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$RenH_2$ – A Stand-Alone Sustainable Renewable Energy System

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1. Introduction

Rural and remote sites electrification, where grid connection is almost impossible in terms of cost and geography, is nowadays an important market for renewable energy based electricity production systems. It is becoming largely consensual that autonomous electricity production systems based on renewable energies are the most competitive economical option, when compared with solutions based only on conventional diesel generators.

The main issue, related with renewable energy based autonomous systems, is the intermittent nature of the renewable resources, namely, solar and essentially wind. The variability of these renewable energy sources turns difficult its synchronisation with the load pattern. Therefore, some sort of additional regulation systems capable of performing such matching are required. In the past, conventional diesel generators have been the preferred solution to ensure the perfect balance between generation and load. In most cases, batteries are associated as a low energy storage device, in order to somehow lighten the diesel generator operation. These types of systems fall under the general classification of *hybrid systems*.

It is well-known that diesel generators have several disadvantages, the main ones being that its operation is far from being environmental friendly and the fuel is difficult and expensive to provide at remote sites. Thus, the current trend is to focus on energy storage solutions that are able to dismiss the diesel generators. The basic general idea is to store the energy produced in excess during low demand periods and to recover it in the peak hours.

However, the problem remains as the basic conventional energy storage solution is battery-based. Batteries are being worldwide used for ages and its technology is nowadays maturing, reliable and very well understood. Most batteries used in hybrid systems are of the lead-acid type. There are several other types, such as, nickel-cadmium, lithium-ion, but these are generally either too expensive or too unreliable for practical application. In spite of their numerous advantages, battery technology has experienced little advances in recent years. Their known drawbacks, such as low energy density, limited number of full discharge cycles, self-discharge and environmentally unfriendly characteristics, still persist. Therefore, batteries are only envisaged as short-term storage devices.

In order to minimise these recognised pitfalls, alternative energy storage solutions have come to force. One of the most promising is the production of hydrogen through the electrolysis of water. This hydrogen is to be subsequently used to generate electricity through fuel cell technology or even in a combustion engine linked to an electrical generator. The same basic idea as for batteries applies: electrical energy in excess during off-peak hours is used to produce hydrogen, which is later used to generate electrical energy in high demand periods. In this way, the known limitations of the diesel/battery solutions are overcome and a cleaner and more efficient stand-alone electrical production system is achieved. Moreover, hydrogen is an environmentally benign and sustainable fuel and provides long-term storage facilities.

The main objective of this project is the development of a fully autonomous system, in which every component is based upon renewable energies. In this way, a renewable energy autonomous production system based on the hydrogen technology is proposed. This type of systems can be designated as *Stand-Alone Sustainable Renewable Energy System* (SASRES).

The proposed SASRES is composed by three generators – PhotoVoltaics (PV), wind turbine (WTG) and fuel-cell (FC), two loads – an effective load bank and an electrolyser, two buses – AC and DC, and several advanced power electronics converters. Briefly, the system runs under two basic operating modes: 1) whenever there is enough PV and wind power available, the load is supplied through these generators and hydrogen is produced in the electrolyser; 2) when the load demand is higher than the renewable based generators production, the load is supplied from the operation of the fuel-cell. It is worth to mention that the successful integration of multiple generating sources must rely on complex controls to ensure correct sharing of the intermittent renewable energy and controllable fuel-cell generation to meet the demand of the variable load. A general scheme of the overall system is presented in Fig. 1.

The obtained system is a suitable choice regarding the actual stand-alone systems based upon diesel generators and lead-acid batteries. Several benefits can be listed as far as the proposed hybrid PV/WTG/FC system is concerned: improved reliability and energy services, zero emissions and noise pollution, continuous power, increased operational life and efficient use of energy. Therefore, this hybrid system meets the sustainability and environmental respect criteria regarding the energetic solutions of the future – zero emitting either on production or consumption.

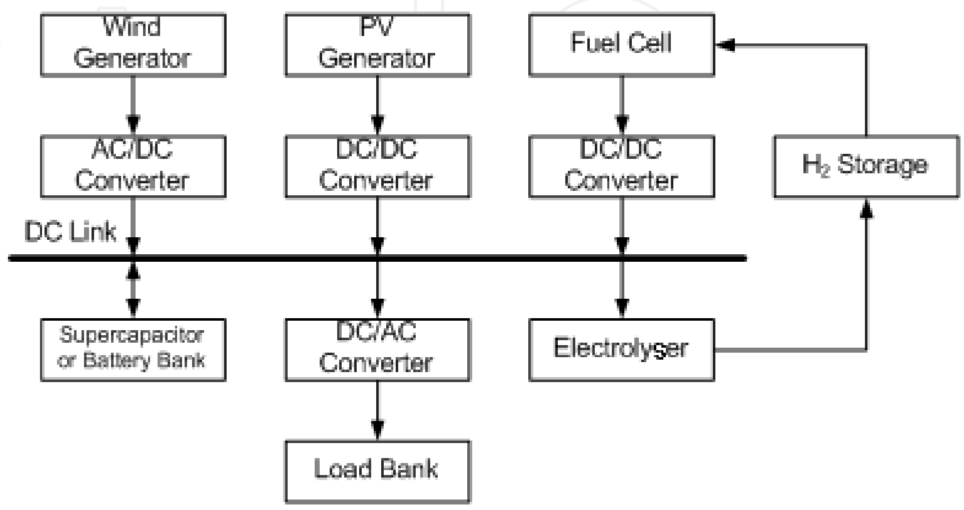

Fig. 1. General scheme of the overall system

This paper presents the proposed PV/WTG/FC stand-alone system supported by totally renewable hydrogen production. The dedicated experimental test prototype is described and the correspondent modelling approach of each component and overall system is introduced. The principles of the implemented control strategy are presented, so that proper behaviour of the system is achieved and its operation can be predicted. Some results obtained both from the experimental test facility and from the implemented software model are presented and discussed. Finally, some conclusions regarding the overall behaviour of the system and the sizing of its components are drawn.

