FUEL CELL INNOVATIVE REMOTE ENERGY SYSTEM FOR TELECOM (FIRST)

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1. PROJECT GOALS

This report describes the performance of a system based on photovoltaic power coupled with a hydrogen fuel cell for a remote telecommunications application. Two experimental systems were built and tested in Madrid, Spain, during the period 2000 to 2004.

The main objective of the project “Fuel cell Innovative Remote energy System for Telecom” (FIRST) is the evaluation of the introduction of hydrogen and fuel cell technologies into renewable power systems for remote telecom applications. The goals are to improve power availability while demonstrating reductions in cost and size compared to conventional solar power systems.

Two demonstration systems based on photovoltaic generation have been chosen for this purpose; the evaluation has covered operational and economic aspects of their performance.

2. GENERAL DESCRIPTION OF PROJECT

Photovoltaic power systems are widely used in telecommunication applications when AC mains are not available due to the remoteness of the location, reliability or safety issues. However, the deployment of solar power systems depends on the amount of available solar radiation. The variability of solar radiation usually requires some form of energy back-up such as batteries or a diesel generator. Alternatively the use of fuel cells in combination with solar power could improve power availability and system reliability.

Two novel approaches for a power supply application in the range of 150 W and an energy consumption of 3.6 kWh/day have been developed and tested within this international and interdisciplinary collaborative project:

2.1 Showcase 1: PV–Fuel Cell Hybrid System

In this system a fuel cell is deployed with photovoltaics along with batteries for short-term energy storage. Effectively the fuel cell acts as an emergency system for powering the telecoms equipment. Hydrogen is delivered to the system externally. The main advantage of the addition of the fuel cell is that power system availability is increased. With a good maintenance schedule it is possible to ensure that the telecommunication system will be properly powered with availability very close to 100%. Maintenance requirements compared with the alternative of a conventional diesel generator will be reduced significantly.

In telecommunication applications a relatively large PV array and batteries are required to ensure high availability of the telecoms equipment. If a fuel cell is added which operates for only a small percentage of the time (roughly 10%), the PV array size and batteries could be reduced by more than 25% with a significant reduction of visual impact. These figures are based on a telecoms installation in Madrid (Spain). A higher size reduction can be achieved in Central and Northern Europe (more than 50%).

2.2 Showcase 2: PV system with long term energy storage

Solar energy excess generated during sunny periods is stored in the form of hydrogen in metal hydrides. The hydrogen is produced by an electrolyser and consumed when required by the fuel cell. This system enables the use of solar power systems in places where operation of conventional back-up systems is not possible or would incur very high costs. The use of solar power increases the system availability while reducing the maintenance costs significantly. This system has the following features:

- It fulfills safety regulations for hydrogen.
- The Advanced Energy System is built inside a compact rack.
- Outdoor telecommunication specifications are fulfilled in terms of temperature and reliability.

In order to fulfill the strict telecommunication requirements in these Showcases it was necessary to develop specific elements that improve the actual state-of-the-art of the fuel cell balance of plant:

- A medium pressure, high efficiency electrolyser (30 bar);
- A reliable fuel cell system, which can operate for one year within a wide temperature range (between -25 and +45ºC), and which fulfils the specific outdoor telecommunication specifications with respect to life time, reliability, quick and easy maintenance;
- A charge regulator for easy adaptation to different voltage levels and generator peak power, required for a PV system based on CIS technology;
- Advanced hydrogen storage (metal hydride) systems that store the energy in a compact way fulfilling hydrogen safety regulations;
- A sizing tool that allows the design of the most cost effective system for a given load and location fulfilling all socio-economic requirements defined by the user.

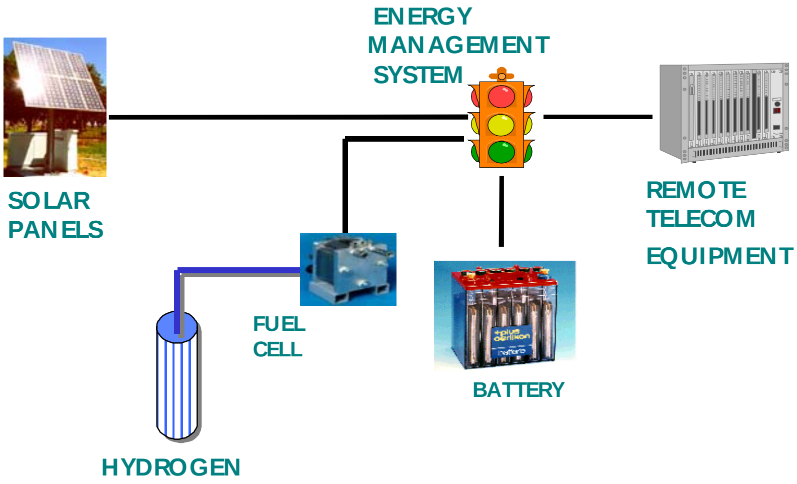


Figure 1: Main components of Showcase 1

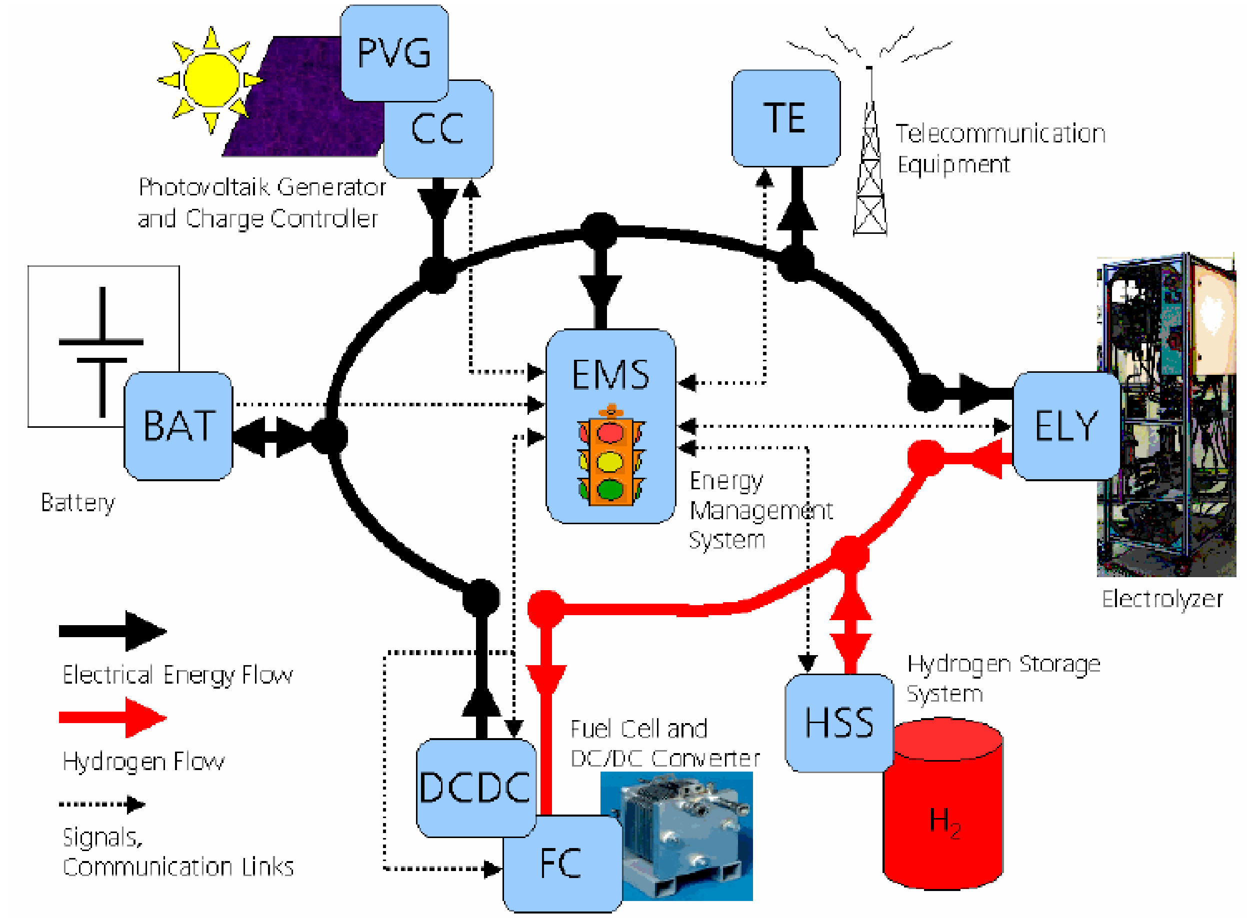


Figure 2: Flow diagram of the Showcase 2 system

The main components of the two Showcases are depicted in Figures 1 and 2.

