PEM FUEL CELLS IN REAL CONDITIONS (EPACOp)

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1. PROJECT GOALS

The objective of the EPACOp project (Expérimentation de 5 Piles A Combustible sur sites OPérationnels) was to test in real conditions five fuel cell units based on Polymer Electrolyte Membrane (PEM) technology for residential and commercial applications.

Four main goals have been identified and achieved during this three year project:

- To validate the appropriateness between the PEM Fuel Cell technology and the target market (residential and small trades).
- To assess the behavior and performance of these fuel cells during a significant time connected to real thermal and electrical loads of buildings. It enabled the construction of an operating database taking into account different conditions (e.g., types of load, geographic situations, weather conditions). This database will be used to validate operating models for these types of fuel cells.
- To improve our knowledge on fuel cells and to anticipate the necessary evolution trends of the technology in order to reach the final specifications in collaboration with manufacturers.
- Finally, experimentation must allow us to create and transfer “fuel cell” competence to others in the installation, operating and maintenance sectors.

2. GENERAL DESCRIPTION OF PROJECT

In 2002, Gaz de France decided to test in real conditions five “RCU-4500 V2” Fuel Cell prototypes manufactured by HPower (in 2003, HPower and Plug Power merged).

The testing sites were chosen in accordance with the fuel cell prototype characteristics, and in order to submit the prototypes to various types of environment and applications. For instance, the required electrical load was between 1.5 and 20 kW and the heat network to the fuel cell had to be a low temperature one. Gaz de France chose to install them in local communities all across France:

- The city hall of Petite Synthe, Dunkerque
- The traffic control center, Dunkerque
- The National Polytechnic Institute of Lorraine, Nancy
- The office and public lighting of Feytiat’s town, Limoges
- The Scientific and Technic Building Center (CSTB) in Sophia Antipolis

Those locations shown in Figure 1 are representative of the French geographic differences. The choice allows evaluation of the influence of the climate on the performance of the fuel cells. The five units were installed in these four cities in France from November 2002 to June 2003.

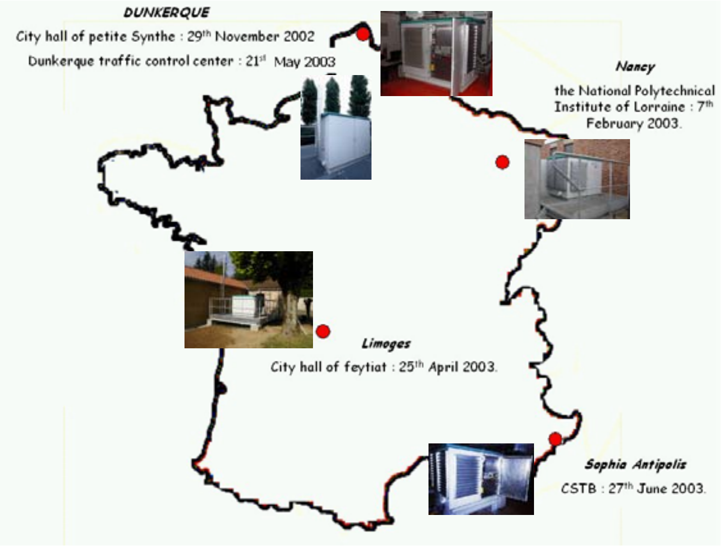


Figure 1: Location of the project sites

The operating period of fuel cells began on September 2003, for the first one, and on November 2003 for the last one. The period for experimentation was two years.

Table 1: Members of the EPACOp research partnership

Gaz de France: Project leader, operation and maintenance of units on sites, coordination of the scientific program.
The Process and Energy Center (CEP) of the Ecole des Mines de Paris: Study of the operation and optimization of the design of the global system
The Laboratoire des Sciences du Génie Chimique (LSGC), Analysis and performances evaluation of the reforming part.
The Groupe de Recherche en Electrotechnique et Electronique de Nancy (GREEN), Study of the electrical part (Fuel cell Stack and power conversion)
The Laboratoire d'Energétique et de Mécanique Théorique et Appliquée (LEMTA), Evaluation and analysis of HPower performances and efficiencies
The Ecole des Mines de DOUAI, Evaluation of performances and comparison with other equivalent systems (Gensys 4C/PlugPower)
The Scientific and Technic Building Center (CSTB) Measurements on sites and data transmission
Association Lorraine for the Promotion of Hydrogen and its Applications (ALPHEA) Technical and regulation aspects of Fuel Cell system installation in Germany.

2.1 Partners

In 2002, the project was approved for financing by the French Fuel Cell Research and Innovation Network (PACo: Réseau Pile A Combustible). This network was created by the French Research Department in 1999 to increase the development and dissemination of fuel cells. It has been replaced in 2005 by PAN-H (Plan d'Actions National sur l'Hydrogène et les piles à combustible).

The EPACOp project is co-financed by four regional delegations (Nord Pas-de-Calais, Lorraine, Limousin and Provence-Alpes-Côte d'Azur) of the French Agency for the Environment and Energy Management (ADEME, Agence Gouvernementale de l'Environnement et de la Maitrïse d'Energie). The members of the research partnership and their main responsibilities within the project are listed in Table 1.

2.2 Financing

The global cost of the project is EUR 2.4 million (~USD 3 million) composed of

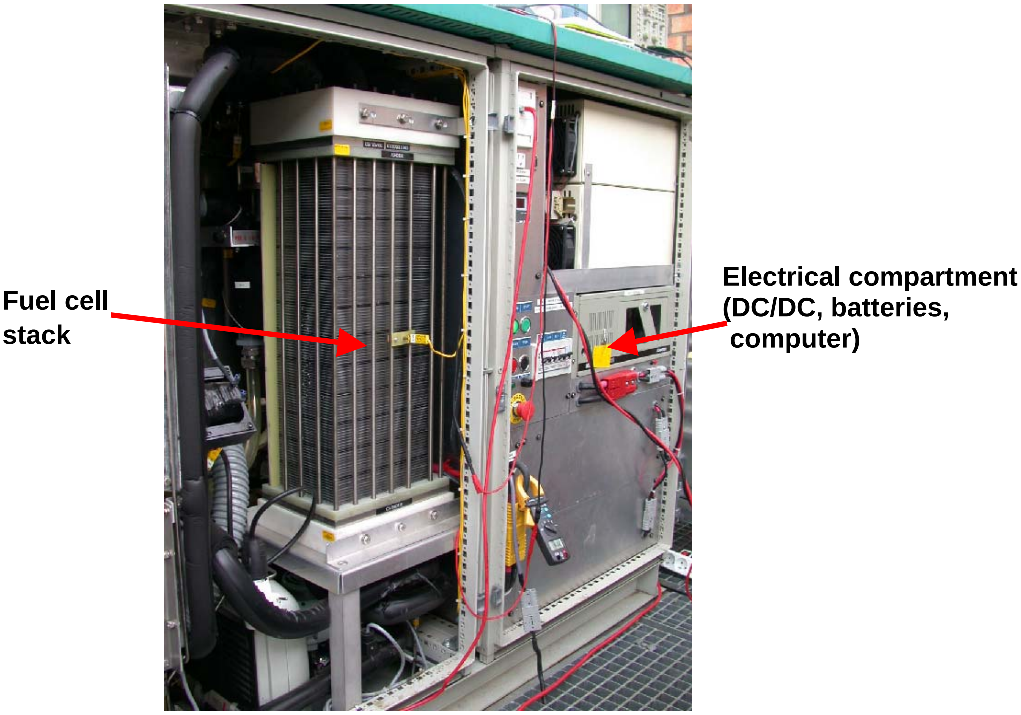
- EUR 1.8 million for operating
- EUR 0.6 million for equipment investment (EUR 0.3 million to buy the fuel cells)

