FEMAG

Project number: COOP-CT-2004-508119

Project acronym: FEMAG

Project title: Flexible Ecological Multipurpose Advanced Generator

Instrument: Cooperative Research

Thematic priority: 6.1 – "Sustainable Energy Systems"

Second year periodic activity report

Period covered: from 15/09/2005 to 14/03/2007	Date of preparation: 10/03/2007
Start date of the project 15/09/2005	Duration: 30 months
Project coordinator name Alfredo Picano	
Project coordinator organisation name Labor S.r.l.	Revision 1.0

SECTION 1 Project objectives and major achievements during the reporting period

1.1 Overview of project objectives

The project arises from the consideration that Fuel Cells offer a potential impressive advantage over existing technologies for local power generation, but require a substantial effort to be adapted and designed to a variety of applications and load profiles.

It is in fact universally acknowledged that Fuel Cells can be successfully integrated into hybrid systems together with components such as supercapacitors, backup batteries, low pressure hydrogen storage, simplified control systems, in order to meet the requirements of a large number of applications, while targeting cost reduction (especially by means of decrease of FC size and its control requirements), reliability, flexibility and compactness.

Under this respect, FEMAG targets an energy generator based on the integration of a fuel cell with supercapacitors and eventually an ancillary battery pack, for the flexible supply at variable power of small portable non automotive devices.

FEMAG proposes to develop a product which is based on Fuel Cells, but is combined with all the components required to make its application flexible, simple and able to satisfy not only the base power consumption, but also relative peaks of consumption of associated machines, within utilisation profiles prefixed at the design stage.

The main FEMAG generator goal is to avoid the Fuel Cell to be forced to sustain highly dynamic load, since the variable power supply is one of the main reasons of the stack lifetime reduction.

The durability of PEM fuel cells is a major barrier to the commercialisation of the stacks for transportation power applications and commercial viability depends on improving the durability of the fuel cell components to increase system reliability and to reduce the system lifetime cost by reducing the stack replacement frequency.

It’s well known, as it’s widely reported in scientific literature, that the main reason of efficiency reduction of stacks is the Pt catalyst particle size growth, which reduces the active reaction surface: the particle dimension increasing is more evident if the fuel cell operates under drive-cycle rather than in stationary conditions.

In Figure 1 the results reported by Los Alamos National Laboratory and obtained by long time durability tests are illustrated: it’s self evident that the average Pt particle size is greater when a drive-cycle is imposed, while under a steady-state operating condition the stack durability is clearly longer.

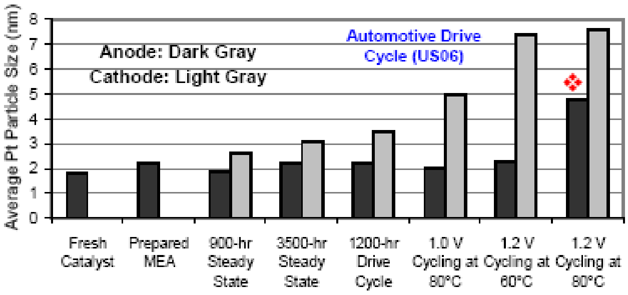


Figure 1 – Average Pt particle size before and after durability experiments.

The FEMAG architecture is able to convert the dynamic loads, typical of many applications, in stationary ones using ancillary power storage systems as supercapacitors and a backup battery, which supports the FC, and a intelligent DC/DC converter that manages intervention priority of FEMAG components in order that:

- the supercaps have the highest intervention priority in supplying the load and they are dimensioned, according to a specific application, in such a way that they have the capability to supply every power peak (e.g. start-ups) required by the load.
- the FC is the second component in order of priority to intervene and doesn't "see" peak power requirements.
- the backup battery intervenes when the power demand exceeds the FC nominal power.

Therefore, it's a worth assessment that FEMAG philosophy surely increases the PEM fuel cell stacks durability since it avoids dynamic variability of power load requested to the cell inhibiting the Pt particle growth and maintaining an high efficiency of conversion for a longer time.

A remarkable target market for such systems exists, composed of all those companies manufacturing systems potentially suitable to be supplied by fuel cells, but of size and value lower that those presently requested for an ad hoc development of similar systems. For this reason, average values for output power and appropriate utilisation profiles for such operating machines has been defined, aiming at characterising a family of modular products, defined by their base (or constant) energy consumption.

The project targets the following **overall objectives**:

- Define and test suitable **design configurations** for small and medium electric power systems based on PEMFC, realizing two FEMAG generator prototypes for a wheelchair (300W stack) and an AGV (1.5kW stack)
- Develop **symbiotic hybrid modes** to effectively meet the varying load requirements of each specific application at the lowest cost and the most responsive operating mode
- Identify adequate **set of components** for such systems (batteries, ultra-capacitors and controllers)
- **Certify the boundary conditions** within which such systems are able to operate reliably.

- Develop and demonstrate and **advanced expert system** for the **design of complex generators** based on FCs in a wide range

The expected **tangible outcomes** of the FEMAG project are:

1. A **multi-purpose highly engineered autonomous generator based on FCs**, suitable to be scaled in the range from 0.125 to 1.5 kW, to meet a variety of high value applications
2. A design methodology allowing to design optimised FC based systems starting from general operating specifications
3. A parametric description allowing to assess potential substitution savings and benefits
4. An **expert system** for the design of a full range of FC based generators
5. **Two specialised demonstration systems**:
    - A **wheelchair** for disabled people – this is indeed an ideal application for fuel cells, because the typical load profile is very irregular, and long range is a fundamental requisite
    - An industrial **AGV** (Automated Guided Vehicle) for the transportation of finished goods inside an industrial area.

The **scientific goals** of the programme are:

1. To investigate and define the differences in the performance envelope of fuel cell based systems in the two extreme cases of:
    a. fuel cell dimensioned to give the **full maximum power** and follow the load profile.
    b. fuel cell dimensioned to **work at constant power**, and system dimensioned to follow the energy peak requirements using ancillary power storage systems like low discharge batteries, fast discharge batteries, and supercapacitors.
2. To establish a definition and comparison system between the cases 1.a and 1.b above.
3. To study the applicability of FEMAG generator system to many other potential application.
4. To patrimonialise and formalise the knowledge generated into an **expert system** for the design of complex systems based on FCs

The results of his theoretical study will both serve as basis for the manufacture and test of the technological systems under this same study, and as a literature case for the design and dimensioning of fuel cell based systems in the applications of light industrial and home orientated applications.

The **technological goals** of the programme are:

1. To select the correct mix of technologies to support and enhance the fuel cell based systems, in the various fields of application targeted.

2. To manufacture a prototype system for each significant application chosen depending on the results of the scientific study.
3. To validate the result of the scientific findings of the programme.
4. To submit the innovation of the design to the end user industries and consequently enhance the potential use of the fuel cell based system in a new and/or broader range of application
5. To obtain a parametric description of the economic savings obtainable by the new design in each of the applications

The approach proposed by FEMAG is very original and with impressive replication potential, since, further to the development of prototypes optimised by experimental design for the specific target applications of the project, it envisages the application of advanced mathematical methodologies in order to **formalise and patrimonialise the knowledge generated by the project** into an **expert system** for virtual design of integrated generators based on FCs.

The state-of-the-art in this reference sector of hybrid FC based systems has not changed significantly, and all the assumptions at the base of the project remains fully valid.

1.2 Recommendations from previous review

No previous recommendations received.

1.3 Objectives and achievements of the reporting period

The first year of the project was characterised by the following overall objectives:

1. Specify the application features and load characteristic for the classes of applications foreseen for the FEMAG generator, i.e. wheelchair and industrial AGV (**WP1**).
2. Provide a draft configuration of the FEMAG generator, to be validated and likely improved after testing (**WP2**).
3. Better explicit the underlying concept of the FEMAG project under the point of view of the integration of different components (**WP2**).
4. Investigate and update the knowledge of low pressure metal hydrides systems for hydrogen storage (**WP3**).
5. Develop the mathematical modelling of targeted hybrid systems (**WP4**).
6. Develop a laboratory test bed (**WP4**)

The last point was not completed because of logistic standpoint as reported in the first year periodic activity report. Therefore the objectives in WP4 has been finished in the second year period.

The second reporting period has been characterised by the following overall objectives:

1. **Development of a laboratory test bed (WP4)** – development of a laboratory configuration in which the characteristics of the FEMAG devices and of proposed applications can be properly tested and measured, together with a controller able to manage the different power flows. The FEMAG High Energy prototype (industrial AGV application) has been realized on laboratory bench, while the Low Energy prototype has been assembled in a “plug-in”

box and tested on a wheelchair. All the tests and evaluations have been performed in Labor laboratories.