2.3 Partners and project organization

The partners listed in Table 1 have carried out the tasks required within the project.

Table 1: Partners and their responsibilities

INTA: Instituto Nacional de Técnica Aeroespacial	Project coordination Hosting and operation of Showcase 1
AIR LIQUIDE	Hydrogen and air supply systems and control
FhG-ISE: Fraunhofer Institute for Solar Energy Systems	Electrolyser, Energy Management System
CIEMAT: Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas	Hosting and operation of Showcase 2
ICP-CSIC: Instituto de Catálysis y Petroleoquímica, Consejo Superior de Investigaciones Científicas	Metal hydride seasonal storage system and purification units
NUVERA Fuel Cells Europe	PEM fuel cell stacks
WUERTH Solergy	PV generators, MPP charge controller

There is a Board of Interest formed by INABENSA (E), GREENCELL (E), CHLORIDE (E) and ISOFOTON (E), who are stakeholders in hydrogen energy systems and have joined in all technical discussions. The overall budget of the project was 3.400.000 € (USD 4.15 million). The project started in March 2000, and had a duration of 4 years. It was supported with a 50% contribution by the EC under contract ERK5-CT1999-00018.

3. DESCRIPTION OF COMPONENTS

3.1 Top level configuration

After the analysis of the telecommunications systems that can be located in remote locations and therefore working in stand-alone conditions (no AC mains) the Alcatel system EVOLIUM^{TM} WLL(A9800) was selected for this project due to the following reasons:

- The system's radio equipment is designed for rural areas
- EVOLIUM^{TM} WLL(A9800) systems powered by PV generators have been widely installed in low altitude locations. The Showcases of the FIRST project could help to extend the capabilities at higher altitude locations.
- The power and voltage range of this equipment is easily extrapolated to other systems.
- The system is easy to test under real conditions.

EVOLIUM^{TM} Wireless Local Loop (WLL A9800) is a digital radio access system designed to supply high quality telecommunication services from a telephone exchange to subscriber groups distributed throughout suburban and sparsely populated areas.

Within this project, a unit has been chosen which supports up to 32 wired subscribers. The corresponding energy system must fulfill the following conditions:

- The average traffic of telecom equipment amounts to 0.2 Erlangs. This requires an average power consumption of 145.6 W.
- The energy system must be able to power the telecom equipment in all the traffic telecom range from 132.76 W (0 Erlangs) up to 197.4 W (1 Erlang).

Based on these assumptions and on information obtained from the project partners, all the components of Showcase 1 have been sized by computational simulation with meteorological data of the last 20 years.

Table 2: Sizing parameters of the Showcase 1 system

Fuel cell		16 A, 36 cells
Hydrogen storage		4 bottles with 8.8 Nm^3
DC/DC converter	output power	300 W
PV generator	type peak power inclination orientation	CIS 1580 W peak at STC 45º 155º (north at 0º)
Battery		48 V, 360 Ah

The sizing procedure aimed to minimize the overall lifetime costs of the system while supplying an availability of 100%. Lifetime simulations of the complete system have been performed for various combinations of elements and locations. The system selected for the location of Showcase 1 in Madrid was sized assuming a limited amount of hydrogen bottles. It is summarized in Table 2.

3.2 PV generators

Both Showcases have PV generators as main source, the panels are provided by WUERTH, are based on thin film $CuInSe_2$ (CIS) technology and have a peak power of 1.6 kW for Showcase 1 and 1.5 kW for Showcase 2. The 24 modules for Showcase 1 are shown in Figure 3. With a total surface of 15.9 m^2, they have achieved an average efficiency of 8%. Together with the special mounting equipment, the modules were installed on the INTA facilities in June 2001.

Figure 3: CIS Solar panels for Showcase 1

The 22 thin film $CuInSe_2$ (CIS) modules for Showcase 2, together with the MPP charge controller and the complete mounting equipment have been installed at CIEMAT facilities in July 2002. The panels reached an average efficiency of 10%. The total power of the PV system is 1422 W_{peak}. The PV modules are connected to a lead acid battery system with a capacity of 19 kWh, allowing the load to be supplied autonomously for 5 days.

3.3 Electrolyser

The PEM electrolyser for Showcase 2 has been developed and manufactured by the Fraunhofer Institute for Solar Energy (FhG-ISE). It produces hydrogen at 30 bar without any mechanical compressors.

During the first period of the project (2000-2001) a pilot electrolyser with one cell was designed, constructed and tested at FhG-ISE. In order to improve its performance a partial redesign was undertaken, including changing materials: expensive Titanium sintered plates were replaced by expanded Titanium metal which is available at a lower price. Using this new material it is possible to work without the need for flat gaskets since variations of thickness and uniformity are lower compared to the Titanium sintered plates. The latest design used cheaper only O-ring seals. Tests proved tightness showing minimal pressure losses at 45 bar over 45 min.

At the same time the design of the electrical contacts of the power circuit could be improved too. The stack pressing end plates were electrically isolated. Due to this a connection of stacks in series is possible without any repercussions meanwhile piping can be installed along both sides of the stack.

The required power of the electrolyser was estimated at approximately 1 kW. With a voltage supply of 48 V_{DC} the resulting current was approximately 20 A. Given an expected current density of 0.7 A/cm² the active cell surface was estimated at approximately 30 cm².

The electrolyser was sent to Air Liquide on February 2002. Its main components are shown in Figure 4.

Figure 4: Electrolyser components (Showcase 2)

Due to the use of new materials for the bi-polar plates a significant cost reduction in the hardware was achieved. These savings in material funded the research on the new plates. According to the project specification, the electrolyser was to operate at 30 bar to allow the charging of the hydride storage bottles even in the summer at higher ambient temperatures. The electrolyser has a fully self-contained control unit, which performs safety tests, the start-up and shutdown procedure and the procedure for removal of water to avoid freezing in winter conditions. The larger system management controller only sends a start or stop signal or a signal for water removal or refilling. The problem of avoiding freezing of the membrane in the winter is not completely solved. A heat exchanger and appropriate insulation have been installed to allow using waste heat from the fuel cell to avoid freezing of the membrane.

The electrolyser is connected directly to the battery. This was decided by a majority of the consortium during the design phase of Showcase 2. In fact this results in very low production rates if the electrolyser is operated at low battery voltages (only happens for test purposes). The current intake depends exponentially on input voltage.

3.4 Hydrogen storage

For Showcase 1 the hydrogen used is stored in four bottles holding 50 liters at 200 bar. The electronic management system (EMS) controls the running of the fuel cell depending on the availability of hydrogen from the storage system; the flow of hydrogen is controlled by two pressure switches.

The Hydrogen Storage System (HSS) for Showcase 2 was developed and manufactured by ICP-CSIC. It is based on a $LANi_5$ – type metal hydride containers, with a capacity of 70 Nm^3 of hydrogen.

The function of the HSS is to store the hydrogen obtained by water electrolysis (at pressures near 30 bar) during summer (temperature range from 15ºC to 40ºC), using excess electric energy produced by the solar panels. During winter (from –10ºC to 15ºC) this hydrogen will be used by the fuel cell to generate enough electricity to operate the telecommunication equipment. The EMS is in charge of taking decisions about storage charging and discharging operations, as well as taking emergency actions prompted by the temperature and pressure data from sensors in the HSS.

The two main subsystems of the HSS are the metal hydride cylinders and hydrogen purification units.