Proposed innovations

Taking the performed state of the art assessment into consideration, several innovations can be found in the proposed SASRES. Although those innovative aspects are identified in the core of the paper, hereafter we list the three most significant ones.

1. No diesel generator is foreseen what makes the proposed system a real SASRES, as it is totally based on renewable resources. This way, energy production is clean and environmentally friendly with no CO_2 emissions.
2. The layout of the SASRES is remarkably elegant. All the generators are connected to a common DC bus and all the loads are connected to an AC bus.
3. Advanced power electronics is used in order to provide efficient power management. This allows dismissing the battery, which is another significant environmental benefit.

2. Brief Review of the Literature

Hybrid renewable based systems with hydrogen storage have been in recent years and are currently still being a highly demanded research topic. A lot of research is being done, making it impossible to take account of all the relevant published research on the topic. To offer the reader some technical guidance, this chapter is divided into sections, each one concerning a particular research domain.

2.1 Demonstration projects

A number of demonstration hybrid renewable based systems are in operation all over the world. Based on (Sovacool et al., 2006), three examples of such systems, located in Europe, are presented in chronological sequence.

In the island of Utsira, Norway, the first large-scale test wind-hydrogen system has been installed in 2004 and is described by (Nakken et al., 2006). The plant produces hydrogen through an electrolyser when there is excess of wind energy available; it provides electricity to domestic customers via a fuel cell and a hydrogen combustion engine when the wind turbine slows or stops. The main components of the system are: i) a 600 kW WTG; ii) a 48 kW (10 Nm^3/h) electrolyser; iii) a 5 kW compressor to increase the pressure of the hydrogen to a maximum of 200 bar; iv) a 12 m^3 H_2-storage tank having enough capacity to cover the customer's demand for 2-3 days with low wind; v) a 10 kW fuel cell and a 55 kW hydrogen combustion engine/generator; vi) a 5 kWh flywheel and a 100-kVA synchronous machine stabilizing the local grid; vii) and a 35 kWh battery providing emergency back-up power. The domestic customers connected to the plant have a peak demand of approximately 50 kW. (Nakken et al., 2006) states that after one year of operation, an average availability of approximately 90% has been achieved and the power quality is reported to be good.

At the northernmost part of the United Kingdom, in the island of Unst, 200 miles north of the Scottish mainland, a hybrid wind-hydrogen energy system is in operation since 2005, in the framework of the PURE (Promoting Unst Renewable Energy) project. (Gazey et al., 2006) explains that on the island, two 15 kW wind generators, whose design is based on the concept of using a permanent magnet generator and a direct drive, provide electrical heating for five office buildings. During times of low electricity demand or high wind speeds, the WTG send their excess electricity to a hydrogen electrolyser. This device demands between 2 and 7 kW to produce a daily average of 2 kg of hydrogen daily. Stored in a high-pressure container, the hydrogen is then dispensed to fill hydrogen canisters that power a hybrid electric car with a 1.2 kW daily plug power fuel cell. The system also contains a 5 kW backup power supply that utilizes another fuel cell and inverter. This system uses the hydrogen to power the office buildings during the times of no wind turbines operation.

Another demonstration project exists on the island of Lolland, Denmark, whose details can be found in (Jensen et al., 2007). The project, known as the ''Lolland Hydrogen Community'', opened in May 2007 and intends to be the first full-scale hydrogen demonstration facility for residential fuel cells that generate heat and power. Phase I of the project began in early 2007 with the installation in ten homes of combined heat and power (CHP) units that draw on hydrogen-based fuel cells. A centralized electrolyser splits oxygen from hydrogen, with the latter gas stored in low-pressure tanks that are connected to the fuel cells in the houses. As reported in (Jensen et al., 2007), the demonstration plant consists of an energy container with two 4 kW electrolysis installations and two PEM (Proton-Exchange Membrane) fuel cell stacks with an installed capacity of 2 kW and 7.5 kW. This installation is not directly based on local renewable resources, as the electrolyser requires a mains power supply; however, it is indirectly powered by grid integrated wind generators, following a strategy of production of hydrogen in periods with high wind power and low consumption.

2.2 Research oriented projects

In the framework of EU or governments research funded projects, several installations have been raised and are operating. A comprehensive survey of these projects can be found in (Yilanci et al., 2008), (Zoulias et al., 2008) and (Zini et al., 2009). Some of these projects are hereafter reported.