2. **Development of the Expert System (WP5)** – development of an expert system, based on experimental and simulation results obtained, from the prototypes and Simulink models, in order to formalise and patrimonialise the knowledge generated by the project and to make easier and faster the design of novel FEMAG generator for every application fields.

3. **Testing on High Energy Prototype (WP6)** – testing report on the lab-bench high energy prototype, composed by a 1.5 kW MES-DEA Fuel Cell stack, 6 58F/15V supercapacitors pack, 3 1000 Nl metal hydrides Treibacher tanks and the innovative DC/DC converter which manages the priority of intervention according to the FEMAG philosophy. The main scope is to demonstrate the improvements in using the FEMAG generator in comparison to unassisted fuel cell imposing highly dynamic power load profiles and to assess the FEMAG control management functioning.

4. **Testing on Low Energy Prototype (WP6)** – testing report on in box assembled low energy prototype, composed by a 200 W Beijing Fuyuan Fuel Cell stack, a 10F/50V Nesscap supercapacitor, 2 300 Nl metal hydrides UDOMI tanks and the innovative DC/DC converter, integrated on a wheelchair and tested on field. The Low Energy prototype has been directly tested on field, integrating it in a wheelchair for disable people in order to evaluate the performance of the FEMAG power generator. The prototype is “plug-in”, giving the possibility to unplug and plug again in other items.

5. **Technical and economical assessments (WP7)** – evaluation of the technical and economical perspective possibilities of FEMAG power generator to be an important market asset in many operational fields. A design of a potentially applicable FEMAG generator for many applications is performed by the Expert System and by the Simulink model. Moreover a stringent economical evaluation is made to assess the competitiveness of hydrogen based power system to today’s power supplier devices.

6. **Exploitation and dissemination of results (WP8)** – adequate implementation plan to provide visibility to project results by means of a FEMAG web portal and some marketing actions.

The main achievements in relation to the above described objectives can be summarised as follows:

1. The laboratory test bed has been developed for the FEMAG High Energy. A complete prototype composed by the aforementioned items (1.5 kW ME-DEA Fuel Cell, 6 58F/15V Maxwell supercapacitors, 3 1000 Nl metal hydrides Treibacher tanks and the innovative DC/DC converter which manages the priority of intervention according to the FEMAG philosophy) has been prepared in the Labor laboratory with the collaboration of Tor Vergata researchers.

   A complete measurement system (pressure transducers, temperature sensors, a gas flow meter to measure the inlet hydrogen flow) has been designed to supervise all the dynamic variations of the operating conditions. Instead the Low Energy prototype has been designed to be assembled in the wheelchair on board in order to test the FEMAG generator functioning on field. Therefore, all the Low Energy generator components have been assembled in a case.

2. An Expert System has been realized by MOLNET, based on the test-bench results and simulations by Simulink model. Two FEMAG generator systems are considered: the first is the architecture depicted in Figure 2, composed by the fuel cell stack + SC pack + DC/DC converters, which is the one actually realized in the prototypes. The first architecture Expert System has been modelled using experimental results obtained in the Labor laboratory. The second architecture is the complete (Figure 3), in which a backup emergency battery is integrated as well. Since the experimental results of the project were not enough to build a complete and comprehensive ES, they were complemented with the results of the Simulink model simulations.

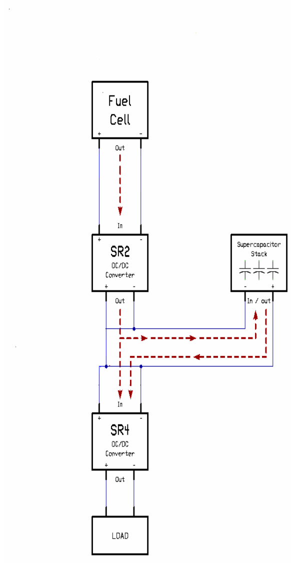


Figure 2 – FEMAG power bus without backup battery

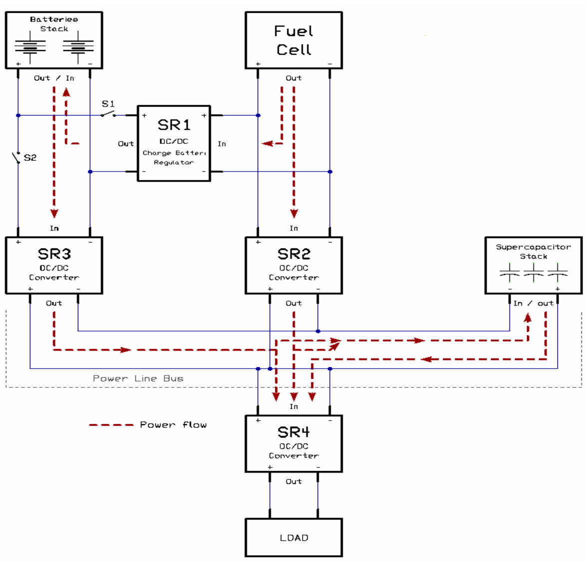


Figure 3 – Complete FEMAG architecture

3. The experimental test bed of the FEMAG High Energy prototype has been integrated. The measurement system (Figure 4) is able to measure temperature, pressure and gas flow of hydrogen stream from the tanks to the anodic channel of the stack and inlet/outlet cooling water temperature in the tank cooling circuit in order to evaluate the heat produced when the tanks are charged, the heat consumed when the tanks are discharged.

   All the data of the cell are collected using the Electronic control unit ECU and sensors integrated in the stack. The load profiles are imposed using an electronic load commanded by a Labview software designed and implemented by Labor.

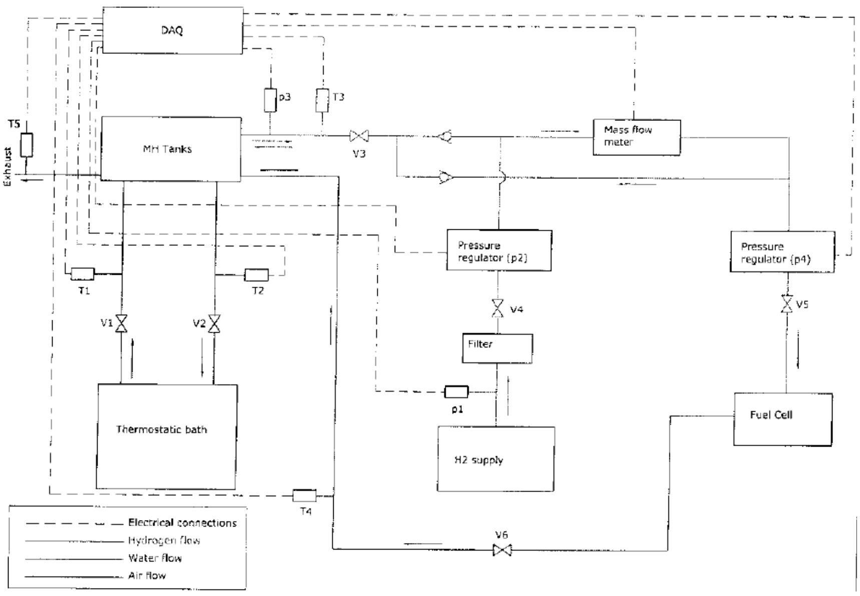
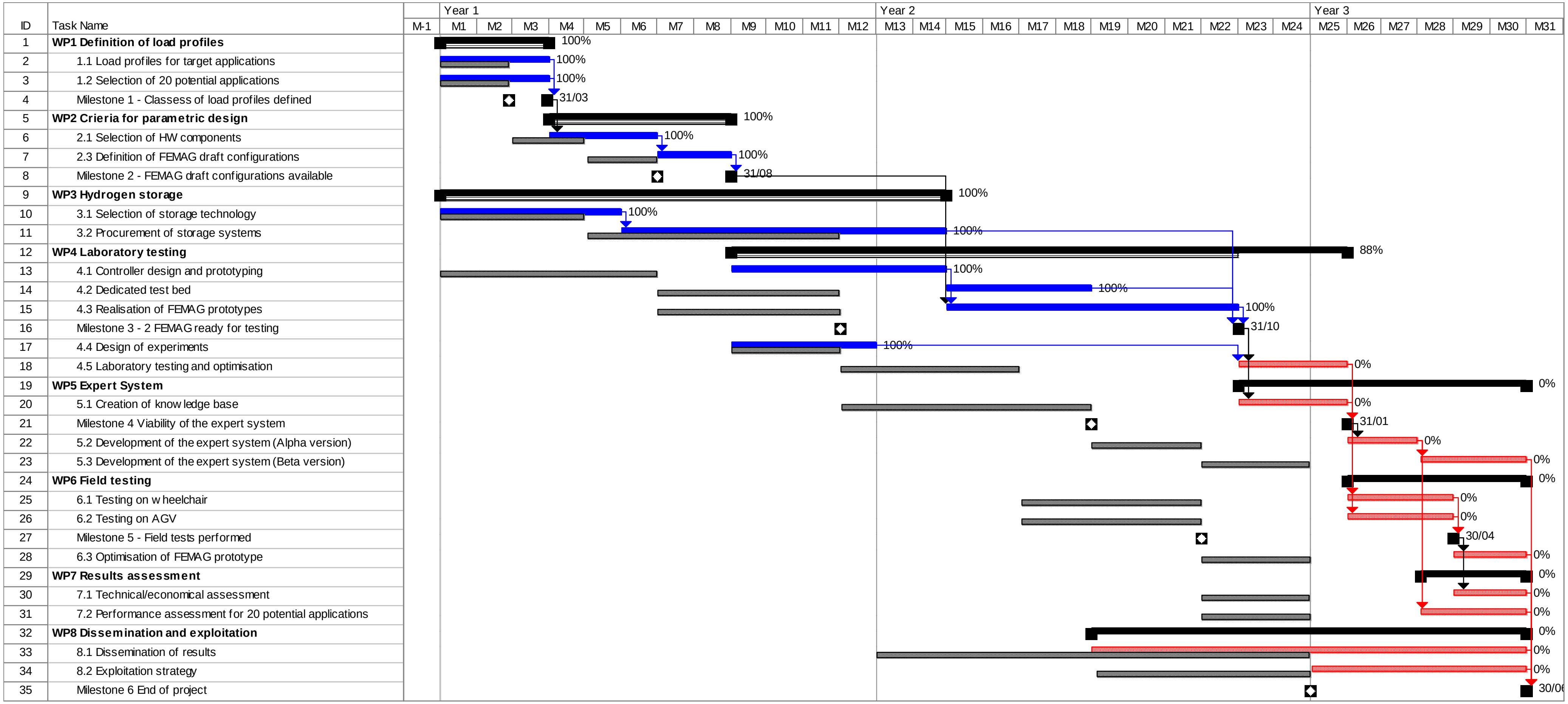