The EPACOp project is co-financed by ADEME (37%) and Gaz de France (47%).

3. DESCRIPTION OF COMPONENTS

RCU-4500 V2 is a Micro Combined Heat and Power (MCHP) unit based on a natural gas (NG) reformer and a PEMFC (Proton Exchange Membrane Fuel Cell). The unit and its functional diagram are shown in Figures 2 and 3; the main technical specifications are given in Table 2.

Figure 2a: The HPower FC system inside a closed enclosure



Fuel cell stack

Electrical compartment (DC/DC, batteries, computer)

Figure 2b: The RCU-4500, door open on the side of the stack

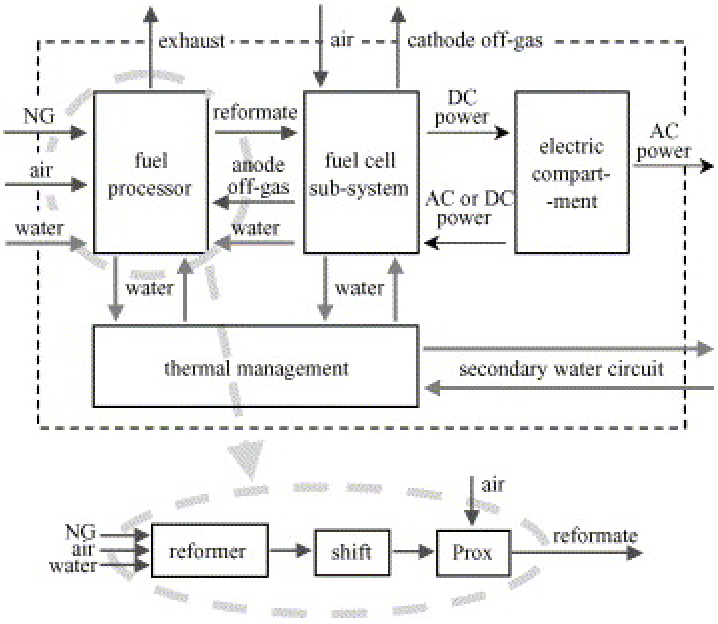


Figure 3: Functional diagram of the NG-fed cogeneration PEMFC system

Table 2: Main specifications for the RCU-4500 V2 Fuel Cell

Dimensions		
height	m	1.42
length	m	1.60
width	m	1.14
Weight	kg	1500
Power		
electrical	kW	4
thermal	kW	5.6
Connection to network		
Natural Gas	mbar	20 or 25
Electrical grid	V/Hz	230/50, parallel connection
Building heating network	°C	50 to 60
Energy management		Electricity oriented

For analysis of operating units and research purposes, special care was taken about the stack and the fuel processing sub-systems. These two parts represent the most important contribution to the complexity and the cost of the whole system.

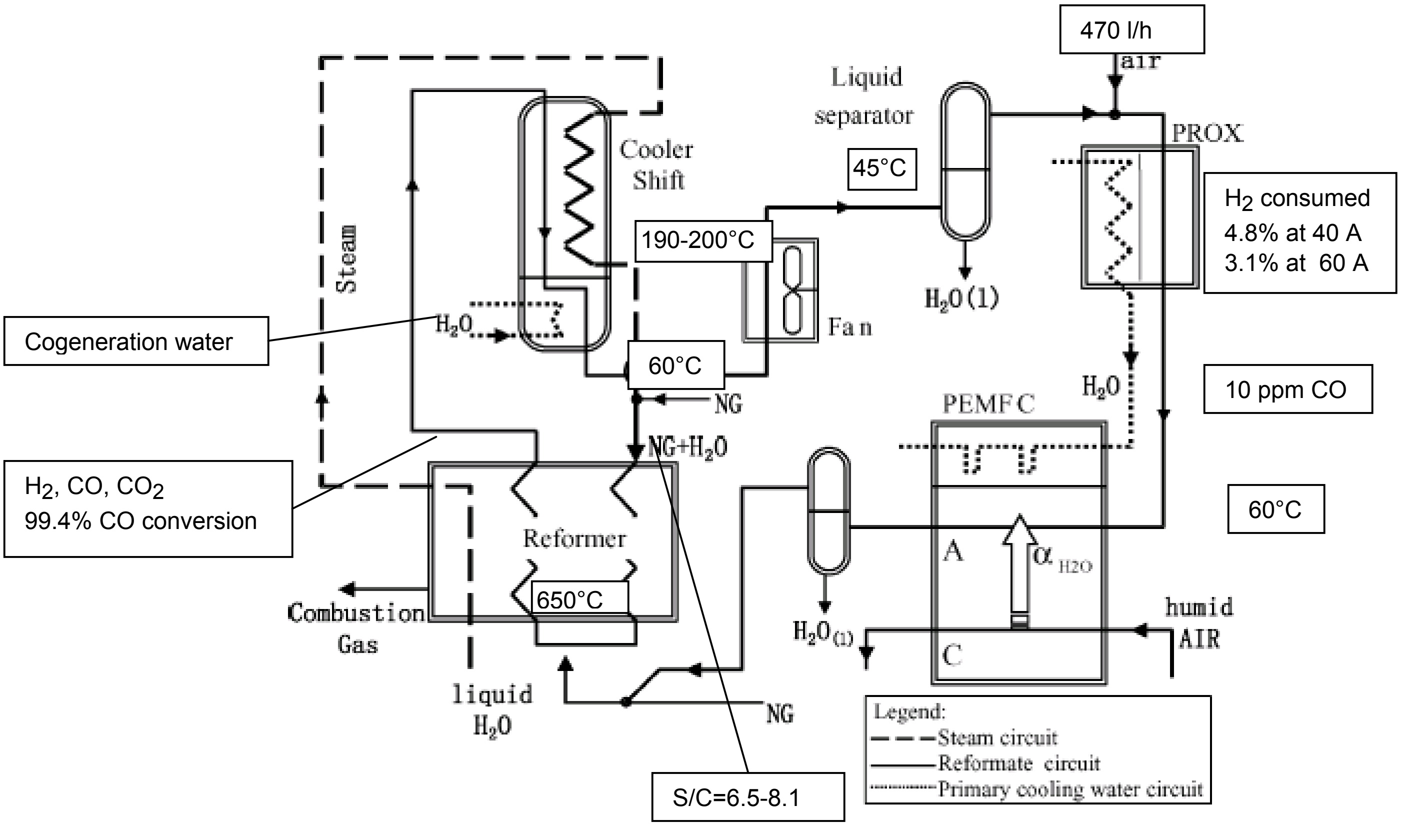


Figure 4: Diagram of the reforming sub-system.