The EU FP5 project "Cluster Pilot Project for the Integration of Renewables into European Energy Sectors using Hydrogen" (RES2H2 in brief) started in January 2002 and is concerned with the design, installation, operation and optimization of two different wind-hydrogen systems. One unit is installed in Gran Canaria, Spain, the second in Keratea, approximately 40 km south of Athens, Greece. The Greek facility has been in operation for over three years now (started 2005). Details of the Greek installation are available in (Varkaraki et al., 2006) and (Varkaraki et al., 2008), for instance. The system is composed of a 25 kW water electrolyser, metal hydride tanks filled with a LaNi5-type alloy and a hydrogen compressor for filling hydrogen cylinders, all powered by a 500 kW WTG.

As described in (Chaparro et al., 2005), a stand-alone system to convert direct solar energy in hydrogen has been studied in Spain within the EU FP5 project FIRST (Fuel cell Innovative Remote System for Telecoms). The system has been designed to supply a power of 200 W, without interruption, from a 1.4 kWp PV field (thin-film technology). The electrical energy produced is stored in batteries (20 kWh total capacity) to smooth PV fluctuations. A PEM electrolyser produces hydrogen at 30 bar and feeds directly seven metal hydrides tanks of 10Nm3 capacity each. Metal hydrides work under pressure control in the temperature range 0–40ºC. Hydrogen is converted back to energy in a 275 W PEM fuel cell.

A stand-alone renewable energy system employing hydrogen storage has been built within the Hydrogen and Renewables Integration (HaRI) project at West Beacon Farm, Leicestershire, UK. As remarked by (Gammon et al., 2006) and more recently by (Little et al., 2007), before the start of the HaRI project, the existing renewable energy devices included two 25 kW WTG, a 13 kWp PV array and two micro-hydro turbines with a combined output of 3 kW. Further sustainable energy features include a 10 kW heat pump, and a 15 kWel, 38 kWth CHP unit. The above mentioned authors explain that the addition of a hydrogen energy storage system to the existing supply network was proposed as a means of testing the feasibility of a stand-alone system. The three primary components of the newly installed hydrogen based system are a 36 kW electrolyser, pressurized hydrogen storage cylinders with a capacity of 2856 Nm^3 of hydrogen at 13.7 MPa, and two fuel cells, 2 kW and 5 kW rated power.

Outside Europe there are some demonstration projects underway. The hydrogen production test facility located at Kuala Terengganu, East Coast of Peninsular Malaysia, can be mentioned and is presented in (Sopian et al., 2009). A 1 kWp PV array consisting of 12 amorphous silicon modules to operate nominally at 24 VDC is installed together with a 1 kW WTG, equipped with a permanent magnet generator. The voltage is regulated and converted to 24 V on a power controlled centre. A set of deep-discharge batteries bank with a capacity of 1000 Ah acts as a buffer between the PEM electrolyser and the power sources. The above mentioned (Sopian et al., 2009) presents results of the validation of a complete performance model of the hybrid PV–wind hydrogen production system against experimental results.

In the framework of university research, several projects have also been developed. Some examples are also presented, again following a chronological sequence.

A Multi-component Laboratory for Integrated Energy Systems has been established at the University of Applied Sciences, Stralsund, Germany. As early noted by (Menzl et al., 1999), one feature of this laboratory is a windmill–electrolyser system for carbon dioxide-free hydrogen production. (Menzl et al., 1999) continues by describing the system components: a 100 kW WTG equipped with a two-speed asynchronous generator, a 10 kWp PV installation consisting of mono-crystalline, poly-crystalline and amorphous cells, a 20 kW alkaline pressure electrolyser delivering hydrogen at up to 25 bars without using a compressor, a hydrogen storage tank with a geometrical volume of 8 m^3, a 370-W PEM fuel cell, a catalytic burner with a thermal power output of 21 kW converting hydrogen directly in thermal energy, a cogeneration plant with a power output of 30 kWel, 70 kWth, fed by natural gas and a diesel generator.

Agbossou (Agbossou et al., 2001) reports that at the Hydrogen Research Institute (HRI), Canada, a test facility is installed since May 2001. The system consists of a 10 kW WTG and 1 kWp PV array as primary energy sources. The excess energy with respect to the load requirement is stored as electrolytic hydrogen through a 5 kW electrolyser and utilized to produce electricity as per energy demand through a 5 kW PEM FC system. This facility allows experimental results to be obtained as in (Agbossou et al., 2004), which is always a much appreciated plus.

Recently (beginning of 2006), a new 5 kWp solar-hydrogen system was installed at Pamukkale University, Turkey. This integrated clean energy system consists of some major components such as sun tracking and fixed PV panels, charge controllers, batteries, inverters, a deionizer, a PEM electrolyser, metal hydride tanks and PEM fuel cells. Further information on this research facility can be found in (Ozturk et al., 2007).

2.3 Software tools

With the purpose of simulating the behavior of stand-alone renewable based systems, either dedicated or adapted software programs have been developed. In (Turcotte et al., 2001), a review of the main available tools is presented. A selection of references regarding the main sizing and simulation tools follows.

HOMER (Hybrid Optimization Model for Electric Renewables) is a sizing and optimization tool developed by NREL (National Renewable Energy Laboratory, USA). Alam (Alam et al., 2007) shows that it is able of comparing different system configurations and components sizes, by automatically running many simulations.