Figure 4 – FEMAG High Energy measurements system layout

4. The FEMAG Low Energy prototype has been installed directly on a wheelchair. The complete system assembled has been inserted in a box and plugged in the wheelchair. The system has been tested in field and results have been reported.
5. Technological and economical issues have been assessed under several respects. Twenty potential applications have been proposed and a FEMAG configuration for every application has been hypothetically designed. The main scope is the evaluation of the real possibilities to integrate the hydrogen-based power generator in many operational fields in a technical and economical point of view, and to set the perspective goals to reach in the next future in order to make these systems, as FEMAG generator, effectively competitive with today's power generator.
6. A web portal has been realized (www.femag-project.net) and an implementation plan has been made to explore all possible market applications at world level and possible marketing strategies

The GANTT chart related to the second reporting period is reported in **Errore. L'origine riferimento non è stata trovata.**.



1.4 Problems encountered and corrective actions

Some problems have been encountered on the consortium and technical sides.

Consortium Management problems:

1) Some partners haven’t given the contribution expected and a re-organization of the work has been made.

2) In the first months of 2006 partner n°5 Enertron entered into the insolvency procedure. Enetron exited the contract at the end of the 1st period (before the start of the insolvency procedure) and Enertronix, the new company which has originated from the competences of Enertron, entered in the project.

On the technical side

1) Late availability of laboratories (already mentioned in the 1st year activity report) impacting on the starting date of FC tests. This issue has prevented Labor from starting promptly the testing task. A preliminary characterization of the FCs (Nexa Power module and Beijing Fuyuan FYD-200) has been performed by TU Graz, but the integration of the prototype started with a considerable delay.

2) Insolvency procedure of a FC supplier (Palcan). The manufacturer was selected for the delivery of a 300W stack, but, after the negotiation and the order confimation from the Consortium, the company has been closed. The insolvency of Palcan impacted on the Consortium activities, that has seen a delay of three months for the selection of an alternative FC supplier the negotiation and the additional lead time for shipment.

3) Enhanced model of the power system. Seeing the limited choice on the FC market, that impacted on the availability of data for the expert system design, the Consortium decided to exploit more resources, made available to LABOR by UniTorv, to refine the model that describes the overall power system.

4) Purchase of H_2 MH tanks. UniTorv proposed to the Consortium the purchase of the tanks as off-the-shelf component. The Technical Annex was not up-to-date with the latest market proposals, and no relevant innovation was expected during the design and manufacture of the tanks, with respect to the suitable solutions identified as results of the project activities.

All these problems have been faced and proper solutions identified implemented. However an extension of 6 months of the project duration was required and accepted.

SECTION 2 Workpackage progress of the period

2.1 WP4: LABORATORY TESTING

2.1.1 Objectives

Overall objectives:

Perform laboratory testing

Task 4.1 Controller design and prototyping – Labor will realise the controller which will manage the FEMAG generator; the system will interface the controller board embedded into the FC, and manage all the phases of charge and discharge of components. The system will be equipped with a MCU with an ADC unit, with temperature and flow sensors and power switching devices. The following parameters will be constantly measured:

Current flow from the cell	ultracapacitor state of charge
Input/output current from the ultracondenser	Ambient temperature
Input/output current from the battery	Temperature of ultracapacitor
Hydrogen flow	Cell temperature
Battery state of charge	

Data will be constantly monitored to detect possible malfunctions and than operate protection devices to avoid damages to the components; the system will be totally parametrical, the MCU will operate DC and PWM commutations of the components to optimise efficiency and range of the systems, by means of medium power MOS-FET devices according to pre-ser management strategies. The MCU will store on EEPROM operating values.

The controller will be prototyped and debugged, that a second sample will be realised.

Task 4.2 Dedicated test bed – Labor will design and develop a testing system to replicate the load profiles defined in WP2; it will consist in a variable electronic load to be purchased, ranging from 0 to 1.5 kW, interfaced with a monitoring tool realised with LABVIEW; the FEMAG prototype will be also instrumented to monitor significant parameters, such as currents, voltage, temperature; a high frequency ADC converter will be used to monitor current peaks with high resolution; a dedicated data acquisition board will be realised by Labor.

Task 4.3 Realisation of FEMAG prototypes – all necessary components will have been purchased or procured, and Labor will assemble two FEMAG prototypes in its laboratory, with the support of UNITOV and AGT; one prototype will be characterised by a cell nominal power in the lower range of the investigation area (125-250W) and the other one in the upper one (500 –1000 W)

Task 4.4 Design of experiments – a rigorous testing approach will be implemented by Labor and MOLNET by means of Experimental Design; this approach allows to maximise the output of an experimental phase, in full compliance with external existing constraints, typically economical; in this phase the “phenomenon” under experimentation will be described in such a way that a set of comprehensive input and output variables will be defined, including cost issues of the final system. With the use of SNIPER, a specialised and powerful tool for ED, the initial approach of the experimental phase will be designed. The components are varied according to the ED requirements such that each experiment differs in at least one component specification from any other experiment of the series.

Task 4.5 Laboratory testing and optimisation – the two prototypes will be tested by the test system developed in Task 5.1; the system will undergo the prototypes to the classes of load profiles defined in Task 2.3.

2.1.2 Progress

As said above, the WP4 should have been completed during the first year of the FEMAG project but the late availability of the chemical laboratory in Labor premises, because of a (very) late delivery by the external supplier, has delayed the activity.

The following is the progress task by task realised in the first year:

- Task 4.1 has been completed.
- Task 4.2 is on going
- Task 4.3 should have been completed at month 11 but is till on going.
- Task 4.4 has been completed
- Task 4.5 should have been stated at month 12 but did not start yet, depending on the completion of Task 4.3

Therefore, tasks 4.2, 4.3 and 4.5 have been completed in the second year.

Two complete FEMAG prototypes have been assembled and tested:

- Prototype HIGH ENERGY, composed by a 1.5 kW MES-DEA Fuel Cell stack, 6 58F/15V supercapacitors pack, 3 1000 Nl metal hydrides Treibacher tanks and the innovative DC/DC converter which manages the priority of intervention according to the FEMAG philosophy. A test-bench has been realised and a complete measurement system installed.
- Prototype LOW ENERGY, composed by a 200 W Beijing Fuyuan Fuel Cell stack, a 10F/50V Nesscap supercapacitor, 2 300 Nl metal hydrides UDOMI tanks and the innovative DC/DC converter, integrated on a wheelchair and tested on field. The Low Energy prototype has been directly tested on field, integrating it in a wheelchair for disable people in order to evaluate the performance of the FEMAG power generator.

