PEM Fuel Cell Systems for Distributed Energy: Actual Performance, Lifetime and Reliability of a Pure Hydrogen Pre-commercial System

(DEM 43-5)

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Project Overview: Reasons

Distributed Generation

To develop technologies able to support the changes in the future challenges of power network
To reduce the range power (1-100 kW), emissions and costs
To increase in efficiency, availability and life time

Gas Network as a Possibility

Fuel Cell systems, thanks to unique charateristics in terms of efficiency, low emissions, and the opportunity of using NG as a fuel, are ready to be exploited to solve the emergencies and set trends in new energy markets

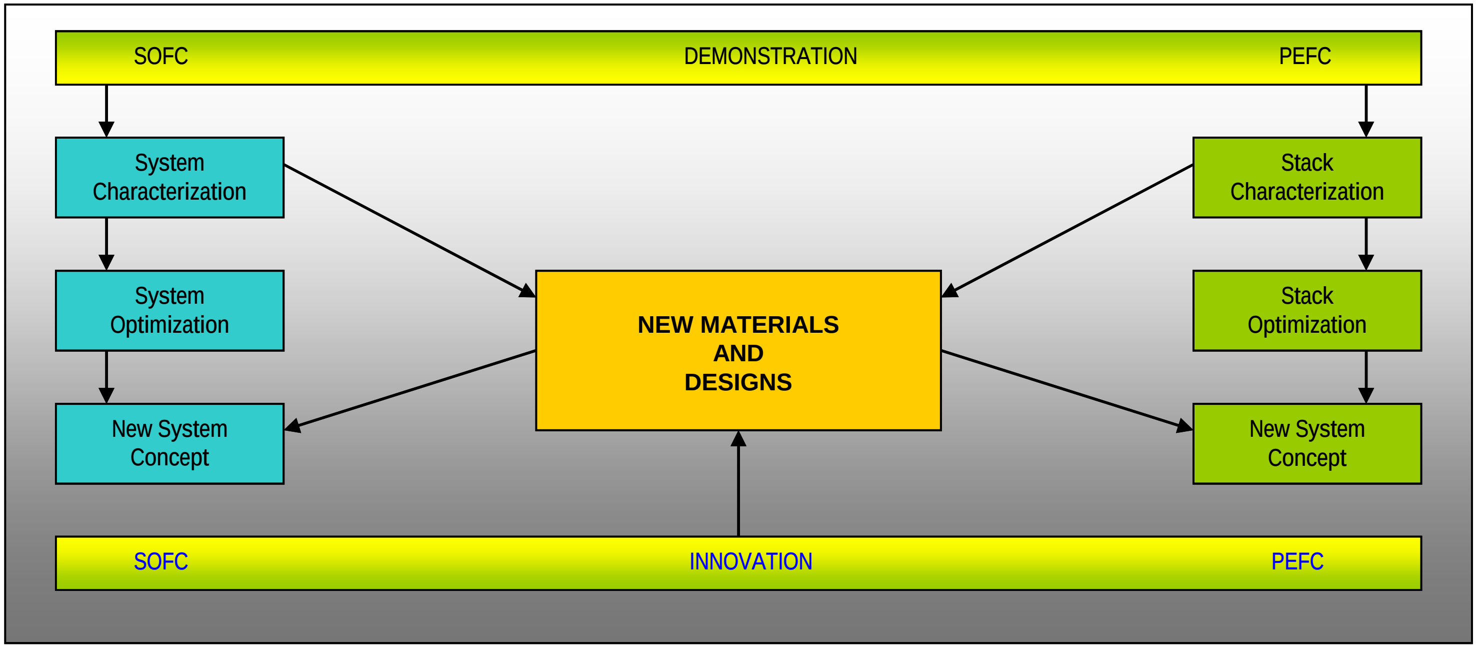
Combining FCs with RWE Technologies

Fuel Cells are simply integrated in plants with RWE technologies (solar thermal, photovoltaic, wind) to become a key element for micro-generation (and CHP)

Incoming Markets

Two challenges have to be faced: increasing lifetime and managing large-scale production

Project Overview: Management & Targets



1) To increase the performance and reduce the costs of SOFC and PEFC by developing materials and designing new stack architectures

2) To develop and to demonstrate SOFC and PEFC systems fed with natural gas for power generation, in CHP mode as well