Hybrid2 (Hybrid Power System Simulation Model), developed by the University of Massachusetts, USA, and NREL, USA, is perhaps the more used hybrid power systems simulation tool. Mills (Mills et al., 2004) highlights an important feature of Hybrid2: it allows the user to include manufacturer specified parameters, such as the wind power curve for a WTG, or the I–V curve of a PV panel. Additionally, Hybrid2 is based on a quasi-steady probabilistic/time-dependent model as noted by (Mills et al., 2004).

TRNSYS (Transient Energy System Simulation Tool) was developed by a joint team lead by the University of Wisconsin-Madison, USA. It is an open architecture research tool based on a modular architecture of FORTRAN code blocks. Hundreds of simulation blocks are available, thus enabling an extensive use of TRNSYS for hybrid systems simulation, where Ulleberg (1999) and Ulleberg (1997) are good examples. TRNSYS is based on an unsteady time-dependent model.

2.4 System modeling

In the literature, several models able to predict the overall behavior of both SASRES and general hybrid systems are available. From the abundant offer in this domain, some examples are selected.

In (Senjyu et al., 2005) a model of the different components and the resulting overall system model are presented. The modeled hybrid system includes wind and diesel generators but no battery, therefore special emphasis is put on the control system. A large number of simulation results concerning different case-studies are displayed.

A stand alone PV system was modeled by Joyce et al (2001) addressing the PV modules, the inverter and the batteries, and the results were validated against data obtained in a 150 W stand alone system installed in Portugal at INETI.

A study regarding the improvement of the utilization of wind power in a Greek island is presented in (Ntziachristos et al., 2005). A part of the energy produced by the WTG is stored in the form of hydrogen and is then delivered to the consumption at constant power through a fuel cell. The model is used to simulate the operation of the system over a year. The focus of the paper is the grid connected operating mode and not the autonomous running. The conclusion stated by (Ntziachristos et al., 2005) is that the operation is possible with fuel cell sizes that reach almost up to 1/3 of the nominal wind-turbine power and overall efficiencies that may exceed 60%.

A comparative analysis of the behavior of a SASRES whose primary resource is alternatively wind, sun or hydro is performed in (Santarelli et al., 2004). Regarding a specific location in Italy, an overall model has been built. This model has been used to produce simulation results of plant operation over a year.

In (Chedid et al., 2007), an interesting equivalent electric circuit of a hybrid WTG/FC system is derived after a complete mathematical model for each component of the studied system. The complete electric circuit is composed of two parts; the first part models a wind turbine driving a three-phase permanent magnet alternator connected to a rectifier and an electrolyser, and the second part models the fuel cell and the load. (Chedid et al., 2007) provides simulation results to determine the values of the main system variables and therefore to predict its behavior.

Advanced algorithms have been applied to hybrid/hydrogen systems modeling. For instance, (Dufo-López et al., 2007) presents a strategy, optimized by genetic algorithms, to control a stand-alone hybrid PV/diesel/battery system with hydrogen storage. In this paper, genetic algorithms are the tool at hand to optimize the various system control parameters. Another instance is the use of fuzzy logic controllers to achieve maximum power tracking for both PV and wind generators described in (El-Shatter et al., 2006). The paper makes use of fuzzy logic to design the appropriate power management of the flows between the system components in order to satisfy the load requirements.

Power management is another issue that has been subject to the attention of researchers. In (Wang et al., 2008) the power management of a SASRES is assessed. The proposed strategy allows appropriate management of the power flows among the different energy sources and the storage unit in the system. The system performance under different scenarios has been verified after the development of a model of the overall system.
The power management subject is also addressed in (Zhou et al., 2008) where a WTG with hydrogen based long-term storage and super-capacitor based fast dynamic storage is studied.
Power electronics is a key issue to achieve proper and cost-effective power management between the different players. That is why, for instance, (De Battista et al., 2006) proposes an advanced control for a wind-electrolysis system, which match the wind power output to the electrolyser power requirements, thus gaining in system performance. This control strategy is developed using concepts of the reference conditioning technique and the sliding mode control theory.

2.5 Economics

Cost assessment of SASRES systems is a matter of great concern and several studies were published on this subject.
In (Ghosh et al., 2003) a comparison of hydrogen storage with diesel generation in a PV–WTG hybrid system is performed from a cost analysis point of view. The critical fuel cost is calculated depending on the seasonal solar and wind energy difference.
Nelson (Nelson et al., 2006) addresses an economic evaluation of a hybrid PV/WTG/FC generation system for a typical home in the Pacific Northwest; furthermore, a comparison to a traditional hybrid energy system with battery storage is performed.
The above mentioned HOMER software is used as a sizing and optimization tool and a sensitivity analysis with wind speed data, solar radiation level, diesel price and fuel cell cost is done in (Khan et al., 2005) for a remote house in Newfoundland, Canada.
The "discounted cash flow" method, with the "levelized energy cost" as a financial indicator, is used for the economical analysis of an application regarding a stand-alone hybrid PV/WTG/FC system incorporating compressed hydrogen gas storage in Cooma, Australia; the results of this investigation are reported in (Shakya et al., 2005).
All these studies point to the same conclusion: hybrid/hydrogen systems are at the edge of becoming the cost-effective choice for the electrification of remote areas, providing that the cost of the electrolyser and fuel cell decreases a little in the near future.