- The HSS has seven cylinders containing approximately 700 kg of metal hydride with the chemical composition: La (23.7%) Ce (2.64%) Ni (58.9%) Al (0.01%) Sn (0.03%). The metal hydride alloy was selected to fulfill the operational temperature and pressure specifications and discharge conditions. The operating temperature of this type of metal hydride ranges from 0 to 50ºC. Its adsorption behavior is shown in Figure 5. The HSS is able to store 70 Nm^3 of hydrogen.
- Two types of purification units can selectively be used to purify the hydrogen:
  - Water retention over adsorbent materials, i.e. zeolites and/or activated carbons,
  - Oxygen removal from hydrogen based on a Pd catalyst (Deoxo).

Taking into account that the HSS is a high-pressure system containing hydrogen, stainless steel materials have been used in the construction of all components (tubing, valves, regulators, etc.). The HSS also incorporates a relief and a rupture disk valve. These two mechanical elements will release the stored hydrogen if the HSS surpasses its safe operating pressure of 28-30 bar. Any gas release is safely vented to atmosphere. The two valves, relief or rupture, act when: (1) an unexpected high ambient temperature occurs when the metal hydride is fully charged, or (2) the electrolyser pressure exceeds its normal value. Additional safety elements include two non-return valves, one placed after the pressure regulator and one placed between the purification units and the metal hydride storage cylinders. These elements prevent the hydrogen from flowing back into the pipeline.

The general safety equipment needed for hydrogen systems is also in place: A hydrogen sensor is installed in the room where the Showcase 2 is operated. If an alarm is triggered, the facility is purged with outside air.

The system was completed on May 2002, delivered for integration to CIEMAT, tested and connected to other units of the prototype (Showcase 2). An instruction manual for the operation of the hydrogen storage system has been edited and distributed to the consortium partners. During the installation it was found that the high weight of the hydrogen containers presented a structural problem: the building structure had to support more than 1000 kg of storage. Another problem was the operation temperature range: The electrolyser produces hydrogen in summer, when the ambient temperature is about to 30ºC and the room temperature reaches 40ºC. At this temperature the pressure of the HSS increases while the charging capacity is decreased (see Figure 5). In order to increase storage efficiency and avoid safety risks it was decided to install an air-conditioning system to reduce the room temperature in summer.

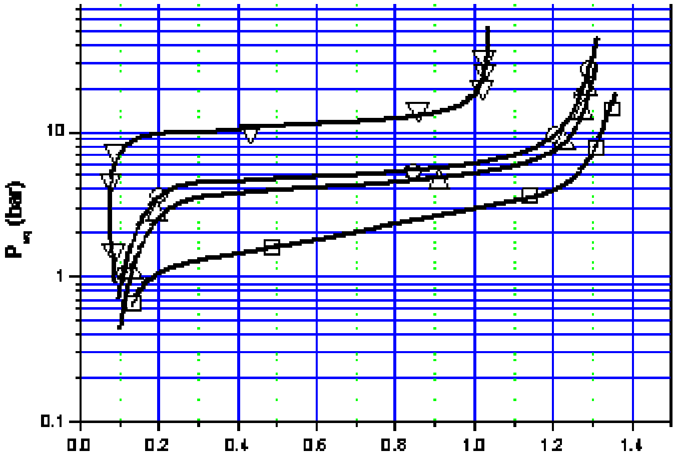


Figure 5: Characteristic curves of the hydrogen retention over the selected metal alloy
□ OºC ○ Ambient temperature (14ºC) ∆ Ambient temperature (12 ºC) ∇ 40ºC

3.5 Fuel Cells

3.5.1 Fuel cells system for Showcase 1

The PEM fuel cells stacks for the Showcase have been provided by NUVERA Fuel Cells Europe. AIR LIQUIDE acted as systems integrators.

The first stack with 27 cells and a power of 330 W (gross) and 275 W (net) was provided by NUVERA on December 2000. It operated with hydrogen at 1.5 bar and with air at atmospheric pressure. AIR LIQUIDE designed and built the fuel cell system prototype. Along with the operating manual it has been sent to CIEMAT in order to test it in real conditions.

Figure 6: Fuel cell system for Showcase 1

The behavior of this stack was unsatisfactory. The diagnosis by NUVERA revealed that 6 of the 27 cells were malfunctioning. The use of pure oxygen as a reactant during the test performed by

CIEMAT turned out to be the main reason for local overheating of the membrane and its consequent damage. The conclusion that the components used to realize the stack were not suitable to operate with this fluid, was confirmed during the subsequent disassembly: evident burn marks have been found inside the stack on the air side. A new stack was assembled and sent to INTA in Madrid in July 2002. There remained some problems caused by the malfunctioning of the hydrogen management system and cell perforation. The stack was again repaired by NUVERA and re-commissioned in January 2003. As the H_2 low-pressure control valve did not properly control the pressure during transient operation (e.g. when the H_2 circuit electrovalves open and close), INTA replaced the valve and added a pressure safety valve to protect the fuel cell from high gas supply pressure.

The system was commissioned again at INTA with AIR LIQUIDE and NUVERA. This time, the behavior of the system was satisfactory over several hours of testing, although the performance was a little lower than expected. Following these tests NUVERA and AIR LIQUIDE allowed INTA to start its tests with the fuel cell controlled by the EMS.

The performances of the operational stack after almost 2 months of operation are shown in Figure 7, and its main characteristics are summarized in Table 3.

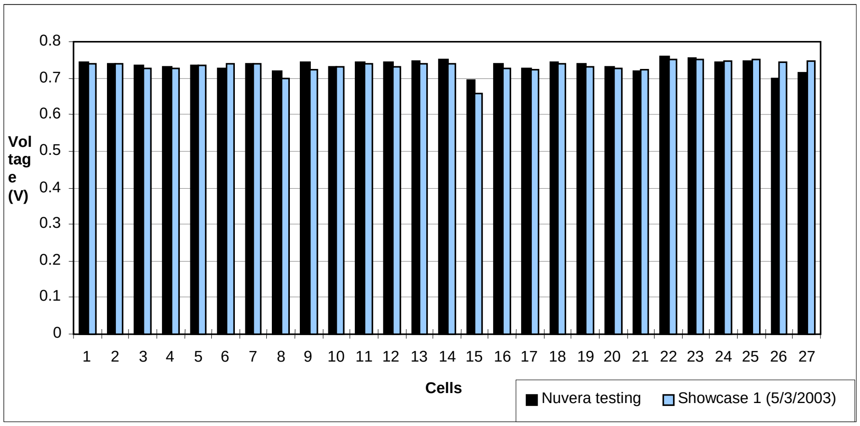


Figure 7: Performances comparison at 12 A (1.5 bar)

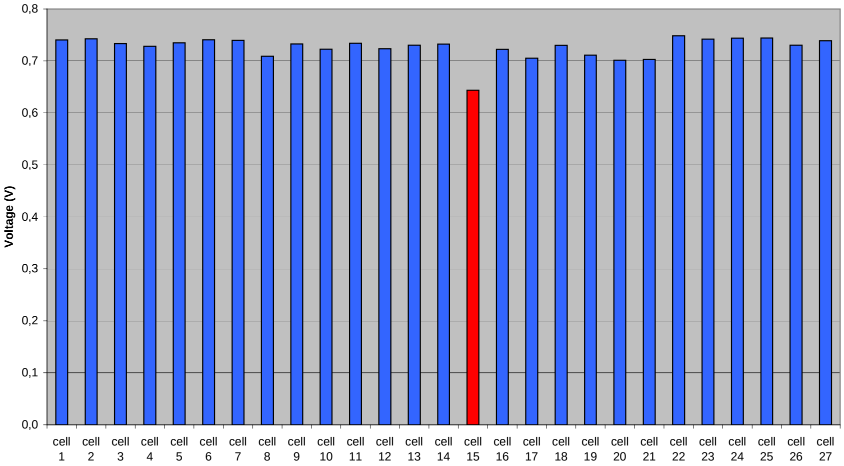


Figure 8: Single cell voltage of 27 cells in Showcase 1

In the operation of the fuel cell system the DC/DC converter is tuned to drain 7.8 A from the fuel cell system. The maximum gross current draw is about 11.7 A (including the fans and the cooling system power draws). The voltage of the fuel cell is about 19 V, so the net power drained from the fuel cell system is about 150 W, while the gross power is about 220 W.