The fuel processing subsystem schematically depicted in Figure 4 is composed of

- a steam reforming reactor,
- a water gas shift reactor, and
- a preferential oxidation reactor.

The natural gas is first admitted to a sulphur trap for removal of the odorant compounds such as H_2S, COS or $(C_2H_5)_2S$ generally added before distribution. The natural gas is then blended to steam and injected into the reformer, where it is transformed into a hydrogen rich mixture. The steam-reforming reactor is made of a tubular catalyst bed, where a mix of steam and NG ("feed mix") produces mainly hydrogen, carbon monoxide and dioxide and a burner where combustion of NG ("NG fuel") and anode off-gas brings heat to support the endothermic reaction in the bed. Exhaust gas is cooled warming up the feed mix to the temperature required for the series of reforming reactions (about 650°C). These reactions are not complete and the outgoing gas contains not only carbon dioxide and hydrogen but also methane and carbon monoxide. The steam is fed in excess (Steam to Carbon molar ratio S/C between 6.5 and 8.1) in order to displace the equilibrium toward the products side and to inhibit amorphous coke formation. Natural gas also contains hydrocarbons heavier than methane (ethane and propane) but their concentration is low and these molecules are fully decomposed at the reformer temperature.

The cooler-shift eliminates by oxidation most of the carbon monoxide remaining in the reformer outlet gas. Although depending on the gas flow rate, CO conversion is high (99.4% at I =40 A and 98.6% at I =80 A). The reformate is also cooled in two stages: first, high temperature heat (190–220°C) is captured by the steam that is then injected in the reformer; second, the cogeneration water further cools the gas through a second heat exchanger, which reduces the temperature of the outgoing gas mixture down to about 60°C. Consequently, the major part of steam condensates inside the exchanger. Then, the reformed gas flows through another heat exchanger where it is cooled by the ambient air (depending on the season, the measured ambient temperature was between -3°C and 35°C). The fan speed is controlled so that the gas temperature at the exit is about 45°C. The liquid-separator evacuates the condensates, which are recycled in the steam boiler.

The preferential oxidation reactor (PROX) is a catalytic reactor that eliminates the remaining carbon monoxide by preferential oxidation in the presence of a small amount of air. CO strongly chemisorbs onto the anode catalyst (Pt) and its maximum admissible concentration in the reformed gas is 10 ppm. The PROX intake airflow is constant (470 l/h). Part of the oxygen reacts with carbon monoxide and another part reacts with hydrogen. Oxygen concentration measurements carried out at the PROX outlet showed that it is entirely consumed. Consequently, the amount of hydrogen consumed in the PROX depends on the gas mixture flow rate (4.8% at I=40 A and 3.1% at I=80 A). A heat exchanger guarantees the temperature to be about 60 °C at PEMFC inlet.

The fuel cell sub-system is composed of a stack and its auxiliary equipment. The stack is made of 120 cells with an active area of about 200 cm^2 per cell. It delivers 1 to 7 kW DC. It is operated at low pressure (less than .2 bar g) and at a temperature between 60 and 65 °C.

4. INTEGRATION OF COMPONENTS

All the components have been selected and matched by the manufacturer. Integrated control software is part of the RCU-4500. The electrical part design of the RCU-4500 developed by HPower is shown in Figure 5. An inverter (AES SMD) connects the DC bus (RCU-4500) to the

AC bus (load and grid). The RCU-4500 is connected to the load in parallel with the grid so that the load has always at least one electrical supplier, even if the unit shuts down.

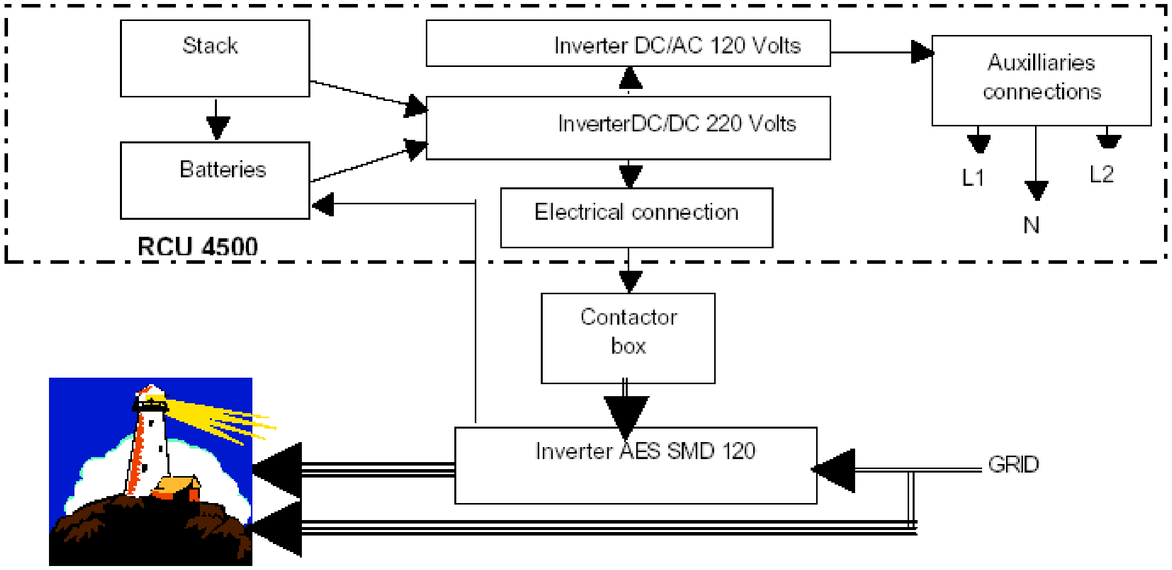


Figure 5: Electrical Design of RCU-4500 Fuel cell unit

The system control strategy is to follow the electrical load. The stack runs at a fixed level of current. Lead-acid batteries allow meeting the electrical demand, which varies quickly.