Project Overview: Partners

Research Centers & Universities	CNR-ITAE	Coordinates the project and leads the working teams SOFC and PEFC materials development SOFC and PEFC systems development and demonstration
	CNR-IENI	SOFC and PEFC materials development
	INSTM	SOFC and PEFC materials development
Materials & systems manufacturers	NUVERA FUEL CELLS	PEFC systems development and demonstration
	Durantes Vincunt	PEFC materials development
Power & Natural Gas Suppliers	Enel	PEFC systems demonstration
	Eni	SOFC systems demonstration

Project Overview: Research Themes

Systems

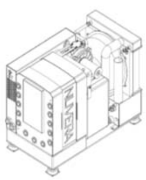
SOFC

R&D of two SOFC systems based on 1 kW stack (Juelich and TOFC)

Natural Gas Pre-reformer (Haldor-Topsoe)

Natural Gas Desulphurisation

PEFC



R&D of 5 kW class plug-in systems fed with pure hydrogen (CHP evaluation)

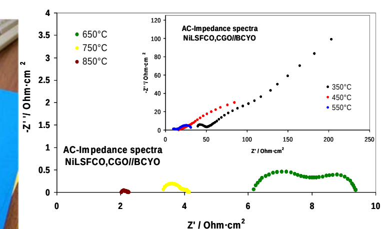
R&D of 5 kW class plug-in systems fed with NG (CHP evaluation)

R&D of 25 kW and 150 kW systems fed with pure hydrogen

Materials and Components

SOFC (T ↓)

Development of ceramic electrolytes for cells based on anionic and protonic conduction to reduce working temperatures



PEFC (T ↑)

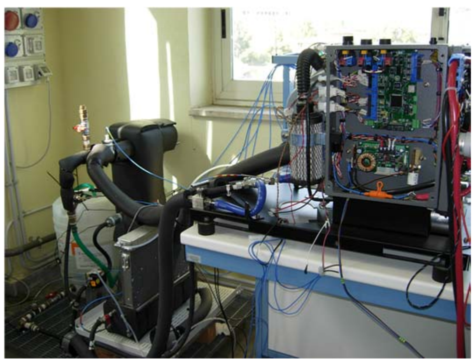
Development of membranes and MEAs to increase working temperatures (T>100°C)

Development of a 250W stack working at high temperature (120<T<130°C)

PEFC Systems Development Activity: The Testbench

Electrolyser and purification stage for continuous hydrogen production

The LAB bench with the e-load



The test bench for the recovered heat measurement

The LAB bench with the AC/DC for grid connection

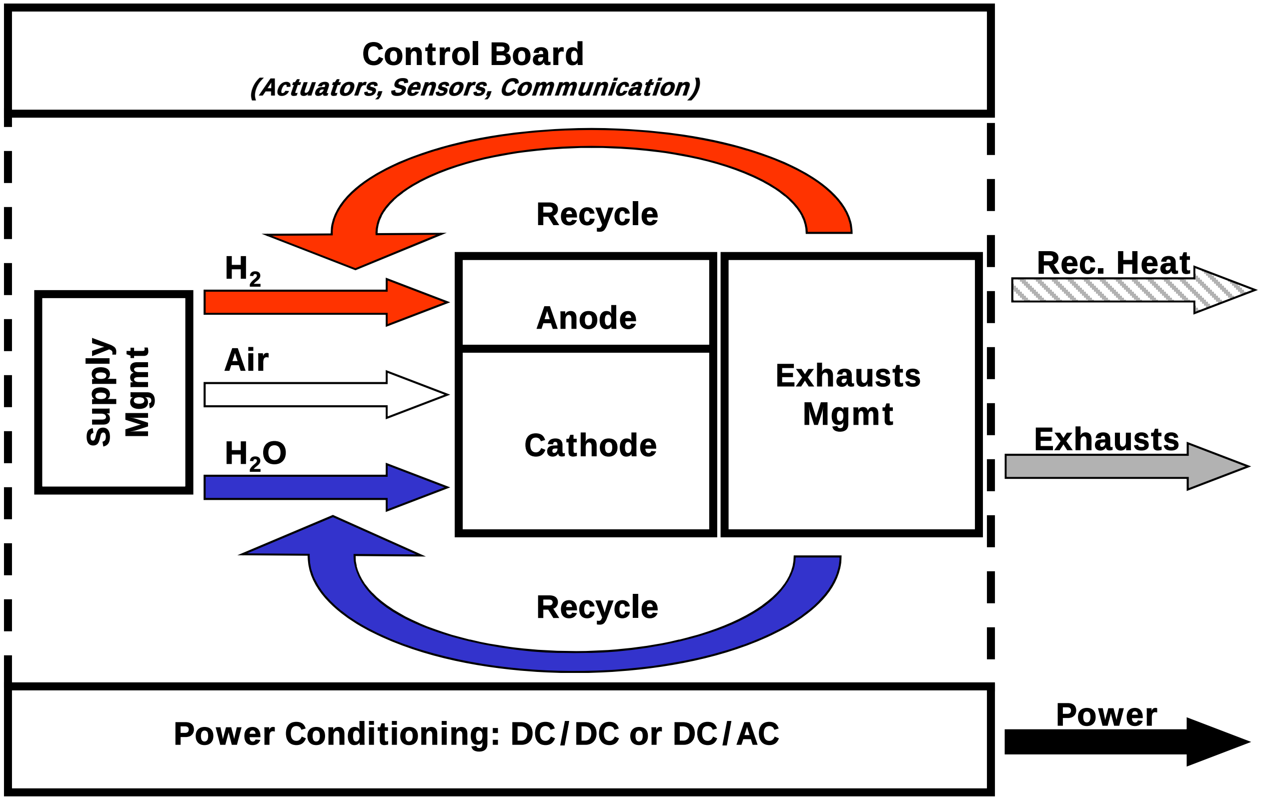
The testbench is comprised of two main sections: a hydrogen-production system, and test and data acquisition equipment.

