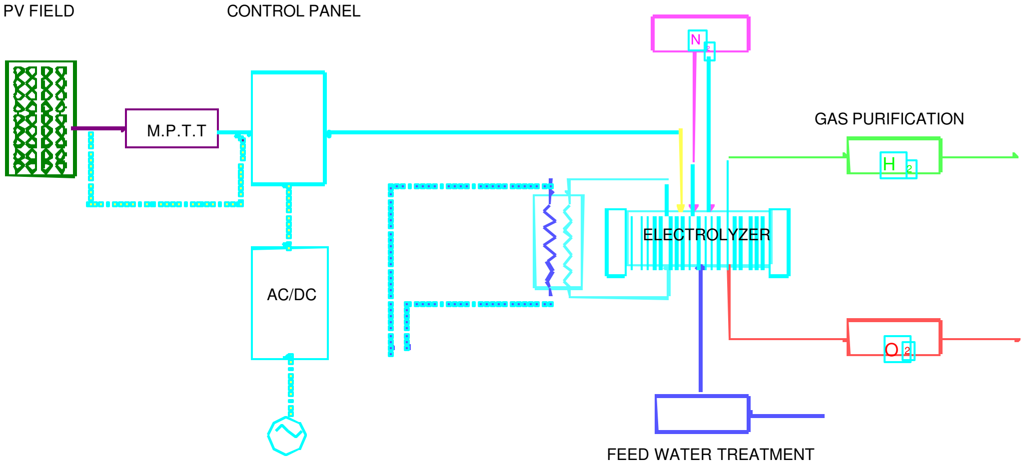


Figure 6.2: Schematic view of PV and electrolyzer

The electrolyzer can be powered in three different ways:

- Direct connection mode from the PV array (with constant or variable number of active electrolyzer cells), or
- Through the Maximum Power Point Tracker, or
- By means of an AC-DC converter.

This last option has been used to characterize the electrolyzer under steady state conditions.

3.1.1 Photovoltaic Field

The PV field, shown in Picture 6.1, is composed of 144 modules (36 cells each), 30% of which have 8 connectors to place output voltages and currents at intervals of 9 cells (4.5 V and 3.35 A). This flexible module configuration enables the installation of different matching systems and adjustment of the PV field and electrolyzer's operation.

The first experiment was performed under the direct coupling mode with a PV configuration of 36 parallel strings and 117 cells connected in series (3 1/4 module).

3.1.2 Electrolyzer

The electrolyzer, shown in Picture 6.2, is equipped with an adjustable control unit that allows both automatic and safe operation, and different operation modes. To provide optimum direct coupling with the PV field, the control unit can select the number of operating cells as a function of the solar radiation:

- 24 cells: 120-90 A (1000-720 W/m^2)
- 25 cells: 90-60 A (720-500 W/m^2)
- 26 cells: 60-30 A (500-200 W/m^2)

3.2 Phase II - Storage System

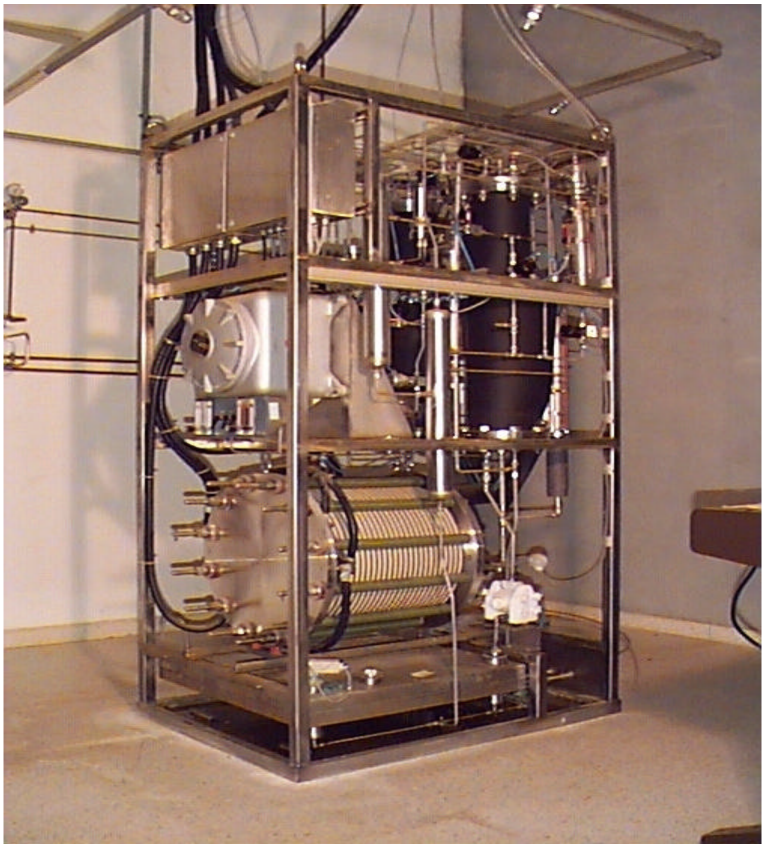
The hydrogen produced by the electrolyzer is initially stored in an intermediate buffer, from which it can be transferred to one of the two storage systems: metal hydride storage or pressurized gas (at 200 bar). Tables 6.3 and 6.4 summarize the characteristics of the metal hydride and pressurized gas systems, respectively. The storage system is shown in Picture 6.3.

3.2.1 Metal hydride storage

The metal hydride storage system consists of an intermediate buffer, a hydrogen purification unit, a metal hydride container and a cooling water supply system. Suitable instrumentation and sensors were prepared in order to control the system and acquire data for later evaluation.

The intermediate buffer is connected to the electrolyzer hydrogen delivery valve. Once set point pressure is reached, hydrogen passes through the purification unit and fills up the hydride container.

Picture 6.1: Photovoltaic field



Picture 6.2: Electrolyzer

Table 6.3: Hydride Storage

Intermediate buffer:
  Geometric capacity: 1000 l
  working pressure: 6 bar

Purification unit

Hydride container:
  Manufacturer: GfE mbH
  HIDRALLOY C20, based on $TiMn_2$
  Nominal capacity: 24 m^3 hydrogen
  designed pressure: max. 10 bar (80°C)
  discharge pressure: min. 2 bar (70°C)
  charge pressure: min. 2 bar (15°C)
  weight: approx. 210 kg
  dimensions: approx. 1600 x 300 mm

Table 6.4: Pressurized Gas Storage

Intermediate buffer:
  geometric capacity: 1000 l
  working pressure: 6 bar
Purification unit
Air driven gas booster compressor:
  Haskel Energy Systems
  model: AGD4-AGT 15/30
  two units, three stage
  inlet H_2 pressure: min. 2.6 bar
  outlet H_2 pressure: max. 240 bar
  air driven pressure: min. 6.2 bar
Compressed air supply:
  air compressor, 10 H.P.
  two cylinders, two stages
GN_2 supply:
  Steel bottles B50, 10 Nm^3, 200 bar

Picture 6.3: Storage System: intermediate buffer (left), horizontal hydride container tank (middle), and 200-bar bottle and compressor (right).

The hydride storage container consists of a pressurized tank filled with metal hydride powder, a cooling/heating shell, water supply and hydrogen supply provided with safety and shut-off valves. This hydride container was manufactured by GfE mbH, from Nürnberg, Germany.

A solar thermal collector facility supplies hot water at 80°C. Cooling water at 15°C is available on site.

3.2.2 Pressurized gas storage

The pressurized gas storage system uses the same intermediate buffer and the purification unit as the metal hydride storage system.

When hydrogen is stored as a compressed gas, hydrogen passes from the intermediate buffer to a two-stage air driven gas booster compressor that increases the hydrogen pressure to 200 bar. Hydrogen is bottled in metallic cylinders with 8.8 Nm^3 of hydrogen capacity at 200 bars. The hydrogen purity is measured by a Teledyne analyzer. Additional sensors and manometers give information about the process. Nitrogen gas is available on site to proceed with shut-down and start-up under safe conditions.

3.3 Phase III - Fuel Cells

A 10 kW PAFC supplied by ERC was installed at the end of 1993. The PAFC system also consists of a methanol reformer to permit operation with methanol. The general layout of this subsystem is displayed in Figure 6.3, and the plant is shown in Picture 6.4.

3.3.1 10 kW Phosphoric Acid Fuel Cell

The stack has 135 bipolar single cells connected in series that supply a maximum current of 125 A and 85 volts. The open circuit voltage is 130 V.

The electrolyte is 98% PO_4H_3 and the electrodes are fed countercurrently with H_2 and air. The unit is cooled by air in cross flow every fifth cell. Atmospheric air is used for equipment and cathode feed.

3.3.2 Methanol Reformer

To test the operation of the power plant with fuels other than pure hydrogen, a methanol reformer has been coupled to the fuel cell. The reformer consists of a catalyst bed of Cu-Zn, a vaporizer-heater, and a liquid fuel burner (methanol) during start up and hydrogen burner when coupled with fuel cell tail gas. The operating temperature is about 370°C and the methanol/hydrogen conversion rate amounts to >90%.

3.4 Auxiliaries

Several auxiliaries have been used to assure proper operational behavior of the system:

- Feed water treatment unit
- Gases supply section
- Fire protection system
- Uninterrupted power supply
- Cooling/heating water supply unit

The feed water treatment unit consists of activated carbon filtering as pretreatment and ionic exchange resins filter bed as final treatment of the electrolyzer feed water.

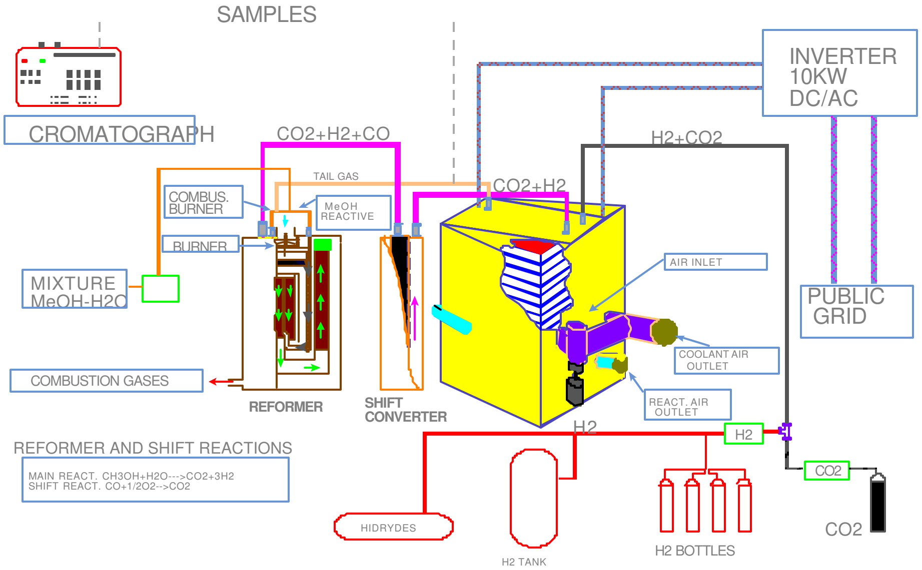
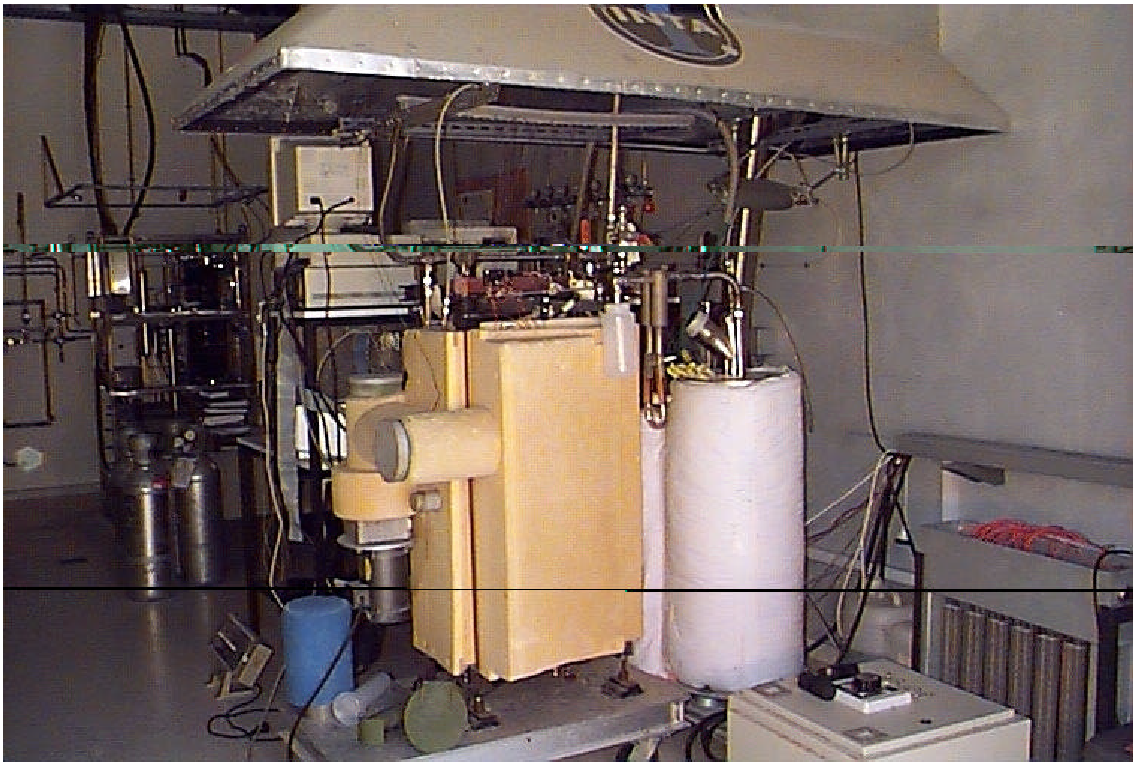


Figure 6.3: Schematic view of the 10kW PAFC Power Plant



Picture 6.4: Phosphoric Acid Fuel Cell

The gas supply section provides gases for electrolyzer pneumatic control and inertization during start up and shut down (nitrogen), and compressed air for the PAFC and for the air driven compressor operations.

The fire protection system for the facility includes adequate sensors and a control panel for taking appropriate actions, if required.

Uninterrupted power supply enables proper operation of the control systems and sensors in case of loss of electricity from the public grid.

Cooling/heating water supply facilities provide cooling for the electrolyzer and hydride container during the charging process and heating of the hydride container during the discharging process.

4. INTEGRATION OF COMPONENTS

The PV configuration (number of panels in series and in parallel chains) was calculated as a function of the electrolyzer characteristic curve. The optimum configuration is a perfect match between the maximum power line of the PV field and operating characteristic line of the electrolyzer. Unfortunately, it is not possible to get such a “perfect” match between both systems, so that it is necessary to use a DC-DC converter (Maximum Power Point Tracer) to follow the maximum power line of the PV field. In this project, a new approach to solve this problem was used: modifying the number of operating cells of the electrolyzer. In this way, the characteristic curve of the electrolyzer was “adapted” to the Maximum Power Line of the PV Field.

Figure 6.4 shows how the electrolyzer characteristic lines change by operating with 24 cells between 1000 and 700 W/m^2, 25 cells between 750 and 500 W/m^2 and, finally, with 26 cells for a global radiation lower than 500 W/m^2. The hydrogen production section is decoupled from the utilization by the storage system.

The control system of the facility was designed in a decentralized way, so that each subsystem has its own independent control system.

In the electrolyzer control cabinet the correct operation of the electrolyzer is supervised by adjusting the number of operating cells for optimum match with the PV Field (in case of variable cell number operation). The system also takes any necessary action to adjust the electrolyte temperature, and hydrogen delivery pressure to the specified set point. It also checks the hydrogen purity to send the hydrogen to storage or to vent, in case of unacceptable purity. If a dangerous composition is detected, the control system shuts down the electrolyzer.

The storage control system provides several actions in order to guarantee proper operation. The controller takes action in case of high or low pressure in the intermediate buffer, in case of abnormal pressure and temperature inside the hydride tank, when the chemical composition of the hydrogen stream is out of limits. Finally, it checks cooling water availability to prevent overpressurization of the hydride container.

The PAFC control system adapts the hydrogen flow to the stack according to the load level requested. It also controls the temperatures and voltages of the reformer and stack to ensure proper operation of the system.

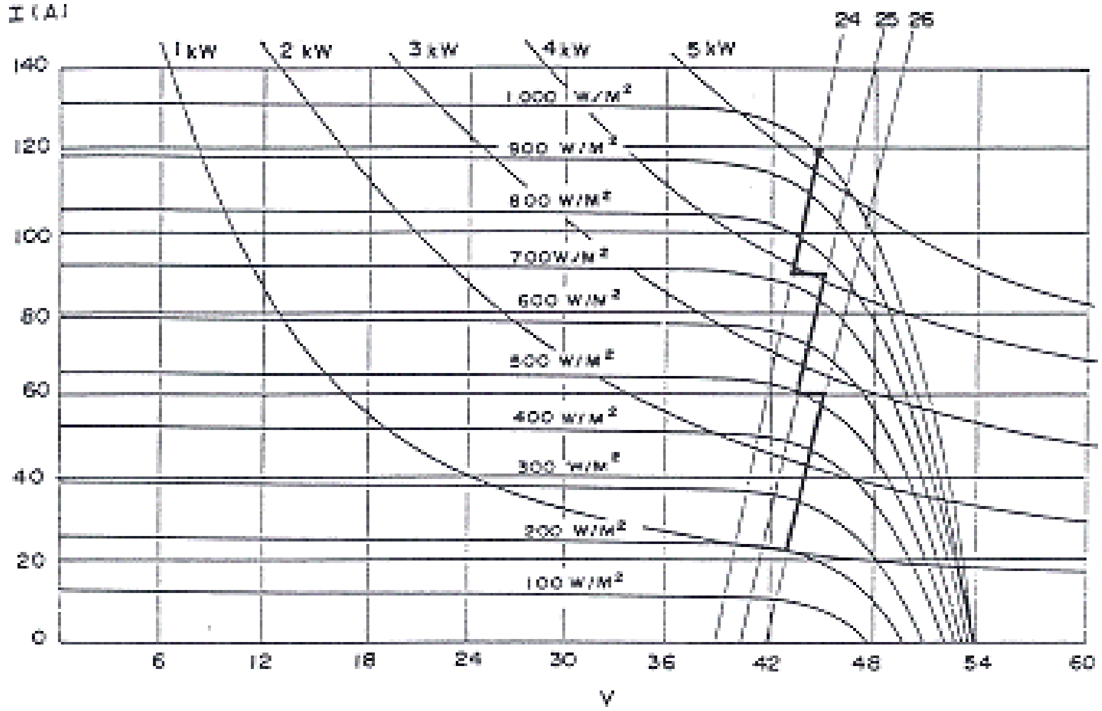


Figure 6.4: Regulation strategy of electrolyzer cell number as a function of solar radiation

5. OPERATIONAL EXPERIENCE AND PERFORMANCE

The use of a storage system between production and utilization section has the advantage of decoupling production and utilization operations. Based on this decoupling, components of the facility were evaluated in several steps.

5.1 Phase I - Solar hydrogen production section

Hydrogen production operated automatically for one year, in one of two operation modes:

- Direct connection between the PV field and electrolyzer with a constant number of operating cells (24)
- Direct connection with varying number of electrolyzer operating cells (from 24 to 26)

The main objectives of the test plan were to:

- Determine voltage, Faraday, and energy efficiencies of the electrolyzer during the testing period
- Calculate energy efficiency of the photovoltaic field coupled to the electrolyzer
- Study the global energy efficiency of the system and the dependence of operating/climatic conditions on such values
- Analyze the control system behavior, especially on cloudy days
- Perform a reliability study of the components
- Propose actions to improve the system’s global efficiency

To meet these objectives, the system was instrumented and evaluated using methods proposed in literature.

Tests started in November 1992 and ended in October 1993. During this period, 122 tests were performed, for a total of 723 operating hours and accumulated hydrogen production of 408 Nm^3. Of these 723 hours, the system operated 392 hours under constant cell mode, and 331 under the varying cell mode.

The system was operated for 104 days from sunrise to solar noon and 18 from sunrise to sunset.

The electrolyzer was characterized under predefined steady state conditions for 150 operation hours. Thus deterioration is easily detected.

5.1.1 Experimental Results

This section presents experimental results of daily and yearly behavior analysis and the influence of the number of cells on the system's behavior.

Daily behavior of the system

Figure 6.5 presents the analysis of Faraday, voltage, and energy efficiency evolution for a sunrise-to-sunset operating day. It shows that the Faraday efficiency is very close to 100%, excluding the sunrise and sunset period when global solar radiation is lower than 400 W/m^2. The density current feeding the electrolyzer is low, thus the voltage efficiency is high. Regarding the electrolyzer energy efficiency, values between 70% and 80% were reached during almost all of the operating period, with the exception of sunrise and sunset.

Figure 6.6 presents photovoltaic field and global system efficiencies for a day of operation. During sunrise, the PV efficiency increases continuously as the match between PV field and electrolyzer improves. At solar noon, the efficiency decreases due to high PV cell temperatures. PV field efficiency ranges from 8% to 9%. Global system efficiency, a product of the former efficiencies, is between 5.8% and 6.5% for almost all the operating period.

Daily efficiencies were:

PV field efficiency:	8.34%
Energetic electrolyzer efficiency (LHV):	69.65%
Global system efficiency:	5.71%

During the test period it was noted that daily efficiencies strongly depend on the duration of operation. Figure 6.7 and Figure 6.8 present daily Faraday, voltage, energetic and global system efficiencies as a function of the operation period. Assuming that operation starts under the same conditions, the average Faraday efficiency increases with operating hours for the period. An asymptotic tendency can be observed.

Yearly evaluation of the system

Yearly evaluation of the system was done using daily average results of the different variables.

Figure 6.9 presents the evolution of the daily global efficiency of the system as a function of operating hours. Each value represents one daily global efficiency of the system during the testing period, and range from 5.2% to 6.3%. The dispersion observed is due to diverse operational conditions: test duration, climate conditions, and operation mode.

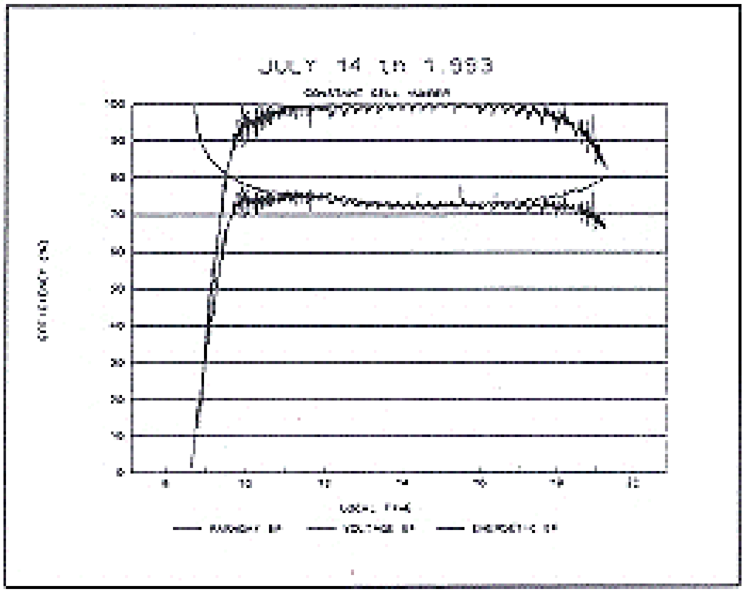


Figure 6.5: Evolution of Faraday, voltage and energetic electrolyzer efficiencies during one day

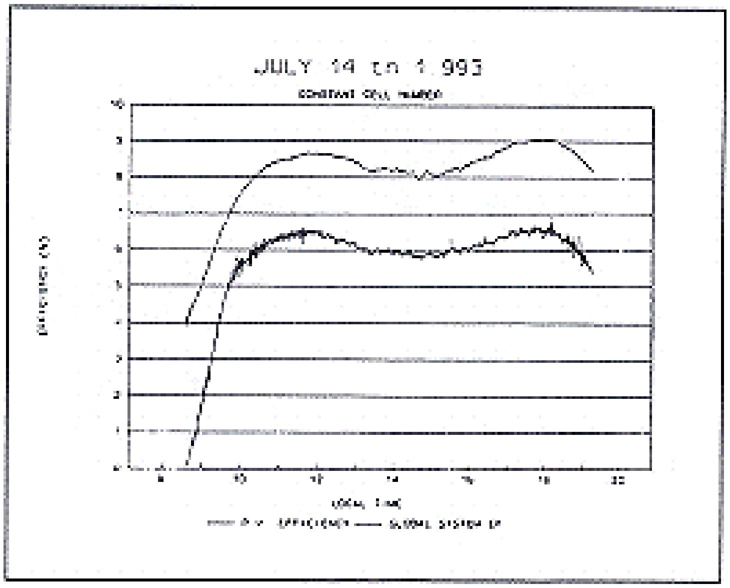
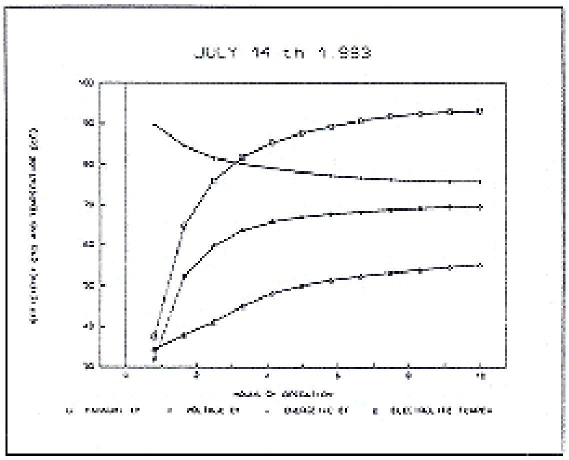


Figure 6.6: Evolution of PV and global energetic system efficiencies during a day of operation



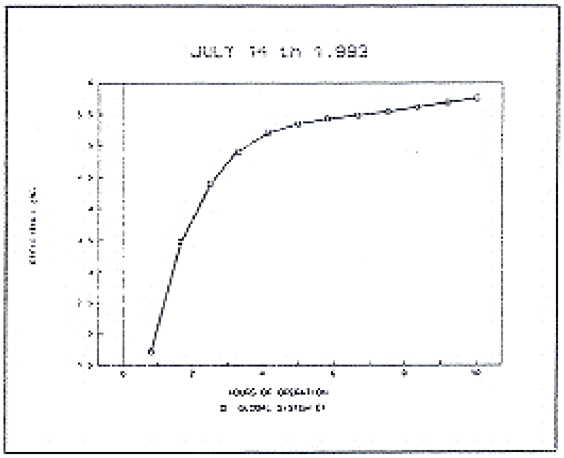


Figure 6.7: Influence of test duration on daily efficiencies and electrolyte temperature

Figure 6.8: Influence of test duration on daily global system efficiency

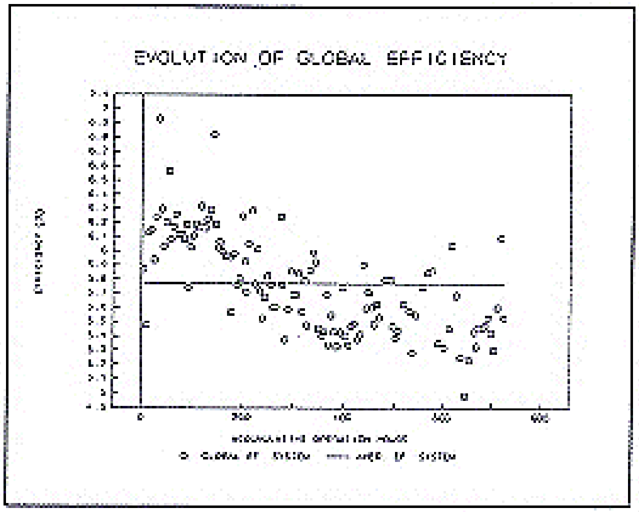


Figure 6.9: Evolution of global system efficiency during the testing period

Figure 6.10 presents the global energy balance of the system applied to 122 operational days. All the efficiencies in this figure refer to incident energy on photovoltaic field (100%).