The power drained from the fuel cell is lower than intended due to the fact one of the cells in the stack has a lower voltage than the others (about 0.65 V at 7.8 A net). The comparison of the single cell voltages is shown in Figure 8.

As increasing the power draw could lead to deterioration of this voltage ultimately causing damage to the cell, it was decided to reduce the fuel system power demands in order to increase its reliability.

The last objective was to let the fuel cell run in real conditions, in order to test the reliability of the system and its stability.

3.5.2 Fuel cell system for Showcase 2

The specified performance criteria were:

- Good performance and response time with cold start up;
- Cold start up after storage at temperatures below 0ºC;
- Capability of operation in wide range of temperature;
- Start Up of the fuel cell with and without electrical energy buffer.

Tests with a 10 cells stack similar to the one used in Showcase 1, led to the development of start up and shut down procedures able to guarantee reliable performance in cold conditions. The following characteristics were extracted from these tests:

- Mean time between frozen to operation: 5 min.
- Time from OCV to nominal operating conditions: approx. 3÷5 min.

At the same time an innovative shut down procedure was introduced which protects the stack from corrosion; in this procedure the cathode side was purged and all oxygen in the stack was consumed by running the blower or an alternative electrical load. This is done in order to minimize the amount of stagnant water in the cells during shut down period.

A 48-cell stack for Showcase 2 has been assembled and shipped to AIR LIQUIDE in April 2002. The fuel cell system design was modified to include a small, PV charged battery and the full system was tested in September 2002. During testing, after some work to optimize the automatic operations of the system an internal leakage was observed together with some problems on two of the stack’s cells, probably caused by a failure of one or two internal sealing gaskets. Allowing the stack to have a slower start-up reduced this leakage problem. However, these problems did not have a significant influence on the general performance after the stack had warmed up. Therefore the stack was shipped to Madrid were it was integrated in the system in January 2003. Tests in March confirmed the utility of the slow start-up to control the internal leakage of the stack; moreover fine tunings made by NUVERA allowed the fuel cells to work in stable conditions. These consisted mainly of increasing the H_2 pressure to about 400 mbar, and of slightly increasing the air pressure while decreasing the airflow. The comparison of the two tests is shown in Figure 10.

The main characteristics of this stack are shown in Table 3.

Table 3: Main characteristics of the fuel cell stacks in both Showcases

			Showcase 1	Showcase 2
Number of cells			27	48
Current		A	8-12	12
Overall voltage		V	20	34
Power	gross	W	220	410
	net	W	170	
Pressure	hydrogen	bar	1.45	1.3
	air	bar	1.2	1.15

The performances of the fuel cell stacks for Showcase 2 before and after the integration in the system are compared in Figures 9-10 and shown to be very similar.

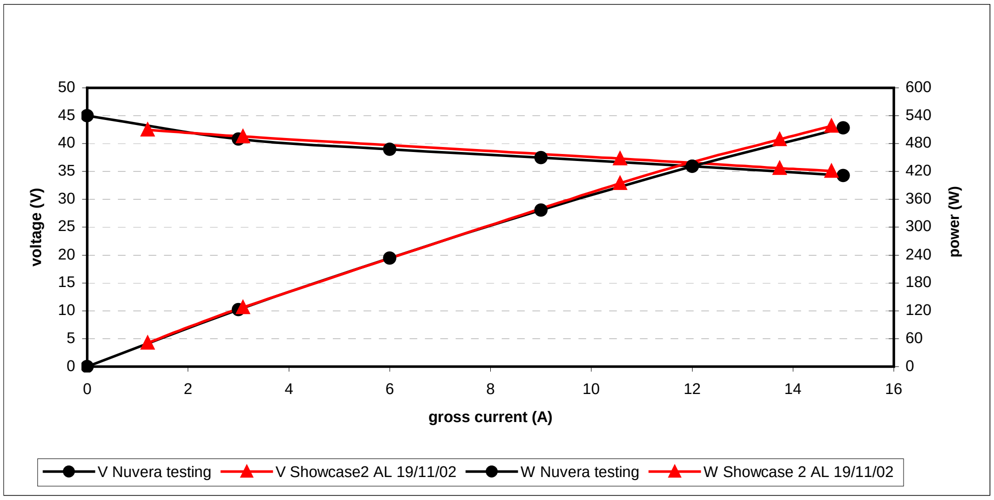


Figure 9: Electric behavior of fuel cell stacks in Showcase 2

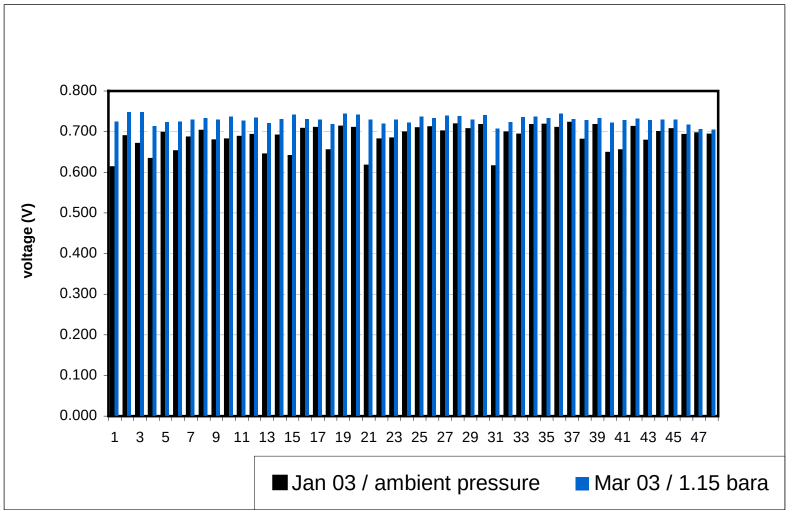


Figure 10: Performance comparison at 12 A for two tests of the Showcase 2 stack

Testing at CIEMAT during the period July ’03 and December ’03 confirmed a power output greater than 360 W and an overall voltage greater than 30 V at the nominal net current of 8 A. As in the operation of Showcase 1 the running time of the full cell was low due to over sizing of the systems PV panels. This meant that recharging of the batteries using the fuel cell was rarely required.

3.6 Other components

The Fraunhofer Institute for Solar Energy Systems (FhG-ISE) has developed an Energy Management System (EMS) for the operation of the two Showcases (Figure 11). The EMS acts as central controlling unit to ensure an uninterrupted power supply to the Telecom Equipment (TE). Power is normally supplied by the large battery system, which is charged by either the photovoltaic generator (PVG) or by the fuel cell. The EMS protects the battery from overcharging and undercharging by monitoring its state of charge (SOC). It controls the fuel cell and PVG based on the battery SOC.

Component control has been improved: A control kernel frequently checks if certain conditions (e.g. limits exceeded, inputs set, times elapsed etc.) are fulfilled to bring a component from one state to another. On entering a new state a list of tasks is executed (e.g. switching outputs, set values etc.). This type of controller also means that components can be changed without the need for re-programming of the controller and future reuse of code is possible.

The EMS has interfaces of different kinds (digital, analogue, serial) to all of the components it is attached to. This shows important information on a graphical display and provides a serial-line interface for setup, maintenance and continuous monitoring or logging of data. Via this connection it is possible to remotely control the power supply system from an operation and maintenance (e.g. the telecom service provider).

The features described are all implemented within a low cost microcontroller platform, using a robust embedded operating system.

As it turned proved impossible to customize the operation of a commercial DC/DC converter for the requirement of the fuel cell system of Showcase 1, the FHG-ISE developed a DC/DC converter for both Showcases. This was designed specifically for the operational characteristics of the fuel cells.