The electrolyser produces pure hydrogen continuously at a pressure of 7 bar (simulating the hydrogen supply from a public grid). The LAB bench is the system to manage data acquisition, the simulation of electric loads, and the safety features (sensors for hydrogen, temperature, etc,), all of which can be controlled and monitored remotely through ADSL and Web.

The management software, developed in a LABVIEW © environment, allows the management and recording of data characteristic of the device being tested, from among which the following are most important:

- stack and single cell voltage
- generated current
- input and output gases and deionized water temperatures
- a count of working hours
- energy produced
- hydrogen consumed effectively.

PEFC Systems Development Activity: The In-test System (α version)



The System is composed of:

- the PEFC stack,

- the Balance of Plant,

- Electronics (Control Board)

- Power Conditioning (DC/DC and/or DC/AC)

PEFC Systems Development Activity: The In-test System (α version)

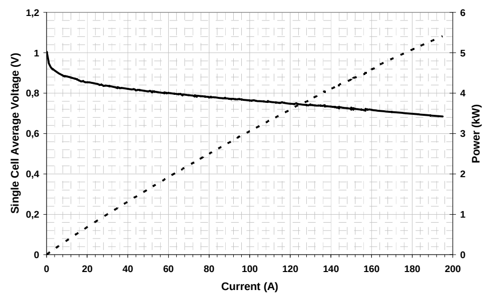
The in-test device is a polymeric electrolyte fuel cell system able to supply power within the range of 0-5 kW and to start up and shut down automatically (plug-in).
FC system features:
- the stack works in dead-end mode, by closing the anodic outlet with a purge valve;
- purges are timed according to the current generated;
- a recirculation of purged hydrogen increases the utilization factor of the anodic gas
- the air blower and the water recirculation pump work during operations at two pre-determined levels only. This implies a reduction in efficiency and does not guarantee the best working conditions for the stack, but it means a faster response to load variations;
- a control and diagnostic board, comprised of numerous sensors that constantly provide the values of all working parameters required for management and safety, manages ancillaries operations.

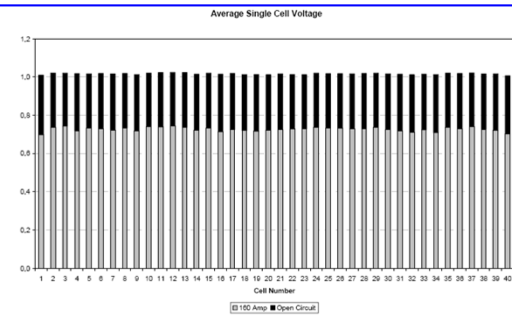
NUVERA stack XDS-900

- 40 in-series cells with bipolar steel plates;
- active area of 500 cm^2;
- MEAs built on commercial products and in-house formulations of the anodic and cathodic electrocatalysts;
- variable working temperature between 65-80° C;
- λa (stoichiometric anodic gas coefficient) of 1.05;
- λc (stoichiometric cathodic gas coefficient) in the range of 2.2-3
- CWI technology was used to gas humidification (the stack is fed with dry gases).