Concerning the heating demand: the RCU-4500 is installed in parallel with traditional heating system based on natural gas boiler. The thermal power supply represents a small part of global thermal needs of the building. In case of no thermal need, a fan, pretty noisy, extracts the heat generated by the fuel cell unit.

5. PERFORMANCE

Data collected from the five units were used to determine their actual electric, thermal and total efficiencies. The results refer either to instantaneous values recorded each 5 min, to stable operating points, or to values averaged over continuous periods of operation ranging from 2 days to one month. An operating point is considered stable when the current intensity remains constant during at least 30 min.

- The electrical efficiency is defined as the ratio of net power, which is AC power produced by the RCU-4500 (after the inverter SMD), to the LHV (low heating value) of total inlet Natural Gas (NG).
- The thermal efficiency is defined as the ratio of the heat captured in the secondary water circuit to the LHV of the inlet NG.
- The total efficiency is the sum of electrical efficiency and thermal efficiency.

5.1 Fuel cell electrical efficiencies

Starting from stable operating points, the electrical efficiency is well approximated by a linear regression as shown in Figure 6. It varies between 47% (HHV) at I = 100 A (58% of the thermodynamic efficiency) and 63% (HHV) at I = 15 A (79% of the thermodynamic efficiency). The active area of a single cell is 217 cm^2 and the maximum current density is 4610 A/m^2 at I = 100 A. A statistical analysis of instantaneous operating points recorded on Limoges' unit between November 20th and December 4th, 2003, indicates that 56.2% of them are above the regression line corresponding to steady state operation (Fig. 7). Furthermore, the relative deviation from this line is less than 2% for 93.1% of them: one can conclude that (in this system) the electrical efficiency of the fuel cell is not sensitive to transient operation.

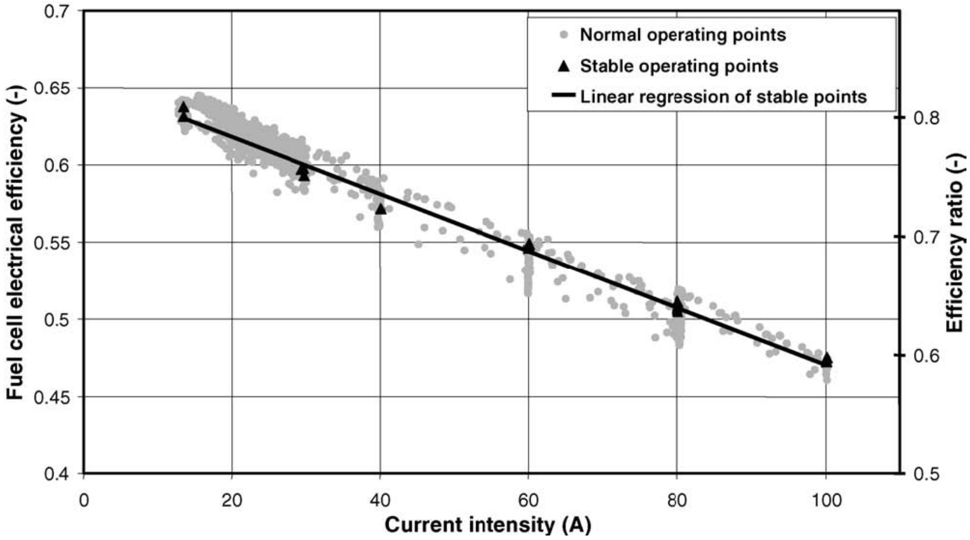


Figure 6: Fuel cell electrical efficiency and ratio to maximum efficiency measured on Limoges' unit between November 20th and December 4th, 2003.

5.2 Systems efficiencies

The units have been extensively monitored in order to assess precisely their operating conditions. Electrical efficiencies of the five units were rather constant at around the value of 16Γ1%. Thermal efficiency varies at higher rates (20-40% at full load) due to differences of the heating demand of buildings. These system efficiencies can be considered as quite low. Nevertheless, they are in accordance with the manufacturer specifications.

5.2.1 System electrical efficiency

Figure 7 shows the dependence of the system gross and net electrical efficiencies as functions of current intensity. The values are low compared to the fuel cell stack electrical efficiency, all the more so considering that the theoretical maximum values are the same in both cases: according to Figure 7, the actual values of the system gross electrical efficiency are between 12 and 30% of the maximum thermodynamic efficiency. These results are confirmed by independent measurements. However, they refer only to the H-Power RCU-4500 V2 units and should not be considered as representative of the current Plug Power products, such as GenSysTM, which are more advanced and which operate in different conditions. It must also be noted that the behavior of the curves is different: the stack electrical efficiency is a decreasing function of the current intensity while the gross and net electrical efficiencies reach an optimum between I = 60 and 80 A. Figure 7 also shows that the difference between gross and net electric powers is high and results in a quite important degradation of the system net efficiency, which becomes very low or even nil at the lowest intensities. The complexity of the electric architecture of the system, which integrates 3 electric converters, is the cause of these high electric losses. These electric losses (including inverters and auxiliaries consumption) can be evaluated by: .7 kW + .3 W_e^{gross}. Another statistical analysis of instantaneous operating points recorded on Limoges' unit between November 20th and December 4th, 2003, indicates that for most of them (84.5%) the system gross electrical efficiency is below the steady state curve. The supplementary loss of electrical efficiency due to transient operation is estimated at about 1.5 percentage points. This corresponds to a relative loss of electric power of about 6%.

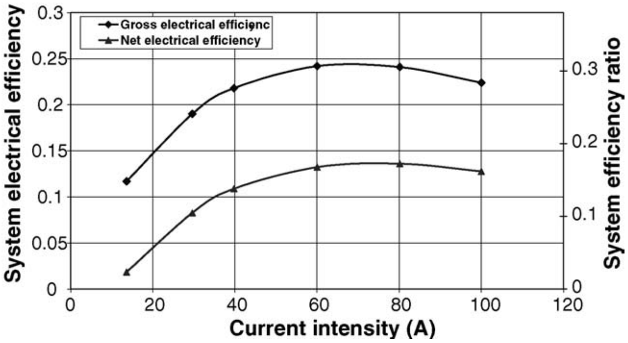


Figure 7: System gross and net electrical efficiencies and ratio to maximum efficiency in stable operation.