Yearly average efficiencies were:

PV efficiency:	8.35%
Electrolyzer energetic efficiency (LHV):	69.13%
Global system efficiency:	5.70%

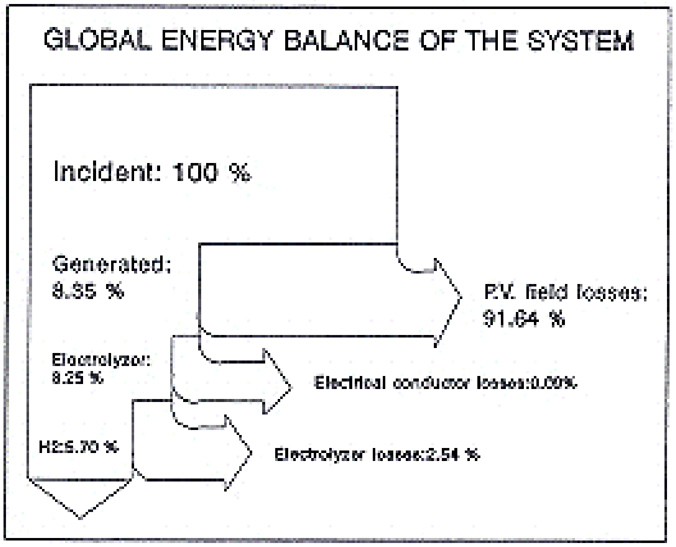


Figure 6.10: Global energy balance of the system for one year period

Influence of operation procedure

Figure 6.11 shows the characteristic intensity-voltage curves of the PV field for global solar radiation between 270 and 978 W/m^2. The intensity-voltage curves of the electrolyzer working with constant and varied number of operative cells have been superimposed.

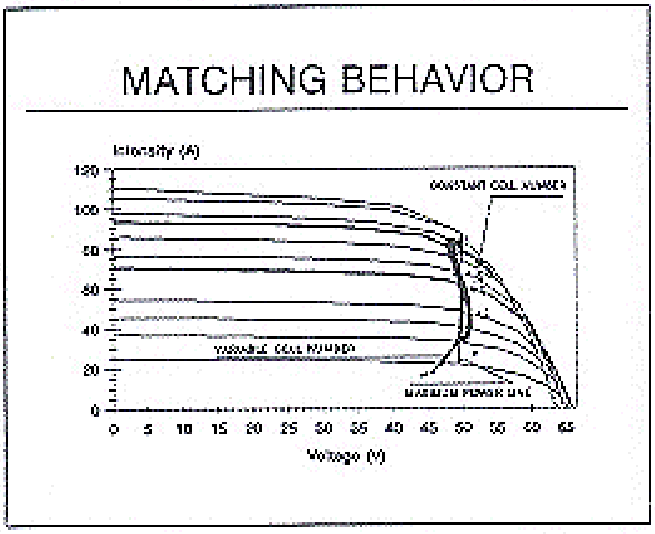


Figure 6.11: Matching behavior of operation modes

It can be concluded from Figure 6.11 that:

- The match between electrolyzer and PV field is slightly improved with a varied number of cells.
- The match is working well with a constant number of cells.

Electrolyzer deterioration

The electrolyzer was characterized every 150 operational hours under standard conditions using the AC-DC converter, to determine any possible deterioration as a function of working hours.

Figure 6.12 shows the electrolyzer energy efficiency as a function of intensity for five successive time periods. As yet, no deterioration has been detected in electrolyzer performance.

5.2 Phase II - Storage Section

In order to characterize the system, the following main components were identified:

- Metal hydride container
- Gas booster compressor

The metal hydride container was characterized during the charging process from a kinetic and capacity point of view.

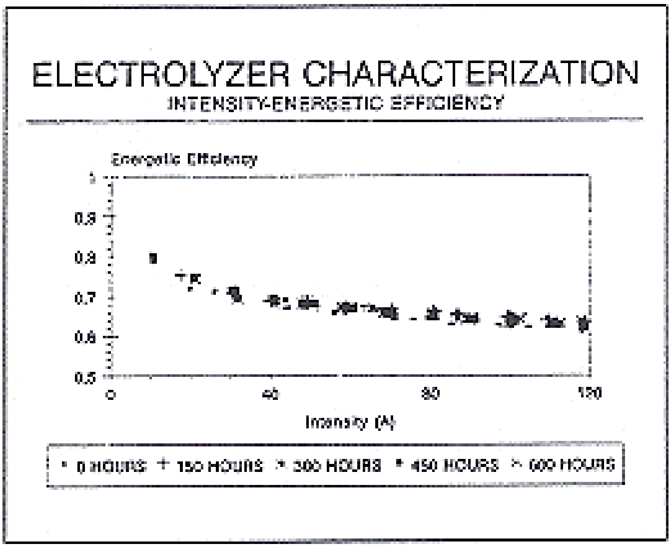


Figure 6.12: Evolution of electrolyzer efficiency during the testing period

In both cases, the initial conditions in the hydride container were:

- Temperature fixed at 8°C
- Hydrogen pressure at 0.5 bar

The hydrogen used had a purity level of >99.999%, with a level of impurities of 3 ppm H_2O and 2 ppm O_2. The charging pressure was limited to <10 bar during the process due to safety considerations.

Figure 6.13 shows the results of the kinetics test. The test focused on obtaining the maximum value of the charging rate. This value was achieved at the initial moments of the process.

The maximum value obtained was approximately 360 Nliters/min. A value around 170 Nliters/min was achieved after 5 minutes, and decreased slowly with time.

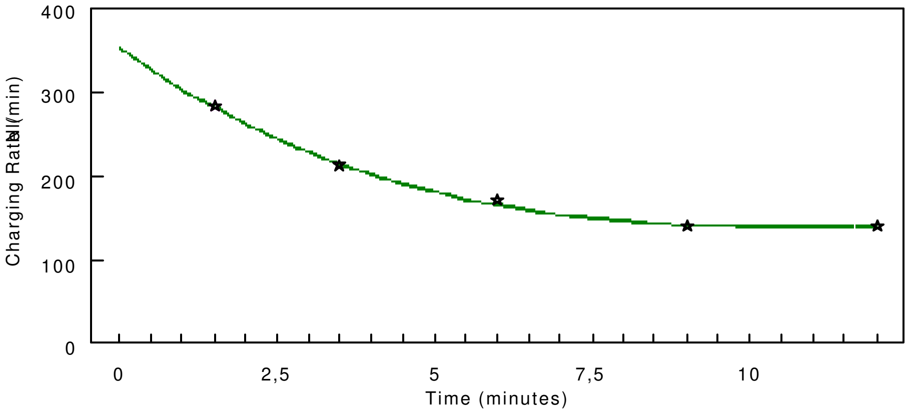


Figure 6.13: Kinetics test of metal hydrides

Figure 6.14 shows the results of the capacity test. From the initial conditions mentioned above, the hydrogen volume absorbed in the charging process was 22 Nm^3, close to the 24 Nm^3 nominal capacity.

The characterization of the other two main components of the system consisted of testing the rate of compression of the hydrogen booster compressor. Figure 6.15 shows the evolution of the volume of hydrogen compressed up to 200 atm in a bottle vs. time. The time employed filling the bottle was 2.7 hours.

5.3 Phase III - PAFC Performance

The electrical efficiency of the PAFC was obtained as a ratio between power delivery and the energy content of the hydrogen flow consumed (based on LHV). The I-V electrical efficiency is shown in Figure 6.16 for a wide intensity range.

Electrical efficiency at nominal conditions is around 50%. For a selected intensity, i.e. 80 A, efficiencies range between 50% and 40%, due to the influence of electrolyte temperature on final efficiency of the system. Since start up of the system, the loss of efficiency is estimated to be 20%. A test program is scheduled to be carried out to determine efficiency evolution as a function of working hours.

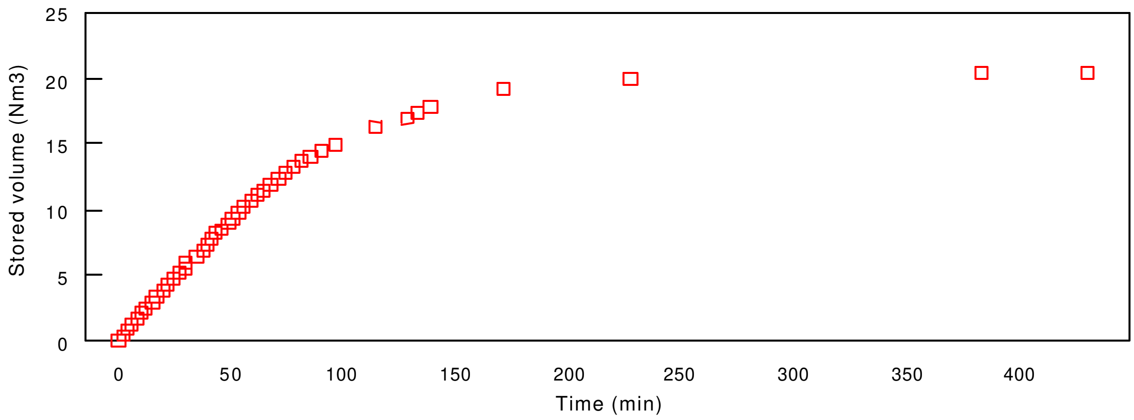


Figure 6.14: Capacity absorption of metal hydride tank

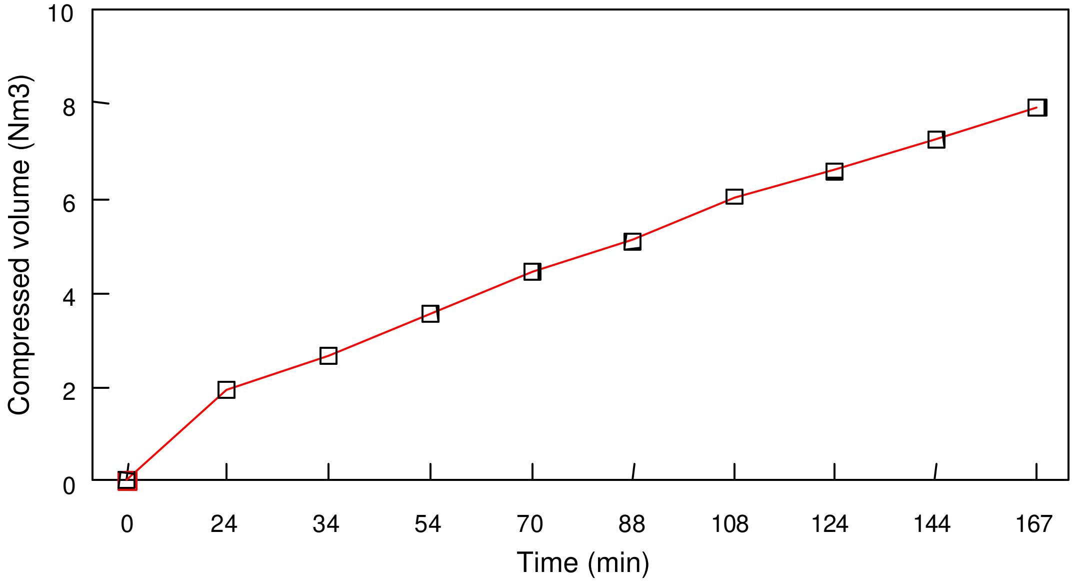


Figure 6.15: Compressor characterization

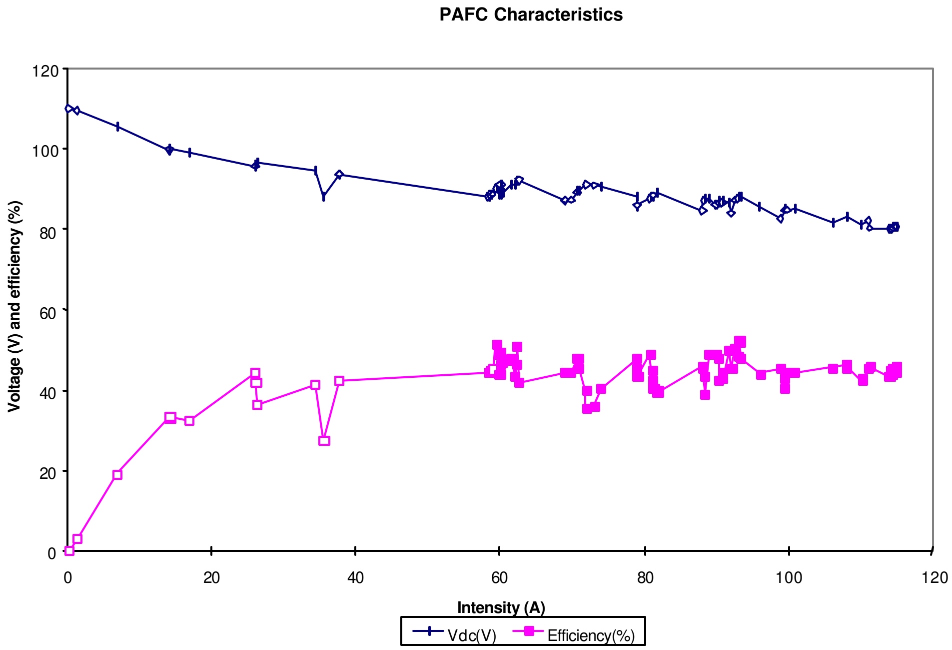


Figure 6.16: Performance of the PAFC

5.4 Integrated operational experiences

In concert with the commercial nature of all components used in the plant, acceptance tests carried out before installation of components showed good agreement with technical specifications given by the manufacturers, so that it was not necessary to modify the preliminary designs for the correct operation of the system.

Integration between the PV field and electrolyzer showed satisfactory results in direct connection mode and very good results operating in direct connection with variable cell numbers.

The PAFC is decoupled from the production section by using the storage section, so there is no real integration between the two subsystems.

The system was in continuos operation for three years until the evaluation program was finished. Since then, the system is periodically operated.

The most critical component of the system was the pneumatic feed water pump of the electrolyzer. No solution was found to the periodic malfunction of the pump. Each year, it is necessary to replace the membranes of the pump.

Due to the operational sequence during start up and shutdown, inertization of the system with nitrogen is required. Some small quantity of nitrogen goes to the storage section, resulting in a decrease of the kinetic absorption rate in the hydride container. Once the effect of such “nitrogen contamination” was evaluated, it was decided to modify the start up and shutdown electrolyzer sequences, minimizing inertization operation.

The time to reach steady state conditions is usually 2 hours from sunrise. During this period, the electrolyzer temperature and, consequently, the efficiency of the system, are below their nominal values. This problem can be solved by isolating the liquid-gas separator vessel of the electrolyzer and by using the AC-DC converter to reach nominal electrolyte temperature in less than 20 minutes.

Using the automatic control system of the production side, this part of the plant is suitable for unattended all-day operation. The utilization subsystem has a manual control system, thus precluding unattended operation.

Finally, it must be stated that it is quite difficult in many cases, to find components of optimum size for small-scale integrated facilities such as this one.

6. DATA ACQUISITION SYSTEM

This system registers the operational parameters of the PV field, electrolyzer, storage system, PAFC, and auxiliary subsystems. It also records data on a computer hard disk for later evaluation and enables a graphics monitor presentation of the plant status and trend diagrams.

Configuration of the data acquisition system is based on an external bus, connecting a number of distributed acquisition cards with the host computer. Commercial software (Iconics GENESIS) was used for the acquisition and surveillance functions. The PAFC data acquisition system is composed of a DataLogger FLUKE HYDRA and National Instrument internal PC Card. The software used is LabWindows from National Instrument.

The following signals are read and stored by the system:

- Photovoltaic field:
  - Intensity and voltage
  - Cell and ambient temperature
  - Global solar radiation on the panel's plane.
- Electrolyzer:
  - Voltage and intensity
  - Electrolyte inlet and outlet temperature
  - Hydrogen flow
  - System pressure
  - Hydrogen and oxygen analysis
  - Hydrogen and oxygen separator's level.
- Hydrogen storage system:
  - Hydrogen purity
  - Water temperature at inlet/outlet of hydride container
  - Hydride container inlet/outlet hydrogen pressure
  - Hydride container water flow
  - Hydride container hydrogen flow
- PAFC System:
  - Voltage and current of the system

  - Voltage each 10 cells (fourteen measurements)
  - Mass flow of hydrogen and of carbon dioxide
  - Stack temperature at 15 locations
  - Reformer temperature at 13 locations
  - Mass flow of methanol to reformer
  - Chromatographic analysis:
    - Composition of gas at exit of reformer burner
    - Reformed gas before and after shift conversion
    - Gas composition at anode and cathode exit

- Utilities:
  - Cooling water flow
  - Inlet and outlet cooling water temperature
  - Feedwater temperature and conductivity
  - Pressure losses

Any abnormal events that trip an alarm are also recorded.

7. PUBLIC ACCEPTANCE AND SAFETY ISSUES

There is no special public sensitivity concerning production and use of hydrogen in Spain. It is considered an industrial gas whose main risks are derived from its flammable nature and its storage at high pressure. From a legal point of view (regulation that must be taken into account to design industrial installations) hydrogen is treated in the same way as natural gas. There are special regulations concerning materials that come in contact with hydrogen.

Taking into account the lack of legislation concerning use of hydrogen in several fields (i.e automotive), a project funded by the EU under the THERMIE program is underway with participation by INTA. The main goals of the European Integrated Hydrogen Project are:

- Identification of deficits impeding harmonization of rules, regulations, licenses and approval procedures.
- Harmonized approaches to develop standardized rules, regulations, licenses and approval procedures
- Preparation of a more profound basis for discussion
- EU wide accepted improved safety equipment
- Preparation of concepts for standardized infrastructure components.

8. FUTURE PLANS

INTA's next step toward introduction of these technologies is directed to the use of major components in the automotive sector. The focus is centered on the storage system and the PEM fuel cell. A collaborative project with an automotive company, with participation of a university, is under way in a regional project aimed at bringing promising high technology to an energy-intensive consumer application, i.e., vehicles.

9. CONCLUSIONS

INTA's solar hydrogen production, storage and utilization facility has been in operation successfully for a long period of time. The main objectives have been reached and great interest from the scientific community concerning the potential of these technologies for human use continues.

Chapter 7
CLEAN AIR NOW:
SOLAR HYDROGEN FUELED TRUCKS

1. PROJECT GOALS

Encompassing the second largest city in the United States (Los Angeles), the South Coast Air Quality Management District (SCAQMD) suffers from the most severe air pollution problems in the nation, and its population endures some of the world's worst air quality. This area also offers the greatest potential for development of hydrogen fuel. Ozone, particulate matter (PM10), and carbon monoxide are the most dangerous pollutants identified in the district. Replacing fossil fuels with hydrogen would eliminate both of these pollutants along with the majority of all carbon-based emissions.

Clean Air Now (CAN) has formulated a master plan to develop and demonstrate the hydrogen energy economy. The integrated "Hydrogen Corridor" will extend from the Pacific Ocean at CAN's El Segundo, California solar hydrogen site to the renewable hydrogen and fuel cell program in Palm Desert California. Southern California offers an excellent test bed for the complete infrastructure of a hydrogen economy.

2. GENERAL DESCRIPTION OF PROJECT

Started in August 1994, the CAN Solar Hydrogen Vehicle Project demonstrated a practical application of renewable hydrogen. The demonstration featured a solar energy hydrogen generating system, fueling station, and a small fleet of Ford trucks with internal combustion engines (ICEs) converted to use hydrogen. CAN oversaw, directed and managed the overall project. Other team members included the Xerox Corporation; The Electrolyser Corporation (currently Stuart Energy Systems Inc.); Praxair Incorporated; Solar Engineering Applications Corporation (currently Photovoltaics International, LLC); Kaiser Engineering; City of West Hollywood; W. Hoagland & Associates, Incorporated; Touchstone Technology; the University of California, Riverside, College of Engineering – Center for Environmental Research & Technology (CE-CERT); Matrix Construction and Engineering, Incorporated; and the Energy Technology Engineering Center (ETEC). An aerial view of the facility is shown in Picture 7.1.

The hydrogen-powered utility vehicle fleet was operated by the Xerox Corporation in El Segundo and by the City of West Hollywood. The project was funded by the White House Technology Reinvestment Project (contracted through the U.S. Department of Energy), CAN, SCAQMD, and the rest of the project team.

The goal of the CAN-Xerox project was to demonstrate the use of solar-generated hydrogen as an alternate clean fuel for utility transportation vehicles. This project utilized state of the art, "off-the-shelf" technology including photovoltaic (PV) electricity generation and water electrolysis production of hydrogen.

The hydrogen-fueled CAN Ford Ranger trucks represented a significant advancement in the development of ultra-low emission vehicles (ULEVs). By using hydrogen fuel, these trucks eliminated air pollutant emissions of CO, CO_2, and unburned hydrocarbons, while significantly reducing emissions of nitrogen oxides (up to 90%). Hydrogen produced from electrolysis of water powered by PV electricity, is a clean, practically inexhaustible power source for automobiles.

Picture 7.1: Aerial view of Xerox-Clean Air Now facility

3. DESCRIPTION OF COMPONENTS

3.1 Hydrogen Production System

The intent to produce hydrogen without polluting emission dictated that the hydrogen be produced without aid from the utility grid. Shown in Figure 7.1, the stand-alone system consisted of a PV array, an electrolyzer, and a compressor. The electrolyzer as well as the hydrogen compression system operated directly from the PV array.

Sun tracking Fresnel lens concentrators formed the bulk of the PV array, supplemented by a fixed panel array. The single axis tracker array consisted of forty sub-arrays with 12 tracking concentrators each. Each sub-array had an electronic sun-seeker tracker, which at dusk returned the concentrators to point towards the east overnight to better sense the morning sun.

The extruded acrylic Fresnel lenses concentrated the sun’s energy ten to fifteen fold onto the single crystal silicon cells, which were mounted on an extruded aluminum heat sink that acted as a heat exchanger to the ambient air. Two sizes of concentrators, 11” and 15” in width, were used in the array. The concentrators were approximately 11.5 feet in length. Each panel (12 modules each) produced 550-750 W.