PEFC Systems Development Activity: Stack and Whole System Characterizations

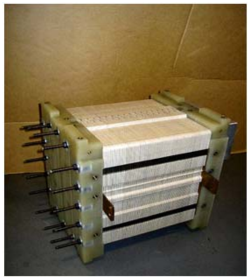
The tests performed allowed characterization of the behavior of the systems, both in terms of 24/7 durability and with extremely variable loads. Experiments to determine the main system features developed as well as performance were carried out according to FCTESTnet protocol:
- stack and system characterization (polarization and working curves),
- load-following behaviour,
- lifetime and durability.

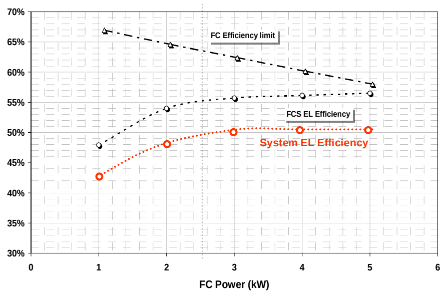


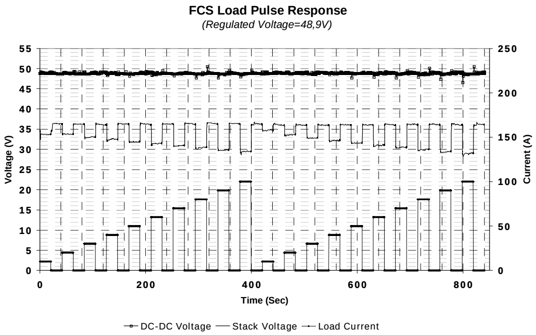


The stack works in the OCV-0.7 Vcell, namely in the beginning of the ohmic region.

The difference in the cell voltage at 160 Amps is caused by water content in the cell and is a transitory phenomenon.





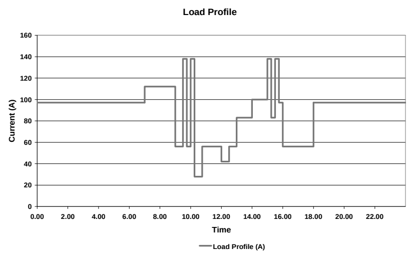


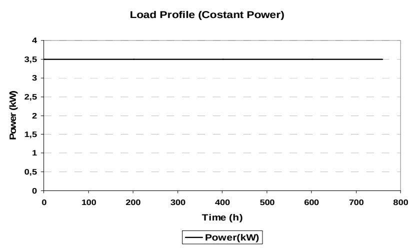
The FC system's efficiency in the range 2.5–5 kW was verified during the tests at 51% based on H_2 LHV (ASME PTC 50 protocol).

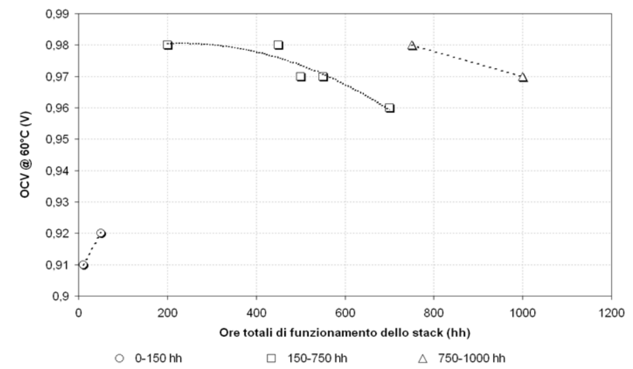
Both in regulated and in un-regulated modes, the system has a fast response.

PEFC Systems Development Activity: System "Lifetime" Tests

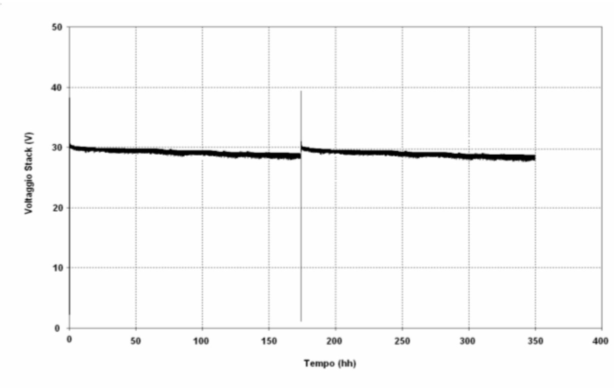
Load profiles used for the "lifetime" test. The first one simulates a typical dwelling's load, variable during the day and steady at night. The second profile was used to verify the FC behavior at a constant load.