5.2.2 System thermal and total efficiencies

Electric and energy meters allow evaluating mean values of the net electrical, thermal and total efficiencies over periods of operation ranging from a few days to a full month. These values take account of all the thermal and electric losses, including start up time (90 min) during which the units are supplied with natural gas without producing electricity. An analysis of all data recorded during more than one year shows that the net electrical, thermal, and total efficiencies are very low. The global mean value of current intensity (averaged for all units and weighted by the length of the operation periods) is 36 A, which is quite far from the optimum range (60–80 A, Fig. 7). As a consequence, the global mean electrical efficiency is only 9.2%. The global mean value of thermal efficiency is 29%, meaning that heat recovery must be improved drastically.

5.2.3 Example: One day of operation

Results given hereafter are from the unit of a town hall in the district of Dunkerque, on a day of November 2003. It was fed with natural gas from Groningen, which has a rather small LHV (9.1 kWh/Nm^3) because of a relatively large concentration of N_2 (about 10%). That day, the unit ran on its four main levels of gross DC power (from 2.6 to 5.8 kW), which are controlled by the current demand of 30–80 A.

An example of the power provided by the fuel cell system to the load is presented in Figure 8. It shows the capability of the system to operate in a dynamic mode and to satisfy the needs of a real load profile. The mmain performance and operational conditions are given in Table 3.

Two main conclusions can be drawn from the curves given in Figure 8 representing the electrical power of different parts of the system during a whole day:

- The electric load (black line) is supplied simultaneously by the unit (red line) and by the electrical grid (pink line). During the day, the unit is able to supply the totality of the load, except when load power exceeds about 5 kW (occurs around 6 PM) where the electrical grid has a significant contribution.
- An important part of DC power supplied by the stack is consumed by auxiliary equipment: this is the gap between orange and red line. This consumption represents 40 to 50 % of stack DC output at full load.

Note that the period before 8 AM is unusual: the unit was **not** connected to the load so that (load) = (grid) and (net output) = null (the whole gross DC power is consumed by auxiliaries).

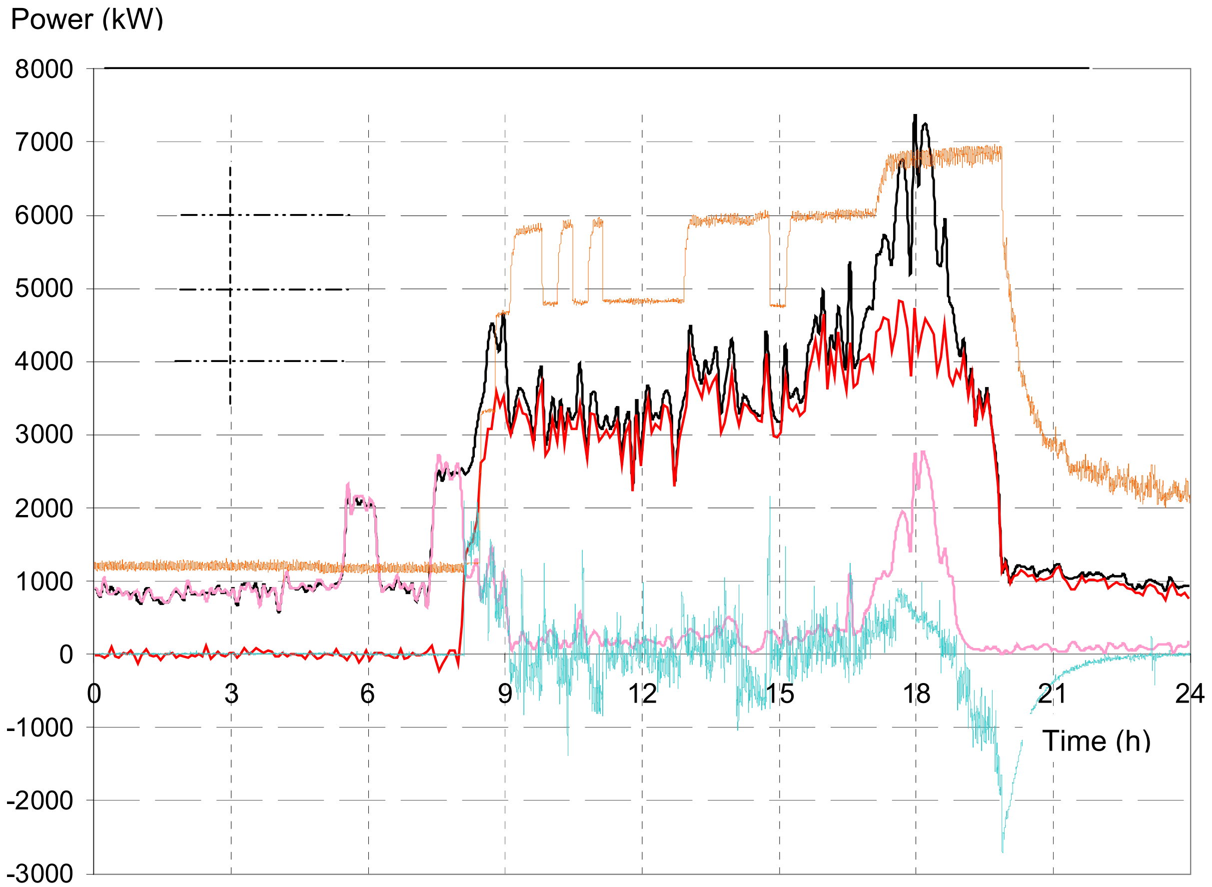


Figure 8: Typical operating curve over a day (December 15th, 2003).

Black line: electrical load of the building
Red line:: net power (unit output)
Pink line: electrical power supplied by the grid
Orange line: Gross power (Stack output)
Blue line: electrical power supplied by batteries

Table 3: Performance and operational conditions of Petite Synthe Unit

Current demand	A	30	40	60	80
V_{stack}	V	86.5	84.0	78.2	71.5
Electric DC power of stack	kW	2.6	3.4	4.7	5.7
AC power of the whole system	kW	1.4	2.0	2.8	3.4
Heat in secondary water circuit	kW	4.0	5.0	6.0	8.0
NG flow rate	Nl/min	22.2	26.2	31.5	39.3
Energy flow in the inlet NG	kW	12.1	14.3	17.2	21.5
Gross electrical efficiency (DC)	%	21.6	23.5	27.5	26.7
Net electrical efficiency (AC)	%	11.8	13.8	16.1	15.9
Thermal efficiency	%	33	35	35	37

5.3 Difference in performance between the five units

Of course, there was a major difference in term of heat demand between the unit in the south of France, were the climate is warm, and the four others. For this unit, the heat produced had sometimes to be extracted in the air with a fan. This is bad for the global performance of the system, but this problem did not have an impact on the electrical performance of the fuel cell.

Other differences in the behavior of the five units cannot be disclosed for confidentiality reasons.