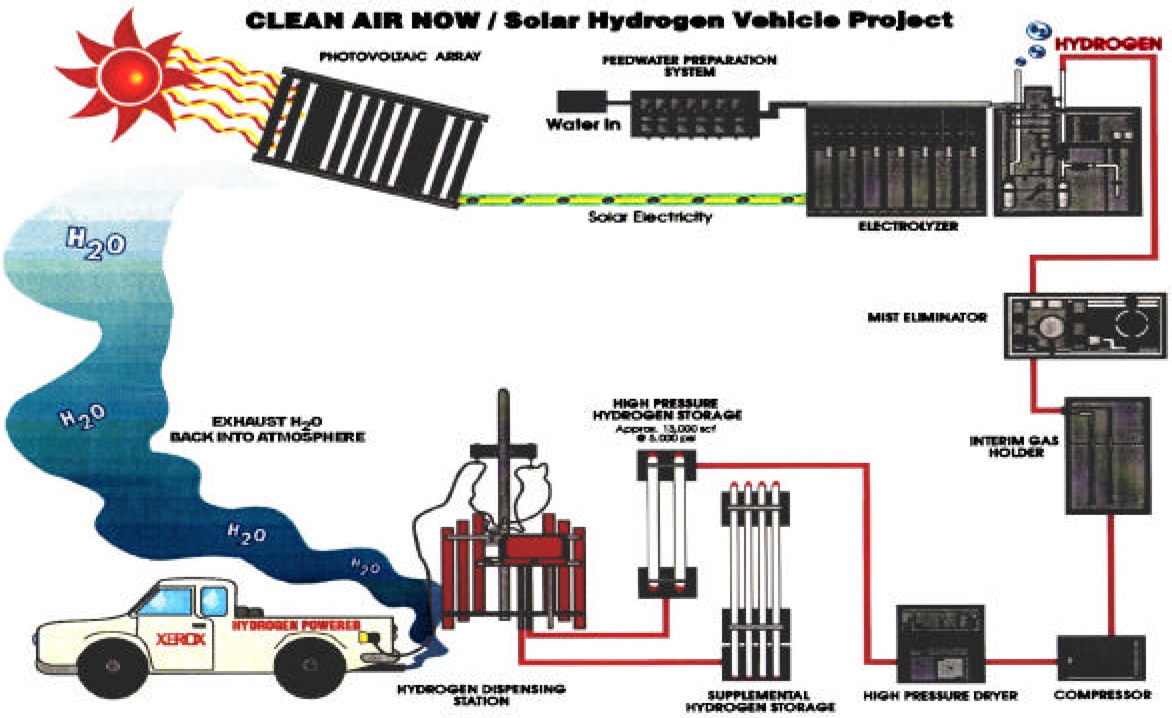


Figure 7.1: Xerox-CAN Solar Hydrogen Production Facility Scheme

Each concentrator yielded several amps at approximately 15 V, and all were connected in parallel. The panels were tied together with cables, and the one adjacent to the bus bar was tied by cable to the bus. The bus was made of ¼" x 6" copper bar, with doubling in the parts that conducted a thousand or more amps.

The PV array power was available to the electrolysis process and to the inverter for the compressor. The inverter required from 500 to 800 A, depending on gas pressure and voltage. The PV array also supplied current to the battery charger to recharge the batteries that maintain the power to the control system at all times.

Water from the city mains was demineralized using a deionizer bed and added to the cell bank to replenish that lost in the electrolysis process. Oxygen and hydrogen are kept separate in the cells by membrane separators. A water seal is used to equalize pressure between the two parts of the cell. The oxygen generated was vented to the atmosphere, while the hydrogen passed through a porous mist eliminator and then to a gas holder that acted as a buffer between the cells and the compressor. The compressor capacity of 404 scf/h was larger than the generating rate of the cells. The compressor ran intermittently, starting when the gas holder was full and stopping when the gas holder was empty. If the compressor was not operational due to a lack of power (i.e., low sun or cloud cover), the hydrogen was vented by the gas holder when full.

The Electrolyser Corporation constructed the electrolysis system in a 40-foot shipping container. Included therein were:

- Eight electrolysis cells, each rated at up to 4000 A, connected in series in order to provide a system with a 16 V nominal rating. The electrolyzer cells are capable of producing up to 400 scf of hydrogen at 48 kW and 16 V.

- A low-pressure gas handling system which releases the oxygen to the atmosphere and provides a low pressure temporary storage of hydrogen production in a 1.5 m^3 capacity gas-holder.
- A 15 hp [11.2 kW] compressor suitable for operation with hydrogen at pressures to 5000 psi, derated to 4200 psi. A dryer stage reduces the water content to attain dewpoints of -40°C expanded.
- A variable speed inverter (designed for operation from voltages as low as 12 V) to provide a “soft start” of the compressor.
- An electrolyzer control and data logging system which allows operation without an attendant and produces a record of the control and production parameters.
- Battery backup power for the controls, such that the control system continues to operate even on rainy days and at night.

The hydrogen compressor is a Compair Reavell, Model 5409, 4-stage, air-cooled, oil lubricated reciprocating type compressor. The compressor operated at 950 rpm, and had a capacity of 388 ft^3/hr at a discharge pressure of 5000 psig. The compressor was driven by a 15 hp motor that operated at 1450 rpm. The power to operate the compressor was derived from the PV array. To preclude damage to the compressor, each stage of the compressor was protected by a safety relief valve. The exhaust of these relief valves was returned to the top of the moisture separator at the inlet to the compressor.

In addition to the aforementioned safety relief valves, there was an interlock within the compressor system, which was used to protect the hydrogen compressor from damage due to high temperature or low oil pressure. When activated, the interlock initiated a shutdown of the compressor.

3.2 Hydrogen Storage and Dispensing

The hydrogen storage system consisted of twenty-four 2200 psig, 22.5 cubic foot ASME storage vessels (holding ~74,000 scf of hydrogen at 2200 psig) and two 5000 psig, 26.6 cubic feet ASME storage vessels (holding ~14,000 scf of hydrogen at 5,000 psig). The two 5,000 psig vessels were the only vessels filled from the electrolysis system. The 2,200 psig vessels were filled by an external hydrogen supply source, and were only used when hydrogen was not available from the two high-pressure storage vessels. The two high-pressure vessels were protected with two safety relief valves, one valve on each vessel, with each relief valve set to relieve at 4,600 psig.

The hydrogen dispensing system consisted of an Automotive Natural Gas Inc. (ANGI) fueling post, piping, and valving. The ANGI fueling post used a dual-hose rated for operation at 5,000 psig. The system was termed a “fueling post” simply because there were no automatic dispensing or metering functions provided (Pictures 7.2 and 7.3). The piping and valving downstream of the high-pressure storage vessels were all designed to operate to at least 4,600 psig. The dual-hose unit features hose retractors, and the breakaway force was 25 pounds pull on a hose (approximately). These components were protected from overpressure conditions by means of two pressure relief devices installed on the two high-pressure storage vessels. To preclude the overpressurization of the utility vehicle hydrogen storage tanks, a relief valve set to relieve at 3,900 psig was installed on the nozzle side of the dispensing system, with a gas regulator set at 3,500 psig.

Picture 7.2: Refueling the Ballard Fuel Cell Bus at the CAN Solar Hydrogen Refueling Station

Picture 7.3: UCR1 at Solar Hydrogen Refueling Facility

3.3 Balance of System

The power distribution and control system consisted of a battery system, a controller/inverter, and a control panel. The battery system consisted of a 24 V, 265 Ah battery bank, a 1,000 W inverter (nominal 24 V_{DC} to 120 V_{AC}), and a 24 V_{DC}, 30 A battery charger (120 V_{AC} input). Battery capacity was sufficient to power the control functions for 48 hours. Power from the PV array was applied to the inverter through a fusible switch. The inverter supplied regulated 120

V_{AC} power to the battery charger. The battery charger charged the 24 V battery bank with a regulated voltage and current, tapering the charge when the batteries were full. The inverter was remote-controlled from a Programmable Logic Controller (PLC). Only when the PV array current was greater than 200 A would the battery charging system be operated.

The batteries supplied power to the control system day and night. Most of the equipment and electronics operated directly from the 24 V_{DC}. However, a few devices required 120 V_{AC}, and this is supplied through a 250 W auxiliary inverter. The controller/inverter was a variable speed motor drive for operating the three-phase compressor motor. It operated directly off the photovoltaic array and provided controllable, regulated AC voltage at 208 VAC to the motor. It was comprised of a DC boost converter, followed by a DC to AC inverter, and a control board to provide all run, monitor, and fault operations. The control panel contained two main sections: Control and Data Acquisition. The control panel included the control, annunciation, and instrumentation systems for the plant. It was dedicated to the 24 V_{DC}, 12 V_{DC}, and 120 V_{AC} devices. The PLC controlled the compressor, battery charging system, solenoid valves, and the DC switch. It also performed the annunciator function.

When operated at full capacity, the electrolytic cells consumed approximately 12 liters (3 gallons) of water per hour. The electrolyte feedwater was filtered and demineralized using a system of filters and an ion exchange resin bed. This prevented scaling of the electrolytic cell system and maximized electrolytic cell performance. A conductivity meter and cell were supplied for measuring the conductivity of the water to the plant.

3.4 Vehicles

In 1994, under contract from SCAQMD and CE-CERT, Hydrogen Consultants Inc. (HCI) (Currently Hydrogen Components, Inc.) and Advanced Machining Dynamics (AMD) converted a Ford Ranger truck to use a hydrogen fueled ICE, known as UCR1. UCR1 used a constant volume injection (CVI) system that delivered timed and metered quantities of hydrogen to each cylinder. Fuel metering was controlled fluidically with trimming by an electronic pressure regulator using exhaust oxygen feedback.

The CAN/Xerox project included funding to provide similar truck conversions to be used by the Xerox maintenance staff, and also for a truck to be used by the City of West Hollywood. These trucks were used for short runs around the Xerox buildings, and on local streets. The truck converted for the City of West Hollywood used the freeways to go to El Segundo for fuel. Whereas UCR1 had an automatic transmission, the CAN trucks used manual transmissions – which improved low speed acceleration. These trucks were dubbed CAN1, CAN2, and CAN3. CAN1 and CAN3 are owned by the Xerox Corporation. CAN2 was the property of the City of West Hollywood.

The original vehicles were equipped with a 2.3-liter, 4-cylinder gasoline fueled engine, five speed manual transmission, standard steering, and 3.08:1 rear drive gears. Conversion to hydrogen fuel included cylinder head modification for increased air flow, increasing piston displacement to 2.85 liters, addition of a roots type supercharger and intercooler, 4.10:1 rear drive gears, and a CVI system.

The emissions control system consisted of an electronically trimmed fuel injection system with exhaust oxygen feedback, a positive crankcase ventilation system and an oxidation catalyst. The lean burn engine was held in a closed loop control with a constant fuel-air equivalence ratio of less than 0.45 where oxides of nitrogen are very low. There were no other significant pollution emissions with hydrogen fuel.

At the request of Praxair Corp., the first Xerox truck was fitted with two Comdyne aluminum/fiberglass tanks having an internal volume of 3.70 cu.ft. Subsequently, EDO Canada provided two carbon fiber, 3600 psi tanks having an internal volume of 5.64 ft^3 each, mounted in the bed of each truck. These tanks used approximately 50% of available bed space and allowed a range of about 144 miles. These EDO tanks reduced tank weight by 58% and increased range by 52%.

Using an intercooled supercharger instead of a turbocharger, and increasing engine displacement to 2.85 liters, provided low speed performance at least as good as a standard unit, despite operating at less than 50% of the stoichiometric fuel-air ratio. The compact, lightweight EDO fuel tanks allowed the vehicle to be used as a practical and useful truck. If regulations are changed to permit storage of gaseous fuels on board vehicles at pressures in the range of 5500 psi to 7000 psi, increases in range and payload will make such vehicles very practical low emission transportation modes.

To accommodate the modified engine, hydrogen fuel system, and CVI system, several modifications to the chassis and body of the trucks were required. A large capacity air-to-air intercooler was fabricated from components by Allied Signal Corp. and mounted in front of the engine-cooling radiator. The single-row radiator was replaced with a two-row Modine radiator, located 1.5” aft of the original location. Engine intake air was routed through a relocated stock throttle body to the supercharger, the intercooler, and a modified stock intake manifold, and into the engine.

All gasoline fuel system components were removed and discarded. Removal of the gasoline fuel system saved weight and offset some of the weight of the new system.

Hydrogen tanks, transversely mounted at the front of the truck bed, were protected by side impact structures. CAN1's Comdyne manufactured aluminum/fiberglass tanks were protected by a tubular steel structure around the valve end of the tanks. The EDO tanks required extensive bed modification. To accommodate the long tanks, it was necessary to truncate the rear wheelhouses and to install 3” square steel beams between the outer skin and the inner bed walls for crash protection. An added benefit of the EDO tanks was a reduction in weight of 130 kg, compared to the Comdyne tanks.

Steel sheet covers were installed over and behind the tanks to protect them from damage by dropped objects or shifting cargo. The fuel pressure gage, primary regulator, and flow control valves located in the bed were also protected by these covers.

4. OPERATIONAL EXPERIENCE AND PERFORMANCE

4.1 Solar-Hydrogen Production Facility Performance Data

From the very beginning of the project, one of the guiding principles was to ensure all parties felt safe with the hydrogen technologies that were implemented. The facility was designed using industry standards and applied accepted practices to all the systems.

ETEC performed assessments of the system. Once ETEC gave the facility "safe to operate" ratings, and the El Segundo (California) Fire Marshal agreed, the Building Department issued the final inspection permit.

The codes & standards applied by ETEC to perform the safety and failure mode assessments include:

- NFPA 50A, Standard for Gaseous Hydrogen Systems at Consumer Sites, 1994 Edition.
- NFPA 52, Standard for Compressed Natural Gas (CNG) Vehicular Fuel Systems, 1992 Edition.
- NFPA 70, National Electrical Code, 1993 Edition.
- ASME/ANSI B31.3-1993, Code for Chemical Plant and Petroleum Refinery Piping.
- ASME Boiler and Pressure Vessel Code - 1986, Section VIII, Rules for the Construction of Pressure Vessels.

The performance of the solar-hydrogen production facility was first measured for three days in November 1996. Production of hydrogen began just before 9 a.m. Five hours of good production were observed on average, with the days' compression being terminated by the coastal haze at 2 p.m. Figure 7.2 shows the gradual increase in pressure from 2950 psi to 3450 psi, in the storage tanks (PressExit). The current in the PV array (I_{array}) follows insolation. The current drawn by the inverter (I_{invert}) indicates when the compression system is running. These results show that in November, about 5 hours of production per day took place, and it is estimated as many as 10 hours of production per day are possible in August. (No hydrogen production data from August are available, though PV output was measured over several months.) The production is thus expected to be over 7 hours per day on average, with approximately three compression cycles per hour. At an average current of 1800 A through the eight cells, the system is expected to generate 225 scf of hydrogen per hour.

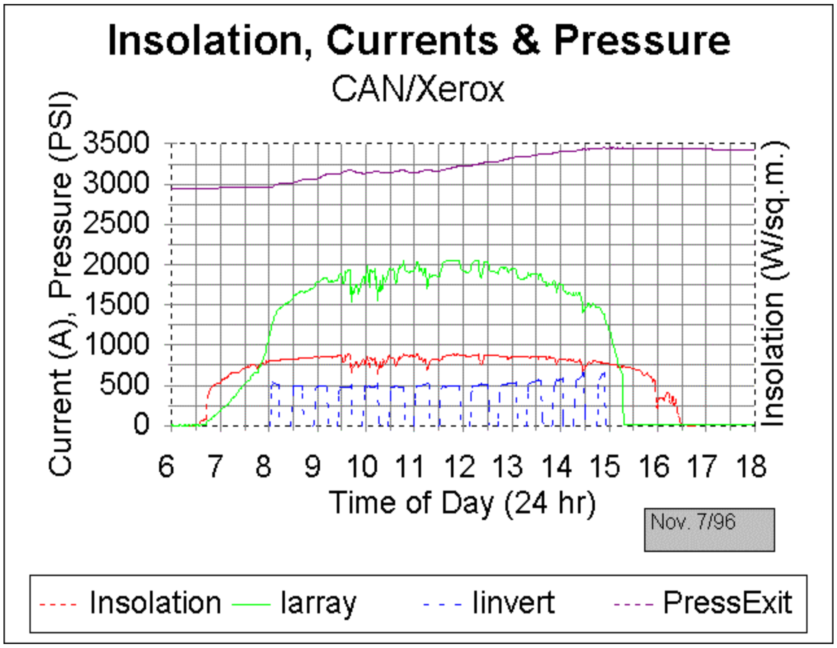


Figure 7.2: Insolation, Currents and Pressure

4.2 Vehicle Performance Data

Since this was a “deployment” project there was no funded R&D. There were, however, ancillary improvements to the original design and some of the component integration specifications: the ICE retrofit (improved low end performance over UCR’s truck); the hydrogen generation components (stand-alone capability, data acquisition); and the PV concentrator lens (increased efficiency).

4.2.1 Initial Check-Out

A top-level systems analysis of the CAN1 vehicle retrofit verified that the design was implemented in a safe and skillful manner. Also, the functional readiness of the vehicle and operability of the hydrogen-related safety devices were checked out. CAN1 was inspected by the Energy Technology Engineering Center (ETEC) and was found to meet the general requirements of the retrofit design; however, there were some deviations.

The major problem encountered in the initial checkout tests involved the hydrogen sensors. Neither the H_2 sensor in the truck bed nor the H_2 sensor under the hood in the engine compartment operated properly when the vehicle was delivered. As a result, a design change was made to allow the H_2 sensors to be wired directly to the battery rather than to the ignition. Thus, a hydrogen leak would be detected before the ignition is turned on, which is an improved safety feature.

During the leak check of the high-pressure hydrogen systems, two very small hydrogen leaks were found in the Swagelok joints between the fuel pressure gage and fuel feed valve. In an isolated system, the leaks resulted in an 8% pressure decay during a 24-hour period. It was decided that the two leaks were too small to impact any of the testing to be done at ETEC. These leaks were repaired prior to final vehicle service testing.

4.2.2 Refueling Evaluation

An evaluation was made of the fuel fill modifications necessary to refuel the vehicle with hydrogen. The stock gasoline fill port had been removed and replaced with a CGA-350 fill port for hydrogen service. The other end of this CGA-350 fill port screwed into a ¼-in NPT port that attached to the hydrogen tank lines. The vehicle was always grounded prior to attaching the CGA-350 fill line.

In order to perform the refuel operation, the Rocketdyne H_2 Lab constructed a H_2 fueling station. A total of seven refueling operations were successfully performed by ETEC without any problems or apparent damage and wear to the CGA-350 fitting.

4.2.3 Safety Tests

The objective of the safety tests was to assess safety issues during situations that were expected to be encountered during the life of the vehicle. These included the presence of a mixture of hydrogen and air in the exhaust manifold (such as during vehicle stalling), loss of ignition in one or more cylinders, and oxygen sensor failure. These tests also served as verification of the ECM sequencing for start-up and shutdown. All the safety testing was performed with the vehicle stationary and the hood closed, and the engine running in idling mode.

Fuel starvation-restart safety tests

The objective of the fuel starvation-restart test was to determine if any restart problems existed as a result of the engine running out of fuel. This test also verified the proper ECM sequencing for start-up and shutdown. No safety issues were identified based on these fuel starvation-restart tests.

Stall-Restart Safety Tests

The objective of the stall-restart tests were to determine if any unburned hydrogen that accumulated in either the intake manifold or the exhaust system from an engine stall created a safety hazard when the engine was restarted. The engine ran and idled the same after these tests as it had before the tests were performed.

Failed Oxygen Sensor Safety Tests

These tests were performed to determine if the engine could run safely and be restarted with a failed oxygen sensor. A failed oxygen sensor maintains the electronic pressure regulator in open-loop control of the air/fuel ratio; therefore, the air/fuel ratio is fixed and cannot be adjusted by a signal to the electronically controlled pressure regulator. There was no noticeable difference in how the engine either started or idled with the oxygen sensor either on or off. However, when the engine was idling with the oxygen sensor on and the oxygen sensor was then turned off, the engine stalled. Although the engine stalled when the sensor was turned off (failed oxygen sensor), it did not create a fuel system safety hazard.

4.2.4 Service Tests

Service tests were performed to assess the general operability of the hydrogen fueled vehicle and to get a very preliminary indication of any degradation in performance which could have resulted in subsequent hydrogen safety issues. Initial service testing was performed on a network of mountainous roads with uphill and downhill grades as steep as 12.5% within the ETEC complex.

The following data were gathered during the service tests:

- From the very beginning of the service testing, the vehicle ran very sluggishly during acceleration. Even while accelerating downhill, the engine seemed to cough, causing the vehicle to lunge rather than to accelerate smoothly. At times, the engine made a very strange pinging or clattering sound while the vehicle was being accelerated, regardless of the direction or degree of the road grade. Since the engine did not make this strange sound continuously, it appeared to be caused by the engine not being adjusted and tuned for hydrogen service while under relatively high torque. None of these strange sounds was detected during the safety tests, which were performed while the vehicle was stationary and the engine idling under very low torque. Most of the problems manifested themselves at speeds below 35 mph with the vehicle in the first three gears. The vehicle seemed to run quite well at 36 mph in 3rd gear and 45 mph in 4th gear.
- Because of engine restart concerns due to condensation forming in the combustion chamber and on the spark-plug electrodes, if the engine stopped while it was cold, a series of cold start-restart tests were performed. After the vehicle had been parked outdoors all night after the refueling operation, the cold engine was started and then immediately shut off. This test

was repeated a total of five times and each time the engine started immediately. Even though there was a large amount of condensation formed during these tests, none of the condensation prevented the engine from restarting. Examination of the sparkplugs showed them to be very clean.

- A series of tests was performed to simulate a failed oxygen sensor by turning the oxygen sensor off. With the oxygen sensor off, the engine started immediately; however, when the vehicle was driven, the engine ran very rough and stalled three times. It was determined the vehicle definitely needs the oxygen sensor on and operating in order for the engine to run properly.
- A quart of oil was added to the engine, after only 223 miles of initial service testing. Although there may have been some oil consumption because the engine had just recently been rebored, the loss of oil was probably due to an oil leak at or near the engine/transmission interface.
- A total of 240 miles were driven during the initial service testing. Each time the vehicle was refueled, the trip odometer reading, hydrogen tank pressure, and approximate ambient temperature were recorded. It was assumed that the tank temperature was approximately the same as the ambient air temperature. This information was used to calculate the fuel consumption. During initial service testing, the average mileage rate was 7.04 miles/lb, equivalent to 14.73 miles/gal of gasoline. Contributing factors for this low mileage rate were: engine not properly tuned, mountainous test road, low speeds, and some testing with the oxygen sensor off.

5. ENVIRONMENTAL ASPECTS

A single Federal Test Procedure (FTP) dynamometer was run on the CE-CERT vehicle, showing carbon-based emissions to be extremely low, and average NO_x emissions of 0.37 g/mile. This can be compared to the ULEV standard for NO_x of 0.2 to 0.3 g/mile (over 100,000 miles). Other dynamometer tests gave evidence of the engine control system having operational characteristics prone to high NO_x under certain conditions.

The three CAN trucks, although expected to be identical, operated notably differently. This became evident in constant speed dynamometer tests done in conjunction with CE-CERT. The NO_x tests varied depending on the truck, with the best of these vehicles maintaining below 35 ppm NO_x at full throttle over a range of speeds. This suggests a capability of operating at sub-ULEV emissions under the worst of conditions. The most powerful truck, CAN2, operated with a richer mixture, had higher NO_x test values.

A single FTP75 test procedure was run on the high performance truck, CAN2. Total grams per mile results (as compared to the ULEV standard and proposed EZEV standard) are given in Table 7.1. It is evident that the hydrogen-fueled truck handily meets any of the standards for CO and HC, but the NO_x only meets the high mileage ULEV standards.

6. OTHER EXPERIENCES

The hydrogen-fueled trucks were operated from December 1995 to July 1997. Although the trucks, PV system, and electrolyzer performed to expectations, the compressor needed the most maintenance, and in fact was down for three months prior to December 1995.

Table 7.1: Comparison of Emissions in g/mile

	CAN2	ULEV 50,000 mi.	ULEV 100,000 mi.	EZEV
CO	0.052	1.70	2.1	0.170
HC	0.003	0.04	0.055	0.004
NOx	0.299	0.20	0.3	0.020
Total	0.36	1.94	2.455	0.194

The system produced about 1800 scf H_2/day in the summer and roughly 1200 scf H_2/day in the winter months. The solar array generated roughly 34.5 kW (2300 A at 15 V) during the summer months and about 18.2 kW (1300 A at 14 V) during the winter months. CAN1, with the smaller Comdyne storage tank, carried 1500 scf of hydrogen and had a range of 60-65 city miles and 90 highway miles. CAN2 and CAN3 with the larger EDO tanks carried approximately 2300 scf H_2 and had a range of 110 city miles and 140 highway miles. The trucks require 22 scf H_2/city mile and 16.5 scf H_2/highway mile. The solar production facility provided 1800 scf H_2 per day in the summer months, sufficient for 82 city miles, or 109 highway miles.

The greatest trouble spot in the system was the compressor. After causing the three-month delay, the compressor ran without any major problems. It was felt that if the compressor performed a heavier duty cycle, it would have run into more problems.

Another problem was the needle valves used in the high compression lines. The seals didn’t hold and minor leaks occurred. Ball valves were then used to replace the needle valves. The ball valves were easier to turn at the correct turning torque. The problem was solved, and it is recommended that ball valves should always be used in high-pressure lines.