The OCV value is affected by continuous operating hours linked to the membrane swelling phenomenon, which increases hydrogen crossover at the cathode. The membrane swelling phenomenon and others, like flooding in the cells, reduce the stack voltage gradually. Stopping operations, the stack improves in performance with little irreversible reduction remaining.



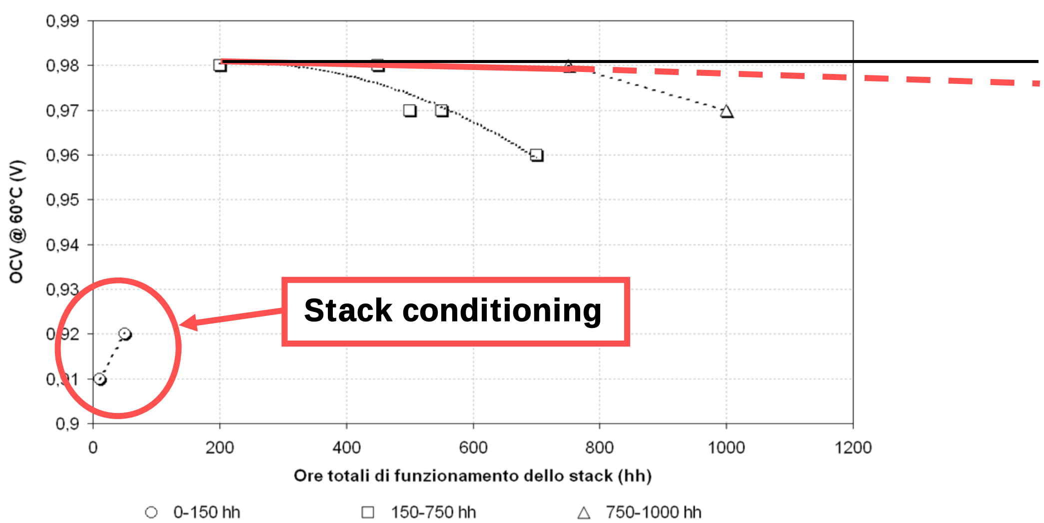
Critical parameters after the first 1,000 working hours:

- 70% of failures were attributed to the electronics;

- 30% to the ancillaries (cartridge of deionization and air compressor);

- FC stack decay rate ~ 40 $\mu Vh^{-1}cell^{-1}$

PEFC Systems Development Activity: System "Lifetime" Tests



Decay Rate	Load	Author
40 $\mu Vh^{-1}cell^{-1}$	*Pulsed and steady*	
2.6 $\mu Vh^{-1}cell^{-1}$	*Steady*	*Polevaya [1] (NUVERA FC)*
51-52 $\mu Vh^{-1}cell^{-1}$	*Pulsed*	*Polevaya [1] (NUVERA FC)*
6 $\mu Vh^{-1}cell^{-1}$	*Steady*	*Knight et al. [2]*
120 $\mu Vh^{-1}cell^{-1}$	*Pulsed*	*Amphlett et al. [3]*

The irreversible performance reduction is similar to data published.

References

[1] O. Polevaya, Nuvera Fuel Cells, 2nd Annual International Symposium Fuel Cells Durability & Performance December 2006
[2] K. Washington, Fuel Cell Seminar 2000, pag. 468, Portland, USA, 2000
[3] S.D. Knights, K.M. Colbow, J. St-Pierre, D.P. Wilkinson, Journal of Power Sources 127 (2004), 127-134
[4] M. Fowler, J.C. Amphlett, R.F. Mann, B.A. Peppley, P.R. Roberge, Journal of N. M. for Electrochemical Systems (2002) 255

PEFC Systems Development Activity: "Lifetime" Test Results

The system generates power with an average efficiency of 51% and a capacity factor of 74%. This factor is the relationship between average power generated and peak power of the device and is useful in determining how it can be used effectively.