Figure 11: Energy management system for Showcase 1

The EMS for Showcase 2 was delivered for integration to the premises of AIR LIQUIDE in June 2002. Some improvements were added, based on the experience from Showcase 1. This EMS also controls the running of the electrolyser in daylight hours in summer using SOC and ambient data. Additionally a DC/DC converter for fuel cell operation and MPP charge controller from Wuerth are integrated into the EMS. These components together with the electrolyser (manufactured also by FhG-ISE) and the fuel cell system were integrated at AIR LIQUIDE facilities and sent to CIEMAT in Madrid. They are now operational in Showcase 2.

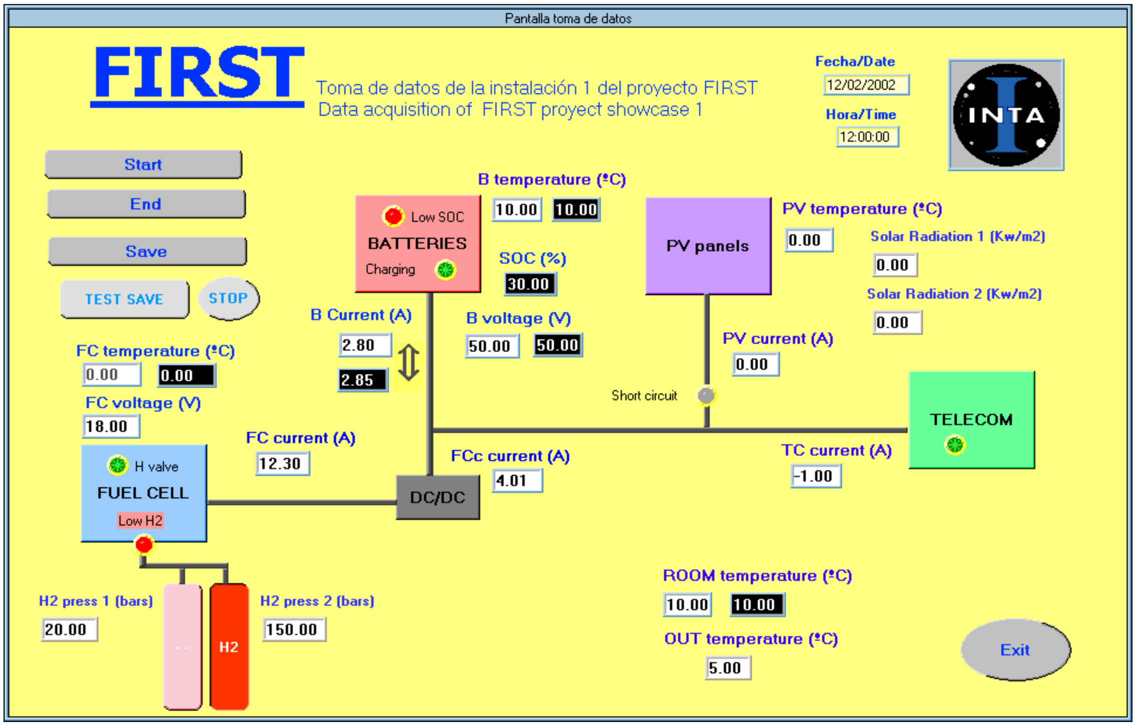
4. INTEGRATION OF COMPONENTS

4.1 Showcase 1

The process of integration of the Showcase 1 has been divided in three different phases: the design of the software and instrumentation of the data acquisition system (DAS), the Laboratory integration and the Field integration. As the fuel cell system was received much later than the other systems, it was simulated using a power source in the laboratory and in part of the field integration. It was integrated at the end of the testing process.

4.1.1 Software design

The Showcase 1 system is totally autonomous, but to be able to evaluate and control the operation of the whole system, INTA has developed a customized data acquisition (DAQ) system.



Fecha/Date 12/02/2002
Hora/Time 12:00:00
B temperature (°C) 10.00 10.00
SOC (%) 30.00
B Current (A) 2.80 2.85
B voltage (V) 50.00 50.00
PV temperature (°C) 0.00
Solar Radiation 1 (Kw/m2) 0.00
Solar Radiation 2 (Kw/m2) 0.00
PV current (A) 0.00
FC temperature (°C) 0.00 0.00
FC voltage (V) 18.00
FC current (A) 12.30
FCc current (A) 4.01
TC current (A) -1.00
H2 press 1 (bars) 20.00
H2 press 2 (bars) 150.00
ROOM temperature (°C) 10.00 10.00
OUT temperature (°C) 5.00

Figure 12: Monitoring screen for Showcase 1

The C++ DAQ program uses the graphical interface of the LabView tool (from National Instruments), which includes the protocols for communication, calibration of variables, monitoring and the saving of performance data. The program communicates with both the data logger Fluke/Hydra and the EMS via an RS-232 link and includes an interactive screen that allows the user to decide when to start and stop the process of reading and monitoring and how to save the data. The data may be scanned every 20 seconds (DAS variables) or 60 seconds (EMS variables). The interface of the real-time display on the screen is shown in Figure 12.

The complete list of variables is presented in Table 4.

Table 4: List of variables in data acquisition system of Showcase 1

#	Variable	Measured by
1	Room temperature	Hydra (channel 1) + EMS (par.34)
2	Outdoors temperature	Hydra (channel 2)
3	Batteries temperature	Hydra (channel 3) + EMS (par.31)
4	Fuel cell temperature	Hydra (channel 4) + EMS (par.33)
5	PV panels temperature	Hydra (channel 5)
6	Batteries current	Hydra (channel 6) + EMS (par.29)
7	Fuel cell current	Hydra (channel 7)
8	Converter current	Hydra (channel 8)
9	PV panels current	Hydra (channel 9)
10	Telecom equipment current	Hydra (channel 10)
11	Solar radiation (45º)	Hydra (channel 11)
12	Horizontal solar radiation	Hydra (channel 12)
13	Low SOC alarm	Hydra (channel 13)
14	Low H_2 alarm	Hydra (channel 14) + EMS (par.35)
15	H_2 pressure 1	Hydra (channel 15)
16	H_2 pressure 2	Hydra (channel 16)
17	State of charge controller	Hydra (channel 17)
18	State H_2 valve	Hydra (channel 18)
19	Battery voltage	Hydra (channel 19) + EMS (par.30)
20	Fuel cell voltage	Hydra (channel 20)
21	State of charge batteries	EMS (parameter 1)

4.1.2 Laboratory Integration

The DAQ software was integrated together with the Hydra, the EMS, the batteries, the DC/DC converter, the electronic power source (to simulate the fuel cell), and an electronic load as a power consumer. The operation and communication between the EMS and the subsystems was tested; the EMS had to continuously measure the current in/out of the battery for calculating its state of charge (SOC).

4.1.3 Field Integration

The system components including the fuel cell were installed in a small building at the test site. Before the system was fully operational some testing and commissioning was undertaken including e.g. testing the control of battery charging, testing the interfacing of the system components, the operation of the DAQ, etc. The operational parameters of the EMS were also set during this process. At the end of the commissioning phase the system was made fully operational.

4.2 Showcase 2

4.2.1 *Infrastructure*

Showcase 2 is hosted by CIEMAT, and the location was selected in consideration of the solar access and the available infrastructure (water, electricity and network). The Showcase building has been designed to support the PV panels and a water supply on the roof and also to protect the installation from rain and wind. .

Figure 13: Set-up of the Showcase 2 hybrid system in Madrid, Spain (inside and outside view)

The test room has been equipped with an electric system, air conditioning, a water supply, a computer and connections to the CIEMAT network. Additionally, two safety grids and a hydrogen alarm with connection to the CIEMAT network have been installed.

A picture of the set-up and of the building hosting Showcase 2 is shown in Figure 13.