3. System's Components

The main goal of RenH_2 project is the fully study of low power stand-alone totally renewable power supply systems. The project comprises model development and prototype implementation and integration of the different components, namely:

- Photovoltaic cells
- Wind turbine
- Electrolyser system
- Fuel Cell
- Power electronics converters
- Control system

A general scheme of the overall system has already been presented in Fig. 1.

3.1 Photovoltaic System

The Photovoltaic system comprises a 530 Wp PV array with 10monochristaline Isofoton M-55L modules, facing South ant tilted at 45º connected to the 24 V DC bus through a power electronics converter. A pyranometer placed in the plane of the modules measures solar incident radiation. Figure 2 depicts the PV array installed at INETI's campus.

3.2 Wind Generator

The wind generator is a 750 W Aerocraft AC752 with 2.4 m diameter, installed at 10 m, delivering 3 phase AC power at a nominal speed of 9 m/s. A power electronics controller rectifies the 3 phase AC power connecting the wind generator to the DC bus. Figure 2 depicts the wind generator used.

Fig. 2. Wind Generator and PV array of RenH2 project

3.3 Fuel-Cell

A prototype proton exchange membrane (PEM) fuel cell with nominal power of 100 W, built by SRE, Portugal, was used in this work. The main characteristics of the stack are presented in Table 1. A view of the power source with already integrated fuel cell and auxiliary system and the fuel cell stack are shown in Figure 3a) and 3b) respectively. The fuel cell uses hydrogen without previous humidification supplied in dead-end mode and an open cathode fed by ambient air.

Fuel cell stack	4 stacks of 24 membranes
Nominal power	100 W
Power density	350 mW/cm2
Ohmic resistance per MEA*	470 mohm/cm2
Stabilized voltage (back-up model)	6,12 and 24 V (Imax=4A)
Charge-Imax (charger mode)	24 V or 48 V
Voltage decay at 0,5 A	3 mV/hr
Useful functioning lifetime	Expected 1500 hr
Start-up	Lithium ion rechargeable battery
Weight	2 kg
Temperature	5 - 40ºC

*MEA- membrane electrode assembly

Table 1. Main characteristics of the PEM fuel cell stack used in this work

(a) (b)

Fig. 3. General aspects of the power supply (a) and the PEM fuel cell stack (b) used in this work.

3.4 Electrolyser

As the idea of producing hydrogen by reforming fossil fuels, such as methane, methanol, ethanol, ammonia, releasing carbon dioxide as a greenhouse gas, is no more an option, due to environmental considerations, H_2 production by means of renewable energy sources is one of the most promising alternative for the future. Among the renewable energy sources, solar energy is one of the strongest options.

There are three pathways for hydrogen production using solar energy: i) electrochemical, by means water electrolysis, using electric energy to promote a redox reaction in a water molecule and producing reduced and oxidized species, namely hydrogen and oxygen, respectively; ii) thermochemical, using solar thermolysis, based on the use of concentrated solar radiation as the energy source of high temperature process heat for endothermic reactions and producing the water dissociation without the redox reaction or solar thermochemical cycles, in which water splitting can be achieved using heat as energy source to create reactive species that can be recycled; and iii) photochemical, where light sensitive

photoelectrodes immersed in an aqueous electrolyte, make up a photoelectrochemical cell, converting light energy into electricity.
Solar thermolysis and solar thermochemical cycles decompose water into H_2 and O_2 without electrolysis, but high temperatures must be achieved (T>2000ºC) and the product gases must be separated to avoid the make up of an explosive mixture. Photoelectrochemical cells are promising but in nowadays only around 18% energy efficiency is attained with TiO_2 as anode. Solar electrochemical seems to be the ideal option, especially for stationary applications. The water electrolysis is made by means an electrolyser working at relatively low temperature using a proton exchange membrane, PEM. These electrolysers show a energy efficiency between 65% and 80%, while the solar photovoltaic energy reach a energy efficiency from 3% to 17%, reflecting a total solar energy-to-hydrogen conversion for solar photovoltaic H_2 production by an electrolyser between 2% and 14%. Nevertheless, although expensive at the moment and presenting reduced energy efficiency, this option is very versatile, can be operate in a large or a small scale, and is totally free of pollution (Licht, 2005).
A 500 W nominal power electrolyser, model LM-1000 from Sandong Institute of Chemical Industry was installed with a maximum hydrogen production rate of 1000 cm^3/min at low pressures going from 1 to 4 bar. The electrolyser has 2 stacks of PEM cells and can work both on AC (230 V) or DC with voltages reaching 25 V which is useful for working directly connected to the 24 V DC bus. Figure 4 depicts the electrolyser. The hydrogen produced by water electrolysis is 99,99% pure and does not need any further purification other than hydrogen dryer before to be fed to the storage system.