7. FUTURE PLANS

Currently, CAN has the opportunity to move from hydrogen energy demonstration to commercialization. They will be splitting the project in two parts, using its assets to enhance the hydrogen infrastructure in Southern California. Xerox Corporation will maintain hydrogen storage tanks and dispensing capability to continue to provide service for their vehicles, as well as to other vehicles that will be operating in the western end of the Los Angeles basin. Hydrogen will be trucked in to supply the facility. The generation portion of the facility, along with a new dispensing station, will be installed at Sunline Transit in the Coachella Valley to provide hydrogen and hydrogen/natural gas blends for buses planned to operate on public transit routes.

Sunline Transit of Thousand Palms has stated that they "are committed to the alternative fuels area, and we want to get to the fuel cells and the use of hydrogen as fast as we can."

The lessons learned by Clean Air Now and the rest of the project partners from the Xerox facility will be used to provide Sunline with a viable and non-polluting source of hydrogen. Clean Air Now and Sunline Transit will be ushering in the hydrogen age within the public transit sector in California.

8. CONCLUSIONS

The Clean Air Now Solar Hydrogen Vehicle Project, at Xerox Corporation, El Segundo, California, represents the first fully permitted, commercially dedicated facility of its kind in the United States. Greater public exposure to the clean energy technologies of tomorrow was effected by the project and all its participants. All aspects of the renewable hydrogen economy were incorporated into the facility by design; from renewable hydrogen generation and hydrogen storage and dispensing, to end-use technology practically applied at a private corporation. The facility demonstrated fully independent hydrogen fuel production and use, creating a virtually pollution-free transportation system.

Clean Air Now continues to work so that someday its facility will no longer be the largest of its kind in America. CAN has entertained thousands of students and other people at the facility, fostering a greater understanding of the benefits of hydrogen energy and cultivating additional efforts.

Chapter 8

SAPHYS: STAND-ALONE SMALL SIZE PHOTOVOLTAIC HYDROGEN ENERGY SYSTEM

1. PROJECT GOALS

The Stand-Alone Small Size Photovoltaic HYdrogen Energy System (SAPHYS) Project was a joint project of ENEA (Ente per le Nuove Tecnologie, l'Energia e l'Ambiente; Italy), IFE (Institutt for Energiteknikk; Norway), and KFA (Forschungszentrum Jülich, Germany), and was supported by the European Commission within the framework of the Non-Nuclear Energy Programme Joule-II. The purpose of the program was to address issues related to global environmental problems caused by the use of fossil fuels, giving rise to changes in global climate. A more extensive use of renewable energy and an industrial transition from a petroleum economy to a non-fossil fuel economy such as hydrogen, could help resolve these problems. SAPHYS was conceived to test and demonstrate safe and effective long-term storage of hydrogen produced by renewable energy using solar powered electrolysis of water, and to regenerate the stored energy into electric energy with a fuel cell.

The objectives of the project were:

- to assess the efficiency of hydrogen used as a storage medium of solar electric energy, and
- to design and test a small SAPHYS system for unattended operation.

2. GENERAL DESCRIPTION OF PROJECT

Even if better performance and operation of plant could be obtained at larger scale, the scope of this demonstration suggested a reduced size plant. SAPHYS plants (of several kWs in size) are proposed for remote and isolated applications such as telecommunication energy systems, isolated houses on small islands, or a remote environmental monitoring station. Such applications could then represent an initial market niche for solar-hydrogen technology.

The system consists of a photovoltaic array that supplies energy to a variable simulated load, backed by battery storage for short-term energy fluctuations. Excess energy from the photovoltaic array is utilized for the production of hydrogen by electrolysis of water. A proton exchange membrane (PEM) fuel cell is included for production of electricity when the solar input is not sufficient and the batteries are nearly completely discharged. The system was designed to operate in a stand-alone (fully automated) mode, with appropriate computer controls and data acquisition.

The construction project lasted 36 months, from July 1994 through June 1997. Automatic operation commenced in September 1997.

3. DESCRIPTION OF COMPONENTS

Most of the components of the system have been assembled at the ENEA Research Centre in Casaccia (near Rome) using the Photovoltaic Hydrogen Test Rig (PHYTR). The two major improvements within the SAPHYS project were the replacement of the electrolyzer stack with an advanced one, and the implementation of an integrated plant control system.

3.1 Photovoltaic Hydrogen Test Rig

The PV array consists of 180 single crystalline modules produced by different manufacturers (Arcosolar, Helios and Italsolar), configured into 8 sub-arrays. The inclination of 50° was chosen in order to increase the winter energy production. All sub-arrays were wired for a nominal 36 V_{DC} operation and 60 V_{DC} open circuit voltage with a rated power of 5.6 kW at nominal conditions (1000 W/m^2; 25°C). Each array is connected directly to the bus bar.

The lead acid battery has a storage capacity of 51 kW, configured as 34 V_{DC}, (1500 Ah).

The hydrogen storage capacity was designed to be at least 300 Nm^3, but the actual capacity is somewhat less. As a consequence, the time of a continuous winter test will be limited. The maximum storage pressure was about 20 bar.

An electronic load is used to simulate the energy/power demand of two isolated houses with typical domestic electric and electronic devices. The summer load profile is characterized by small and short hourly peaks of about 0.4 kW and two high consumption peaks (4 kW in the morning and 2.5 kW in the evening). The daily energy consumption during summer test was 11 kWh.

Ancillary equipment (compressed air, heating/cooling, hydrogen drying and purification, process water treatment, inert gas, electric devices, etc.) and monitoring and control systems were directly powered by the grid, and their energy demand was calculated for the net plant efficiency evaluation.

3.2 Electrolyzer

The electrolyzer section consists of a Metkon-Alyzer Model 0100 electrolyzer unit framework assembled with advanced cells specifically designed and manufactured by KFA for solar application, capable of operating up to 20 bar.

Apart from high energy efficiency and good dynamic performance in intermittent operation, a particularly important requirement for solar-operated water electrolyzer is the possibility of operating the electrolyzer over a wide range with high current yields and sufficient gas purities. To match the actual plant power, the existing electrolyzer of 2.5 kW was revamped for 5 kW, the required power according to the design data specified from simulations. This was done in co-operation with Casale Chemicals S.A. Furthermore, the electrolyzer control was modified to ensure fully automatic operation within the SAPHYS system.

With the aid of the SIMWELLY simulation program, developed at the Research Centre Jülich for design and optimization of alkaline bipolar electrolyzer, the 5 kW pressurized electrolyzer was designed and its performance data evaluated. This included calculation of the current/voltage curves, bypass currents, current yield, energy yield and overall efficiency for a temperature range of 25-80°C. The electrolyzer stack, similarly to the old stack, consists of 17 cells, connected in a bipolar configuration, with a single-electrode surface of 600 cm^2. An overall efficiency of approximately 87% (HHV) was calculated at 80°C and a rated power of 5 kW. This high level of efficiency for a technically advanced electrolyzer was achieved by using state-of-the-art electrodes and diaphragms. The electrode activation must be protected against corrosion by a minimum polarization voltage during electrolyzer down times (1.3 V/cell). Some of the technical characteristics of the advanced electrolyzer module are summarized in Table 8.1.

Table 8.1: Technical characteristics of advanced electrolyzer module

Peak power	5 kW
Cell active surface	6 dm^2
Stack cells	17
Electrolyte concentration	30% KOH
Operating temperature	80°C
Operating pressure	20 bar (max.)
Current[1]	180 A
Cell voltage[2]	1.67 V_{DC}
Module voltage[2]	28.4 V_{DC}
Heat to be removed[1]	580 W
Cell frame materials	PSU 5% G
Electrode materials	activated nickel
Diaphragm	NiO
Bipolar frame	Nickel

1) at peak power
2) at peak power and 80°C

3.3 Fuel Cell

The fuel cell is a Ballard Power Generator System (PGS) 103A solid polymer fuel cell (SPFC) electrical generator. It is rated at 3 kW_{DC} power, with air as oxidant, and it was designed mainly for demonstration and evaluation. Its main features are: the capability to operate at low temperature (about 72°C); its short start-up period; no significant stand-by problems; its simple installation and operation; its quick response to load changes; and its high efficiency.

The PGS, as supplied, includes hydrogen circulation, water circulation and cooling management, temperature control, and a number of additional controls and monitoring devices. It is configured to operate as a stand-alone unit for hydrogen pressures up to 30 psig (3.1 bar) and air system pressures to a maximum of 50 psig (4.4 bar). The system has a limited operating range due to its configuration as a demonstration unit and the design limitations of some of the system components. Its main characteristics are summarized in Table 8.2 and a top view is shown in Picture 8.1.

Table 8.2: System specifications of Ballard fuel cell

System designation	PGS 103 A
Stack cells	35
Electrolyte	Nafion 117
Plate material	Graphite
Active electrode area	232 cm^2
Cooling cells	19
Humidification cells	14
Stack dimensions	49x25x25 cm
PGS dimensions	104x80x37 cm
Stack weight	43 kg
PGS weight	150 kg
Fuel	Hydrogen
Oxidant	oxygen or air
Performance[1]	>21 V_{DC} at 125 A
Rated power (with air)	3000 W
Support system power	<250 W

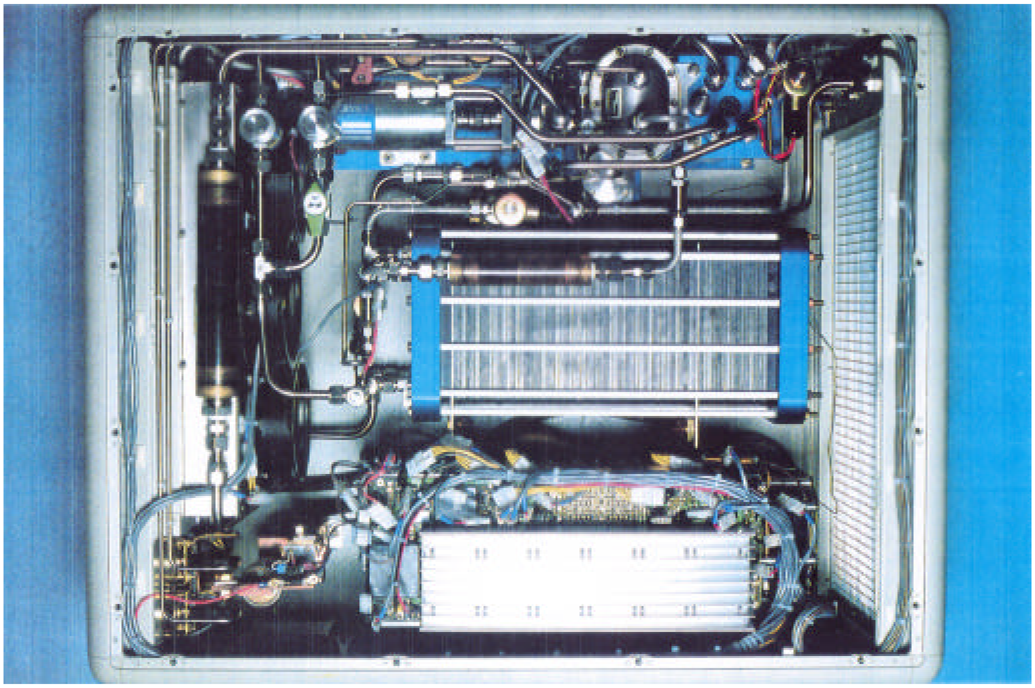
1) at 30 psig H_2/air at 70°C

3.4 Control system

The control system of the SAPHYS plant consists of three separate parts hierarchically organized. These parts are:

- the control systems for the electrolyzer, the fuel cell, and the hydrogen circuit
- the Alarm and Supervision Board (ASB)
- the Master Control System (MCS) performing energy management (EM)

The objective for the MCS is to control the electrolyzer and the fuel cell operation. The outputs from the MCS are the set-points for the currents to the electrolyzer and for the fuel cell DC-DC converters, and digital signals for starting and stopping the electrolyzer, the fuel cell, and related ancillary equipment in a controlled sequence. With the EM algorithm, these outputs are manipulated according to the state of charge (SOC) of the battery, which is estimated by the measurements of battery voltage, current, and temperature. Two methods were developed for battery SOC estimation: simplified (based on the algebraic sum of battery currents); and advanced (including a gassing current model).



Picture 8.1: Top view of the Fuel Cell Power Generator PGS-103 (photo provided by courtesy of Ballard Power Systems Inc.)

4. SIMULATION

In order to perform the SAPHYS system analysis and design, and to develop a control strategy for the system EM, the models of the plant components including insolation and load profiles were built and implemented in the Jülich simulation system, JULSIM program. JULSIM was developed by KFA for their solar-hydrogen plant, PHOEBUS. The EM rationale, based on the control of the SOC of the battery, was developed and optimized for high plant energy efficiency as well as for careful battery operation. Some parts of the code were to be implemented in the actual control system of the plant. The characteristics of the EM are:

- A so-called "five-state-controller" minimizes the use of the low-efficiency gas storage system. Its switching hysteresis minimizes the losses and wear of the electrolyzer and the fuel cell.
- The electrolyzer and the fuel cell are operated in such a way that the battery charge throughput is minimized.

After simulation and evaluation of many annual scenarios, optimized results were used as input for the plant design.

5. INTEGRATION OF COMPONENTS

The integration of components was a major part of the study undertaken for the SAPHYS Project, including:

- the development of a plant modeling program to determine the efficient component integration and basic control logic according to the solar input energy and the user power requirement
- the design, manufacturing and installation of new equipment necessary to implement the stand-alone unattended plant, with particular emphasis on an advanced electrolyzer stack specifically designed for solar application
- the design of a control system (MCS) to implement the basic control logic for unattended operation and energy management
- the modifications on the existing PHYTR (Photovoltaic Hydrogen Test Rig) at ENEA Casaccia Research Centre according to the new SAPHYS design
- experimental testing of the SAPHYS plant and of the MCS
- analysis of results and evaluation.

The PV array supplied energy to the load by a common electric bus bar. A battery storage unit continuously connected to the bus bar stabilized line voltage and compensated for short-term excess or deficit energy from the PV arrays. According to the SOC of battery storage, the MCS activated the electrolyzer or the fuel cell, according to EM rationale. Both pieces of equipment were connected by two separate DC-DC converters controlled by the MCS as well.

6. OPERATIONAL EXPERIENCE

After completion of the plant in the spring of 1997, some continuous test runs were performed to check the actual operation of SAPHYS. The tests identified some problems that were analyzed and almost completely solved. A set of tests was performed to check the correct communication and operation of the programmable logic controller (PLC) with the plant. Some adjustments on the MCS parameters were required to adapt the control system to actual plant dynamics. The loop time for performing the decisions to start and stop equipment and to define the DC-DC current set points was set to 1 minute. This time appeared to be adequate for prompt control action and plant stability.

Analysis of early tests showed a mismatch in the daily algebraic sum of the currents at the bus bar. However, less than the maximum calculated error occurred according to the actual instrument accuracy (1%). The error, due to the harmonic interference between DC-DC converter operation and battery current transducer, was solved by filtering the input signal to the transmitter.

On September 2, 1997, long-term continuous testing began in a fully automatic mode 24 hours a day, seven days a week. Due to the sunny weather of the first test period (two months), data acquired can be considered representative only of the summer operation of SAPHYS. Minor faults in some of the ancillary equipment (demineralization unit, air compression system, and PLC board) caused some short plant stops.

Concerning the implementation of the demonstration system at the ENEA Casaccia Research Centre, the following observations can be made:

- As built, the plant is very complex, and the presence of many components increases parasitic energy consumption and could reduce plant reliability.

- Electrolyzer technology appears to be mature enough for solar application. On the other hand, the electrochemical effects of operation for periods with an intermittent power source and consequent deterioration of yields with time has to be tested.
- The SAPHYS configuration with DC-DC converters separated the electrolyzer from fast voltage fluctuations at the bus-bar level. It does, however, introduce further inefficiencies. The presence of the battery produces a smooth current profile to the electrolyzer, even during temporary periods of low or irregular insolation.
- Although the electrolyzer was demonstrated to be reliable and its operation satisfactory, the same was not true for the auxiliary equipment required for its operation (water demineralization unit, compressed air treatment unit, and inert gas). Due to the small plant size, the equipment has to be simple in order to limit the cost and energy consumption. Faults in auxiliaries operation were the main cause of plant stops.
- The solid polymer fuel cell is suitable for a small-scale system. However, this type of fuel cell can suffer from long stand-by periods and from freezing temperatures. Maintenance should be provided at least once before the wintertime.
- The SAPHYS control system was demonstrated to be appropriate for the plant features. Even if the PLC RTU-210 has a fault, it can be considered a substantially reliable technological approach for SAPHYS control.
- The use of DC-DC converters and a "five state controller," using SOC as the variable to operate the electrolyzer and fuel cell, allows for smooth equipment operation, and in the case of the electrolyzer, a high-current operation with high grade purity hydrogen production. Plant control and operation is more flexible and can be easily optimized. Voltages during operation were found to be more sensitive to load variation and SAPHYS controls, based on bus-bar voltage, rather than on the SOC, which would have been more troublesome. On the other hand SOC, as calculated by the MCS, is very sensitive to current measurement, and discrepancies with actual energy stored in the battery occurs even when a small error in measurement is present. A very accurate measurement and an automatic (or manual) periodic check and reset of the actual SOC were then introduced in the MCS.

7. PERFORMANCE

During the two-month test period between 2 September to 3 November 1997, the system operated for about 1200 hours. Due to the sunny weather during this first test period, the PV array was available to supply energy to the simulated load, and to produce hydrogen; there was no need to use hydrogen to run the fuel cell. Thus, only the performance of the electrolyzer and related DC-DC converter were determined. No year-round plant performance could be evaluated because of the need to obtain experimental data from the energy regeneration section (fuel cell and up-converter).

In general, both electrolyzer and plant efficiencies were very encouraging and compare well with those obtained in similar experiences. The PV array provided a little over one third of its energy to the load (439 kWh) and two thirds to the electrolyzer to make hydrogen (768 kWh). A total of 123 Nm^3 of hydrogen were produced during this two-month period.

The daily behavior of plant operation and performance for a typical sunny day (22 October 1997) is displayed in Figure 8.1.

The lower trace shows the battery SOC course as calculated in the MCS. After a small decrease of battery charge from midnight to about 8:00, there is a continuos charge of battery from that minimum SOC value (77%) due to the solar energy input (upper trace in figure).

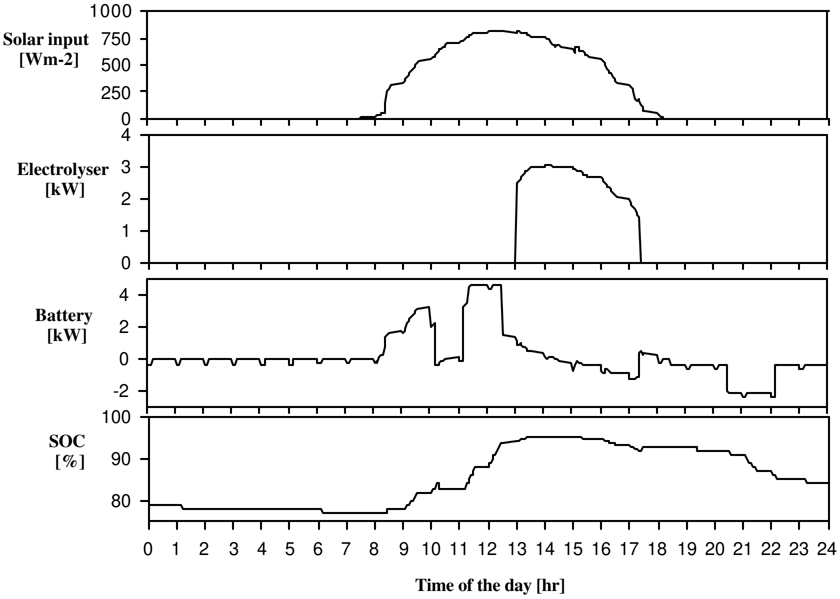


Figure 8.1: Experimental data for a typical sunny day (22 October 1997)

After midday, the SOC reaches the value for starting up the electrolyzer (94%). For the high value of current to electrolyzer, the hydrogen produced has a high grade of purity.

After electrolyzer start-up, the PV array supplies energy both to the electrolyzer and battery. As a consequence of the SOC changes, and according to the SOC-electrolyzer current relationship, the current supplied to the electrolyzer is changed as well. At about 17:30 the electrolyzer is stopped for low current from PV array and from now on, the load is powered by the battery.

The maximum electrolyzer temperature on this day was just over 50°C. The temperature set-point (80°C) for electrolyte external cooling was never reached during the overall test period.

Regarding the load, it can be noticed that the first high power demand (in the morning) is supplied almost completely by the PV array, while the evening peak is provided by the battery alone.

A further behavior is represented by days with significant dynamics that represent the most critical tests for both control system and components of plant (Figure 8.2). In this case (4 September 1997), even with a variable solar input, the use of SOC as a control variable smoothes the signal of set-point of the current to be sent to electrolyzer: The buffer function of the battery in this condition is evident.

The daily average efficiencies of the electrolyzer appear just a little lower than the simulation values (77.4%), but with an average operating temperature in the electrolyzer always below the design value. The cumulative distributions of Faraday, voltage, and electrolyzer efficiencies are shown in Figure 8.3. These values appear encouraging considering, the low operating temperature and taking into account the energy losses for hydrogen flushing at start-up and shut-down and for protective current in stand-by operation. On the other hand, the down converter had an average efficiency of 76.6%, well below the forecast value used during the simulation. The overall efficiency of the hydrogen production section (down converter, cable resistive losses and electrolyzer) was 54.7%.

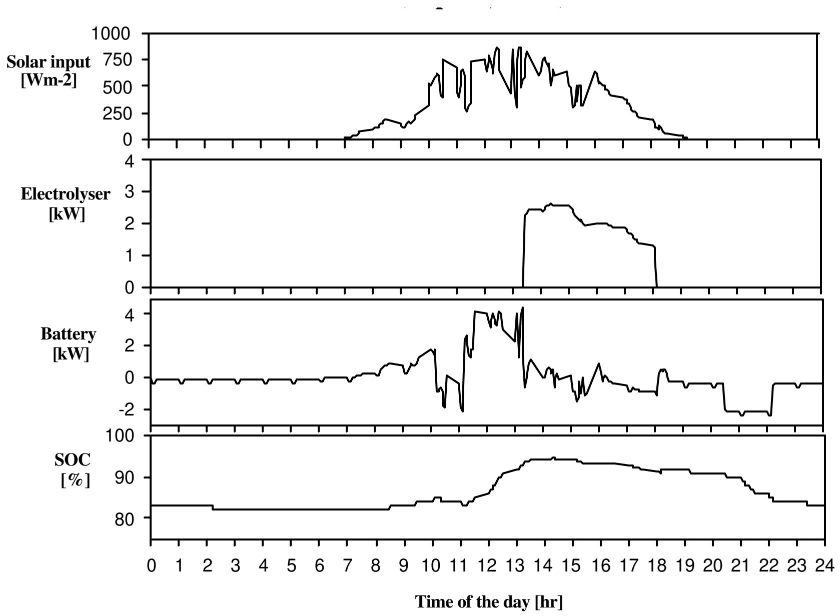


Figure 8.2: Experimental data for a cloudy day (4 September 1997)

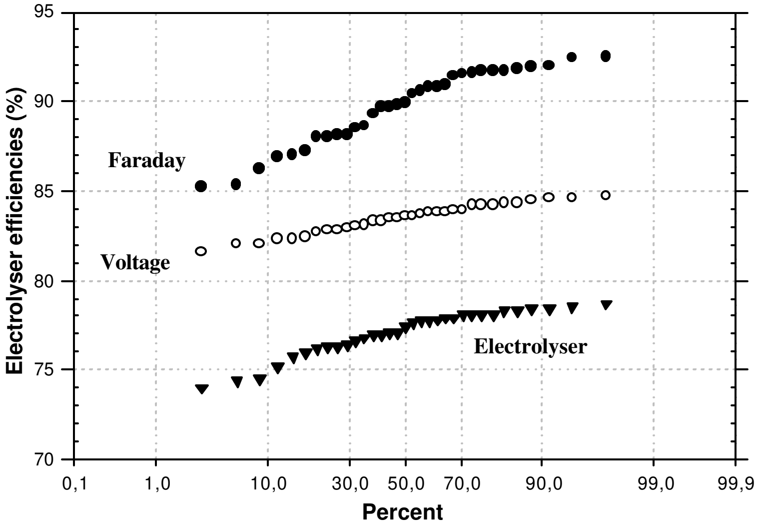


Figure 8.3: Cumulative distributions of electrolyzer efficiencies (2 September - 3 November 1997)

The PV and solar system efficiencies are considered as the ratio of the sum of used energy for supplying load and hydrogen stored energy to either PV or solar input energy. The PV systems efficiency is 71.1% and the solar system efficiency is 5.0%. The latter system efficiency is low mainly as a result of the aged modules of the PV array (about 20 years old) and their obsolete technology.