5.4 Conclusions and perspectives

Although the operation of the fuel cell itself is fully satisfactory, the electrical and thermal performances of the cogeneration units tested are disappointing. The experimental data show that the poor electrical efficiency is due mostly to high electric losses and to the need of vaporizing excess water for the fuel-reforming process (worsened by the reforming of a large excess of natural gas). It is shown that in terms of reforming efficiency, significant improvements are achievable.

It also appears that whatever the installation, the electricity demand is not adapted to the systems. All of them are used essentially at part load, far from their optimum. The poor thermal efficiency is due to the low temperature of the fuel cell and to the presence of a primary cooling circuit (the user’s circuit should be used directly as a cooling circuit).

6. OPERATIONAL EXPERIENCE

Gaz de France is in charge of the operation and maintenance of fuel cells on all sites and asked for local assistance from a regional heating company (Cofathec Service, Chauffage Service) to verify weekly the good operation of the unit and for help during maintenance operations.

The main problems during the operation have been:

- Weakness of batteries: an average of 15 batteries have been replaced on each site. This is due to great load variations associated to different needs of the building. Also, low temperature for outside installations caused batteries to fail.

- Bad quality of pipe and links materials caused cracks and leaks due to high temperature operation.
- The desulfurizer had a limited lifespan due to poor efficiency.

In order to improve the operation, the following measures have been taken:

- In the desulfurization cartridge zeolithe as been used in place of active carbon (Gaz de France studies show an improvement of the activity by a factor of 10). This leads to an increase of the reforming sub-system lifespan.
- Fuel cell operation on a reduced load range results in a significant increase of the stack lifespan.

Gaz de France has noted a slight enhancement of the stack lifespan (+25%) on one of the five units. On that unit the load did vary, but less often and with a more narrow range than other ones. Nevertheless, no specific study about the influence of variation of loads on the lifespan has been done. Typical stack lifespan of the RCU-4500 is around 2000 hours, based on the five units tested.

7. MODELLING

Numerous models have been made by scientific partners (CEP, LEMTA and LSGC) during this 3 years project. All of them have been validated with experimental data from the field. Mass and energy balances were calculated. Reaction rates of fuel processing were determined. Thermal losses were located and potential improvements were identified and quantified.

7.1 Modelling of fuel processing sub-system

One of the tasks was to evaluate the ability of the fuel processing sub-system to convert natural gas in a hydrogen-rich gas. Each one of the three reactors shown in Figure 3 was modeled as a zero dimensional reactor with homogenous temperature and pressure.

Chemical reactions in the steam-reforming reactor:

$CH_4 + H_2O \rightarrow CO + 3.H_2$

$C_iH_{2i+2} + i.H2O \rightarrow i.CO + (2i+1).H_2$ (i>1)

$CO + H_2O \rightarrow CO_2 + H_2$

In the shift reactor:

$CO + H2O \rightarrow CO2 + H2$

In the preferential oxidation (PROX) reactor:

$H2 + O2 \rightarrow H2O$

$CO + 2\ O2 \rightarrow CO2$

Degrees of conversion of reaction taking part in the steam reactor are determined by the equilibrium law (equilibrium constant and partial pressures) for the requested physical conditions, i.e. temperature of reaction of 650 °C and total absolute pressure of 1.5 bar. The modelling of the two other reactors was much simpler.

The composition of the outlet gas of each reactor was calculated, as well as measured by gas phase chromatography. A comparison of calculated and measured values of the composition of the outlet gas of the steam-reforming reactor (unit of Petite Synthe) is shown in Table 4. This was done for three levels of power, corresponding to three stack levels of current: 40 A, 60 A and 80 A (full power).

Table 4: Modeled and measured composition of gas out of the steam-reforming reactor

Stack current	40 A		60 A		80 A	
	model	measured	model	measured	model	measured
H2	76.3	78.1	76.0	76.1	75.6	76.2
CO2	16.6	15.1	16.1	15.4	15.3	14.8
CH4	0.17	0.29	0.31	0.38	0.61	0.86
N2	2.57	3.22	2.60	2.83	2.65	2.84
CO	4.39	5.61	4.98	6.32	5.83	7.07
O2	0.00	0.10	0.00	0.04	0.00	0.02
Sum	100.0	102.4	100.0	101.0	100.0	101.7
Conversion rate of CH4 (%)	99.1	98.4	98.3	98.0	96.8	95.5

It can be seen that calculated composition and measured one fit pretty well. In particular, the calculated conversion rate of CH4 is very similar to the measured one.

Note that, in this table, water is not taken into account because water cannot be measured by chromatography. It as been shown by another way that vapor represents about 50 % of the gas.

7.2 Modelling of the stack sub-system

This part consists of calculating the stack DC power knowing flow rate and composition of inlet gas and the stack current, which is the stack control parameter.

Assuming complete electrochemical reactions, the fuel cell hydrogen consumption is proportional to the current intensity, whatever the fuel excess.

The fuel cell polarization curve is experimentally determined from a regression of the data:

$$E_{\mathrm{FC}}(\mathrm{V}) = 96.7 - 0.27I; \quad \Delta_{\max} E_{\mathrm{FC}} = 4.5\ V;$$
$$\Delta_{\mathrm{mean}} E_{\mathrm{FC}} = 0.74\ \mathrm{V}; \quad R^2 = 0.993.$$

It is linear, showing that as usual, the fuel cell is used in the operating range where variations of activation polarizations (as functions of the current) are small compared to those of the Ohmic drop while concentration polarizations remains negligible.

The accuracy of the model is validated by the comparison shown in Figure 9 of the gross and net electrical efficiency (defined in section 5) with experimental data.