4.2.2 *Energy management and data acquisition*

A data acquisition system has been set up to log the operation of the different components. Data are retrieved through a data logger (Fluke/Hydra) and the central energy management system (provided by Fraunhofer Institute FhG-ISE), and stored in a computer using a program developed by CIEMAT. The data collected comprise different system parameters, such as the incident solar energy, photovoltaic current, voltage and temperature. The parameters measured from the battery set are current, voltage and temperature, and are used to calculate the state-of-charge of the batteries. The production of hydrogen is monitored via the current, voltage and temperature of the electrolyser, and the pressure and temperature of the hydrogen storage system. Close characterization of the fuel cell is carried out by measuring the voltages of the single cells, the total voltage, current and temperature.

4.2.3 *Time schedule of integration*

The fuel cell system, electrolyser and EMS were integrated in a compact skid during 2001 in Axane (France), and sent to Madrid during 2002, along with the other components of Showcase 2: batteries, hydrogen storage system and PV solar panels. In January 2003 the electrolyser was successfully integrated and some problems caused by transport and a long period out-of-service were rectified.

The fuel cell showed a damaged membrane on one cell. This membrane was replaced by a new one in June 2003.

After the initial integration of the whole system it was necessary to install some new additional components for the Showcase operation:

- some new sensors for PV temperature and solar radiation, for room and electrolyser temperature;
- bottled N_2 and H_2 for testing of the fuel cell;
- two shunt resistors for the fuel cell current;
- an electronic load to simulate the power demand.

Showcase 2 was in full operation from June 2003 until March 2004, with one year of delay due to problems in the developments of the new elements. The initial schedule of the whole FIRST project as well as its extension are shown in Table 5.

Table 5: Schedule of FIRST project

Activities	2000				2001				2002			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
1. Showcase1:												
• Top level Specification		■										
• Elements		■	■	■	■							
• Integration and test					■	■						
• Operation							■	■	■	■		
2. Research and Development of new elements	■	■	■	■	■	■	■	■				
3. Showcase 2:												
• Sizing elements				■	■	■	■	■	■			
• Integration and test							■	■	■			
• Operation										■	■	■

Activities	2003				2004			
	Q1	Q2	Q3	Q4	Q1			
Operation of Showcase1		●	●	●	●			
Operation of Showcase 2	■		●	●	●			

Initial Project Schedule ■ and Extended project period ●

5. OPERATIONAL EXPERIENCE

5.1 Evaluation of Showcase 1

The objective of this phase was to operate the whole prototype for at least one year in order to evaluate its performance, reliability and maintenance requirements. Data from the operational phase were also used for verifying the simulation procedures, analyzing the power availability and studying the possibility of reducing the size of the system, reducing the cost of remote telecommunications power supply equipment.

In summer application the fuel cell did not operate because the state of charge of the batteries did not fall below 70% with a continuous telecommunication load of more than 200 W. This was due to a more than adequate power supply from the PV modules.

The PV panels produce electricity with an efficiency of 6 - 8%, however more than 4 hours of solar energy are lost per day due to battery protection measures. In Figure 14 selected data are shown for the two months of April and June 2003. In the last two examples the difference is shown between the solar energy and the energy converted to electricity.

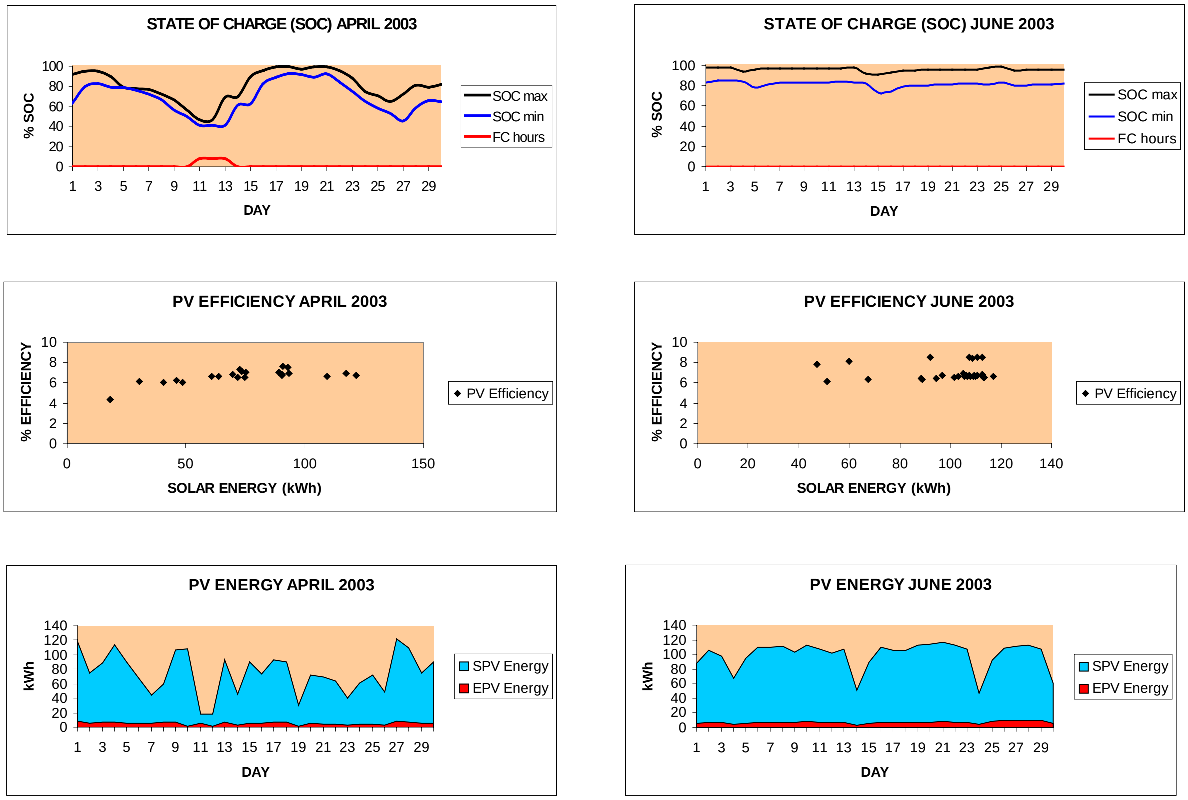


Figure 14: Selected examples of data received from Showcase 1

In winter, a sequence of several days of low solar radiation may lead to a drop in the SOC of batteries to less than 40%. At this point the EMS starts the fuel cell, which may operate for as long as 8 hours. When the SOC reaches 53%, the EMS stops the fuel cell, and PV panels are used to charge the batteries.

During this period the fuel cell has performed satisfactorily, operating for around 250 hours, maintaining the voltage at 19 V, and producing the required current (see Table 5). The telecommunications equipment was operating uninterrupted until January 2004.

From May to November there was enough solar energy available, and it was not necessary to operate the fuel cell system. In these months its operation was simulated using a power unit, resulting in an additional operation time of 200 hours for the control system and balance of plant.

Little maintenance activity was needed except the removal of the water produced by the fuel cell (stored in a receptacle) and cleaning of the PV panels

The batteries reached a state of charge over 60% in spring 2004 with the water-acid level decreasing nearly to a minimum at the end of that period. The performance of the batteries indicated that a water refilling is required every two years.

The hydrogen consumption of the fuel cell was 23 l/h, with a calculated total consumption of 11.500 l per year (corresponding to 500 hours operating time). Thus the total amount of 35.355 liters of hydrogen stored in the 4 bottles (50 liters, 200 bars each) would last more than two years.

The operation data from each system are shown in Table 6.

Table 6: Operation data of the subsystems of Showcase 1

SYSTEMS	Nom Voltage	Nom Current	Power	Efficiency
Telecom	50.7 V	2.1 A	106 W	
Fuel Cell	19.8 V	7.7 A	154 W	44.8 %
DC/DC	50.7 V	2.7 A	135 W	87 %
PV panels (max)	57 V	26 A	1.482 W	9.8 %

During the one-year continuous operation of Showcase 1, only two incidents occurred. They were easily solved, but could be critical to the remote system operation:

- The hydrogen escaped suddenly from the bottles due to a faulty piping connection. There was no safety problem due to the good ventilation area and the buoyancy of the gas. This fault led to a loss of all the fuel and shutdown of the fuel cell. In addition to the safety measures within the installation, this incident highlights the importance of a low hydrogen pressure alarm system, integrated in the EMS, allowing the fault to be relayed to operating personnel.
- The EMS State Of Charge calculation saturated at 90% in September 2004 caused by an error in the control algorithm. This required the system to be reset. In a remote area such an occurrence could present a critical problem. To avoid this it was necessary to improve the Energy Management System software. This modification was then implemented in Showcase 2.