8. FUTURE PLANS

As a result of the SAPHYS project, it was found that the overall performance and operation of such a system could be improved by adopting some design guidelines such as:

- The operating bus-bar voltage should be increased so as to reduce current (and cable section area).
- As many "off-the-shelf" electric items (switch, fuse, DC-DC converter) as possible should be used.
- The plant should be compact, so as to reduce cabling and electric losses between equipment.
- The measurement accuracy of the currents to and from the battery for SOC calculations in the MCS should be increased.
- A single DC-DC converter for both electrolyzer and fuel cell connection should be used if the SAPHYS configuration with the DC-DC converters is adopted.
- A major breakthrough would occur if a single, reversible piece of equipment performing both electrolyzer and fuel cell operations could be developed.
- The balance-of-system components should be minimized to decrease passive energy consumption and increase plant reliability.
- Considering the fact that the plant is located remotely, and is operated in an unmanned mode, the number of alarm and monitoring circuits could be minimized without compromising safety.
- A six-month scheduled maintenance should be sufficient for a well-designed SAPHYS.

At the beginning of the project, it was planned that the SAPHYS experimentation would be carried out for at least one year. Some equipment and control systems had to be tested in wintertime and their performance compared with the forecast data used during the design phase. Tests were to be performed according to the test plan and be mainly aimed to check up on the control system, system performance, and thermal and electrochemical equipment behavior. Post-test analysis and evaluation were to be conducted to determine how various components have been affected by the demonstration.

In particular, the following aspects were to be investigated:

Fuel cell:

> The energy regeneration phase, during which stored hydrogen is converted into electric energy, has to be tested.

Hydrogen purification section:

The performance of the hydrogen dryer and de-oxidation unit just after the electrolyzer has to be thoroughly tested with the installation of further analytical instruments.

SOC calculations:

The advanced SOC calculation method (with gassing current) in energy management has to be used and checked against the present simplified method (that sums battery current algebraically to update SOC). Better methods have to be developed to avoid discrepancy between the calculated and the actual SOC value.

MSC improvements:

An adaptive algorithm is needed to determine whether variable SOC limits, according to external conditions (e.g. weather conditions), could be implemented in MCS.

Electrolyzer current set-point calculation in EM:

Presently the set point of the current to be supplied through the down converter to the electrolyzer is calculated proportionally to SOC. An alternative method is possible: The current can be adjusted to continuously compensate for the battery current, summing up or subtracting the previous battery current value from the previous down-converter current set-point. This method should be faster than the present one and should reduce the high current flow between the battery and electrolyzer during the start-up of the latter.

Overall plant performance:

After operation of all the sections of the plant it will finally be possible to evaluate the performance of the overall plant against the estimated value in the design phase. The actual energy consumption of the auxiliary components and devices should be determined and added to the simulated load to obtain the actual efficiency of a stand-alone photovoltaic hydrogen energy system.

Comparison of experimental data with simulation:

Using the JULSIM simulation code, the output of simulation runs will be compared with experimental data from the plant, and model parameters will be adjusted accordingly.

Due to the fact that there are no more funds and no supporting program available for the SAPHYS project, the plans to record performance and gain experience in the energy regeneration section (fuel cell and up-converter) in an all-year-round plant operation will have to be continued on a voluntary basis. Unfortunately, continuous runs over longer periods of time will not be possible with these boundary conditions.

9. CONCLUSIONS

From the experience with this project, it may be concluded that there are no insurmountable technical problems associated with hydrogen production by PV-powered electrolyzer. Field observations show that PV-H_2 systems are feasible and reliable enough, and require limited maintenance.

Electrolyzer technology appears to be mature enough for solar application. On the other hand, the electrochemical effects of operation for periods with an intermittent power source and consequent deterioration of yields with time has to be tested.

Although the electrolyzer was demonstrated to be reliable and its operation satisfactory, the same was not true for the auxiliary equipment required for its operation (water demineralization unit, compressed air treatment unit, and inert gas). Due to the small plant size, the equipment has to be simple in order to limit the cost and energy consumption. Faults in auxiliary operations were the main cause of plant stops.

The adoption of a straightforward configuration (e.g. one pressurized, reversible electrolyzer/fuel cell unit without a purification section and directly connected to the bus bar, a cheap gas holder for hydrogen storage, a higher operating voltage), as well as the increase of the plant size, may render this type of energy storage more competitive in remote applications.

At the present time, the complexity and high costs of solar hydrogen systems of this type limit the applicability to isolated locations where high costs for electricity and fuel could create conditions favorable for on-site energy production and storage (e.g. in Antarctic or space bases). Of course, those harsh conditions pose other critical problems for solar-hydrogen plants. In these types of application, energy efficiency of equipment and system often represent a less important point than energy availability and plant reliability.

Chapter 9

HYDROGEN GENERATION FROM STAND-ALONE WIND-POWERED ELECTROLYSIS SYSTEMS

1. PROJECT GOALS

Over recent years, it has been recognized that the combustion of fossil fuels has significantly increased the proportion of carbon dioxide in the atmosphere, with many postulating that this has and will continue to cause changes in global climate. A continuing net global temperature rise and increasing occurrence of extreme climate events are anticipated during the forthcoming century. It is therefore imperative that energy systems based on the utilization of non-fossil sources be developed and exploited as early as possible.

The existence of considerable wind resources in remote places and the high costs of supplying electricity in those places suggest that these might be the first places to benefit from a switch to a hydrogen-based fuel economy. To date, the possibility of using wind power to generate hydrogen has received little attention, despite several major programs investigating the integration of solar photovoltaic power plants with electrolyzers for renewable hydrogen production.

This project was conceived to examine the reasons for this disparity and to explore whether the more irregular power output of a wind turbine (compared to a solar photovoltaic power module) would cause additional problems for a standard water electrolyzer designed for constant power input.

The project sought to determine how best to control a wind turbine to produce a smooth power output, to examine the tolerance of an electrolyzer to fluctuating power inputs, and to design and build a small scale (< 10 kW) stand-alone wind hydrogen production system.

The use of short-term energy storage using batteries or flywheels was also considered, both to provide additional power smoothing and longer term operation of the electrolyzer.

The economics of wind hydrogen systems operating in remote places was assessed.

The major objectives of the project were:

- assessment of hydrogen electrolysis systems undergoing intermittent operation
- comparison of wind turbine operational strategies for dedicated stand-alone hydrogen production
- assessment of overall economics of a wind hydrogen system
- assessment of the suitability of the technology for use in small community power systems

2. GENERAL DESCRIPTION OF PROJECT

A demonstration wind-powered hydrogen production plant has been designed, procured, and constructed, and preliminary tests have been performed. Back-up studies, aimed at determining the tolerance of conventional electrolyzers to input power fluctuations and the potential for smoothing the output from wind power generators, have been carried out in parallel. In all cases, experimental results have been backed up by theoretical analysis and computer simulation, resulting in models of component and system operation at various levels of detail.

The project partners were:

- Energy Research Unit, Rutherford Appleton Laboratory (RAL), United Kingdom
- Casaccia Research Centre, ENEA, Italy
- Institute for Technical Thermodynamics, DLR Stuttgart, Germany
- Department of Engineering (LUED), University of Leicester, United Kingdom

ENEA was responsible for the design, construction, and monitoring of the wind-hydrogen demonstration system at the Casaccia Research Centre; LUED for the development of wind turbine control strategies and for operation of the wind-flywheel storage system at RAL; RAL for dynamic and logistic modeling; and DLR for economic modeling. RAL was also responsible for co-ordinating the work program and providing overall management of the project.

The division of responsibilities between these partners is shown in Figure 9.1.

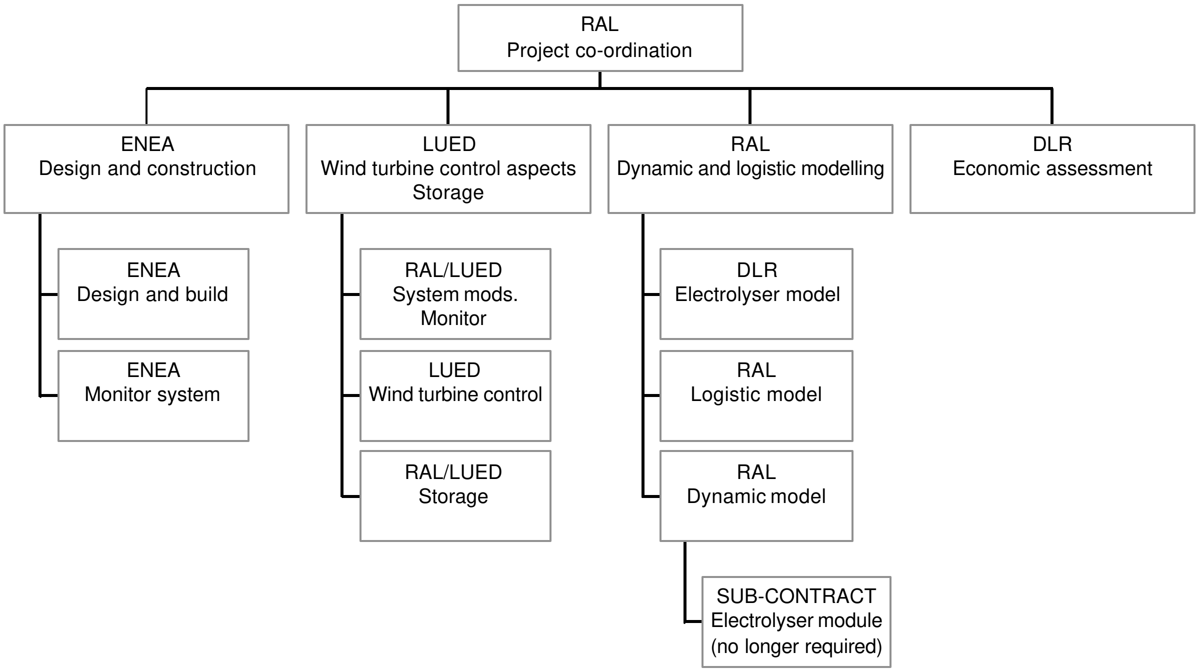


Figure 9.1: Project organization chart

The original project conception was that the demonstration system would be specified and built at ENEA's Casaccia Research Centre in parallel to experiments on the wind turbine control rig at RAL's Wind Test Site. Existing wind turbines on both locations could be utilized. It was planned to develop electrolyzer and systems models in parallel with the experimental program, and to assess the performance with these tools.

The project was funded by the European Commission under the non-nuclear energy (JOULE) program (contract number JOU2-CT93-0413). The project started on 1 April 1994. The original timescale was 2 years, but this proved inadequate for procurement, installation, and testing of the electrolyzer, so a 9-month extension was allowed.

3. DESCRIPTION OF COMPONENTS

3.1 Wind Turbines

Two wind turbines were used during the course of this project. The North Wind L-916, sited on the Wind Test Site at RAL, was modified in various ways to assess the potential for smoothing the power output. The Riva Calzoni M7S, at the ENEA Casaccia Research Centre, was used as the basis for the prototype wind-hydrogen system. Both turbines are very small compared to standard commercial wind turbines, but this was necessary in order to keep the overall project costs within reasonable bounds and it was considered that representative results could be obtained at this scale.

The North Wind L-916 was manufactured by Northern Power Systems of Vermont, USA, and installed at RAL's Wind Test Site in the mid-1980s. It is a down-wind, free yaw design with a two-bladed, teetered rotor of 9 m diameter and a rated power of 14 kW at 11.5 m/s. The turbine is of unusual design and incorporates a number of features not normally found in standard machines designed for grid connected operation:

- power regulation is achieved by a full-span passive pitch mechanism
- the turbine rotor is directly coupled (i.e. there is no gearbox) to the 48-pole synchronous generator with wound field poles.

This turbine was originally designed for fixed speed operation but has been adapted to also run at variable speed for the current project. In fixed speed operation, the generator power is determined entirely by the torque produced by the turbine rotor. Any fluctuation in aerodynamic power, resulting from wind turbulence at the rotor, is directly transmitted to the grid without much attenuation. Correct and rapid control of the turbine rotor torque is therefore important to avoid large fluctuations in the output power. If pitch control is used for this purpose, fast changes in pitch angle are required. With full-span passive pitch and fixed rotational speed, this is difficult to achieve due to the inertia of the blades and the limited pitching effort since no additional contribution from centrifugal forces is available.

In the case of a variable speed wind turbine with a power-electronic converter, the generator torque can be controlled independently from the turbine rotor torque. A change in wind speed results in a mismatch between the instantaneous aerodynamic power and the extracted power and hence in an acceleration or deceleration of the turbine and generator. On reaching rated power, the converter output is kept constant and any surplus in aerodynamic power is used to accelerate the rotor. Due to the position of the center of gravity of the blades and the presence of flyweights at the pitch axes of the rotor, the speed increase leads to higher centrifugal forces. This results in an increase in pitch angle until a new equilibrium position is found, where the aerodynamic power matches the generator power at rated output. For variable speed operation on 50 Hz grid, the variable frequency AC output of the synchronous generator must first be converted into DC power and then inverted into AC power at the grid frequency. This was accomplished by a combination of a simple diode rectifier with a line commutated inverter (LCI).

Thus, variable speed wind turbines can easily be controlled to produce a much smoother power output than the more common constant speed machines.

The wind-hydrogen demonstration system was designed around the existing 5.2 kW Riva Calzoni M7S wind turbine and 330 Ah (nominal) battery energy storage system at the ENEA Casaccia Research Centre near Rome. This turbine, shown in Picture 9.1, drives its synchronous generator at variable speed. The resulting variable frequency AC power output is rectified and supplies a DC bus that feeds the electrolyzer and the battery storage.

Picture 9.1: The Riva Calzoni M7S wind turbine

The wind regime on this site is not particularly favorable (annual mean wind speed of 2.7 m/s), which led to a specification of power rating for the electrolyzer lower than would be optimal for a more windy site. Modeling results carried out by project members suggested that cost and operational benefits could be realized by down-rating the electrolyzer with respect to the wind turbine. For such a stand-alone application, the economic optimum depends on the wind regime of the site, the rating of additional energy storage components, and the utilization potential for excess electricity. For the Casaccia site, a preliminary estimate of the most suitable electrolyzer rating was carried out using the E-WISDA logistic simulation program, developed by ENEA in a previous JOULE project. These studies resulted in the conclusion that a 1 kW_e electrolyzer would be suitable for this application.

3.2 Electrolyzer

The main criteria driving the electrolyzer specification were:

- simple, fully automatic operation
- simple installation (in terms of auxiliary equipment)
- favorable behavior in intermittent operation
- access to main operating parameters for experimental purposes
- limited cost (due to budget limitations)

Electrolyzers at this rating did not prove to be readily available. A tender exercise was carried out between four manufacturers: The Electrolyzer Ltd. (Canada), Ammonia Casale SA (Switzerland), von Hoerner System GmbH (Germany), and Idroenergy (Italy).

The main features of the electrolyzer specification were:

- nominal power of 1-2 kW
- manufacturer to state whether pressurized or atmospheric pressure operation
- nominal voltage preferably in the range 30 - 110 V_{DC}
- able to withstand intermittent operation
- safely withstand operation at very low current values
- a control system able to perform automatic operation for start-up, operation, stand-by, and shutdown
- guarantee on safety aspects and fulfillment of standard regulations; inclusion of internal safety procedures, which shall be activated, if necessary, by the control equipment without any external intervention
- inclusion in the delivery of a water treatment section, in order to permit operation of the plant from a main water supply
- protection devices including, at least:
    - maximum current
    - maximum voltage
    - minimum current (if applicable)
    - minimum voltage (if applicable)
    - maximum pressure
    - maximum temperature
    - minimum temperature (if applicable)
    - maximum concentration of oxygen in hydrogen
    - low inert gas pressure (if applicable)
    - explosion meter inside the cabinet
    - water conductivity
- ambient temperature in the range -10°C to + 40°C
- provision of basic sensors and transducers

The tender from von Hoerner System GmbH was selected since it was the only one reasonably close to the project budget. The system had the following main features:

- 2.25 kW nominal power

- 50 V nominal voltage
- pressurized operation (20 bar)
- fully automatic operation (with the exception of an electric current limitation of less than 20 amps during start-up, to be implemented separately)
- no need for system inertization and cell polarization after shutdown
- ability to hold the internal pressure for some days (or weeks) in “stand-by” condition, and immediate re-start of the process whenever the current was supplied again

The measurement of hydrogen flow rate was derived from pressure and temperature measurements performed on a 50 liter/20 bar bottle positioned at the hydrogen gas outlet.

The electrolyzer is shown in Picture 9.2. It was designed to operate in three possible “normal” states: start-up, normal operation, and shut-down.

Picture 9.2: The 2.25 kW electrolyzer

Start-up: The start-up phase corresponds to starting the process with an initial pressure less than the nominal (20 bar). During start-up, the device operates at variable current, with the following limitation: I<20 A unless the internal pressure is >3 bar. At higher pressures, low current levels are not recommended, in order to reach the nominal pressure as soon as possible. During start-up, no gas is sent to the storage bottle, while some gas is vented to the atmosphere in order to maintain its quality within safety limits.

Normal operation: When the nominal pressure is reached, the device begins to supply hydrogen to the storage bottle. The current can be varied in a range from (nominally) zero to maximum current (47 A). However, current values lower than 20 A are not recommended in order to maintain a good gas quality.

Stand-by: The stand-by phase corresponds to operation with zero input current. In such conditions, the device does not produce any gas flow to the bottle but should be able to hold the internal pressure (for some days or weeks, as claimed by the manufacturer, von Hoerner System (vHS) GmbH), while waiting for restoration of the current supply (i.e., as soon as wind or solar power is available).

3.3 Other components

The step down DC-DC converter was selected after a detailed market evaluation. It comprises three 800 W units (each a standard industrial production isolated converter manufactured by Power Control Systems) working in parallel that can supply a voltage linearly variable from 7 to 50 V, controlled by a 0-10 V_{DC} signal.

The battery storage unit comprises 54 series-connected lead-acid cells with a nominal voltage of 2 V each and a nominal capacity of 330 Ah, for a total nominal capacity of 35.6 kWh. The full extent of this large capacity is probably not completely available, due to battery aging (the batteries were installed in 1988). No measurements have been made in order to determine the currently available capacity but it is anticipated that this should still be in the range of some tens of kWh.

The project site is shown in Picture 9.3.

Picture 9.3: Project Site at ENEA Casaccia

4. INTEGRATION OF COMPONENTS

4.1 Matching of components

The main criteria in designing the plant were:

- to exploit as much as possible existing equipment, comprising the 5.2 kW wind turbine, battery storage rated at 330 Ah - 110 V_{DC}, and two dump loads
- to permit the investigation of different control strategies for wind-hydrogen generation

Two options were examined for the electrolyzer supply from the wind turbine generator (WTG):

- introduction of a voltage transformer at the WTG output, with direct connection of the electrolyzer and of a section of the battery pack to the common 50 V bus
- connection of the electrolyzer through a DC-DC controllable converter

The second option was selected since the first would have had frequency limitations and would have imposed the need to heavily modify the existing electric board, controllers, and 110 V lines. In addition, such a converter permits a degree of freedom in the electrolyzer current.

4.2 Basic scheme of plant

The basic scheme for the complete plant is shown in Figure 9.2.

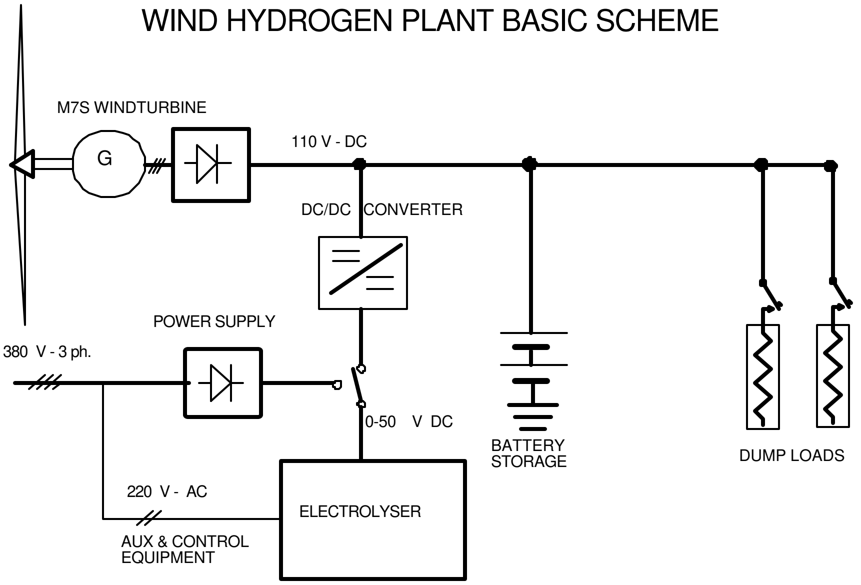


Figure 9.2: Basic scheme for demonstration wind-powered hydrogen generation plant, ENEA Casaccia Research Centre

The plant comprises the wind turbine, the electrolyzer unit complete with its built-in controllable power supply, battery storage, a DC-DC controllable converter, and two dump loads (0.5 and 2 kW) controlled by two voltage actuated relays. The auxiliary equipment (electrolyzer pumps, valves, control equipment, and water demineralization unit) for the demonstration plant are supplied by the grid for convenience. Clearly, for a truly autonomous system these would need to be supplied from the wind turbine and battery.

The M7S wind turbine drives its synchronous generator (G in Figure 9.2) at variable speed. The maximum voltage is limited by a field regulator, acting on the field current. The resulting variable frequency AC power output is rectified and supplies a DC bus that feeds the electrolyzer and the battery storage.

The electrolyzer plant can be operated in two modes:

- **wind-powered**: The electrolyzer current is controlled by the DC-DC step down converter, while the current to the battery storage will not be controlled. The battery will act as an energy buffer, and the dump loads are controlled in order to limit the maximum voltage to the battery to prevent overcharging (and to limit the generator voltage in case of a controller fault, which could damage the turbine)
- **from the controlled power supply:** The electrolyzer is supplied by the controllable power supply, either manually or PC-controlled to emulate the operation from a different type of plant (e.g. using measured RAL time series power data from the North Wind L-916 wind turbine, or other synthesized time series of electrolyzer current). The manual operation of the power supply being useful to execute tests or carry out a functional check of the electrolyzer behavior

Since the project is concerned only with the production of hydrogen, not its large scale storage or utilization, the product gases are released to the atmosphere. The hydrogen, stored initially in the 50 liter bottle, is released by a maximum pressure valve set at 20 bar, while the oxygen is released directly to the atmosphere. Three oxygen pipes and four hydrogen pipes have been installed (comprising gas release coming from normal gas production, safety valves, and supplies to gas quality measurement equipment).

4.3 Plant control

The main components of the control scheme are shown in Figure 9.3:

- WTG centrifugal speed controller, that acts on the blade pitch angle in order to limit the wind turbine speed to less than 300 r/min (on low speed shaft)
- WTG voltage controller, an electronic device chopping the field current in order to limit the maximum generator voltage
- dump load controllers, the connection state of the two resistor dump loads (0.5 and 2.0 kW) controlled by two voltage actuated relays that limit the maximum voltage in case of a fault in the generator voltage controller
- electrolyzer controller, a Klockner Moeller PLC (programmable logic controller) of the SUCOS PS3 series, that can autonomously manage all operating and fault conditions of the electrolyzer
- plant controller, that controls the connection state of the electrolyzer to the DC bus and the amplitude of current supplied to the electrolyzer (when connected). A PC-based solution has

been selected for its flexibility and ability to be used also for the experimental data acquisition and processing.

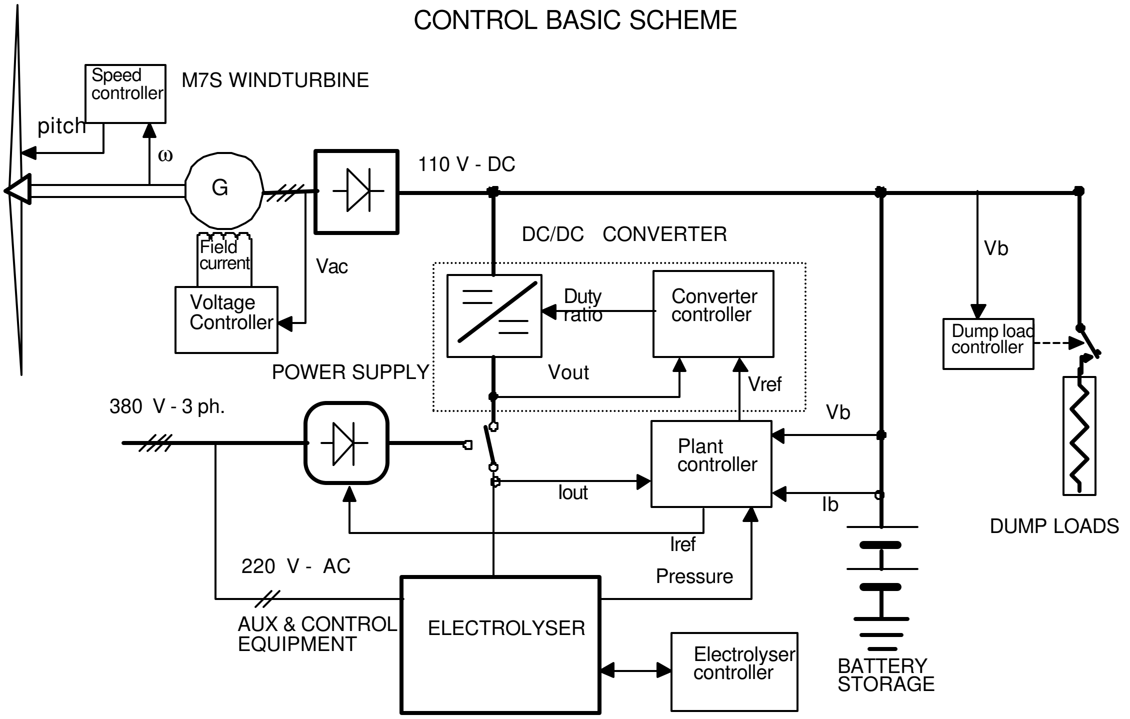


Figure 9.3: Scheme of control system for demonstration wind-powered hydrogen generation plant, ENEA Casaccia Research Centre

The basic control strategy is quite simple. The electrolyzer is:

- "**connected**" if the state of charge (SOC) of the battery is sufficient and the generated power > 0 for a significant time, or
- "**disconnected**" if the SOC of the battery is insufficient for a significant time.