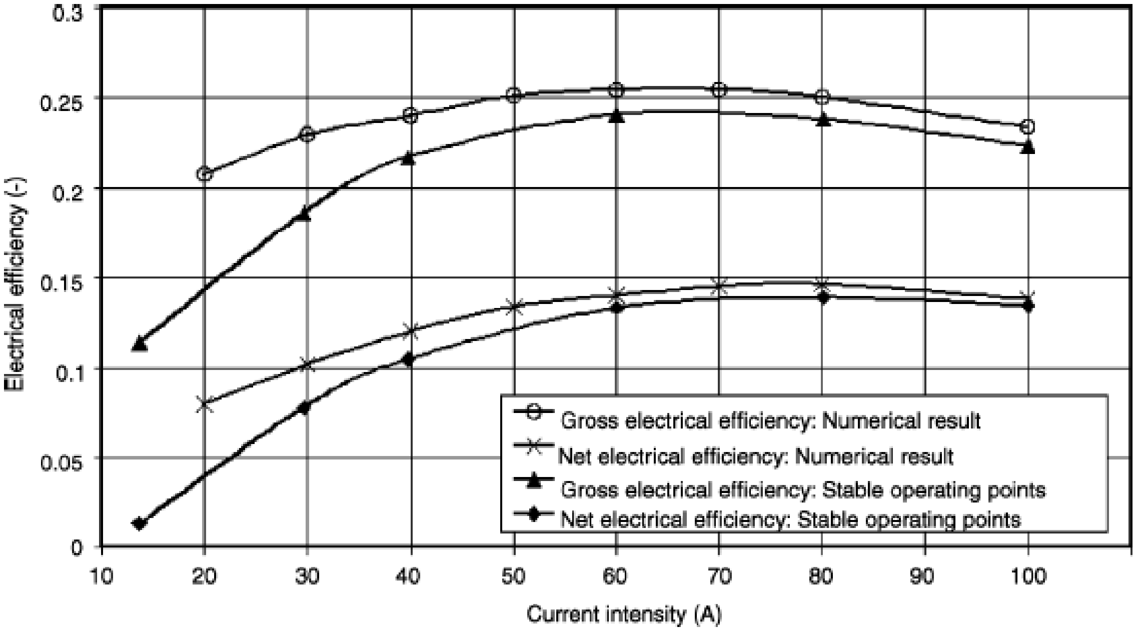


Figure 9: Comparison of calculated efficiencies with experimental data

7.3 Modeling of the whole system

In order to evaluate the contributions of different parts of the system and how they are linked, a steady state model of the whole system (minus the electric compartment) has been made. Thermoptim®, a software developed by *Ecole des Mines de Paris* to calculate complex thermodynamic cycles, has been used for this purpose. The model has been fit to experimental data; then it has been used to evaluate the potential to enhance electrical and thermal efficiencies. It has been shown that, with 2005 state of the art best stack performance, the electrical efficiency could reach 35 % and the thermal efficiency 55 %. Results of this modeling are property of Gaz de France and confidential.

7.4 Conclusions

Models really helped Gaz de France and its partners to better understand the system operation and to identify the ways the prototype could be improved and optimized. Firstly, models were used to assess precisely the internal performance of the system. Efficiency of different subsystems was calculated at full load and part load. Secondly, they were used to evaluate the improvement of efficiency that can be achieved thanks to a re-designing of the whole process, integrating likely assumptions from scientific literature.

8. DATA ACQUISITION

An integrated data acquisition system, developed by the manufacturer, allows the measurement of all major internal parameters of the system in operation.

The following data were measured and recorded:

- Temperatures of the process: boiler, steam reforming, shift and preferential oxidation (PROX) reactors, stack (inlets, outlets, cooling circuit), secondary circuit (domestic cooling stream inlet and outlet temperature)

- Pressures: boiler, stack inlet, cooling circuit
- Volume flow rate: inlet natural gas, cooling circuit, secondary circuit
- Stack current and voltage, system AC power output, current and voltage of battery bank.

The system has been completed by an external data acquisition sub-system, installed in the framework of the project to acquire environment information such as inlet natural gas consumption, and electricity feed in the grid. In order to evaluate the performance of the reforming and purification processes, some gas analyses at several specific points of the system have been conducted. The integrated acquisition system records data with 20-sec steps; the additional one with 5-min steps. Both are available in Excel™ format.

9. ENVIRONMENTAL ASPECTS AND SAFETY ISSUES

The only emissions of NOx and CO of the units tested are the ones due to the burner of the steam-reforming reactor. Like gas heaters, the intermittent working of the burner induces peaks of CO emissions. However, in order to enhance the performance of the system, tests have been conducted to make it work at a constant rate of power. As an example, the emissions measured on the unit in Sophia Antipolis are shown in Table 5. They are compared with the “Bleu Angel” label values for a gas-fired calorific-value boiler (< 70 kW) (standard RAL-UZ 61). It is obvious that the emissions from the fuel cell unit are lower than the regulation constraints.

Table 5: Emissions of the Sophia Antipolis unit, in comparison with standard values

		Sophia Antipolis Fuel Cell unit		"Blue Label"
		intermittent mode	constant mode	
CO	mg/kWh PCI	>38	15	< 50
NOx	mg/kWh PCI	>16	9.7	< 60

10. REGULATORY ASPECTS

To guarantee safety for the users and the consumers, the “European Conformity” (EC) mark is the visual symbol, which attests that the product is in conformity with the essential requirements of safety of one or more directives known as "News Approaches" adopted by the European Union. In all the cases, the EC mark is affixed by the manufacturer who takes the responsibility to declare the conformity of his products to the requirements of the directive. Several directives can cover the same product.

The following rules apply for an establishment on operational site:

- If the product already has an EC mark, it can be installed without any additional approval.
- If the product is a prototype without EC mark, the obligation of marking depends on the site of the experimentation. For experimentation in a research center, EC mark is not obligatory. In all the other cases, EC mark is required. It is valid for only this prototype in the environment where prototype is installed and for a limited duration. A bringing together with the notified organizations (for France: AFNOR, LCIE, Bureau Veritas) is then carried out in order to make sure that the product filled all the requirements of safety with respect to the goods and the relative people.

In the absence of official regulations dealing especially with Fuel Cell technology, the RCU-4500 has to fulfill the following Directives:

- Machinery 98/37/EC
- Gas Appliances 90/396/EEC
- Pressure Equipment 97/23/EC
- Electro-Magnetic Compatibility (EMC) 89/336/EEC
- Explosive Atmosphere (ATEX) 94/9/EC
- Low Voltage 73/23/EEC

If some requirements are not filled, additional safety equipments will be installed on the site in order to validate these requirements.

10.1 Requirements for fuel cell systems used in the EPACOp Project

10.1.1 Machinery Directive, Gas Appliance Directive, Low Voltage Directive

The prototype H POWER fuel cells of EPACOp project were not marked EC. Each EC mark of the five units has been obtained (see Table 6) in several stages:

- Writing by Gas de France of a referential draft relating to the Directive and in collaboration with Manufacturer HPOWER and AFNOR (French Association of Standardization) because no normative text relating to the fuel cells was available.
- Set up of technical dossier in three specimens by the manufacturer with the assistance of Gaz de France,
- Realization of the tests by Gaz de France and writing corresponding reports,
- Obtaining single EC mark for each fuel cell and delivered by AFNOR.

Table 6: Dates of the EC mark

Experimental Site	Dates of EC mark
Town hall / Petite Synthe	January 31st 2003
Traffic Offices / CUD	October 15th 2003
NPIL / Nancy	October 15th 2003
Town hall / Feytiat	October 15th 2003
CSTB / Sophia Antipolis	October 15th 2003

10.1.2 Explosive Atmosphere Directive

LCIE (Laboratoire Central des Industries électriques), a subsidiary of Bureau Veritas, studied the fuel cell system RCU-4500 V2 from HPOWER according to the requirements of the Explosive Atmosphere Directive.