5.2 Test results obtained in Showcase 2

Data obtained from two typical days, one with and one without hydrogen production, are compared in Figure 15. The graphs show (a) incident solar radiation, (b) photovoltaic converted power, (c) battery state-of-charge, (d) power consumed by the electrolyser, and (e) metal hydride pressure. The graphs illustrate how hydrogen production effectively increases the overall conversion efficiency of the system by increasing the energy storage capacity. The significant energy values for two summer days with and without generation of hydrogen are given in Table 7.

Table 7: Energy data comparing two summer days

		with H2 (kWh)	without H2 (kWh)
Incident solar energy		90	88.7
Converted to electricity:	Photovoltaic	5.7	3.7
	Fuel cell	0	0
Consumed:	Load	3.2	3.2
	Electrolysis	2.2	0
	EMS	0.5	0.5
Stored (LHV)	Hydrides	1.67	0

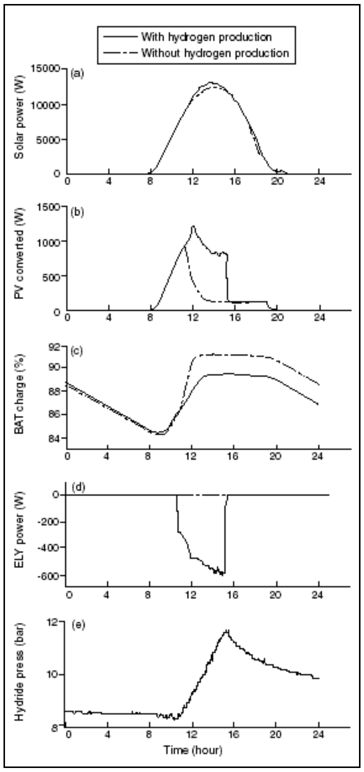


Figure 15: Data corresponding to two days, with (–) and without (· – ·) hydrogen production

The incident solar energy shown in Figure 15a was measured with a calibrated monocrystalline silicon solar cell, without correction for spectral mismatch. In the absence of hydrogen production, the overall photovoltaic conversion efficiency is reduced by the controller after mid-day from 9.9% to 4.1% to avoid overcharging of the batteries. On the other hand, with the capability to store energy in the form of hydrogen, the excess solar electricity can be consumed by the electrolyser and converted to hydrogen. In this case photovoltaic conversion continues until the electrolyser stops, which is set at 15:30. The system now converts 6.5% of the daily incident solar energy. This value can be improved up to 9.9% through optimization of the energy management. Production of hydrogen amounts to 0.5 Nm^3, with a 76% energy conversion efficiency (LHV) for the electrolyser. In summer the solar energy is high enough to power both the load (2.7 kWh/day at a constant current demand of 2.5 A) and the electrolyser, without requiring any power from the fuel cell.

The effects of the hydrogen generation and storage in the metal hydride system are shown in Figures 17d and 17e. The energy management system sets the electrolyser to work during the hours of maximum solar irradiance, at noon (Figure 15d). The pressure increase in the metal hydride alloy is followed by a transient pressure drop about six hours after the hydrogen production time (Figure 15e). This reflects the slow kinetics for the absorption of hydrogen by the metal hydride. The hydrogen production rate amounts to 0.3 Nm^3 per day.

5.3 Summertime behavior of Showcase 2

Data corresponding to the summer-time behavior of the system are reported in Table 8. In this period the solar daily incidence amounts to 81.9 kWh, of which 4.9 kWh is converted (6%). This energy is enough to maintain a high state-of-charge of the batteries (87% average), together with daily production of hydrogen, and continuous powering of a 2.5 A load. The energy consumption is distributed between the load (69%), the electrolyser (30%) and the energy management system (around 1–5%). The 0.33 Nm^3 of hydrogen produced daily (1 kWh, LHV) will provide 0.5 kWh, assuming a 50% conversion efficiency in the fuel cell.

It can be estimated that at the end of the spring/summer period the hydrogen produced will give almost one month of total autonomy to the system. In this way, the system is able to ensure continuous provision of up to 200 Wp, 24 hours a day, throughout the 365 days of the year.

Table 8: Data corresponding to summer period (daily average)

Incident solar energy	81.9	kWh
Photovoltaic conversion	4.9	kWh
Electrolyser consumption	1.5	kWh
H_2 produced	0.33	Nm^3
Load energy consumption	3.4	kWh
Batteries state-of-charge (average)	87	%
Energy management consumption	0.5	kWh

5.4 Summary

The operational experience with Showcase 1 has shown that the power system availability is improved considerably with the electrolyser, fuel cell and the hydrogen storage system. With a single, cheap maintenance service once a year it is possible to assure that the telecommunication system will be properly powered with a reliability of 100%.

A lot of solar energy is lost during summer days by the controlled reduction on PV output to prevent overcharging of the batteries. It may thus be possible to reduce the system costs by reducing the number of batteries and the number of PV modules.

After testing the summer time behavior of the Showcase 2 system, the following conclusions can be drawn:

- The generation of hydrogen could potentially increase the solar energy conversion rate from 4.1% to 6.3%.

- 1 kWh per day is being stored as hydrogen. At the end of the summer this could provide 1 month continuous autonomy to the system (without photovoltaic conversion)
- Improvements to the energy management system are necessary to increase the hydrogen production rate so that a 9.9% energy conversion rate can be achieved.
- The use of the metal hydride storage system proved problematic in the Madrid climate, due to the high temperatures experienced in summer and low temperatures in winter. A conditioning system had to be added in order to cool the storage tanks so that hydrogen could be stored safely in summer. The tanks had to be heated by the conditioning unit in winter to enable release of the stored hydrogen.

6. ENVIRONMENTAL ASPECTS AND SAFETY ISSUES

6.1 Size Reduction

In telecommunication applications a relatively large percentage of modules and batteries are used to assure the required high availability target. If a fuel cell is added and which operates for only a small percentage of the time (roughly 10%), the PV array size and number of batteries could be reduced more than 25% with a significant reduction of visual impact and cost. This target is based on an installation placed in Madrid (Spain) where the Showcases are situated, but a higher size reduction can be achieved in Central and Northern Europe (more than 50%).

6.2 Safety Regulations

All the components of the system have been designed and manufactured according to the safest procedures for hydrogen materials with special attention to hydrogen embrittlement. A short survey of the regulations in the partner's countries was made concerning rules for small high-pressure hydrogen storage.

This system is intended to be operated in a remote area. There are no particular safety problems, because in a well ventilated building the hydrogen leaks disappear away without hazardous situations arising.

All the equipment has been designed to fulfill the Electrical Safety Regulations in order to prevent against electrical shock, fire and damage to property.

7. COSTS

Within the sizing procedure a lifetime simulation of the complete system has been performed. In this analysis the costs are calculated according to standard economic procedures, with the main criteria of a 100% availability of for the system. Different variations were calculated to size the system (1. -3. and 6. for the location Madrid)

1. Standard set up with CIS modules and maximum load during night-time
2. Standard set up but with hydrogen costs reduced to 50% of original cost calculation
3. Standard PV-battery system without fuel cell
4. Standard set up with CIS modules and maximum load during night-time but located at Freiburg (Germany)
5. Standard PV-battery system without fuel cell but located at Freiburg (Germany)

6. Standard set up but with a limited amount of hydrogen.

The main conclusions of this sizing were:

- There are no cost reductions of a hybrid PV-fuel cell system compared with a pure PV system for this application (150 W and Madrid). However, hybrid systems are characterized by an important size reduction (more than 40% in solar panels) in comparison with simple PV systems.
- If the same system would be installed in a high latitude location (Freiburg), a hybrid system would be significantly more cost effective than a PV system (25% cost reduction).