The test and measurement layout which has been developed has the target to provide an adequate amount of information about the performance of the hybrid system proposed by FEMAG, which is composed of the aggregation of the following items:

- a fuel cell
- a supercapacitors pack
- a low pressure metal hydrides system for hydrogen storage
- a controller with its built in control strategy

Such a system is supposed to be evaluated respect to the capability to supply **highly dynamic variable loads** (power vs. time) at given electrical specifications (e.g. nominal voltage of an electric motor).

The proposed philosophy of the FEMAG generator consists in making it possible that instantaneous load fluctuations with different dynamics are supplied by one specific component showing the best matching with such dynamics; in very simple terms, this means that the supercapacitors are supposed to supply the highest peaks, the fuel cell the steady load, the backup battery is supposed to enter the playground only when the other two mentioned components are not able to perform for their insufficient instantaneous available power rate (please read D2.2 for further details).

The proposed monitoring and measurement system is required to monitor and provide information not only about the capability of the overall aggregated system to supply conveniently the variable load, but also to inform **about the power transfers which take place among the components during transients**; this information is necessary to improve the control system of the FEMAG generator, optimising power flows, priority of intervention of components respect to the load and charging/discharging phase with the aim of cope with the largest load dynamics.

As a consequence, a relatively high number of measurement points is required; the resolution of the measures has also to be defined according to the load dynamic.

FEMAG requires also the generation of a high number of test information in order to generate the knowledge base required to produce an expert system for the automatic sizing and dimensioning of a FEMAG class generator respect to a generic load, even if this requirement has been mitigated by the development of a system model in Matlab Simulink to be used simultaneously; it is therefore necessary to develop a system which is very friendly in its use, allowing a simple definition of variable test conditions and production/management of output measures.

In order to satisfy such requirement, it has been decided to develop a specialised SW architecture with national Instrument Labview, a tool which provides an exceptional capability in managing and representing experimental data, together with the compatibility of a large family of data acquisition HW produced by National Instruments itself.

Another important issue concerns the possibility of defining easily test conditions corresponding to any possible highly dynamic load; it is therefore required a test system in which the boundary conditions can be easily changed, with extensive logging (boundary conditions and test results) .

The consortium has developed in Labview a simple and effective system to create, replicate, edit and store test conditions corresponding to large variety of real conditions.

It has to be reminded that this test system is necessary to test the FEMAG prototype versus the capability to perform a high number of cycles, in correspondence of every load profile configuration; therefore tests are supposed to last quite long, and a considerable amount of data is expected to be generated; the easy management and visualisation of these data has to be taken into account.

The main outcome from the FEMAG project was expected to be the assembly of two prototypes integrating the FEMAG advanced hybrid generator architecture. In particular, these prototypes should demonstrate the ability of the power system to cope with different kind of loads; to that end, two demonstration systems were built, targeting different applications:

1. a wheelchair for disabled people (low-end prototype);

2. an Automated Guided Vehicle (AGV) for the transportation of finished goods inside an industrial area (high-end protype).

Of these two systems, the first has been completely developed: an electric wheelchair has been purchased, and its battery pack and power management section replaced with a “low-end” FEMAG generator, so that an actual FEMAG wheelchair is available for testing in LABOR laboratories.

On the other hand, the AGV prototype has not been actually built, due to its more demanding size and driving range, but a “high-end” FEMAG generator has been assembled in laboratory and subjected, by means of a variable electronic load (already described in D4.3), to the same load profiles that are usually encountered in the normal operation of an AGV.

Both prototypes share the same architecture, based on the FEMAG generator concept (Fig. 5), albeit with different components due their different size and load requirement. More specifically, the physical components implemented are:

1. one PEM fuel cell;
2. a metal hydride tank package for on-board hydrogen storage;
3. a supercapacitor pack;
4. two electronic DC/DC converters;
5. one electronic controller for efficient power management.

It is important to observe that in the actual configuration chosen for the implementation of the prototypes the battery pack, which in the FEMAG concept is supposed to be able to cope both with some steady loads temporarily exceeding the nominal or instant power of the FC, or also contributing to supplying peak loads together with the supercapacitors, has not been included, because simulations carried out with the previously developed model of the FEMAG system (D2.2) based on the typical loads of the applications for which the prototypes have been developed, showed that the battery pack would not have been much used by the system. Eliminating this component from the system, therefore, helps greatly in reducing its size and weight, without compromising its effectiveness.

The architecture of the FEMAG HE (High End) prototype differs from the general FEMAG architecture in that the blocks SR1 and SR3 are not implemented, since the batteries stack is not integrated into the power train; actually there is a battery, with the aim of powering the fuel cell controller on, but this battery is managed by the FC controller itself and for this reason it could not deliver power to the load. On the contrary the LE generator, installed on the wheelchair, implements a complete FEMAG architecture (where SR1 and SR£ are hosted on the same electronic board) since the fuel cell doesn’t manage the battery by itself.

The two converters have the following tasks (for more details, see D4.1 & D4.2):

- Controller SR1 – this block represents a switching regulator which checks if the Fuel Cell is supplying less than what available and directs the power to the battery pack for recharging. The control feedback is provided by the difference between the current supplied by the Fuel Cell and the current flowing to the load; this also involves implicitly that the supercapacitor stack is recharged with priority respect to the battery, since it is located close to the load, and SR1, Sr2 and SR3 look at it as part of the load itself (the very low internal resistance of the supercapacitors gives it priority).

- Controller SR2 – this block represents a switching regulator which has the task to manage the priority of intervention of the Fuel Cell in supplying the load; the output DC voltage from this block is kept constant until a threshold is reached, corresponding to the maximum steady power which can be supplied by the Fuel Cell; beyond this threshold, the output DC voltage is reduced with the aim of keeping constant the power supplied by the cell; in fact the reduction of the output DC voltage gives priority to the other power sources to supply the load, especially the battery pack.