Fig. 4. Stand-alone system's electrolyser, fuel-cell, and electrolyser's DC/DC power converter

3.5 Hydrogen Storage

An AB5 type intermetallic alloy, namely LaNi5 containing Al as a substitution element, was chosen as a storage option. This allowed adjustments of the equilibrium pressure and absorption kinetics of the base metallic hydride, making the modified alloy appropriate to be charged using a low pressure PEM electrolyser as well as the fuel cell selected for the present application. Furthermore, since weight is not an issue in stand-alone systems applications, the present storage option represents a more compact solution (by a factor of 3) when compared with high pressure compressed gas. Figure 5 shows the hydrogen storage reactor used in this work, containing alloy LaNi4.7Al0.3 with capacity for 1500 NL H2, which allows more than 20 hours autonomy to the system when running on the fuel cell as sole power supply.

Fig. 5. Hydrogen storage reactor containing LaNi4.7Al0.3 alloy with a capacity for 1500 NL H2.

The process of hydrogen absorption/desorption in metal hydrides is best illustrated by pressure-composition-temperature profiles, denoted as PCT curves - the pressure at a given H-content increases with temperature and is a direct consequence of the thermodynamics associated with the hydriding reaction (1).

$$M + x/2\ H_2 \Leftrightarrow M\text{-}Hx \tag{1}$$

Previous to the selection of the alloy, the thermodynamic properties and the absorption/ desorption capacity of LaNi5 and LaNi5-yAly alloys were studied using a purpose built Sievert-type apparatus to draw the PCT curves. LaNi5-yAly, absorption/desorption cycles were implemented for alloys with different contents of Al ($0 \geq y \leq 0.4$) at different temperatures (Van't Hoff diagrams). The increase in aluminium content in LaNi5 alloy decreases the equilibrium pressure of the hydride. It was evident that the Al content in the alloy increases the enthalpy of formation and therefore the stability of the metal hydride, consequently smaller pressures are needed to charge the alloy (4 bar at 20ºC) but higher temperatures are required for desorption, ~60ºC. The alloys can absorb hydrogen at sub-atmospheric pressures at ambient temperature. A slight decrease in the hydrogen storage capacity was noticed.

3.6 Power Electronics Converters

As the fuel cell operates in a wide range voltage output, a fuel cell DC/DC converter is used to connect it to the DC busbar. To guarantee a good performance and stability, the fuel cell output current should be continuous. Hence, a DC/DC converter topology with a continuous input current must be selected. For this project a SEPIC (Single-Ended Primary Inductance Converter) was chosen and presented in Fig. 6.

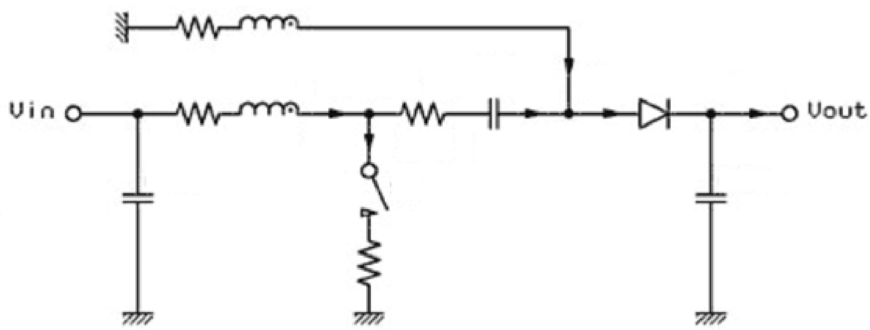

Fig. 6. SEPIC topology

This topology, where its input voltage range can overlap the output voltage, is based on the well-known Boost Converter discussed in (Ismail, 2009). In steady-state conditions the mean voltage across inductance L_1 remains zero, forcing the voltage across this inductance during the time the switch S is on to be equal to the voltage experienced during the switch off time. This leads to relationship (2), where V_o is the output voltage, V_i the input voltage, V_d the diode's forward voltage drop, α the duty cycle and A is called the Amplification Factor (neglecting the parasitic resistances).

$$(V_o - V_d)/V_i = \alpha/(1-\alpha) = A \tag{2}$$

The DC/DC converter control is performed as a current source (adopting a current control scheme). The power value to be outputted is applied as a reference value, and the control acts in order to obtain the current corresponding to the desired power output value. Once the fuel cell power limit is reached, the converter control switches to a voltage control scheme.

Since the DC busbar voltage operates in 24 Vdc and the AC busbar voltage is 230 Vrms it was necessary to consider another power electronics converter toperform DC/AC conversion and also amplifying the voltage. Both of these tasks could either be accomplished by connecting an inverter to the DC busbar followed by a 50 Hz transformer (AC/AC voltage gain) or by connecting a switch mode DC/DC converter to the DC bus bar (DC/DC voltage gain) followed by an inverter. A DC/DC voltage gain (switch mode DC/DC converter) is preferred in order to limit the physical size and the cost of the system. Hence, a system with a voltage source switch mode DC/DC converter followed by an inverter has been selected, as presented in Fig. 7.