The conclusion of the dossier set up by Gaz de France with the support of the manufacturer is that the system was not subjected to the requirements of the Explosive Atmosphere Directive.

10.1.3 Pressure Equipment Directive

Bureau Veritas, the official international organization (www.bureauveritas.com) for the assessment of QHSE (Quality, Health, Safety, Environment) and Social Accountability

Management, studied the fuel cell system RCU-4500 V2 from HPOWER according to the Pressure Equipment Directive. Again the conclusion is that the system was not subjected to the requirements of the Pressure Equipment Directive.

10.2 Regulatory Aspects concerning the installation

All decrees and standards mentioned in this section refer to national laws and can be found in French on the Internet.

10.2.1 Grid Interface

The electricity produced by the generator feeds the electrical supply network at a frequency of 50 Hz:

- in single-phase current 230 V with $P_{el} \leq 18$ kVA
- in three-phase current 230/400 V with. $P_{el} \leq 250$ kVA

Connection with the electrical grid must follow the requirements of the decree of 17 March 2003 relating to the technical specifications of design and operation for connection of a generator to a public network distribution.

The electric installation is primarily made up of three elements:

- the power cable, which is connected to the electrical supply network of the user,
- the regulation components of the electric production sub-system (for the acquisition of information),
- the decoupling protection to the grid.

The choice of a decoupling protection falls to the producer. The producer must take into account the compatibility with the technical connection requirements of the network. His propositions are then submitted to the distributor for approval.

The technical requirements of the distributor target the maintenance of:

- the performance and coordination of the protection plan,
- the contribution of the generator to the operation of the electric system and its economy
- the quality of services for users of the network.

In order to be in accordance with grid interface requirements, Gaz de France installed for the EPACOp Project external decoupling protection with the agreement of the Distribution Network Operator (DNO).

10.2.2 Electrical installation conformity

The electrical connection of a generator, on an existing installation requires the intervention of an accredited organization in order to check that the requirements related

- to standard NF-C15 100 on the installations low voltage,
- to the safety regulations approved by the decree of 25 June 1980 relating to safety against the panic and fire hazards in the establishments receiving public,
- to the particular provisions approved by the proper authority (article GN4 of the safety regulations) are respected strictly.

The five experimental sites of the EPACOp project obtained the electrical conformity.

10.2.3 Gas compliance certificate

According to the type of building, the gas fitter is held to establish after realization of any installation comprising of fixed gas piping, a compliance certificate attesting that this one is in conformity with the regulation in force.

The five experimental sites of the EPACOp project obtained the gas compliance certificate.

11. PUBLIC ACCEPTANCE

All five units have been installed in public buildings such as universities, city halls or offices. All people made the system welcome and no trouble with public acceptance occurred. During the site selection phase, many cities and regions applied to host a fuel cell unit all across the country. Locals, city and region councils are really enthusiastic about installing and operating such new technologies. Most of people living or working near the unit are really interested in new technologies of energy production and asked for a “Fuel Cell tour”.

12. COSTS

Cost analysis is one major objective in the project and has been done in the different phases. Both installation costs and system capital and operating costs were recorded.

12.1 Installation Costs

Installation costs have to be considered carefully because they represent an important part of the global operation cost of a field test project (around 70'000 EUR per unit installed). It is shown in Figure 10 that the costs are well distributed between studies, electrical works, thermal works and civil engineering. These costs remain very high and can be compared to the proper costs of the fuel cell itself.

The studies costs could be reduced easily. The consultant firm works were necessary because EPACOp project was a first experiment in real conditions. In the case of a new experiment with the same type of fuel cells, these costs could be reduced to 5,000 EUR.

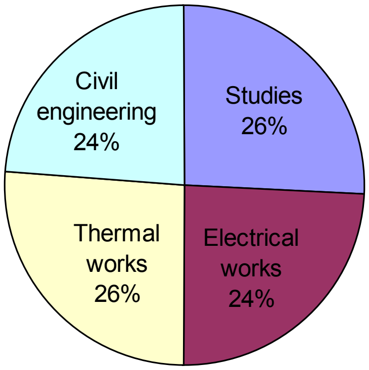


Figure 10: Average installation cost for each site

The civil engineering costs are not representative of a tertiary experiment. Indeed, as a first field-test operation, a special effort has been done for communication purpose. This item could be easily reduced to EUR 5,000.

Electrical and thermal network connection costs could be also reduced in two ways:

- Better fuel cell integration into the building, if it is planned during the building design phase.
- Development of plug-and-play connections by the fuel cell manufacturer in accordance to French building constraints.

12.2 System Capital and Operating Cost Analysis

System capital costs are one of the major barriers to the development of fuel cells and have to be taken into account from the beginning of all projects dealing with fuel cells.

The manufacturing cost including components and labor costs of the HPower module has been estimated to 85,000 EUR (around 21,000 EUR/kW_{el}).

Based on manufacturer experience, we have extrapolated the actual system cost at prototype status to a series production of 100 000 units. It seems that we could achieve a system cost of 27,000 EUR (6'800 EUR/kW_{el}).

Two technical functions are the most expensive: electricity production (34% of the global cost), and hydrogen production from natural gas (37% of the global cost)

13. LESSONS LEARNED

The EPACOp project allows Gaz de France to acquire a unique know-how on installation, operation and maintenance of Fuel cell systems on sites. This knowledge also allowed identification of barriers to integration of MCHP units on commercial and residential on the following topics:

- Technical barriers:

  The research program led to identify some improvements on components and sub-systems to improve performances of the system (efficiencies and emissions). Moreover, the customer needs (electric and thermal demands) have been specified in order to achieve a more appropriate match between the system energy production and the building needs.

- Regulation barriers:

  To install and operate a MCHP system on site, an extensive documentation is required (CE mark of the product, grid connection authorization, guaranties…). Gaz de France has followed the entire regulation track and identified all steps to follow in order to operate in good conditions fuel cell system according to the French regulations. Based on these lessons, Gaz de France is more and more involved in French and European workshops to include MCHP and fuel cells into the actual and future regulations.

- Economic barriers:

  Based on an analysis of installation and operation costs and a value analysis of the H Power product, Gaz de France has evaluated the cost target of the fuel cell product in order to achieve profitability. Major cost-effective parts and several ways to decrease production costs have also been identified.

The second major result of the project was the identification of additional research and development topics needed to optimize fuel cell systems. Some components (pumps, inverter…), materials (membranes, catalysts…) and processes (gas, thermal…) need some further developments. Based on EPACOp results, Gaz de France will use this knowledge to participate in future development projects.

14. REFERENCES

Many other data and results of this project are already available in literature:

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