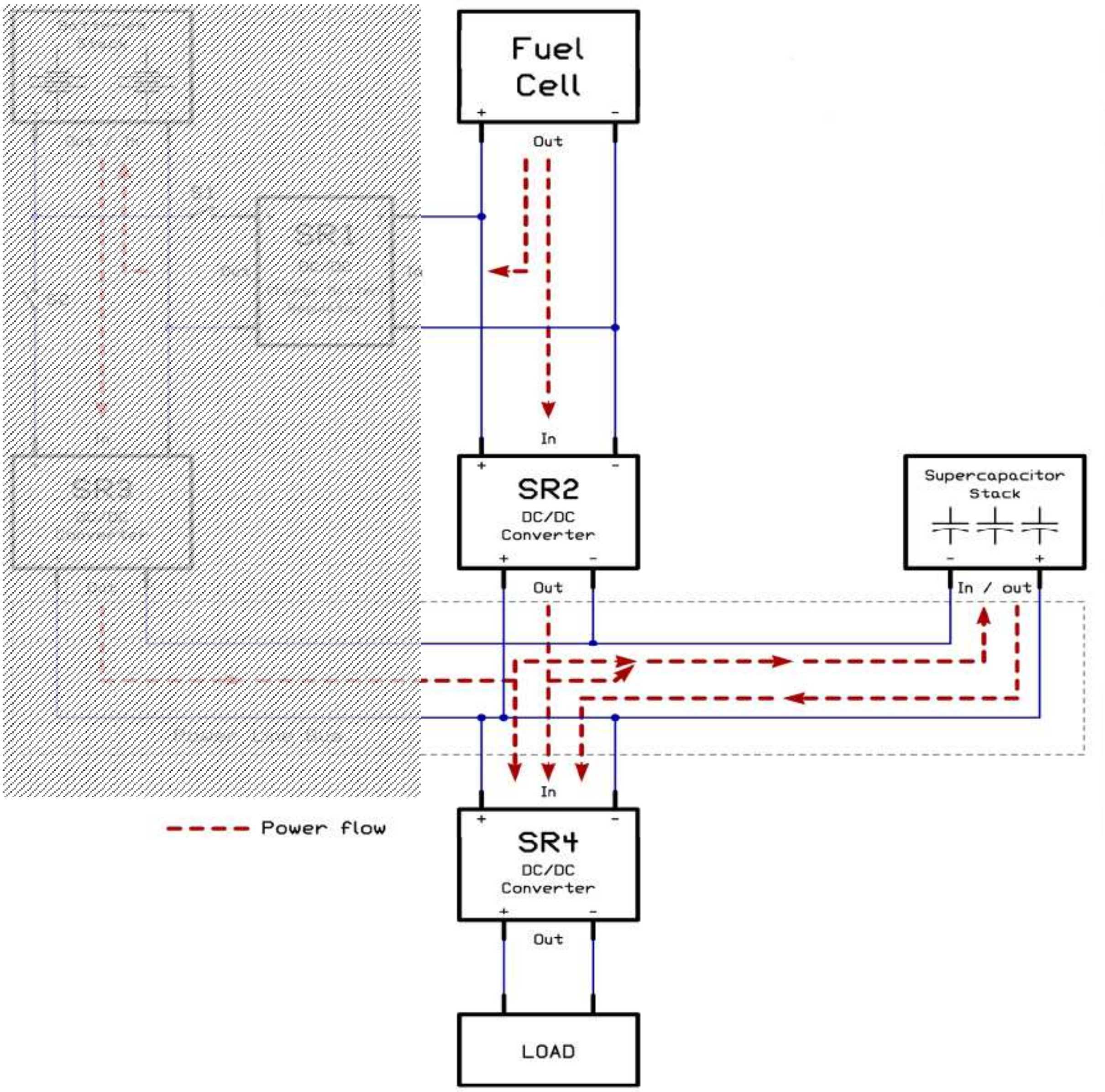


Figure 5 - FEMAG architecture

A series of sensors and data acquisition tools are furthermore used to monitor the prototypes' behaviour under different loads.

The following paragraphs contain a description of each of the abovementioned components.

2.1.2.1 Low-end FEMAG prototype (electric wheelchair)

The fuel cell selected for the low-end application (electric wheelchair) is the FYD 200 manufactured by the Chinese company Beijing Fuyuan Century Fuel Cell Power Limited Corporation (http:\\www.fyfuelcell.com). The architecture of the fuel cell is quite simple, including only the fuel cell stack and an air blower used to feed the stacks with the oxidant (air). The resulting device is rather compact, which is a very positive feature in this particular application.

A pressure regulator and an air filter, which are needed for the proper operation of the fuel cell, have been added in LABOR facilities.

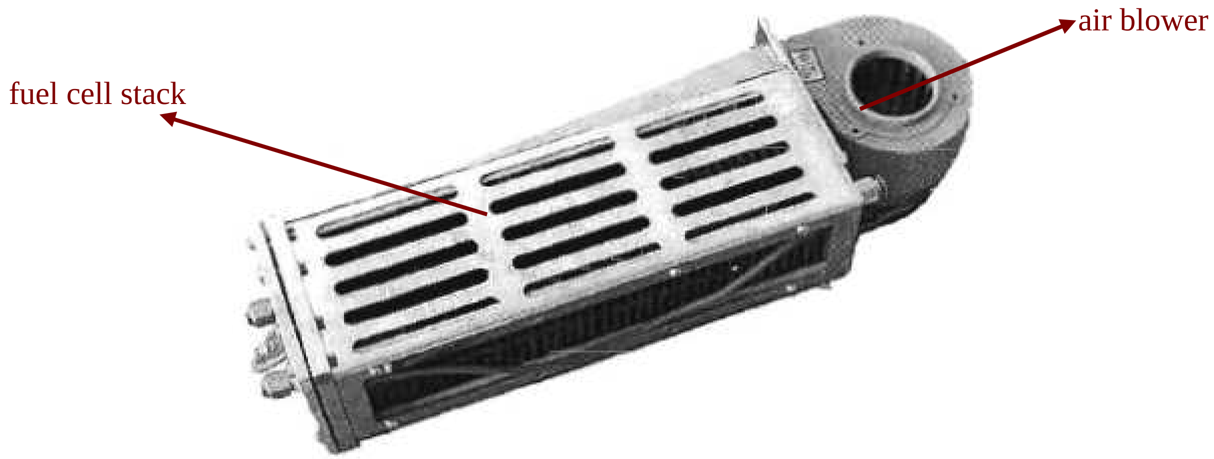


Figure 6 FYD 200 Fuel cell generator

The most important characteristics of this fuel cell are:

- rated voltage: 24 V
- rated current: ≥ 6,5 A
- rated power: 200 W
- max. power: 250 W
- open circuit voltage: ≤ 45 V
- environment temperature range: 5-40 °C
- operating temperature range: 40-70 °C
- operating voltage of air blower: 7-22 V
- fuel pressure: 0,2-0,3 bar(g)
- start-up time: 5 s
- hydrogen purity: 99,98%

The fuel cell voltage vs. current curve is shown in the following figure.

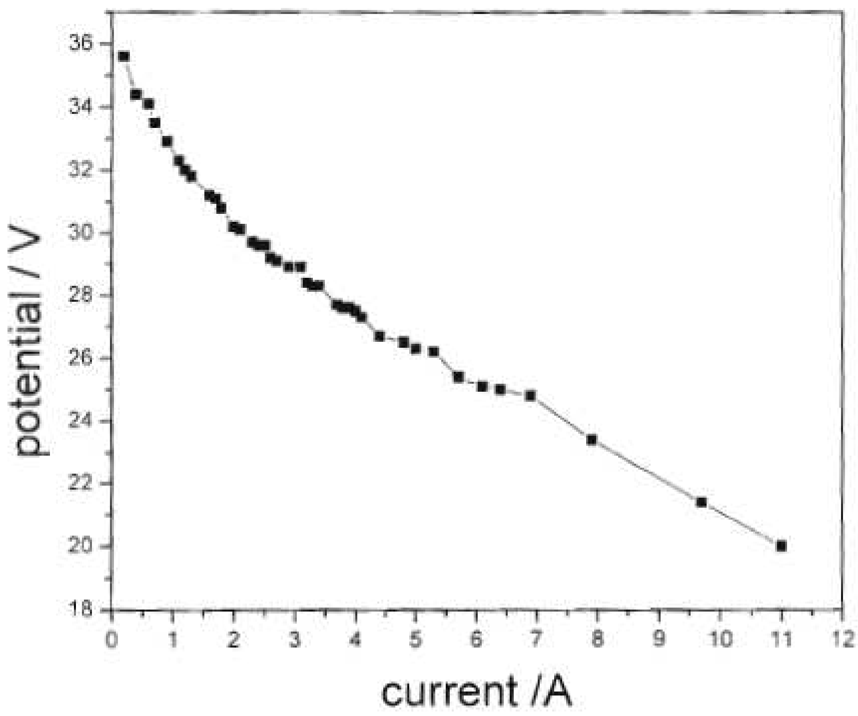


Figure 7– Voltage-current curve of the FYD 200 fuel cell

2.1.2.2 High-end FEMAG prototype (AGV)

The high-end prototype has been equipped with a fuel cell manufactured by the Swiss company MES-DEA sa (www.mes-dea.ch). The DEA 1.5 fuel cell, still a prototype product, is composed by the fuel cell stack, the feeding air blower and the cooling air blower (fig. 8). It has the following technical specifications:

- max. power: 1,5 kW
- unregulated DC output voltage: 36-57 V
- number of cells: 60
- hydrogen consumption at full load: 20 stl/min (0,1 kg/h)
- max. operating temperature stack: 63 °C
- hydrogen pressure: 0,4-0,5 bar(g)
- ambient temperature: 0-35 °C
- type of cooling: forced air cooling
- stack size: 410 x 235 x 140 mm
- stack weight: 4,5 kg
- overall system weight: 7 kg