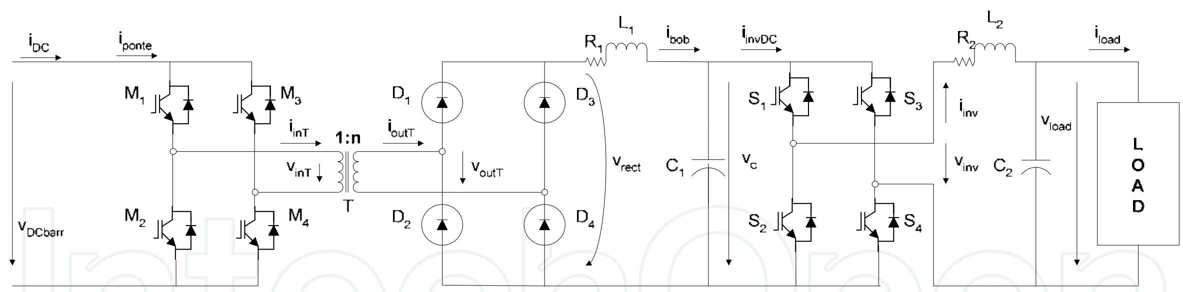

Fig. 7. DC/AC busbars power electronic converter

The wind generator is connected to the DC busbar through a standard diode rectifier followed by a DC/DC Buck converter. The PV array system considers a DC/DC boost conversion, presented in Fig. 8, with MPPT capabilities. Experimental results are presented in Fig. 9. The electrolyser is connected to the DC busbar through a standard controlled DC/DC power converter. This converter was already shown in Fig. 4, along with the electrolyser and the fuel-cell.

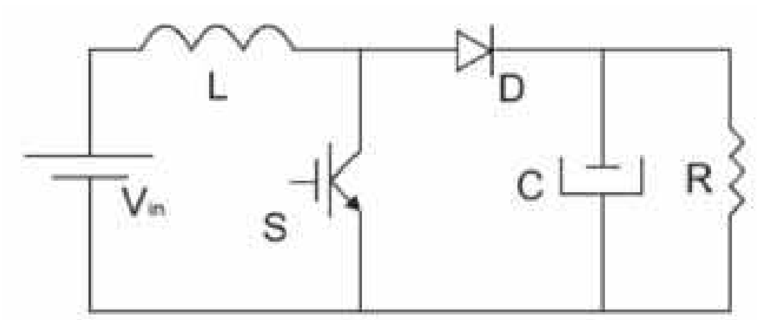

Fig. 8. PV array DC/DC boost converter

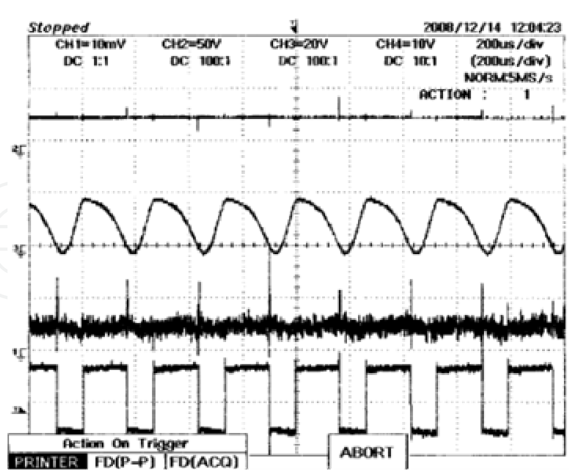

Fig. 9. PV DC/DC converter experimental results: output current, output voltage, input voltage and command signal

3.7 DC Link Busbar

The DC link acts as interface between the production sub-system and the electrical load. In the production sub-system one can consider the Photovoltaic Modules, the Wind Generator and the Fuel Cell. Whenever there are no renewable resources available the control system relies on the fuel cell in order to provide the power demanded by the load. However the fuel cell may not be sufficient to rapidly satisfy load-changing demands. In this way a DC buffer is mandatory. One can establish a set of batteries or supercapacitors to meet sudden load changes. Supercapacitors are a better choice because they are devices that provide higher power densities than conventional batteries. Their charge/discharge times can be extremely fast, reliable, maintenance-free and present long lifespan. A supercapacitor bank with a series of 5 parallel branches of 11 standard 2600F/3.5V supercacitors allows keeping the DC voltage between 23V and 27V, over the 24V DC busbar.

4. Control Strategy

The control of the overall system is a fully automated process that, regarding the sensor array information, establishes a set of controls that will run all of the system's components.
The sensor array includes information from all available data, however only some of them are essential for control purposes:

- wind and solar energy;
- H_2 conditions;
- fuel-cell power;
- AC and DC busbar voltages;
- load requirements.

The control considers the following set of main commands:

- electrolyser set-point and command;
- fuel-cell set-point and command (including its DC/DC converter);
- DC/AC converter set-point.

One should note that both the PV generator and the wind generator should generate the maximum energy available. Fig. 10 presents the power conditions, acquired from the sensor array, for two consecutive days. It presents the output electric power of the wind generator and of the PV system, the load power and its difference to the produced power.