These potential cost reductions of the overall system have been obtained under the assumption that the cost of the fuel cell is reduced in agreement with the predictions of experts, including the European Commission (See the document: “A Fuel Cell Research, Development and Demonstration Strategy for Europe up to 2005.”). This prediction shows that fuel cell cost for stationary applications will be lower than 1000 € (1200 USD) per kW by 2005.

8. REMARKS ON FUTURE POTENTIAL

The integration of the proposed technologies will open new markets to the use of fuel cells, based on the integration of renewable energy sources.

In this context, some advantages of the proposed configurations (Showcases 1 and 2) are:

The generation of electricity by means of fuel cell units is a very promising alternative to some standard devices used in uninterruptible power supply systems: batteries and diesel generators: Batteries are heavy, voluminous and non-ecological devices and its replacement by a clean, high-density energy storage system looks very attractive. Diesel generator drawbacks are also well known: noise, low efficiency, very high maintenance requirements and pollution.

A future system in which batteries are completely substituted by hydrogen will allow easy monitoring and controlling: Lead-acid batteries (which are widely used nowadays in telecommunication applications) are very difficult to monitor, and the possible occurrence of sudden death is very difficult to predict. In our solution, by monitoring the fuel tank it is possible to know how many hours of energy are available.

The power system availability is increased considerably. The PV generator and the fuel cell are redundant power generators. Even in case of a failure in one of the two components the system can still be supplied with energy.

Conventional photovoltaic stand-alone power systems have batteries as energy storage system and, normally, during the summer season, these batteries are fully charged early in the morning. One of the targets of this project is to develop a system that stores all the wasted energy in order to be used during the winter. Lead-acid batteries are no adequate solution for a seasonal storage of the energy.

The maturity of these technologies is closer every day and the market will demand soon these new products. The Board of Interest of the project is convinced that these innovative solutions mean an important improvement over the existing technologies.

9. CONCLUSIONS

A PV hybrid system has been designed for autonomous power supply of telecommunication equipment. The sizing of the components has been done by lifetime cost optimization using the simulation tool TALCO. Additionally, the rules for operating the system taking have been deduced from the results of simulations over the lifetime. An Energy Management System has been designed in a way it seamlessly uses those rules for its control decisions. Robustness and the possibility of future series production have been emphasized.

The operational experience with Showcase 1 at INTA has shown that it is possible and commercially interesting to utilize hybrid systems for telecom equipment, if the fuel cell had a competitive price. The use of hydrogen with PV panels instead of diesel generators decreases the pollution and the maintenance activity and increases the availability of the telecom equipment.

The evaluation of this system during the summer period concluded that the PV panel size is bigger than needed for this geographic situation (Madrid). Integration of an electrolyser with this system increased the conversion efficiency of solar radiation by reducing the need of PV power production when the batteries were fully charged. Major difficulties encountered with the fuel cell during the integration phase, were caused mainly by poor control of operational parameters. . The subsequent development of a dedicated control system, lead to 280 hours of good performance with no operational problems.

With an effective control and alarm system communicating any unexpected trouble via telephone, a near 100% availability of the system can be achieved with only a simple, low cost maintenance of the system required every two years.

Operational experience with Showcase 2 has been gained in the test system at CSIC in Madrid. Summer operation has been investigated. An analysis of the electrolyser operation showed that less hydrogen was produced than expected from design parameters. The main cause is the temperature behavior of the electrolyser stack. This problem could be solved by operating the stack at a voltage (up to 2.3 V per cell) during start-up, increasing heat production and subsequently lead to a higher hydrogen production rate. Technically, this can be done either by a reduction of cells in the stack or by an additional DC/DC converter. The second possibility is favored as voltage can be adjusted easily to the needs of the hybrid system at different weather conditions. Further work should also be done in including a dynamic model of the electrolyser in the design tool.

While the component prices (especially those hydrogen components which are not commercially available) heavily influence the overall system profitability, the work shows the practical feasibility to build complex hybrid systems.

The main partners have reached the following preliminary conclusions:

9.1 Statement by Air Liquide

Mains improvements designed on Showcase 2 system auxiliaries: no water injection, cooling air flow, new control/command, new purge system, new start and shut down procedure contributed to the development state of the art FC auxiliaries. The contribution of the FIRST project to the improvement of the technology has been significant. The design for Showcase 2, and especially the new Control/Command and purge system will help Air Liquide progress the development of Fuel Cell auxiliaries in such a power range. The global power architecture for telecommunication applications is innovative. The FIRST project is a good introduction for FC in telecommunication application, and this technology certainly has a future on this market.

9.2 Statement by CSIC

Hydrogen storage in metal hydrides is an interesting technology for reducing volume and in order to operate at lower working pressures. However the cost and the difficulties in the operation (pressure-temperature behavior during charges and discharges) are serious limitations of this technology. Consequently it appears that, for new installations in the same line proposed by the FIRST project, it would be convenient to use alternative hydrogen storage systems (compressed gas, hydro-dehydrogenation processes, etc).

9.3 Statement by FhG-ISE

The FIRST project clearly shows the very high complexity of such systems. This requires very flexible management and control systems. It was not foreseen that all innovative components would need a complex controller to allow proper operation. For future projects significantly more effort needs to be allocated to control hardware and energy management systems.

It is very valuable to have the systems now in operation to learn about the real world problems and challenges of such components. Nothing can replace field experience. Co-operation among the operators of the Showcases (INTA and CIEMAT) seems to be very constructive and active which helps to analyze and solve occurring problems.

9.4 Statement by NUVERA

The set-up of the fuel cell stack in this application has not been easy at the beginning due to the requirements outside of the company’s standard. After the efforts provided in the design phase and in the real system the main difficulties faced can be resumed as follows:

- The integration in an automated controlled system turned out to be quite tedious; both Showcases had to be re-commissioned several times
- The mechanical resistance of the cells turned put to be a critical quantity in the cold and sometime stressing conditions, especially with respect to the H_2 management
- Need to study and accurately manage dry gas condition on air side (especially with the temperature control)
- Need to control the prolonged shut-down (i.e. through an automated and self-diagnostic operation of the fuel cell and an operational periodic warm-up)

On the other hand it has been possible to achieve important targets:

- Improvements on the stack (in both Showcases) to increase the mechanical resistance and reliability in operating conditions
- Replication of fuel cell performances from test stands to the actual Showcase skids
- Stack working time (in the Showcases), accumulation and system debugging and tuning.

9.5 Statement by INTA

The FIRST project has proved the possibility of using the hydrogen technology in this kind of application. In a conventional telecom system, to assure the essential requirement of high reliability, it is necessary to oversize the PV panels and to provide an auxiliary diesel power unit. This gives rise to high installation and maintenance costs and to considerable pollution in natural areas.

The use of hydrogen fuel cells involves a reduction in maintenance: the stored hydrogen of this project can last one year, while diesel fuel for a generator would need to be replenished more often. The fuel cell needs little maintenance, and it does not produce polluting gases.

In the present situation there is no cost reduction yet. This is due to the high cost of fuel cells, and to the specific geographic situation in Spain, where a lot of solar power is available. However, in a high latitude location this system may lead to a 25% cost reduction, under the assumption that the commercial fuel cell cost will be lower than 1000 Euros per kW.

Once the problems occurring during the integration process had been solved, the system operated with power availability of 100%, power being supplied by the PV panels and the fuel cell when it was required.

10. FUTURE PLANS

INTA is trying to continue the operation of the Showcase 1 in order to evaluate the possible reduction of both batteries and PV panels, along with the minimum hydrogen required, the endurance of the fuel cells, etc..

At the same time INTA want to improve this prototype by introducing a commercial electrolyser in order to evaluate the operation of a complete system producing hydrogen with the excess of solar power, but using commercial elements (electrolyser, compressor, tanks).

The system installed in Showcase 2 is not going to continue in operation. The elements of the system are being returned to their owners.

11. CONTACT INFORMATION

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