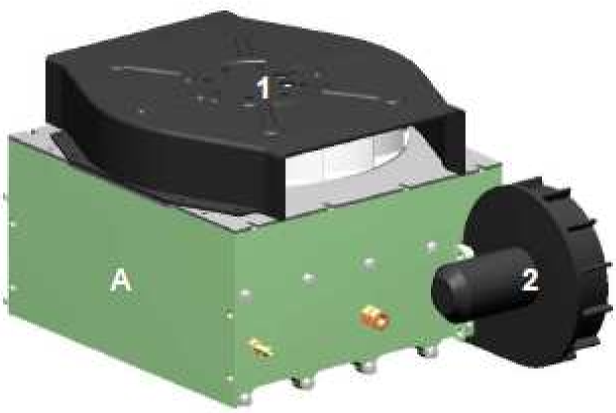
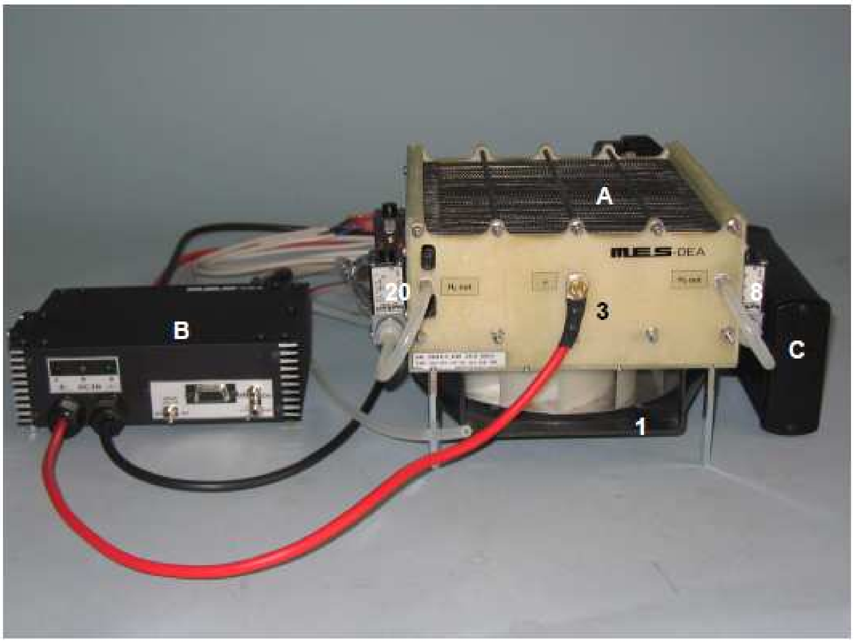


Figure 8 - 1.5 fuel cell: (A) fuel cell stack; (1) cooling air blower; (2) feeding air blower



The previous figures show in detail the overall architecture of the whole DEA 1.5 system, including the fuel cell stack with its auxiliaries (fig. 9), the Electronic Control Unit (ECU, and the cooling blower control unit. The numbers and letters in the figures designate the following components:

A: PEMFC stack	5: hydrogen inlet	13: status LED
B: ECU	6. hydrogen purging	14: serial comm. port (RS232)
C: Cooling blower control unit	7: hydrogen main valve	15: signal cable connector
D: Signal wiring	8: hydrogen purging valve	16: starting power cable
1: cooling air blowers	9: start/stop switch	17: external start/stop cable

2: reaction air blower

3: power output terminal (+)

4: power output terminal (-)

10: DC In cable (+)

11: DC in cable (-)

12: DC out cables (load)