The simplest way to control the electrolyzer current is to "simulate" the direct connection of the electrolyzer to the DC bus. In fact, neglecting its power losses, the DC-DC converter can be controlled in such a way as to be ideally "transparent.

A further objective of the project was to permit the investigation of the electrolyzer behavior in connection with different plant configurations, namely with direct connection of the electrolyzer to the Riva Calzoni wind turbine and its associated battery storage bank, or with the North Wind wind turbine at RAL and a more limited amount of flywheel energy storage capacity, or with some other simulated configuration. The computer is able to control the DT-2801 output board in such a way as to control the current delivered by the built-in power supply, according to the time series of current/power.

5. OPERATIONAL EXPERIENCE AND PERFORMANCE

5.1 Electrolyzer

The electrolyzer was commissioned by vHS by the end of September 1996. During the first test campaign, a number of faults and malfunctions developed in the electrolyzer operation. Much of the experimental effort in the first year of testing was therefore devoted to understanding the causes and implementing and testing modifications to the electrolyzer assembly.

Most of the problems were due to high impurity levels of hydrogen in oxygen during operation at low current levels and apparently high impurity levels of oxygen in hydrogen after some hours of stand-by operation, both conditions leading to alarms and automatic plant shutdown. In addition, the rate of pressure loss during stand-by was very high.

The detected causes of these malfunctions were:

- small gas leakage from flanges and pipe connections
- pollution of sensed gas due to diffusion of external air inside the sensor lines during stand-by (specifically this was the cause of the apparently poor hydrogen quality)
- excessive pressure drop mainly due to gas flow to analyzers
- insufficient internal insulation of the anode

After thorough investigation, a number of remedies were introduced:

- checks and tightening of all flanges and pipe connections
- installation of voltage-controlled valves in the gas quality sensor lines in order to prevent pressure drop during stand-by and to prevent pollution of sensor atmosphere (since original plastic non-return valves were found to have been inadequate)
- substitution of Teflon pipes with PVC pipes in gas quality measurement lines

These actions solved most of the problems, with the exception of the bad oxygen quality at low currents. At this stage, the cell stack was returned to the manufacturer who introduced improved anode insulation and complete insulation of the end flange with a special coating. Following these modifications, further tests showed that:

- behavior in intermittent operation is satisfactory, although during stand-by,the pressure drop is still not negligible (approximately 15 bar in 60 hours) - this is probably due, at least in part, to the disconnection of pipework to allow the cell stack modifications and may be solved by further tightening and substitution of seals
- the measured minimum continuous current level for acceptable oxygen quality (defined as 3 % hydrogen in oxygen) is around 25 A (this is of little or no concern if the oxygen is a waste product to be vented to atmosphere)
- hydrogen quality is good, with impurity levels typically of the order of 0.15-0.35% oxygen in hydrogen, for current levels as low as 15 A or less, thereby permitting operation at very low capacity factors

The measured V-I characteristic, shown in Figure 9.4, referred to two typical electrolyte temperatures (measured at the electrolyte outlet, not directly in the stack, which could be 15^{o}C higher) representative of "cold" and "warm" conditions. The data are extrapolated from a number of measurements at different temperatures, since control of temperature for experimental purposes cannot be easily implemented.

The overall cell stack efficiency (relative to the lower heating value for hydrogen) has been found to be typically around 40%, with a maximum of 45% around nominal current. These values are very low compared to the values in excess of 60% found for the HYSOLAR Electrolyzer 2 at DLR.

Most recently, a fault in a non-return valve has allowed KOH solution to enter and damage the demineralization unit pump, causing a cessation of activity on the plant.

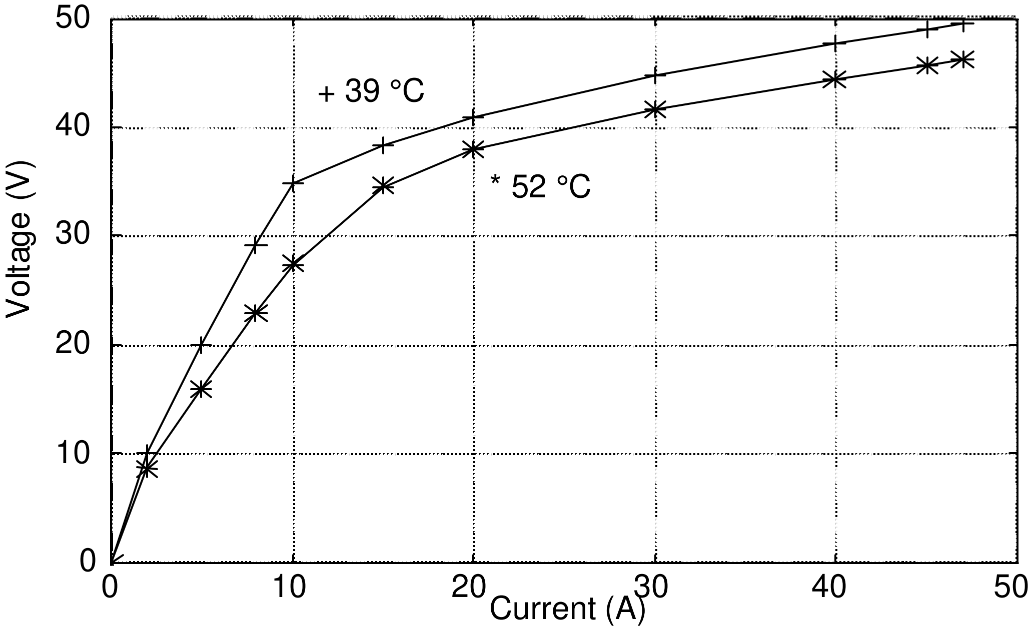


Figure 9.4: Electrolyzer vHS voltage-current characteristics (data extrapolated to 39°C and 52°C)

5.2 Wind Turbine

On the wind turbine side, comparing gain functions between wind speed and electrical output power, it has been demonstrated that variable speed operation can achieve considerable power smoothing benefits:

- below rated wind speed the inertia of the wind turbine acts as a low-pass filter with a time constant approximately equal to the inertia time constant of the wind turbine
- above rated wind speed the output power can be kept virtually constant if the wind turbine is allowed to exceed the rated speed of the equivalent fixed speed machine

In the case of a variable speed wind turbine, equipped with a synchronous generator, the decoupling provided by the AC-DC(/AC) interface removes the resonant mode of direct grid coupling as well as the power fluctuations due to tower shadow and rotational sampling of wind shear over the turbine rotor. The power smoothing is typically effective on time scales of up to 20 seconds.

The power smoothing potential of the variable speed wind turbine can be further enhanced by means of a synchronously linked flywheel energy store, as demonstrated in the system at RAL, or by a battery bank, as used at ENEA. Drawbacks are the increased complexity of system layout with its associated costs, standing losses (which may be proportionately quite large in the flywheel system), and energy transfer losses.

5.3 Further comments relating to intermittent electrolyzer operation

Electrolyzer technology for constant power applications is well established, but the implications of operation with intermittent power sources are little researched. Due to the problems experienced in procuring and commissioning the vHS electrolyzer, additional laboratory tests were carried out by DLR in Stuttgart on the HYSOLAR Electrolyzer 2 to explore the implications of operation with intermittent power sources. These tests indicate that:

- with regard to short term operation, power fluctuations have no significant effect on the overall electrical stability of the electrolyzer
- the magnitude of pressure fluctuations increases and the product gas purity declines, compared to operation at the equivalent constant mean power input
- the decline in product gas purity appears to be affected by power variations on the scale of a few minutes rather than a few seconds

Such medium term and long term power fluctuations need to be taken into account in the design of the electrolyzer (in particular, whether pressurized, or not, and whether potential stabilization is required for the electrodes) and the overall system (e.g. size of battery/flywheel energy storage, control strategy).

The electrochemical effects of operation for long periods (i.e. year after year) with an intermittent power source remain uncertain and lie beyond the scope of the current project. The selection of the most suitable type of electrode, in particular whether to use rare materials and technically advanced but expensive production processes, must lie in the resolution of this question.

6. DATA ACQUISITION

Due to the problems with the electrolyzer plant, few experimental results were obtained.

The basic measurements provided were:

- DC voltage and current to the electrolysis section
- power to auxiliaries
- power to heating device
- impurity level of oxygen in hydrogen (with sample gas treatment including cooling, washing and drying)
- levels of hydrogen and oxygen in the gas separators
- electrolyte temperature in the cell block
- hydrogen flow rate (from integral measurement derived from pressure and temperature measurements performed on a 50 liter/20 bar bottle positioned at the hydrogen gas outlet)

Results were obtained for:

- basic commissioning tests
- hydrogen production tests (volumetric flow rate (Nm^3/h) and efficiency as a function of current and electrolyte temperature)
- impurity levels as a function of current
- dynamic response of the electrolyzer to voltage steps
- variable current tests simulating output from the RAL North Wind turbine
- operation with supply from Riva Calzoni M7S wind turbine

7. SIMULATION

The various systems and their components have been analyzed using a range of different computer models:

- the electrolyzer model SIMELINT has been used to simulate electrolyzer behavior (including overall production volume and gas impurity levels) when connected to either constant or intermittent power sources, and thereby to examine promising control strategies
- a logistic system model, developed in SIMULINK, has been used to examine the effect of component sizing and the hydrogen production potential of sites with different annual mean wind speeds
- an economic model has been used to analyze the overall cost of hydrogen from differently sized systems and to provide a breakdown of how the different components contribute to that cost

Unfortunately the electrolyzer for the demonstration system was supplied too late to be included in the validation of the electrolyzer and system models. The electrolyzer model was validated by the DLR project partners using their Metkon electrolyzer (nominal power 10 kW, constructed within the HYSOLAR demonstration program). The characteristics for the same electrolyzer were used within the system model.

The optimal sizing of the electrolyzer relative to the wind turbine is a complicated function of the site meteorology, including annual mean wind speed (i.e. annual energy production), capital costs of components, gas quality, and the specific application, including availability (or otherwise) of alternative markets for some or all of the wind-generated electricity. For a given application and site, the adoption of a suitable control strategy can significantly increase the annual yield of hydrogen. Example cases studied include:

- an electrolyzer rated at 80% of the power rating of the accompanying wind turbine, where the slight decrease in volume of production and higher auxiliary energy costs (cooling energy) must be offset against the reduced capital cost of the electrolyzer
- an electrolyzer with the same power rating as the accompanying wind turbine, where additional energy storage is available (e.g. batteries) and the electrolyzer is operated continually at part load, resulting in higher overall efficiency and hence an increase in the volume of hydrogen produced

Sizing studies within the project demonstrated that small scale installations, such as the prototype wind-hydrogen plant discussed herein, are not economic, due to the high capital cost of all the ancillary equipment. For this reason wind-hydrogen generation systems are only likely to be viable at large scale (> 1 MW).

8. PUBLIC ACCEPTANCE AND SAFETY ISSUES

Public acceptance was not an issue for the current project.

The design and specification phase of the project took much longer than expected, in part due to the complexity of technical details and the safety regulations concerned with hydrogen devices. This latter point can prove time-consuming for non-specialists in hydrogen technology (which will usually be the case for such an immature technology) and should be considered by anyone planning future projects.

The main aim in defining the plant arrangement was to assure a high safety level in a simple way. To this purpose, the components are located in two different barracks:

- **main barrack**: switchgear cabinet containing all the equipment pertaining to the wind turbine, battery, and dump load control; switchgear cabinet containing the equipment for electrolyzer supply and control (PLC controller); the DC-DC converter unit; data acquisition and plant control equipment
- **secondary barrack**: electrolyzer; water supply/demineralization unit; storage bottle

In order to fulfill safety standards, the electrolyzer barrack includes only a very limited electric plant with IP55 protection. The electrolyzer cabinet is completely gas-proof, and the internal electrical components are explosion proof; inside the cabinet an explosion meter is provided that sends a signal to the electrolyzer PLC in case an explosive environment develops inside the cabinet.

As a further provision, two vents for the internal air have been installed in the barrack roof; one of these vents air from the barrack, the second vents the cabinet internal atmosphere by means of a connection pipe to the cabinet roof.

To fulfill safety standards, the hydrogen pipes release the gas at a height of 5 m from the ground (the standard prescribes a minimum distance of 7.5 m from the electric plants of the main barrack, because they are not explosion proof nor IP55 qualified). To this purpose, the pipes are inserted inside a lattice pole, normally used for holding anemometer sensors. The lattice support structure protects the pipes from possible physical strikes and carries lightning protection.

All the exhausts are made with a gooseneck end in order to avoid water intrusion and a special non-return, flame-arrester valve has been installed in the main pipe end (exhaust from the 50 liter bottle).

9. OTHER EXPERIENCES

The project was carried out against a background of declining government support for hydrogen research in both Italy and Germany, where ENEA and DLR are based. Government support in the UK, where RAL and University of Leicester reside, started out and remains virtually nil.

10. FUTURE POTENTIAL - FUTURE PLANS

The prototype wind-hydrogen plant has had many problems, almost entirely related to the electrolyzer. This indicates an immature and unreliable technology. Further funding to operate the plant has not been forthcoming, but future work must begin by fixing the “conventional” problems relating to gas leaks and pressure drops during stand-by operation, and then investigate the causes of the low efficiency obtained. A long term program is then required to:

- characterize efficiency and gas quality with variable current operation over long periods of time
- run long term tests for estimation of cell life in this application
- optimize control strategy
- estimate optimum size for back-up battery store

On a wider front, the effects of medium term and long term power fluctuations need to be taken into account at the design stage of the electrolyzer (in particular, whether pressurized, or not, and whether potential stabilization is required for the electrodes) and the overall system, including provision for energy storage (e.g. size of battery/flywheel energy storage, control strategy). There remains much work to be done towards defining the optimum control strategy for the system and hence the optimum relative sizing of the electrolyzer. In particular, the trade-off between the higher efficiency and overall yield during part-load operation of an equally sized (to the wind turbine) electrolyzer and the higher capital equipment cost (relative to a smaller electrolyzer) need to be examined on a case by case basis. Some further product development is required to make a truly autonomous system.

The electrochemical effects of operation for long periods (i.e. year after year) with an intermittent power source remain uncertain and lie beyond the scope of this project. The selection of the most suitable type of electrode, in particular, regarding the use of rare materials and technically advanced but expensive production processes, remains an open question that can only be resolved by long-term back-to-back testing of electrolyzers with intermittent and constant power supplies. The experiments should examine whether there is any deterioration of yield with time and whether there is any physical deterioration of the electrodes.

In the longer term, it is required to identify niche markets where such a system can be applied. This is likely to be in a remote site or somewhere where high quality hydrogen and oxygen are required as raw materials for some industrial process. In this latter application, the renewable hydrogen and oxygen must compete with more costly technical gases, exploiting the high purity of the gases produced by electrolysis. A plant in such a situation would provide improved security of supply, particularly if the site has a good wind resource.

The capital cost of a wind turbine and the unit cost of wind-powered electricity have decreased markedly over recent years. The specific capital cost (DM/kW$_e$) of the electrolyzer would be at least 2.5 times that of the wind turbine for a 1 MW size plant. Clearly, if wind-hydrogen systems are ever to become good economic propositions, the capital cost of the electrolyzer must be decreased considerably. This will only be achieved through a concentrated program of research and development to drive down costs. Without such a program, the environmental benefits of renewable hydrogen are unlikely to be realized anywhere other than in isolated communities and niche markets.

11. CONCLUSIONS

A demonstration wind-powered hydrogen production plant has been designed, procured, and constructed, and preliminary tests have been performed. Back-up studies, aimed at determining the tolerance of conventional electrolyzers to input power fluctuations and the potential for smoothing the output from wind power generators, have been carried out in parallel. In all cases, experimental results have been backed up by theoretical analysis and computer simulation, resulting in models of component and system operation at various levels of detail.

Hydrogen produced from wind power represents a clean and versatile fuel, which can be handled similarly to natural gas. It is a storable, versatile energy carrier which has negligible environmental effects compared with the combustion of fossil fuels.

It has been demonstrated that there are no insurmountable technical problems associated with hydrogen production by wind-powered electrolysis. However, intermittent electrolysis technology is at a comparatively early stage of development, resulting in a scarcity of technical data and operational experience. The following general observations can be made concerning the implementation of the demonstration system at the ENEA Casaccia Research Centre:

- the complexity of technical details and the safety regulations concerned with hydrogen devices can make system design and specification time-consuming for non-hydrogen specialists
- from the limited number of tests carried out to date, it is not apparent that operation with variable current or intermittent supply presents any major stability or general operational problems for the electrolyzer; on the other hand, the production and gas quality data show that this particular electrolyzer suffers reduced performance when operated at low capacity factors, and auxiliary storage equipment seems necessary to permit successful operation during periods of moderate wind speed
- the frequency and variety of alarm occurrences is unacceptable and demonstrates the relative immaturity of electrolyzer technology
- the longer term effects of intermittent operation are beyond the scope of the current project and should be addressed by a future project

Further development is required to implement a truly autonomous system. This should cover both control strategy issues and product development to supply power to the auxiliary equipment (electrolyzer pumps, valves, control equipment, water demineralization unit) from the wind turbine/battery system.

Costs of hydrogen from renewable energy sources are currently uncompetitive with fossil fuel derived hydrogen, or, indeed, with grid-connected electrolyzers operated at constant current. It is therefore likely that hydrogen derived from renewable sources will first be used in niche markets where conventional fossil fuels are expensive (e.g. remote areas, islands, and decentralized electricity supply systems) or where high purity gases are required on site. In the latter case, purity levels will, in general, be higher than for fossil fuel derived hydrogen (at least, before expensive purification) and the purity may be further controlled by selecting a suitable operating strategy for the plant.

At current energy prices, hydrogen is only likely to be produced from wind power if excess electricity is available. Such a situation might occur in weak grids that have a limit on the penetration of wind energy.

Chapter 10

PALM DESERT RENEWABLE HYDROGEN TRANSPORTATION PROJECT

1. PROJECT GOALS

The Palm Desert Renewable Hydrogen Transportation Project encompasses the entire energy cycle, from production to end-use. At the proposed solar hydrogen generation facility, a solar array will generate electricity to run an electrolyzer, which will produce hydrogen from water. The hydrogen will be compressed and stored. The stored hydrogen will then be delivered to the dispensing station where it is used to fuel a fleet of fuel cell vehicles. A pictorial representation of the system is shown in Figure 10.1. This transportation system allows the city to use the energy from the sun to power vehicles whose only exhaust is pure water. This demonstration is the first of its type in the United States.

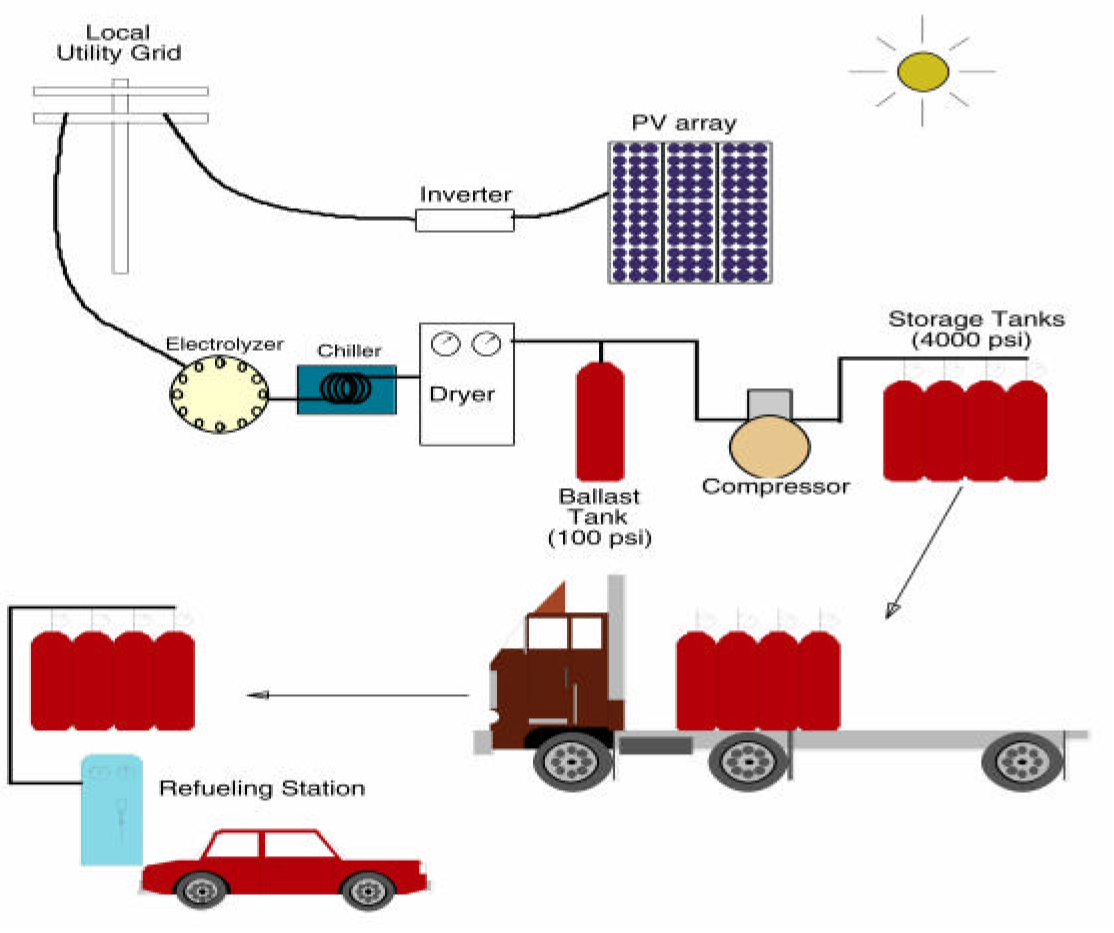


Figure 10.1: Block diagram of proposed hydrogen generation and refueling facilities

The streets of Palm Desert are the test site for the project's mini-fleet of fuel cell-powered, zero emission vehicles. This fleet was complete as of April 24, 1998 and consists of 3 golf-cart-sized personal utility vehicles (PUVs) and 1 neighborhood electric vehicle (NEV). The city is a natural venue for the project because of its good solar insolation, its location in the South Coast Air Basin where air quality is an important issue, and its commitment to environmental technology.

The solar hydrogen generation facility will be sited at SunLine Transit Agency in Thousand Palms, immediately adjacent to Palm Desert. SunLine is the home of a fleet of forty compressed natural gas (CNG) transit buses, the nation's first fleet to convert entirely to CNG. The site currently contains the refueling infrastructure for the buses, so the addition of a solar hydrogen generation facility is a natural step in the company's progression toward alternative fuel transportation systems.

The hydrogen dispensing station will be located at the Palm Desert Civic Center electric vehicle recharging station near City Hall. This site is adjacent to the city park where the PUVs are used and is near the storage area for the PUVs and the NEV. This site was chosen partly for its convenient access and partly as a result of negotiations between Schatz Energy Research Center (SERC) and the City of Palm Desert. This location is a central one that facilitates demonstration and public viewing of the dispensing station.

The objectives of the Palm Desert Renewable Hydrogen Transportation Project are:

- the development and demonstration of fuel cell powered vehicles
- the renewable generation of hydrogen
- the nurturing of new high-tech activities that benefit the environment

2. GENERAL DESCRIPTION OF PROJECT

This project was begun in January 1996 and is scheduled for completion in March 1999. Participants in the project include the U.S. Department of Energy (DOE), the Schatz Energy Research Center (SERC), the South Coast Air Quality Management District (SCAQMD), the City of Palm Desert, SunLine Transit Agency, W.L. Gore & Associates, ASE Americas, DuPont, and Teledyne Brown Engineering.

The first phase of this project entailed the design and construction of the three PUVs. Each PUV consists of a standard E-Z-Go electric golf cart that was converted from pure battery operation to operation with a proton exchange membrane (PEM) fuel cell with a very small battery to supply peak loads. This vehicle has a top speed of 13 mph and a range of 15 miles.

The second phase involved the design and construction of an NEV. This vehicle consists of a Kewet (Danish) electric vehicle that was converted in a manner similar to the PUVs. It has a top speed of 35 mph and a range of 30 miles.