Capacity Factor = Average Power / Maximum Power

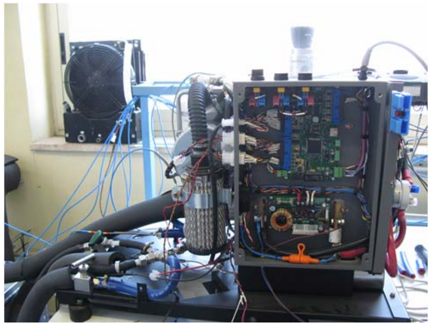
Total hours of operation	Capacity Factor	Power Range	Avg Electrical Effiicency
Start-up			
150	74%	0-5 kW	50.3%
BoP repair and cell substitution			
850	74%	0-5 kW	51%
Total			
1,000	74%	0-5 kW	50.9%

PEFC Systems Development Activity: Targets and Results Obtained at Stage One

In cooperation with NUVERA FC Europe, the first version of the PEFC system was developed and tested at CNR-ITAE

The first tests performed were used to upgrade the systems

5kW PEFC System

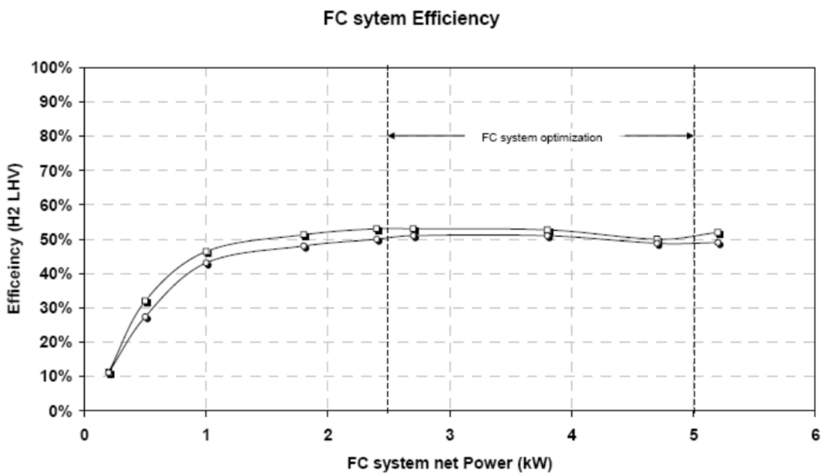


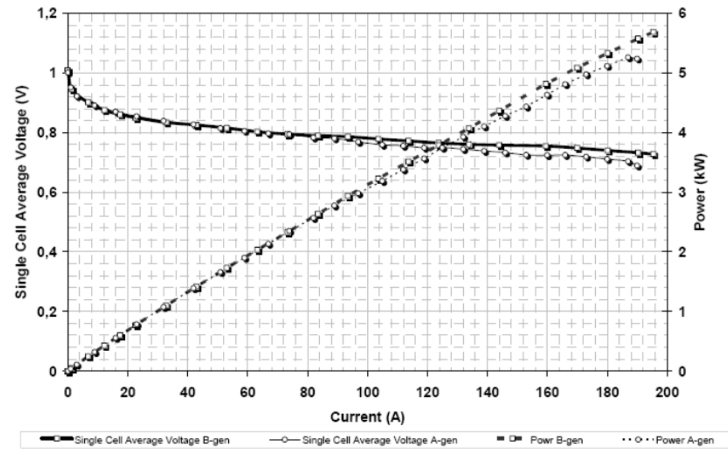
System Specifications	Project Target for the First Version	CNR-ITAE Test Results
Net Power (kW)	5.5	5.5
Load Following	2.5 - 5 kW (no batts)	0 - 5 kW (no batts)
Electrical Efficiency (based on H_2 LHV)	51% @ 5.5 kW	51% @ 5.5 kW
Fuel	Hydrogen 5.5	Hydrogen 5.5 and 5.0
Start-up time (at 10°C)	5 sec. 0-2.5 kW 10 sec. 0-5-5 kW	7 sec. 0-2.2 kW 360 sec. 0-5-5 kW
Life Time	None	1000 hrs
Availability	None	78.5%
Volume	165 L	165 L
Weight	80 kg (no water)	80 kg (no water)

PEFC Systems Development Activity: Improvements on Second Generation (β version)

During the second test stage, two systems of improved generation were assembled and tested under the first stage same conditions (variable loads). Improvements were basically focused on the selection of new stack components, then on the re-design of the BoP in order to reduce consumption.