18: short circuit on/off switch

19: power on/off switch

20: hydrogen auxiliary valve

21: temp. sensors connectors

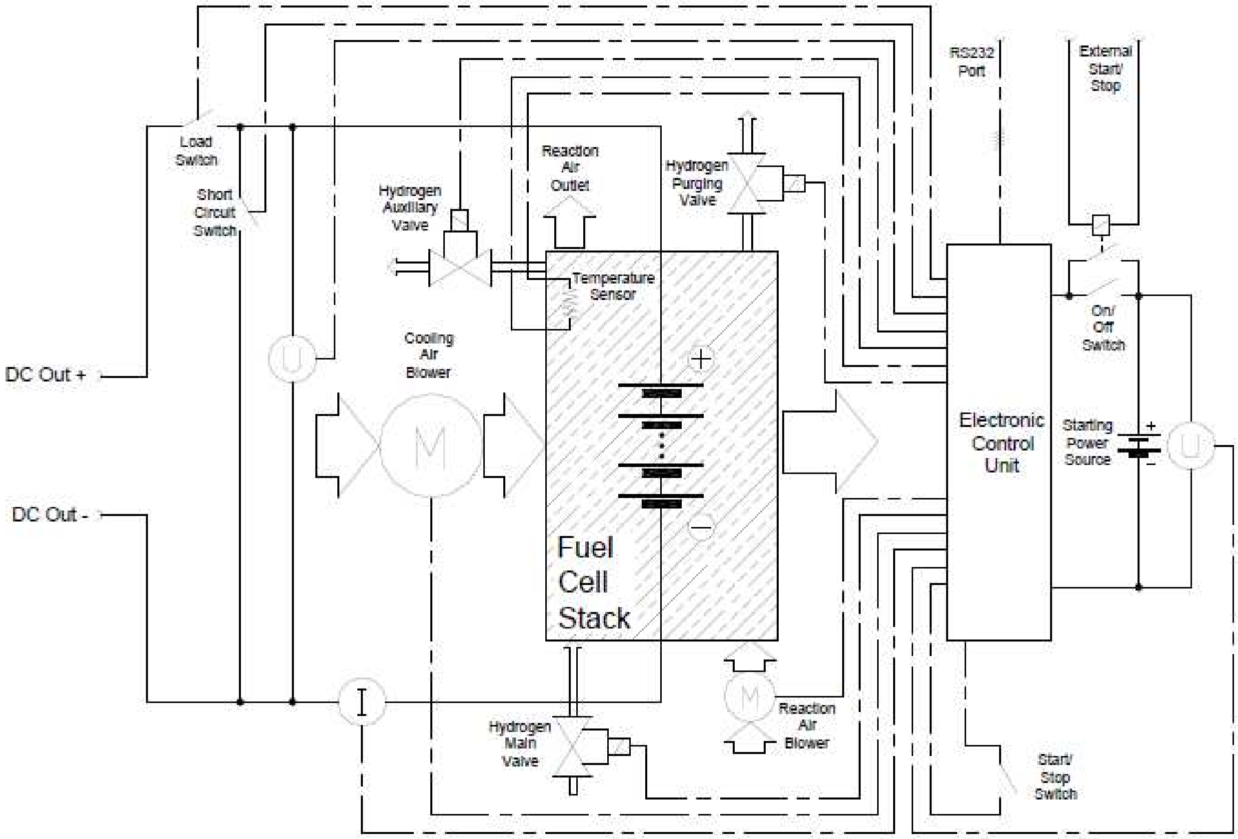


Figure 9 - Simplified DEA 1.5 circuit diagram

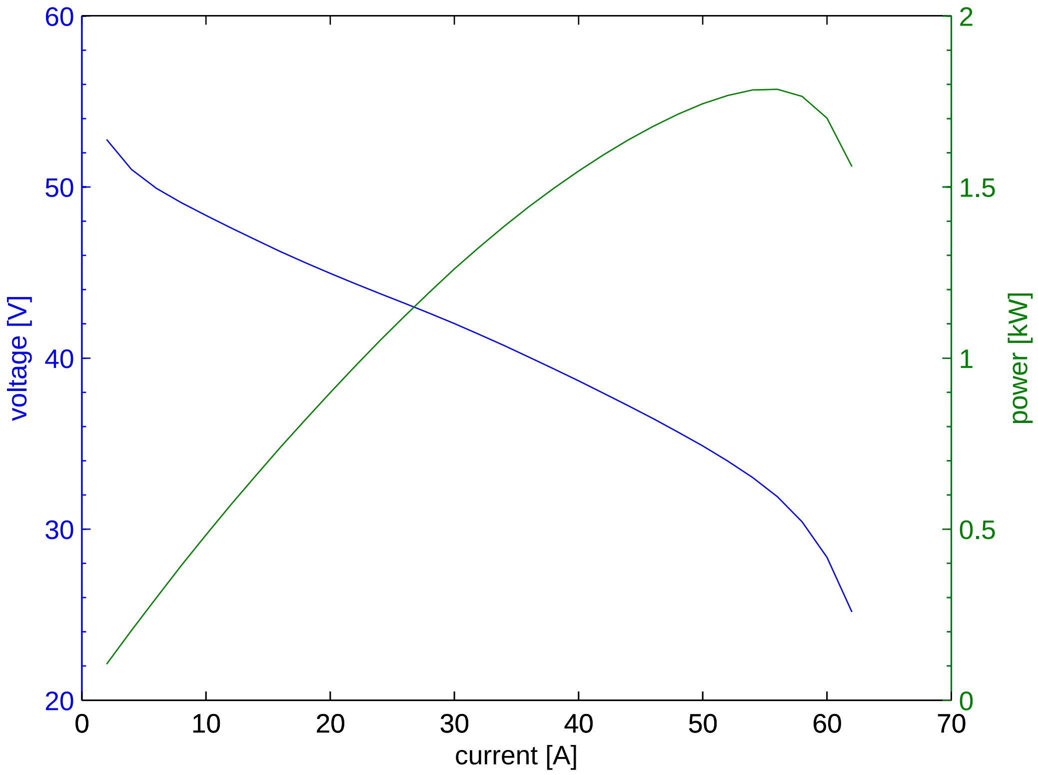


Figure 10 - Performance curves of the DEA 1.5 fuel cell

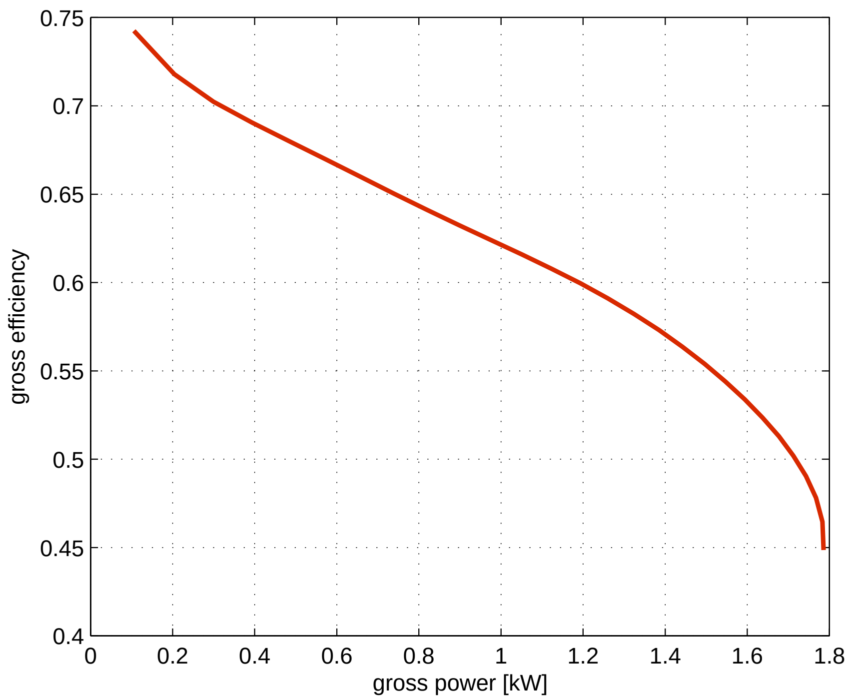


Figure 11 - Fuel cell efficiency based on hydrogen LHV

The last figure shows the efficiency of the fuel cell stack as a function of gross power output. The efficiency has been calculated as the ratio of the single cell voltage (which has been provided as a function of current by the manufacturer) and the theoretical voltage which could ideally be obtained from the reaction of hydrogen to water vapor, which is 1,185 V.

It is important to observe that the efficiency thus obtained does not take into account the auxiliaries that are directly related and connected to the fuel cell, whose power consumption can be estimated at full load as approximately 300 W (fig. **Errore. L'origine riferimento non è stata trovata.** shows that the max. gross power is 1,8 kW, while the max. net power which can be obtained from the fuel cell system is 1,5 kW).

2.1.2.3 Other fuel cells

For the low-end prototype, one module from the German company Staxon, namely the FC40/HLC, has also been tested in LABOR facilities. It is a water-cooled, 360 W PEM fuel cell. Although its modular structure and its nominal performance were quite interesting, this fuel cell was in the end discarded because of the difficulties encountered in the coolant-circuit management and also because of the high power consumption of the auxiliaries (which are not included in the system supplied by the manufacturer). Furthermore, during the tests the fuel cell did not meet the performance declared by the manufacturer, probably because of flooding problems that were not easy to manage. In the end, the fuel cell from Beijing Fuyuan was selected, even though less powerful than the one from Staxon, because the application on an electric wheelchair certainly requires that the overall system be as simple and as smoothly connected as possible.

For the high-end prototype, on the other hand, the NEXA fuel cell from Ballard (see also D2.1) was also extensively tested. Its performance and ease of management are quite impressive, and it has not been chosen for the FEMAG application only because of its considerable size and weight (which are explained by the many auxiliaries and control systems that are implemented on board the fuel cell).

2.1.2.4 Hydrogen Storage

On-board hydrogen storage is achieved, on FEMAG prototypes, using metal hydride tanks. It is worth to remind the main reasons why this storage technology was chosen against its current commercial competitors, namely compressed and liquefied gas.

Compressed gas tanks clearly represent the easiest and quickest method to solve the storage problem, but it raises much concern for its safety features, because it requires very high pressures (tanks up to 700 bar are now being tested) in order to achieve useful storage densities. In the case of the FEMAG prototypes, these concerns must obviously be carefully taken into account.

On the other hand, cryogenic tanks, even though they currently offer the highest storage densities, are certainly not a practical solution, due to their complex management and power requirement, for the FEMAG prototypes, which require instead a safe and easy to manage solution.

Therefore, metal hydrides represent the best available solution for the FEMAG application, since they offer high storage volumetric densities at very low pressures[1]. The main drawbacks of this technology, which prevent its widespread application, when compared to the other hydrogen

[1] M. Gambini, M. Manno, M. Vellini, Metal Hydride Storage Systems: State of the Art Analysis and Integration in FC-Based energy Systems, Proceedings of HYPOTHESIS VII, Merida, Mexico, March 27-30, 2007.

storage technologies, are its poor gravimetric density and slow hydrogen release kinetics. In this case, however, these problems are not particularly significant because metal hydrides' energy storage gravimetric density is anyway higher than that of batteries, which are currently used to power the same applications that represent FEMAG target, and because in the FEMAG architecture it is not the fuel cell but the supercapacitors that respond to the fastest-changing loads.

As a matter of fact, metal hydrides are being used ever more frequently not only in stationary applications (where their disadvantages are less important) but also in portable ones[2], and FEMAG represent one of the first practical proposals to enter also the mobile applications niche.

After these preliminary considerations, it is possible to show the systems that have been implemented in the FEMAG prototypes.

Low-end FEMAG prototype

In this case the best solution found on the market was offered by the German distributor udomi (www.udomi.de), which imports in Europe the metal hydride tanks produced by the Chinese company Tianjin Highland Energy Technology Development Co., Ltd (www.tjhighland.com). The FEMAG prototype for the electric wheelchair is equipped with two MH500 tanks, the main characteristics of which are given below:

- Dimensions: (LxD) 380 mm x 56 mm
- Weight: 5 kg
- Vessel Material: Stainless Steel
- Storage Capacity :500 sl (standard liter)
- Connector: Quick coupling
- Discharge Pressure: 0.5 MPa @ 20°C
- Flow Rate: 3 sl/min (RT 25°C, no heat supply), 7sl/min (20°C water bath)
- Recharge Time: ≤ 30 min, 20°C water bath

The mass of hydrogen stored in the FEMAG prototype is therefore equal to 89,9 g (standard density of hydrogen, at 1,01325 bar and 0 °C, is 0,0899 kg/m^3), with a chemical energy, based on hydrogen's LHV of 120 MJ/kg, corresponding to 3,0 kWh.

The available useful energy can be obtained by means of an average overall efficiency of the power generator, including all devices and converters, which can be estimated (rather pessimistically) as 40%: the resulting useful energy is therefore 1,2 kWh, which is more than adequate to power the electric wheelchair for which this system is intended.

[2] Jadoo Power Systems, Fuel Cell Power Systems for Professional Video Camera Applications, white paper, 2004, available online at http://www.broadcastpapers.com/whitepapers/JadooFuelCellPower.pdf.
C. Potera, Beyond Batteries: Portable Hydrogen Fuel Cells, Environmental Health Perspectives, **115**, 1, pp. A38-A41, 2007.

Figure 12 - MH500 metal hydride tank

High-end FEMAG prototype

In this case, the tanks were purchased from the Austrian company Treibacher AG (www.treibacher.com). In particular, the FEMAG prototype for the AGV is equipped with 2 MHS-1000IHE, where the number 1000 designate the nominal capacity in standard litres, and the acronym "IHE" indicate that the tank contains an Internal Heat Exchanger for fast recharging using cold water in order to limit the temperature increase of the metal hydride during the absorption process, so as to obtain good kinetics for the hydriding reaction[3].

The main characteristics of the MHS-1000IHE unit are:

- nominal capacity: 1 Nm^3
- storage alloy: AUERSTORE©, a patented AB2-type alloy containing Fe, Mn, Ti, V, Zr
- tank overall volume: 2,5 l
- approx. dimensions (LxD): 500 mm x 115 mm
- tank weight: 13 kg
- max pressure: 100 bar
- max pressure for charging: 30 bar
- working temperature: up to 65 °C
- vessel material: stainless steel
- equilibrium pressure: ~5 bar @ 25 °C, ~13 bar @ 40 °C (mid-plateau)

It is worth to observe that the MHS1000IHE storage unit is a pressure vessel manufactured, tested and certified according to TPED ("Transportable Pressure Equipment Directive") 99/36/EC.