All four of these vehicles are currently seeing daily use in Palm Desert.

The final phase of the project consists of the design and construction of a solar hydrogen generation station and a hydrogen refueling station. The design portion of this phase is complete while the actual construction awaits final funding from the DOE.

In conjunction with the delivery of the first vehicle, it was necessary to construct a temporary refueling station so that they could be readily refueled prior to the construction of the solar hydrogen generation station and refueling station. This was done by designing a multi-tank cascade system that utilizes commercially available hydrogen cylinders. This system allows the vehicles to be refueled to approximately 2,000 psig in a matter of minutes. The permanent refueling station will enable us to fill the NEV tanks to 3,000 psig, its design pressure, while the PUVs will continue to be filled to 2,000 psig.

3. DESCRIPTION OF COMPONENTS

3.1 Vehicles

3.1.1 Personal Utility Vehicles

As the first step in the design and construction of the SERC prototype fuel cell PUV, we selected the E-Z-GO golf cart to serve as the platform because it was already established and accepted in the Palm Desert community and used an efficient motor and motor controller. We have added all features necessary to make the cart street-legal in the City of Palm Desert, such as headlights and turn signals, a rear view mirror, seat belts, and brake lights. We then instrumented and tested an original battery-powered E-Z-Go Golf Cart. This provided information on the performance and power demands that the PUV fuel cell power plant would have to satisfy and allowed preliminary system design and sizing of the proton exchange membrane (PEM) fuel cell stack required for the prototype.

Based on these tests, we developed a parallel hybrid design for the system that incorporates three small lead acid batteries to provide power for acceleration and hill climbing. In this role, the batteries provide a small buffer for short-term power demands and are recharged during normal cruising and idling conditions (Picture 10.1).

Picture 10.1: Personal Utility Vehicle with City of Palm Desert Economic Development Director Paul Shillcock commuting to work.

Control of the system was assigned to an on-board computer that permits the PUV operator to start and drive the cart in a straightforward manner. The control computer also provides a laptop computer with real-time information on the status of all PUV systems. The laptop both displays and stores the data for further analysis. The design of the PUV systems and the control software have been reviewed and revised to protect the operator and the PUV by the use of inherently safe hardware design and numerous software safety interlocks.

The PEM stacks developed for powering the PUVs have been designed by SERC to be simple and to have high net efficiency. Consequently, they are designed to run efficiently on air at very low pressure. Although this entails some sacrifice in stack performance relative to high pressure fuel cells, a simple, low power blower (instead of a compressor) can be used to provide the air supply. The small power demand of the blower results in high net efficiency.

The fuel cell stack developed for and used in the prototype was designed:

- to operate throughout the entire range of driving conditions at a voltage compatible with the E-Z-GO motor controller
- to provide sufficient power to cruise at constant speed up a mild incline and still charge the batteries
- to require low parasitic loads for auxiliary systems such as air supply, water circulation, control computer, solenoids, sensors, etc.
- to operate efficiently

To meet these demands, the resulting fuel cell stack contains 64 cells with 300 cm^2 active area. Each cell consists of a membrane and electrode assembly (MEA) that is composed of a DuPont Nafion™ 115 membrane and E-TEK ELAT gas diffusion media. We have altered the platinum catalyst loading on these ELAT's over time. Our initial, or prototype stack, had loadings of 2 mg/cm^2 on the hydrogen side, and 5 mg/cm^2 on the oxygen side. This stack had a peak of output of 4.80 kW$_p$. We began reducing these loadings with the stack for PUV 1 that had 2 mg/cm^2 platinum loading on both sides of the MEA. This stack produced 5.67 kW$_p$. Following this success, we further reduced the loadings for PUV's 2 and 3 to 1mg/cm^2 platinum on each side. These stacks also produced 5.67 kW$_p$.

A typical interaction of the battery and fuel cell during a normal standing start of the PUV is shown in Figure 10.2. The power supplied by the fuel cell is in green, that supplied by the battery is in red. The traction bus power, which is the total power being supplied to the vehicle, is in black. As can be seen from this graph, prior to the beginning of acceleration, the fuel cell is producing approximately 0.75 kW, which is being used to top off the battery and to power parasitic loads such as the blower, solenoids, etc.

The highest power demand occurs during the first second of acceleration. During this initial surge, the battery supplies 5 kW of power to the traction bus, while the fuel cell supplies only about 1 kW. However, after only three seconds, the power demand has dropped considerably, while the fuel cell has ramped up its output to just over 2 kW. This demonstrates the dynamic interplay between the batteries, which are able to provide large amounts of instantaneous power, and the fuel cell which is comparatively slow to respond, but which can provide long term continuous power. After only 10 seconds, the vehicle has reached cruising speed, the traction bus power demand has dropped to 1.6 kW and the fuel cell is not only providing the sole source of power to the vehicle, but is now recharging the battery.

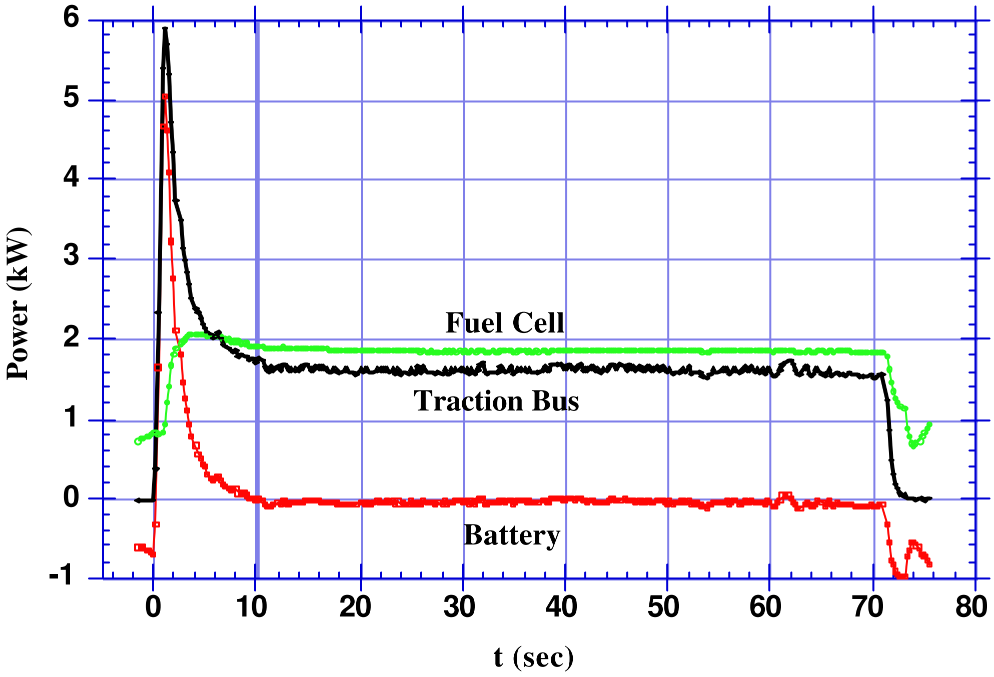


Figure 10.2: Fuel Cell Response during Acceleration

3.1.2 Neighborhood Electric Vehicle

As with the PUVs, the first step involved selecting a base vehicle. We chose the Danish made Kewet because it was a readily available, relatively inexpensive, mass-produced vehicle already being used in Europe exactly as we intended to use it in Palm Desert. Further, and perhaps most importantly, the United States Department of Transportation has certified it as a street legal vehicle in this country.

This vehicle is fully enclosed, unlike the PUVs that do not have doors. It also comes with seat belts and turn signals already installed (Picture 10.2).

As with the PUVs, the vehicle was first instrumented and tested to determine its power requirements and a fuel cell was then built to accommodate them. The main differences between the NEV stack and those in the PUVs are number of cells and membrane material. All of the PUV stacks were made with DuPont Nafion™ 115 while this one uses Gore PRIMEA™ membrane and electrode assemblies. This material provides a higher power density which means that the stack runs more efficiently (uses less hydrogen per mile) and is able to charge the batteries more often.

Specifications for the PUVs and the NEV are given in Table 10.1.

All of the vehicles have been in service for some time now in Palm Desert. PUV1 is used as a daily commute vehicle while PUV's 2 & 3 are used by city personnel for park maintenance. The NEV is used by city officials for routine errands. We have collected a substantial amount of data in this time, which is summarized in Table 10.2. Note that these are real world data, collected while the vehicles were being used by ordinary, non-technical city employees.

Picture 10.2: Neighborhood Electric Vehicle

Table 10.1: Specifications for PUVs and NEV

	PUVs	NEV
Membrane Material	DuPont Nafion™ 115	Gore PRIMEA™
Number of Cells	64	96
Fuel Cell Power @ 600 mV/cell	4.0 kW	9.0 kW
Active Area	300 cm^2	300 cm^2
Fuel Cell Operating Temperature	50 - 60°C (120 – 140 F)	50 - 65°C (120 - 150 F)
Body and Chassis	E-Z-Go Golf Cart	Kewet El-Jet 3
Traction Bus Voltage (nominal)	36 V	48 V
Electric Motor Size	1.5 kW (2.0 hp)	7.5 kW (10 hp)
Top Speed	13 mph (21 km/h)	35 mph (56 km/h)
Range	15 mi (24 km)	30 mi (48 km)
Hydrogen Tank Volume	14 liters	31.1 liters
Gas Storage Pressure	2,000 psig (138 bar)	3,000 psig (207 bar)

Table 10.2:Summary of PUV and NEV Performance in Palm Desert

Vehicle	Delivery Date	Months of Operation	Total Miles (Aug. '98)		Maximum speed		Mileage (mpg equivalent)			
							City		Highway	
			mi	km	mph	km/h	mpg	km/l	mpg	km/l
PUV1	Sept.1996	25	450	724	13	21	65	28	110	47
PUV 2	May 1997	17	450	724	15	24	95	40	120	51
PUV 3	May 1997	17	510	821	15	24	90	38	120	51
NEV	April 1998	6	160	257	35	56	50	21	70	30

3.2 Hydrogen Generation Station

The generation facility consists of a gas generation building, a photovoltaic (PV) array, and the gas processing and storage area. The generation building will house the electrolyzer and related control and monitoring systems. The gas processing and storage area will contain a hydrogen gas compressor and a gas storage unit comprised of four high-pressure storage cylinders. A dispensing unit will be used to refuel the vehicles at a site near City Hall in Palm Desert.

The 430 square foot gas generation building will consist of three rooms: an office/control room, a restroom, and a gas generation room. The office/control room will house a control computer, electrical control and alarm panels, and general office equipment. The gas generation room will contain an electrolytic hydrogen generator and a hydrogen dryer system, both manufactured by Teledyne Brown Engineering. The electrolyzer will produce hydrogen gas at a rate of 20 standard liters per minute (slm) and a pressure of 100 psig. Initially, only sufficient hydrogen to refuel the vehicles will be produced. Eventually, the electrolyzer may run up to 24 hours per day to produce enough gas for SunLine Transit's needs. The electrolyzer and the dryer both have their own programmable logic controllers (PLCs) which will control their operation and will be interfaced with the facility control computer. A one-hour fire wall will separate the gas generation room from the control room and restroom.

The gas generation building will also contain the facility monitoring and data collection systems. These will measure and record various pressures, temperatures, gas flow rates, and power to and from certain components. In addition to providing important input to the safety system, the data will make possible such calculations as net system and component efficiencies.

3.2.1 PV Array

The photovoltaic array will consist of three flat-plate, fixed position, sub-arrays, each of which contains 13 ASE-300 DG/50 modules in parallel. These modules are manufactured by ASE Americas and operate at a nominal 48 V_{DC} and have a peak power rating of 300 W. Each subarray will have a peak power capability of 3.9 kW at 48 V, for a total system output of 11.7 kW.

ASE Americas employs environmentally benign procedures to produce their PV wafers, so there is no hazardous waste stream and the final product contains no hazardous materials. These are state-of-the-art, high efficiency modules designed for utility applications. ASE Americas has agreed to share the cost of these modules and has been an industrial partner since this project began.

3.2.2 Inverters

Each subarray will be connected to a Trace SW5548UPV 4kW peak-power tracking sine wave inverter. These inverters are designed and approved for utility grid intertie. They will receive the nominal 48 V output from the sub-arrays and in turn produce 240 V_{AC} power, which will be connected to Sunline's grid for on-site consumption.

3.2.3 Electrolyzer

In the past, SERC has worked closely with Teledyne Brown Engineering on the solar hydrogen project at the Humboldt State University Telonicher Marine Laboratory. The project uses a solar hydrogen/fuel cell system to run the air compressor that aerates the fish tanks.

One of the main components of the system is Teledyne's Altus 20 electrolyzer. Nearly eight years of experience operating, monitoring, and modeling the system indicates that the unit works well in automatic and independent operation with a PV array. This electrolyzer is a medium pressure, bipolar, alkaline unit. It consists of a 12-cell electrolysis module designed to deliver 20 slm of H_2 gas at a current of 240 A at 24 V_{DC}. Hydrogen is produced by the module at 100 psig. The module contains an electrolyte of 25% (by weight) potassium hydroxide.

In an 8-hour period the Altus 20 produces 9,600 standard liters, enough to refuel all of the vehicles. Daily deliveries of hydrogen could be possible, if necessary. In the future, SunLine probably will elect to obtain a hythane or hydrogen bus, which will be refueled with the balance of the hydrogen produced.

3.2.4 Hydrogen Gas Chiller

A chiller will be used to condense water out of the hydrogen gas stream. The chiller will cool the gas to ~ 20°C, which will remove the majority of the water from the gas stream. This will reduce the frequency of cycling the gas dryer beds. The gas will be cooled in a tube-in-tube heat exchanger. Hydrogen will flow through the inner tube of the exchanger, while a centrifugal pump will circulate the coolant water in the outer tube. The water extracted from the hydrogen gas stream will drain back into the electrolyte reservoir. The chiller will run whenever the electrolyzer is on and generating hydrogen gas.

3.2.5 Hydrogen Gas Dryer

The hydrogen gas dryer is specifically designed to operate with the Altus 20 electrolyzer and is designed to reduce the moisture content of the gas stream to 1 ppm via a desiccant bed. There are two desiccant beds in the dryer, and when one of them becomes saturated, the second unit is switched in while the first is regenerated. The regeneration process consumes hydrogen gas at a rate of 2 slm for a period of 6 hours. The chiller, which acts as a pre-drying unit, reduces the frequency of dryer recycling and therefore conserves hydrogen. Each bed will be used for 60 hours of before being regenerated.

3.2.6 Hydrogen Compressor

A single continuous length of seamless stainless steel tubing enclosed in conduit that is buried below grade will connect the generation building and the storage area. This line will operate at a pressure of 100 psig and will connect to a ballast tank which precedes the compressor.

A Pressure Dynamic Consultants PDC-4 diaphragm compressor will be used to boost the pressure to 4,000 psig. Diaphragm compressors are designed to pump gases that must remain uncontaminated. Gas purity is ensured by separation of the hydraulic oil and hydrogen by three metallic diaphragms that are sealed by o-rings on each side. In addition, diaphragm compressors have essentially no blow-by. Engineering staff at Teledyne Brown recommended PDC Machines. PDC worked with us to make sure that the unit meets Class 1, Division 2, Group B requirements and can operate under the high-temperature conditions that exist in Palm Desert.

We chose the compressor based on our requirements for inlet and outlet pressure (less than or equal to 1000 psig inlet and 4000 psig outlet), flow rate (greater than or equal to 20 slm), gas purity (greater than 99.99%), and low blow-by (less than 0.1%), as well as on the recommendation of the electrolyzer manufacturer. Once these requirements were met, the least-cost option was chosen.

This compressor is equipped with three pressure switches and an internal pressure relief at the intermediate pressure stage (750 psig). The compressor will run whenever the electrolyzer is on, the storage pressure is below 4,000 psig, and the ballast pressure is above 60 psig. The compressor suction pressure will be controlled to a maximum of 40 psig with a forward pressure regulator (provided by the manufacturer). This pressure was chosen in order to limit the compressor flow capacity to a value that matches the Altus 20 hydrogen generator output of 20 slm. A pressure transducer will be installed just upstream of the pressure regulator to monitor the compressor regulator inlet pressure.

The compressor is also equipped with two leak detection systems (one for each stage) and a compressor cooling system. The leak detection systems will shut the compressor down on a fault if a hydrogen gas leak is detected. The cooling system is provided by PDC to produce chilled water for the compressor interstage cooler and process after cooler.

3.2.7 Hydrogen Storage

Choices for hydrogen storage include compressed gas (bulk and cascade), metal hydrides, and liquid hydrogen. Because of their high cost and complexity, we ruled out metal hydrides and liquid hydrogen. We decided on a bulk storage system because it is less complex, which makes it less costly, easier to use, and more robust. The system requires fewer parts and programming and training of attendants will be easier. The initial cost of materials is lower, and the lifetime is longer, for bulk rather than for cascade storage.

Total hydrogen storage in this area may ultimately amount to approximately 12,000 scf. Initially, about 1,100 scf at 4000 psig will be stored in four high pressure cylinders which are rated to 6000 psig, for transportation to the dispensing station. The remaining 10,900 scf (309 Nm^3) of hydrogen gas will be stored in a single high pressure cylinder mounted horizontally and will be used to refuel hydrogen/natural gas blend buses or other hydrogen powered vehicles belonging to SunLine Transit.

3.2.8 Hydrogen Cylinder Transportation Rig

The hydrogen storage system is designed to allow cylinders to be transported between the hydrogen generation facility at SunLine Transit and the hydrogen dispensing station near City Hall.

A storage rig consisting of four interconnected horizontally mounted cylinders supported by a steel cart will be used (Figure 10.3). Two rigs will be built: one will be charged at the generation facility while the other services the dispensing station. The use of individual cylinders would have required manually disconnecting and connecting each cylinder for each delivery. This process would have required significantly more time for delivery and would have increased the chances of a hydrogen leak.

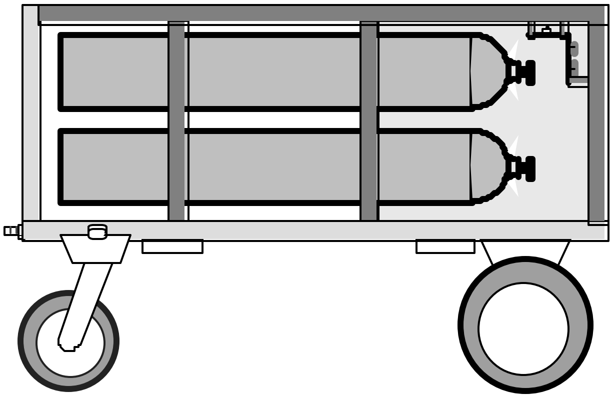


Figure 10.3: Hydrogen Cylinder Transportation Rig

SunLine owns a tilt trailer that they will retrofit with a winch and tie-down connections for transporting the storage rig. This rig consists of 4 cylinders and associated hardware mounted on a manufactured platform truck with four locking pneumatic wheels, two swivel type and two fixed straight type. A pad eye and tie down connections will be added to allow winching and securing the rig onto the transportation trailer. The tie down connections will also be used at the hydrogen generation facility and the dispensing station. Safety chains will secure the rig to the containment wall at each site. If an earthquake occurs, the chains and the locking wheels will constrain the movement of the rig so that the long flexible hoses, which connect the storage rig to the hydrogen system, will not be damaged. The rig will also include forklift sleeves so that it can be moved by a forklift, if desired.

The cylinders are rated to 6,000 psig, have a water volume of 1.32 standard cubic feet each, and are fitted with cylinder valves and pressure relief devices. The cylinder valves have CGA 703 fittings (for high pressure hydrogen).

The four cylinders will be connected through a manifold that includes a pressure relief valve, a pressure gauge, a manual valve, a vent valve, and two quick connect couplings. A dual hose (a high pressure gas hose and a vent hose) will connect to the quick connects. One quick connect allows the storage rig to be connected to the storage area plumbing for charging or to the plumbing at the dispenser storage area panel for dispensing. The other quick connect will provide a means to vent the charging or dispensing hose prior to disconnecting the quick connects.

4. INTEGRATION OF COMPONENTS

4.1 Power Interconnection

We considered three interconnection strategies for the electrolyzer and the PV array: a DC system (where the PVs are directly connected to the electrolyzer); a DC system with maximum power point tracking and a DC-DC converter; and an AC (grid-connected) system, where the PVs feed their power to the grid and the electrolyzer draws its power from the grid.

We chose a grid-connected system to reduce both cost and complexity. With the first two options, there would have been a large number of relays, thicker wires, and other requirements, such as digital control and electrolyzer modification. Maximum power point tracking would have required the purchase of an expensive, made-to-order DC-DC converter. Much of the equipment for a DC system would have been harder to find or more expensive than the equipment for an AC system.

With our grid-connected system, the electrolyzer will be used the way the manufacturer intended for it to be used. Although the unit runs on DC power, it comes with a power supply to rectify the power from the grid. Cost and complexity are reduced, and modifications to the electrolyzer are unnecessary. In addition, the grid will serve as a storage medium for renewably generated electricity. Finally, we will have the option to run the electrolyzer for twenty-four hours a day using green power (which can be purchased in California's deregulated utility environment) to make full use of the hydrogen production capability of the unit.

While designing this system we consulted with Southern California Edison with regard to an appropriate choice of inverters. They recommended that we use either Omnion or Trace inverters as both had been thoroughly tested by the utility for use with their system. A selection of certain models from either of these manufacturers would guarantee rapid approval for connection to the utility grid without the lengthy testing procedure that would be required with other manufacturers. A single Omnion inverter could have handled the power generated by the system, but its cost was substantially greater than three equivalent Trace inverters.

4.2 PV Array Sizing

The photovoltaic system for the Palm Desert Solar-Hydrogen Generation Facility will provide the electrical power to produce hydrogen by electrolysis. The fundamental design criterion for the PV system is that the system's cumulative annual output equals or exceeds the energy the Altus 20 electrolyzer requires to produce the hydrogen sufficient to refuel the vehicles. This quantity of hydrogen was estimated assuming that the three PUVs and one NEV would be refueled five times a week.

The calculation of hydrogen required is as follows. A single refueling for a PUV requires 1380 standard liters (sl); the NEV requires 5200 sl. At five refuelings each week, this amounts to 46,700 sl/week or 2,430,000 sl/year. The Altus 20 electrolyzer produces 20 slm or 1200 sl per hour, so production of the yearly amount of required hydrogen will require 2,020 hours of full power electrolyzer operation during the year. At full output the Altus 20 requires a constant 8.2 kW of AC power to be provided to its AC-DC converter. Thus, to meet the total annual hydrogen requirement, the Altus 20 will consume 16,600 kWh of electrical energy per year. This, then, was the production goal we were seeking in sizing the PV array.

The array was sized by performing simulations using the Transient System Simulation Program (TRNSYS), developed and updated by The Solar Energy Laboratory at the University of Wisconsin, Madison. TRNSYS is a modular program which allows the use of user developed subroutines which can be custom designed to simulate the operation of specific equipment.

SERC personnel have previously developed an extensive array of modeling software that they used to simulate the operation of the Schatz Solar Hydrogen Project in Trinidad, California. This software was designed to be easily configurable to account for broad system variations and as a result, it was very easy to incorporate into TRNSYS.

The solar input data were obtained from the extensive data available from the Department of Energy's Solar and Meteorological Surface Observation Network, Volume III. Although direct data for Palm Desert were not available, extensive data were available for Daggett, a community located approximately 100 miles NNW of Palm Desert and which experiences similar weather. The Daggett data were used and are probably slightly conservative as its location in the "high" desert is somewhat less sunny than Palm Desert located in the "low" desert. This is compensated for, to some extent, by the higher ambient temperatures in Palm Desert.

The Trace inverters have a built in peak-power tracking module with a fairly narrow window of input voltages to accomplish this. As the ASE module's voltage characteristics fall near the lower end of this range under normal operating conditions, we were concerned the array operating voltage would become too low (for the inverter) due to the high ambient air temperatures in Palm Desert. Consequently, the PV sub-routine was designed to monitor the frequency and duration of such occurrences and their effect upon system performance. As it turned out, such circumstances occurred rarely with little effect on performance.

Based on the selected components, the target energy production goal, the solar resource, and various other related parameters, a TRNSYS input file was generated and a series of simulations was performed. The results for an array consisting of 39 ASE-300 DG/50 modules tilted at 30° and facing south are shown graphically in Figure 10.4. As can be seen in the figure, this array was found to generate annual electrical energy of 17,600 kWh, approximately 6% above the production goal. This small excess was judged to be reasonable assurance against less sunny than average years and the possibility that the modules would produce less than their rated power.

4.3 Control System

The purpose of the control system is to monitor and control gas generation and storage, ensure safe system operation, and collect and store operational data. The control system will consist of a Windows-based system control computer (SCC), associated data acquisition and control hardware, and an emergency shutdown circuit. The computer will be located in the control room in the gas generation building. The associated data acquisition and control hardware and the emergency shutdown circuit will be placed in an electrical enclosure that will be mounted on the interior wall of the control room. The control room will be continuously air conditioned to maintain acceptable temperatures for the computer control system. The control computer will communicate with signal and control points that will be located primarily in the gas generation room and the gas storage area.