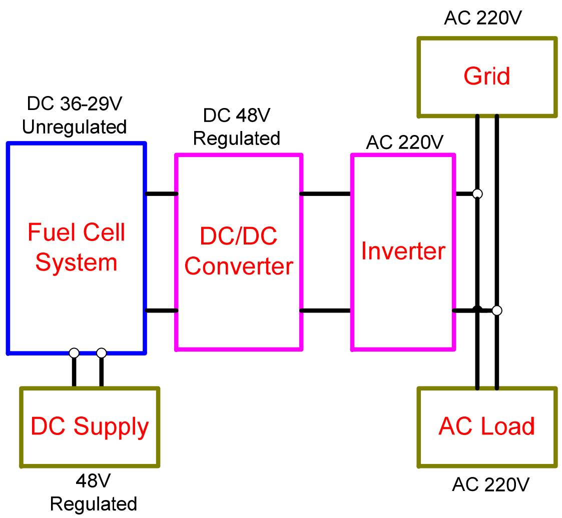
The new system has run up to 1,000 hours continuously with the following performances:
- electrical net efficiency: 54% based on hydrogen LHV,
- load following (0-100% of electrical load) without battery support.



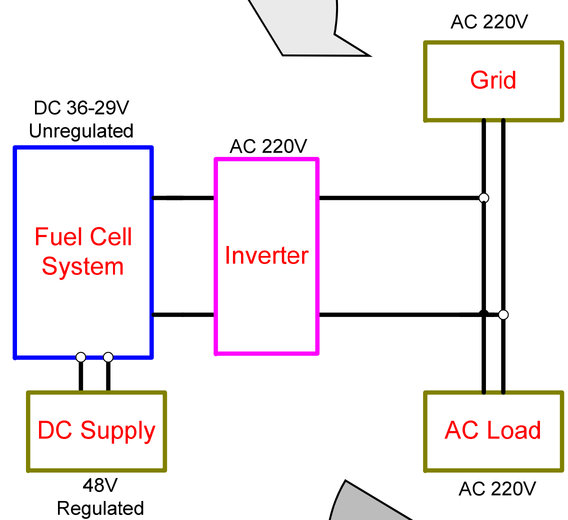


PEFC Systems Development Activity: Power Conditioning for Grid Connection

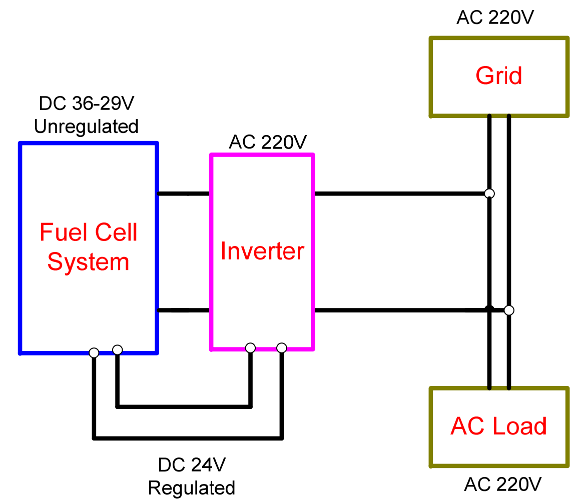
A parallel activity was carried out in order to develop power conditioning for a grid connection. Different solutions were studied and achieved.



Step #1: a DC/DC converter held the voltage stack @ 48Vdc, a DC/AC put the power into the grid.
An external power supply (i.e. battery pack) fed power to the system during start-ups and shut-downs.



Step #2: a DC/AC was selected to be coupled directly with the Fuel Cell stack and to put the power into the grid.
An external power supply (i.e. battery pack) fed power to the system during start-ups and shut-downs.



Step #3: the DC/AC fed power to the system during start-ups and shut-downs

PEFC Systems Development Activity: Power Conditioning for Grid Connection

DC/DC Step-up Converter

A high performance 2 quadrant, crystal controlled, Double Half H Bridge, Interlaced, boost converter, which requires two external inductors.
The switching frequency is about 30kHz. Interlacing lowers input and output voltage and current ripple.