[3] P. Muthukumar; M.P. Maiya; S.S. Murthy, Experiments on a metal hydride based hydrogen compressor, International Journal of Hydrogen Energy, **30**, 8, pp.879-892, 2005.
M. Gambini, M. Manno, M. Vellini, Numerical analysis and performance assessment of metal hydride based hydrogen storage systems, Proceedings of HYPOTHESIS VII, Merida, Mexico, March 27-30, 2007.

Figure 13 - Storage tank from Treibacher AG to be used in the high-end prototype

Based on the same considerations developed for the low-end prototype, it is possible to estimate the useful available energy for the high-end prototype as 4,8 kWh, because the amount of hydrogen stored is exactly four times that of the low-end prototype, and the efficiency should be approximately the same.

2.1.2.1 Supercapacitors

Low-end FEMAG prototype

The supercapacitors to be assembled in the low-end FEMAG prototype have been purchased from NESSCAP (www.nesscap.com), a company based in South Korea specialized in the manufacture of supercapacitors. For this FEMAG application the pre-assembled supercapacitor pack with 10 F capacitance and 50 V maximum voltage has been deemed adequate to its task.

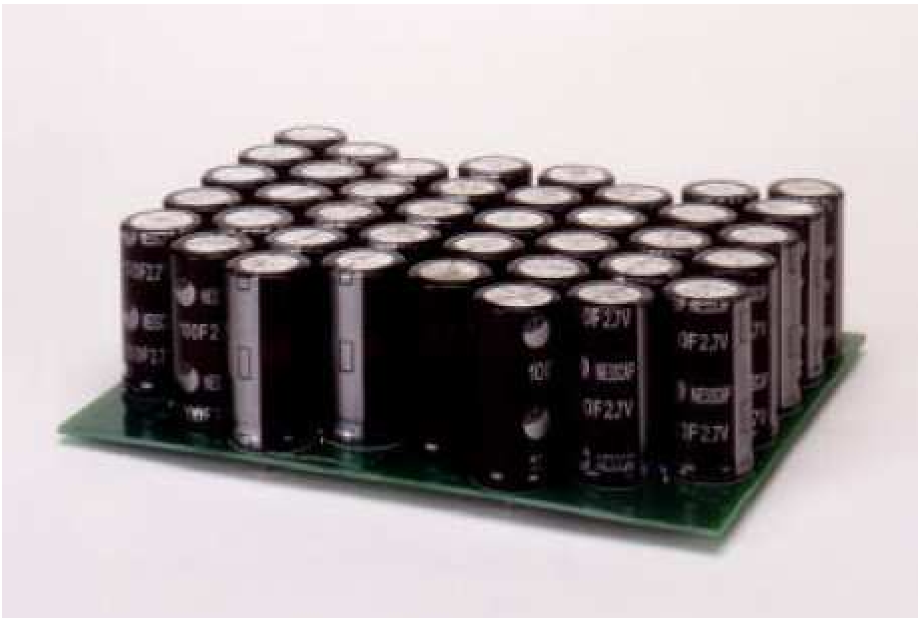


Figure 14 - 50 F, 10 V supercacitor pack by NESSCAP

The pack contains 40 single 100F/2,7V supercapacitors with 20 serial and 2 parallel connections in order to obtain the desired capacitance and voltage. The technical specifications of this package are given in the table below.

Rated Capacitance, C (DCC[1], 25°C)		10 Farads	(1) Discharging with constant current
Capacitance Tolerance		-10% / +20%	
Rated Voltage, V_R		50 V	
Surge Voltage		54 V	
Rated Current (25°C)[2]		38.8 A	(2) 5 sec discharge rate to 1/2 V_R
Max. Current (25°C)[3]		> 106 A	(3) 1 sec discharge rate to 1/2 V_R
Max. Stored Energy (at V_R)		12500J (3.472 Wh)	
Specific Energy	Gravimetric		
	Volumetric		
Specific Power[4] (at matched load)	Gravimetric		(4) Power density at which one-half the energy of the discharge is in the form of electricity and one-half is in heat.
	Volumetric		
Maximum Internal Resistance (ESR)	AC (1kHz)	105 mΩ	
	DC (10A)	135 mΩ	
Dimensions			
Volume			
Weight			
Operating temperature range[5]		-40 ~ 60 °C	(5) |ΔC|< 20% and ESR < 2 times of initially measured value at 25°C, respectively
Storage temperature range		-40 ~ 70 °C	
Max. Leakage Current, L_C(12h, 25°C)		3.4 mA	
Life Time at RT [6]		10 years	(6) |ΔC|< 30% and ESR < 2 times of initially measured value, respectively and LC < specified value
Cycle Life (25°C)[6], [7]		500,000 cycles	(7) 1 cycle: charging to V_R for 20s, constant voltage charging for 10s, discharging to 1/2V_R for 20s, rest for 10s

On the other hand, the technical specifications of the single 100 F, 2.7 V supercapacitor are as follows:

Rated Capacitance, C (DCC[1], 25°C)		100 Farads	(1) Discharging with constant current
Capacitance Tolerance		-10% / +20%	
Rated Voltage, V_R		2.7 V	
Surge Voltage		2.85 V	
Rated Current (25°C)[2]		21.4 A	(2) 5 sec discharge rate to 1/2 V_R
Max. Current (25°C)[3]		> 58.7 A	(3) 1 sec discharge rate to 1/2 V_R
Max. Stored Energy (at V_R)		364.5J (0.1013 Wh)	
Specific Energy	Gravimetric	4.50 Wh/kg	
	Volumetric	5.92 Wh/l	
Specific Power[4] (at matched load)	Gravimetric	6.23 kW/kg	(4) Power density at which one-half the energy of the discharge is in the form of electricity and one-half is in heat.
	Volumetric	8.20 kW/l	
Maximum Internal Resistance (ESR)	AC (1kHz)	10 mΩ	
	DC (11A)	13 mΩ	
Dimensions		ϕ 22 x *l* 45 mm	
Volume		17.1 ml	
Weight		22.5 g	
Operating temperature range[5]		-40 ~ 60 °C	(5) |ΔC|< 20% and ESR < 2 times of initially measured value at 25°C, respectively
Storage temperature range		-40 ~ 70 °C	
Max. Leakage Current, L_C(12h, 25°C)		1.7 mA	
Life Time at RT [6]		10 years	(6) |ΔC|< 30% and ESR < 2 times of initially measured value, respectively and LC < specified value
Cycle Life (25°C)[6], [7]		500,000 cycles	(7) 1 cycle: charging to V_R for 20s, constant voltage charging for 10s, discharging to 1/2V_R for 20s, rest for 10s

High-end FEMAG prototype

The supercapacitors for the high-end prototype were chosen from the BOOTSCAP® series (model BPAK0052 P015) produced by the American company Maxwell Technologies (www.maxwell.com). Size and weight of each supercapacitor are:

- volume: 0,566 l
- length: 216 mm
- width: 69 mm
- height: 38 mm
- mass: 500 g

Its main characteristics are:

- rated voltage: 15 V
- capacitance: 52 F
- energy stored (½V^2/C/m): 3,25 Wh/kg

In order to reach the output voltage required for this application (90 V), 6 supercapacitors have been connected in series. The resulting capacitance is therefore 8,67 F.

The following table gives more insight into the technical specifications of the selected supercapacitor.

Item	Product Specification	
Operating Temperature Range	-40 °C to +65 °C	
Storage Temperature Range	-40 °C to +70 °C	
Rated Voltage	15 V DC	
Capacitance Tolerance	+/- 20%	
Resistance Tolerance	+/- 25%	
Temperature Characteristics	Capacitance Change	Within ± 5% of initial measured value at 25 °C (at -40 °C)
	Internal Resistance	Within 150% of initial measured value at 25 °C (at -40 °C)
Endurance	After 1000 hours application of rated voltage at 65 °C	
	Capacitance Change	Within 20% of initial specified value
	Internal Resistance	Within 25% of initial specified value
Shelf Life	After 1000 hours storage at 65 °C without load shall meet specification for endurance	
Life Test	After 10 years at rated voltage and 25 °C	
	Capacitance Change	Within 20% of initial specified value
	Internal Resistance	Within 100% of initial specified value
Cycle Test	Capacitors cycled between specified voltage and half rated voltage under constant current at 25 °C (500,000 Cycles)	
	Capacitance Change	Within 20% of initial specified value
	Internal Resistance	Within 100% of initial specified value