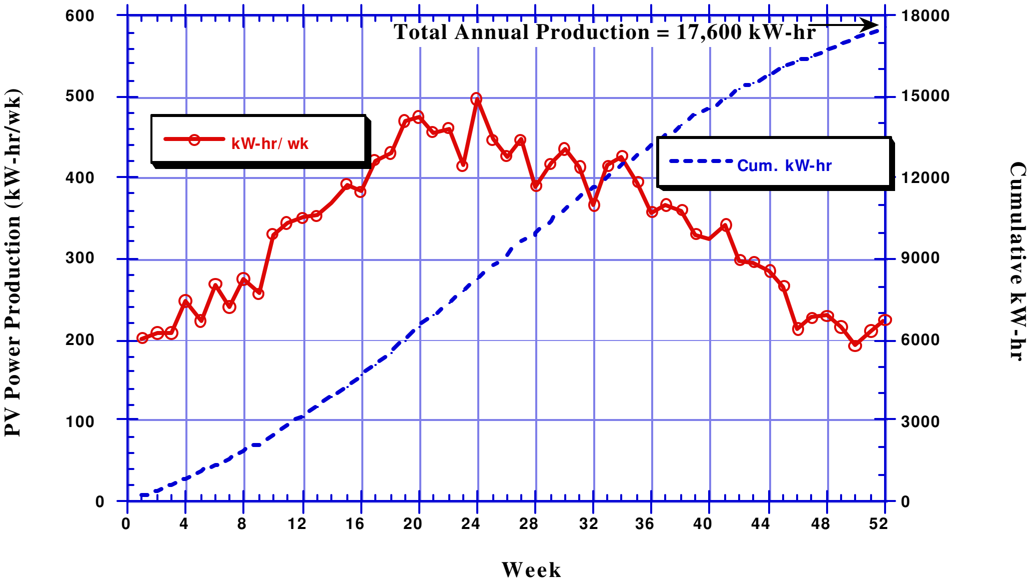


Figure 10.4: TRNSYS Output, Weekly and Cumulative PV Energy Production for 39 Modules

In addition, major components in the hydrogen gas system (electrolyzer, gas dryer, and compressor) will have their own internal control systems that control their operation. These internal control systems allow these devices to operate independently. The system control computer (SCC) will allow these units to operate under their own control mechanisms; however, it will monitor the operational status of these units and will be capable of turning the units on (compressor and dryer) and off (electrolyzer, compressor and dryer). No modifications will be made to the internal control mechanisms of the electrolyzer, gas dryer or compressor.

Generation and storage of hydrogen gas at the hydrogen generation facility will be monitored and controlled by the SCC. To accomplish this, the SCC control system logic will be integrated with the internal control system logic of the electrolyzer, gas dryer and compressor. The SCC will also collect and store operational data for the hydrogen generation and storage system. The SCC will not be relied upon for critical system shutdowns as a hardware-based emergency shutdown circuit will initiate critical shutdowns.

4.4 Emergency Shutdown System

The emergency shutdown system provides a level of safety that is independent of the SCC. If a critical fault condition occurs, the emergency shutdown system will automatically shut down the entire gas generation system.

This circuit is composed of a variety of solid state components and requires a constant voltage input from all of the system critical components. In the event that any of these components enters into an out-of-range or failure situation, the voltage signal is terminated, thus shutting down the entire system. This ensures that a loss of power to any of the safety critical input channels will cause a shutdown. For example, if a wire were to become disconnected from the hydrogen detector, a manual system override button, or any other input channel on the emergency shutdown circuit, a fault would occur and the gas generation system would be shut down.

The components that we have chosen to monitor are discussed in the following subsections.

4.4.1 Watchdog Timer Activated

The watchdog timer is a solid-state relay whose function is to monitor the status of the control computer and to shut down the gas generation system if the control computer hardware or software malfunctions. The control computer software will be required to send a signal to the watchdog timer every 1.6 seconds. If the watchdog timer does not receive a signal within this interval, its normally open contact closure will break power to the emergency shutdown circuit, thereby shutting down the system.

4.4.2 Electrolyzer Differential Pressure Switch Activated

The Altus 20 is designed to maintain a 10 psi differential pressure between the hydrogen and oxygen sides of the gas generation system. Should the pressures approach each other within 3 psi the electrolyzer shuts itself down. By monitoring the output from this switch, the rest of the system will also be shut down if such an event occurs.

4.4.3 Manual System Override (MSO) Button Pressed

There will be four MSO buttons located throughout the site in strategic locations: the control room, the gas generation room, and in two places in the gas storage area. Each of these buttons will be well marked with a sign noting that they are Manual Stop buttons. They will be normally closed push buttons that break the circuit when pressed. This will break power to the emergency shutdown circuit and will activate a system shutdown.

4.4.4 Fire Alarm Activated

The fire alarm can be activated by any of the three smoke detectors installed in the building. One smoke detector will be installed in the gas generation room, one in the control room, and one in the bathroom. This alarm will also be activated if any of the fire alarm pull boxes installed on the site are pulled. One pull box will be centrally located on the front wall of the building near the main door and one will be located at the northern access gate to the site

If the fire alarm is activated, a normally open contact closure will break power to the emergency shutdown circuit, thereby shutting down the gas generation system. In addition to shutting down the gas system via the emergency shutdown system, any event that activates the fire alarm will also sound an audible alarm on site, activate a red flashing light on site, and notify the SunLine Transit Agency’s 24-hour dispatcher of the emergency.

4.4.5 Burglar Alarm Activated

The burglar alarm can be activated by either occupancy sensors or sensors on the windows and doors. This silent alarm system will automatically notify SunLine Transit Agency's 24-hour dispatcher if an alarm is activated. In addition, a normally open contact closure will break power to the emergency shutdown circuit, thereby shutting down the gas generation system.

4.4.6 Hydrogen Detector Activated

The hydrogen detector (C3-HD-1) will be mounted at the highest point in the gas generation room where hydrogen gas is most likely to accumulate if there is a leak. If the detector senses a hydrogen concentration in excess of 1% (25% of the lower combustible limit of hydrogen gas in air), its normally open contact closure will break power to the emergency shutdown circuit, and shut down the system.

4.4.7 Exhaust Vent Position Switch Activated

To ensure that there is always adequate ventilation in the gas generation room when hydrogen gas is being generated, two safety switches have been incorporated into the system. One is a vent position switch. This switch will monitor the position of the operable exhaust ventilation louvers that are going to be installed in the wall of the gas generation room. If the louvers are shut the switch will open, sending a fault signal to the emergency shutdown circuit, causing a system shutdown.

4.4.8 Ventilation Flow Switch Activated

A ventilation flow switch will also be used to ensure that there is adequate ventilation in the gas generation room when hydrogen gas is being generated. This switch will be mounted in the intake ventilation fan housing and will open if the air flow into the gas generation room drops below approximately 500 cf/min (14 m^3/min). This will send a fault signal to the emergency shutdown circuit and will cause a system shutdown.

4.4.9 Power Failure Detected

An Uninterruptible Power System (UPS) will provide conditioned power to the SCC and associated control hardware. This will allow the control system to ride through momentary voltage sags on the power grid without shutting down the system. If the power from the grid is lost, the UPS will detect the power failure. A relay contact on the UPS system will open when grid power is lost. This relay will be used to send a signal to the emergency shutdown circuit that will cause a system shutdown.

4.4.10 Status Beacon

In addition to shutting down critical loads, the emergency shutdown circuit will operate a status beacon that indicates the status of the gas generation system. Three status lights will be mounted in a stacked fixture on the front wall of the building near the main door. The lights will be turned on and off using electromechanical relays. During normal operation the green status light will be lit. When the system is shut down by the fire alarm system (activated by a smoke alarm or fire alarm pull box) the red light will be lit. If the system is shut down due to other less serious alarms (i.e. manual stop button pressed, burglar alarm activated, hydrogen detector activated, watchdog timer activated) the yellow light will be lit.

4.4.11 Electrolyzer External Alarm

In the event of a system fault, the emergency shutdown circuit will shut down the electrolyzer via an external alarm input on the electrolyzer. An electromechanical relay will be used to control this alarm. When a shutdown is activated the relay will open and the electrolyzer will be shut down on an external alarm fault.

5. PUBLIC ACCEPTANCE AND SAFETY ISSUES

The initial impetus for this project came from members of the Palm Desert City Council who approached SERC. At that time, there was a great deal of enthusiasm expressed by the City Council in general, with no apparent impediments. However, over time the membership of the council changed somewhat while the financial state of the city deteriorated. As a result, resistance to the project began to grow. The proposed site for the hydrogen generation facility was challenged by a citizens group seeking the construction of a skateboard park. Faced with this public pressure, and after two years of negotiating with us, the council decided that they would rather have a skateboard park than the solar hydrogen generation station.

The site was then shifted to the campus of The College of the Desert (COD). Again, there was initial enthusiasm and acceptance of the project, but a small vocal minority in the administrative branch of the college was opposed to the project from the start.

During this time SERC took a proactive approach to the safety issue and held a public meeting at which all of the various concerns could be addressed. The meeting was quite successful with the public, the local fire marshal, and many members of COD administration. Unfortunately, the dissenting minority from COD was unswayed and preferred to ask alarmist questions such as the classic “What about the Hindenburg explosion?“ COD had also raised the issue of liability insurance, but COD’s insurance representative, who was invited, failed to attend.

Eventually, COD administrators, acquiescing to the demands of the anti-hydrogen contingent, demanded massive indemnification for the coverage of such environmental disasters as “hydrogen spills“ and the contamination of groundwater and wildlife. When it became clear that the COD administrators would not outright deny permission for the project to proceed, but intended to use extended delaying tactics to achieve their goal, arrangements were made to install the facility at the SunLine Transit Agency. Unfortunately, a great deal of time and effort had already been expended on the design for the COD site.

The SunLine Transit site is already being used as a refueling station for buses that operate on compressed natural gas, so the production and storage of hydrogen was welcomed by Sunline officials. Indeed, Sunline sees our hydrogen station as a natural evolution to a cleaner fuel. As this site is privately owned and quite sizable, no further opposition to this project has been heard. We are now awaiting word from DOE on further funding to complete the station.

Since the inception of this project we have been very concerned with safety. Beginning with the design and construction of the first PUV we have enlisted Hoes Engineering, Inc. of Davis, California to provide us with a detailed safety analysis of all aspects of this project.

Hoes Engineering specializes in the field of safety engineering and has done extensive work for NASA. They have developed an interactive computer program called HAZTRAC that they have designed to help identify and address possibly hazardous elements in any design. The program is used in an iterative fashion with a substantial amount of back and forth between the client (SERC in this case) and Hoes Engineering. They have reviewed almost all phases of our design work including architectural plans, gas handling and storage systems, electrical systems, and refueling systems. All conceivable hazards were identified and addressed in terms of:

- Hazard scenario
- Effect
- Risk assessment
    - catastrophic
    - critical
    - marginal
    - negligible
- Remarks
- Recommendations to minimize risk

We have also consulted them extensively for guidance through the labyrinth of building codes and their application to our project. When construction is complete, they will inspect the installation and review the refueling station software.

6. CONCLUSIONS

Upon its completion, the Palm Desert Renewable Hydrogen Transportation Project will be a unique demonstration of state-of-the-art technology encompassing the hydrogen fuel cycle from production to final use. As the project currently stands, it is already unprecedented in that a small fleet of fuel cell powered vehicles is in daily use by ordinary citizens. The potential for providing Zero Pollution Vehicles to the general public with the attendant environmental benefits can be clearly seen in Palm Desert at this moment.

Chapter 11
OTHER DEMONSTRATION PROJECTS

In this section, some remarks are presented for five additional projects that are listed in Table 1 of the Introduction, but are not covered by detailed reports. A short overview of the main features of these projects is given, as well as presentation of some results.

1. HYSOLAR: 10 kW Test and Research Facility (DLR)

The 10 kW PV-electrolysis test facility was erected by DLR (German Aerospace Research Establishment) on the university campus in Stuttgart during Phase I of the HYSOLAR project. It was the first complete plant for solar hydrogen production in a technical scale in Germany. Since start-up in April 1989 the technical development and the system optimization continued.

In the test facility, several different electrolyzer concepts have been investigated. For solar operation the electrolyzers can be connected to the photovoltaic generator with or without power conditioning unit. Furthermore the electrolyzers can be operated with any other controllable current or power profile fed by grid connected power supplies, thus simulating wind energy profiles from wind turbines located at different sites worldwide. A comprehensive simulation code to calculate system efficiency and annual hydrogen production rate from individual characteristics of components and climatic data has been developed.

Intermittent operation with high power fluctuations and partial load periods results in extreme demands on control, supervision and material selection of the electrolyzers. A first commercial prototype with 600 cm^2 electrode area failed during dynamic and intermittent operation because of stress induced degradation of the low-cost materials. After successful modification and adaptation, the advanced 10 kW electrolyzer fits the requirements of intermittent operation and is used as a test bed for improved electrolyzer components such as electrodes and new separators. In November 1994, special vacuum plasma-sprayed electrodes - developed by DLR - have been integrated into the electrolysis block. These electrodes have exhibited excellent efficiency and stability, indicating a world record efficiency for alkaline water electrolyzers.

A highly sophisticated control system unit has been developed, ensuring safe operation and reliable control of the gas qualities, pressure level, temperature, and electrolyte levels under any operating condition. The complete electrolyzer system concept has been homologated by the German safety authority.

The 10 kW HYSOLAR system is being operated continuously to supply DLR’s fuel cell test facility (PEMA) with solar hydrogen.

2. Solar Hydrogen Pilot Plant (Helsinki University of Technology)

Since 1989 solar hydrogen systems have been studied at Helsinki University of Technology. The work so far has comprised the construction of a small self-sufficient pilot plant for 1-2 kWh/day load, and the development of a numerical simulation program H2PHOTO for system sizing and optimization. In the study under way, special emphasis is placed on the seasonal storage subsystem (electrolyzer, hydrogen storage, and fuel cell), to improve its round-trip efficiency and reliability. This subsystem had been found to be critical for overall performance.

The pilot plant includes the following components:

- 1.3 kW_p a-Si PV-array
- 14 kWh lead acid battery as short-term buffer storage
- 800 W pressurized (max. 30 bar) alkaline electrolyzer
- 500 W phosphoric acid fuel cell
- 200 Nm^3 steel vessel storage
- 0-500 W resistive load.

It was designed and constructed during 1990-1993. The purpose of the pilot plant is to demonstrate the technical feasibility of components and the integrated system. During recent years, the hydrogen production and conversion components have been comprehensively studied and the operation experiences were collected from the whole system from several test runs. Based on thousands of operation hours, the system has generally operated smoothly, but further improvements in component reliability and durability are needed. The numerical simulation program H2PHOTO was primarily developed for system sizing and optimization to estimate the overall performance over extended periods of time. It has been verified against measurements performed in the pilot plant and used to improve the overall efficiency of the pilot plant by comparing alternative control strategies.

In the next phase of the project, additional electrolyzers, hydrogen storage options and fuel cells were studied in a laboratory scale test bench, giving more emphasis to solid polymer technologies. A concise summary of the relative strengths and weaknesses of different types of electrolyzer and fuel cell technologies (J. Vanhanen's PhD thesis) is shown in Table 11.1.

Table 11.1: Comparison of electrolyzers and fuel cells

	Strengths	**Weaknesses**
	Electrolyzers	
Alkaline	- high voltage efficiency - durable	- high parasitic power consumption - complex gas handling - liquid electrolyte (KOH)
Solid Polymer	- compact - low parasitic power consumption - high overall efficiency - pressure difference allowed between H_2 and O_2 sides	- high purity water needed - high overpotentials in some electrolyzers
	Fuel Cells	
Phosphoric Acid	- tolerates impurities - high value waste heat (180°C)	- low electrical efficiency - pre-heater needed - unreacted hydrogen due to open-end stack construction
Solid Polymer	- simple construction - long life-time - low parasitic power consumption	- expensive catalysts - careful control of water management needed
Alkaline	- inexpensive	- high parasitic power consumption - liquid electrolyte (KOH)

3. Hydrogen Production and Use in Fuel Cells (ATEL, Switzerland)

A demonstration plant for hydrogen production and use in fuel cells has been built in Switzerland by the utility company ATEL (Aare-Tessin Electricity Supply Co. Ltd.). Its major components are a 90 kW hydrogen production plant and two 3 kW fuel cells. The PEM electrolyzer (type Membrel, originally provided by ABB) was revised for this application in cooperation with the Paul Scherrer Institute (PSI). It has been in operation since 1991 and has accumulated a total of 6000 operating hours. In an accompanying technical and scientific program, the state of the modules has been checked periodically by measuring the cell voltages and monitoring the gas purities. The accumulated hours during which the electrolyzer has been operating and producing gas, the hydrogen content in the anodic oxygen gas, and the average cell voltage of 120 cells (operating at 10 kA/m² and 80°C) are shown in Figure 11.1. The behavior of the electrolyzer so far does not indicate any signs of membrane failure. This is in contrast to the Membrel electrolyzer in the SWB plant, which had to be shut down due to gas purity problems after a total operating time of only 2300 h.

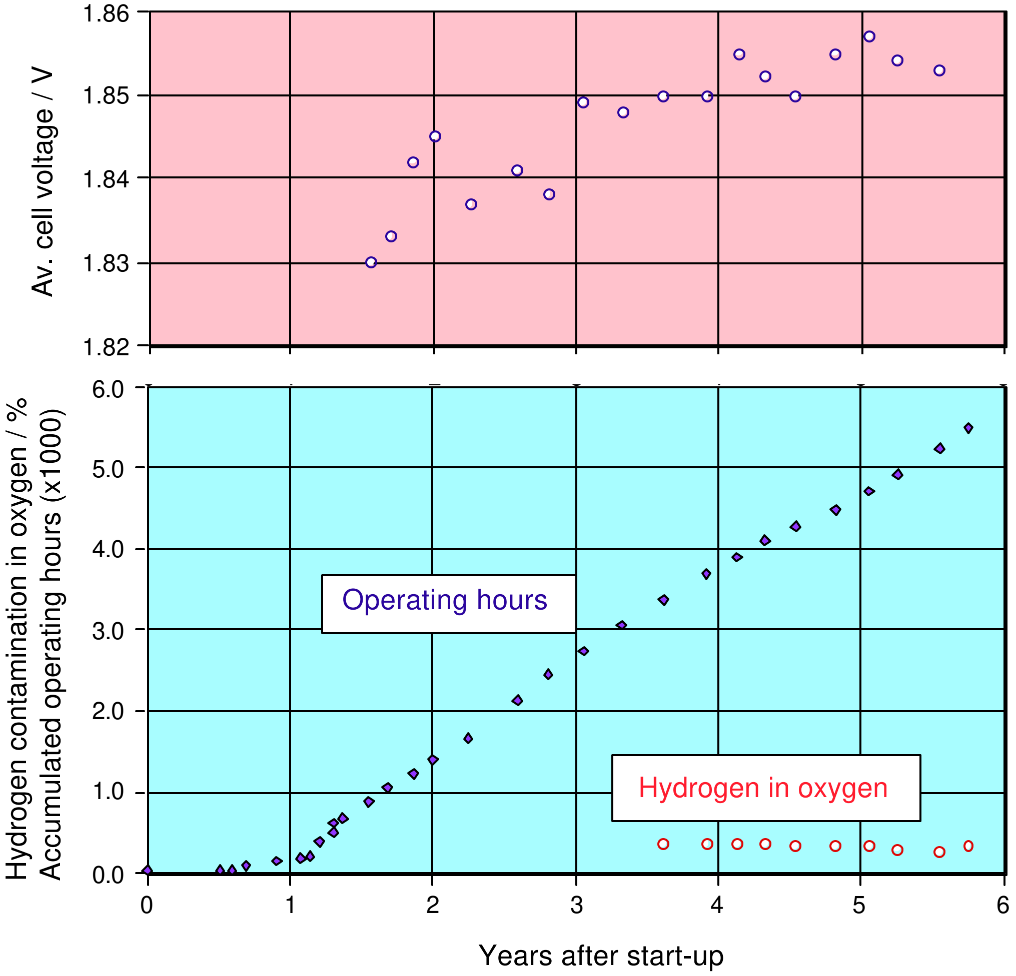


Figure 11.1: Membrel plant ATEL: Average cell voltage, operating hours and hydrogen content in anodic gas

Two 3 kW hydrogen/air PEM fuel cells have been purchased from Ballard Power Systems and have been integrated in the ATEL hydrogen project. The two systems have been operated for 3000 hours each, connected to the grid with a three-phase 10 kW inverter. Voltage controlled starting and operation of the stacks has proved to be the ideal control method. Parallel and series operation of the stacks, immediate load changes, load following and shutdowns did not cause any problems for the generators. Some leakage problems did occur with the first two stacks. Continuous tests with a third, newer stack, integrated in one of the existing systems, were successfully completed.

4. Self-Sufficient Solar House (Fraunhofer ISE, Freiburg)

With the self-sufficient solar house, the Fraunhofer Institute for Solar Energy Systems has been demonstrating the ramifications of supplying the entire energy demand for a single-family home from solar energy incident on the roof and walls, even under Central European climatic conditions (Freiburg). The house, which had no electricity connection, no gas connection and no oil tank during the 5 year project period, is experimental in character (see Picture 11.1). It incorporates a whole range of novel building and energy technologies, which have been tested and improved in detail under real living conditions. The house has been occupied by a family since October, 1992.

Picture 11.1: Self-Sufficient Solar House in Freiburg, Germany

In the first major planning step towards energy self-sufficiency, the energy demand of the house had to be minimized by combining proven energy-saving technology with highly efficient thermal collectors and PV modules. The need for space heating could be reduced to almost zero and, consequently, seasonal storage was not necessary. The demand for electricity was significantly reduced by using energy-efficient household appliances, for a total energy consumption of less than 10 kWh/m^2.

In order to meet the remaining energy demand (during periods without sunshine and for cooking), the decision was made for a hydrogen/oxygen energy storage system. This system is essential to the autonomy of the energy supply, and it also provides the possibility for seasonal storage of solar generated electricity. In summer, PV-generated electricity is used for the electrolysis of water to hydrogen and oxygen, which are stored in tanks (1500 kWh). Flameless combustion of the hydrogen is the source of heat for cooking, and it is also used to heat the inlet air in the ventilation system on particularly cold days. If additional electricity is required, it is produced from the reaction of hydrogen with oxygen in a fuel cell. As it is only operated during periods with little sunshine, the waste heat from the fuel cell at a temperature of about 70°C has been used to provide backup heat for the hot water heater via a heat exchanger.

Due to the problems of the alkaline systems, the Institute developed its own polymer exchange membrane electrolyzer (2 kW). After initial tests showing the unreliability of alkaline fuel cell systems in connection with fully automatic operation, a PEM-type fuel cell stack was purchased from Siemens and installed in the house.

One of the main conclusions of this project was the realization that the losses, occurring due to the difference between real insolation and standard test conditions (to which the efficiencies of solar modules are usually referring) on one hand, and various operating aspects of the electrolyzer on the other hand, have been considerably underestimated. In a typical operating year, 60% rather than the expected 80% of the PV energy was available in the form of electricity. Taking into account the further losses occurring in electrolyzers, fuel cells, batteries and inverters, 44% of the nominal PV energy was actually available as useful energy to the end users. A second conclusion was that due to the rather large differences between the weather conditions in two consecutive winters, energy self-sufficiency could only be obtained by conscientious adjustment of the inhabitants.

5. HYSOLAR: 350 kW Demonstration Plant (KACST/DLR)

The objectives of this task were the design, installation and safe experimental operation of a directly coupled 350 kW concentrated photovoltaic, advanced electrolysis system with compressed hydrogen storage. The plant was installed in the Kingdom of Saudi Arabia at the Solar Village of the King Abdulaziz City for Science and Technology (KACST) research site, about 50 km north of Riyadh. The plant was designed and installed between January 1991 and August 1993 by a joint German-Saudi Arabian team with the help of external subcontractors. After a safety inspection and release of an operation permit by the German TUEV Südwest, the plant started up on August 19, 1993.

The initial four-month test phase lasted until the end of December 1993. Due to the good test results, it was then decided to start the regular experimental operation phase from January 1994 onwards. During the 1994-95 operation phase, solar and grid-connected electrolysis experiments as well as regular solar operation with hydrogen storage for other program tasks were performed. For safety reasons, the electrolysis characteristic measurements were restricted by safety limits, but significant operation and maintenance experience was gained with the world's first technical prototype of a pressurized electrolyzer fuelled by intermittent solar electricity (see Picture 11.2). Although no major deficiencies requiring redesign of subsystems were found, the plant improvement continued to keep up with the latest operation results and the technical development. In order to allow unrestricted solar operation and manually controlled experimental electrolysis operation as well, the control program has been designed to have two operation modes: fully automatic solar or grid-connected operation; and semi-automatic or manual grid connected operation mode of the electrolyzer.

The complete system is actually in operation to produce hydrogen on demand for the research activities of KACST on hydrogen utilization and fuel cells at Solar Village. In the near future, a maintenance program, mainly of the PV field, is planned and includes some reconstruction of degraded components. The PV field, with Fresnel-lenses to concentrate the sunlight point focused 33 times onto mono-crystalline Si-cells, has operated efficiently and nearly continuously under extreme temperature conditions, including temporary sandstorms.

Picture 11.2: HYSOLAR Process Room with 350 kW Electrolyzer in Riyadh