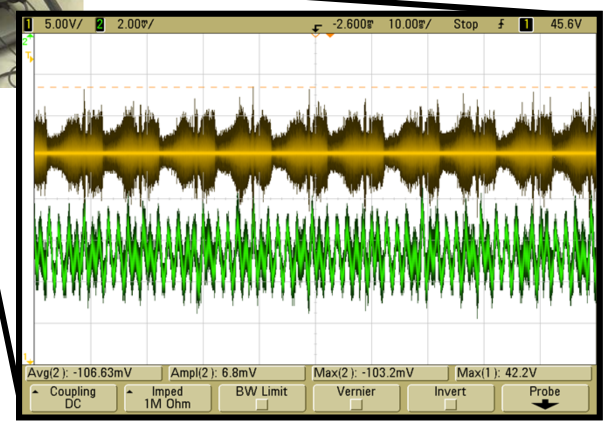
ZAHN ELECTRONICS, INC.

DC/AC Inverter

An advanced inverter able to draw a constant current from the DC source (FC) which can be set by the user.
A 100Hz power ripple was registered at the DC/AC outlet.
It was generated by the grid (in Europe the grid is 50 Hz).
In accordance with other authors, a reduction in power was noted; this was due to the ripple but was negligible (0.5-2%) in respect to the losses in the DC/AC (10-12%)

DELTA

Input (DC)		Output (AC)		DC Aux Output	
Nominal voltage (V)	36	Nominal voltage (V)	230	Voltage (V)	24
Voltage range (V)	30 … 75	Voltage range (V)	195 … 265	Current (A)	40
Nominal current (A)	140	Max. "gross" current (A)	28,0	Power (W)	1000
Max. current (A)	160	Max. connector current (A)	23,0		
Current limitation (A)	180	Max. power (W)	5800		
Current ripple (A_{Pk-Pk})	< 1.0	Max. connector power (W)	4800		
Current rate of change (A/s)	33	Power factor	0,06875		
		Frequency (Hz) (automatically synchronized)	50 + 0.1 or 60 + 0.1		
Max. power (W)	6000	Efficiency (%)	> 88.5		



PEFC Systems Development Activity: Targets and Results Obtained in Stage Two

α version

β version

Comparison between first and second (upgraded) FC system versions

System Specifications	α version	β version
Net Power (kW)	5.5	5.5
Load Following	0 – 5.5 kW / no batts	0 – 5.5 kW / no batts
Electrical Efficiency (based on H_2 LHV)	51% @ 5.5 kW	**54%** @ 5.5 kW
Fuel	Hydrogen 5.5 and 5.0	Hydrogen 5.5 and 5.0
Start-up time (at 10°C)	7 sec. 0-2.2 kW 360 sec. 0-5.5 kW	7 sec. 0-2.2 kW 360 sec. 0-5.5 kW
Life Time	1000 hrs	**>** 1000 hrs
Availability	78.5%	**89.5%**
Volume	165 L	165 L
Weight	80 kg (no water)	80 kg (no water)

PEFC Systems Development Activity: Conclusions

The demonstration aimed to identify the parameters on which development must be focused in designing a prototypal device that meets the requirements of commercialization in the short-to-mid term; it showed that significant improvements must be made:

Increase BoP components' reliability

Increase electronics' reliability

Improve water management in the stack and in the whole system

Looking at the entire project results …

Combining the PEFC and NG reformer didn't bring about the desired perfomance due to:
- the complexity of the BoP;
- MEAs life-time (CO poisoning).
These features don't allow the same performance ensured by hydrogen FC systems in the short term.

SOFC systems are better solutions for DG applications because of :
- higher temperature of the exhausts (CHP);
- more flexibility in fuels;
- more resistance in CO.

PEFC systems fed with pure hydrogen are probably better solutions for RWE as a result of:
- quicker response times,
- shorter start-up times;
- reduced costs.

PEFC Systems Development Activity: Conclusions

Tests have shown that the PEFC systems fed with hydrogen already meet the requirements of commercialization in short-to-mid term for residential applications, which were the focus of this project.
This implies the possibility to create energy districts with:
- centralized production of hydrogen either from natural gas or from renewable sources
- power management through dedicated distribution grid
- on-site power production through PEFC systems.
All this is possible now although the costs remain a limitation if these are to be exploited on a large scale.

Natural Gas
Exploitation of the existing "well developed" network
SOFC or PEFC systems in the range
>1 kW and <100-200 kW
CHP and cold production

Hydrogen
Centralized production of hydrogen from natural gas and/or from RWEs
CO_2 sequestration
Combining with sustainable transportation