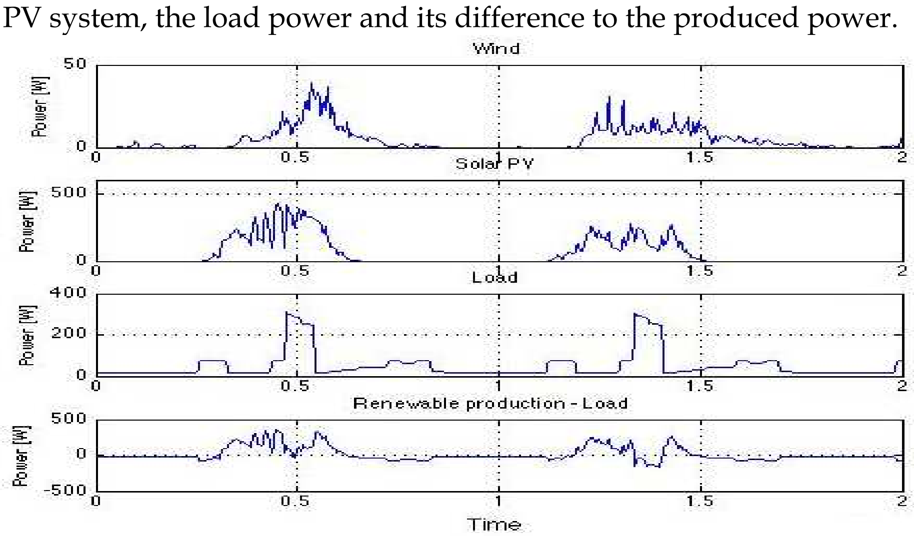

Fig. 10. Renewable power supply and load demand

The basic control idea is that the electrolyser generates hydrogen whenever there is an excess of solar or/and wind energy. This means that if the solar and wind energy are more than enough to demand the load requirements its excess should be used to produce hydrogen. Whenever the wind and solar energy are insufficient to face the load demand the fuel cell uses the stored hydrogen to produce the required lack of energy. The control algorithm flowchart is presented in Fig. 11.

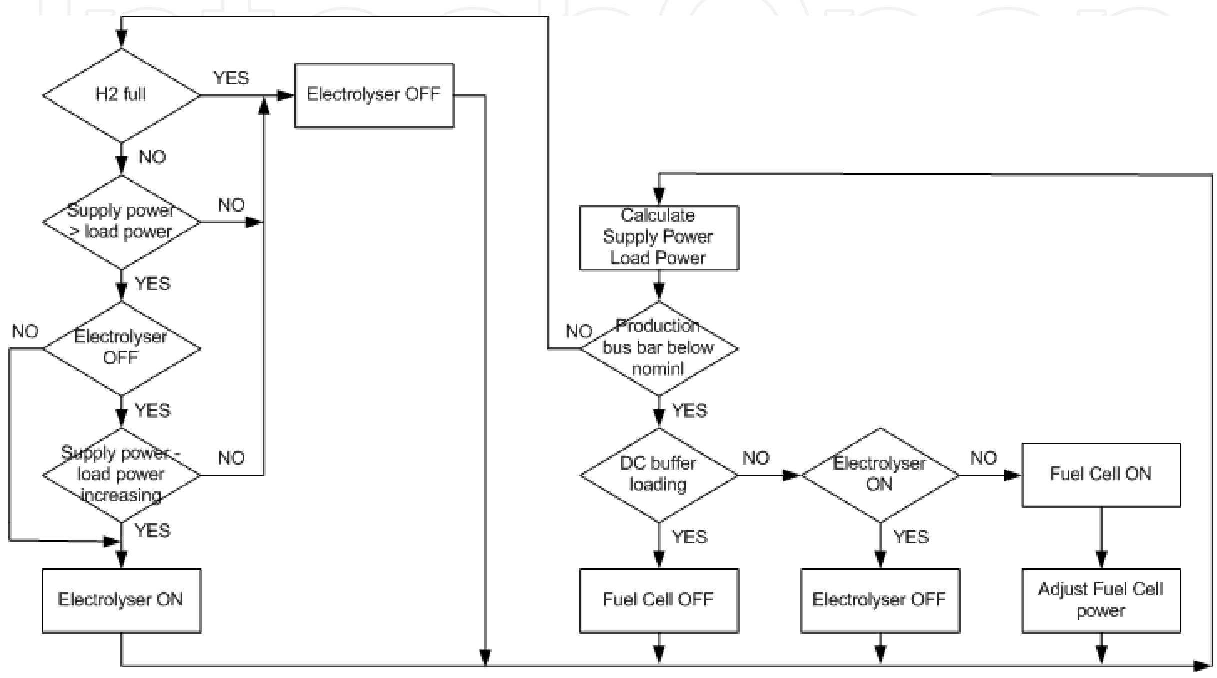

Fig. 11. $RenH_2$ system control strategy flowchart

At this time it is important to note that a building management system is considered in order to manage the load demand: if the overall power in insufficient to cover the load demand non essential loads are disconnected and only reconnected whenever the generated power is in conditions of supplying the considered load.
Several interlocks are considered to protect the system. A typical example is the one that does not allow the electrolyser and fuel cell to work at the same time, thus the electrolyser should only work when in presence of excess power.
The considered control scheme runs as follows: First the produced and demand power are computed. If the produced power covers the demand one should consider the following issues. If the hydrogen tanks are full then the electrolyser is switched off. If not and the excess produce power can run the electrolyser, then the electrolyser is switched on. If the produced power does not cover the demand the electrolyser should be switched off, if it was running. Then the fuel cell should be switched on and its set-point be adjusted to cover the power demand.
Fig. 12 presents the fuel cell and electrolyser electrical power correlation with the H_2 state-of-charge. One can see that whenever there is enough input power the electrolyser produces hydrogen, increasing its state-of-charge. Lack of renewable input power forces the fuel cell to operate decreasing the amount of stored hydrogen.

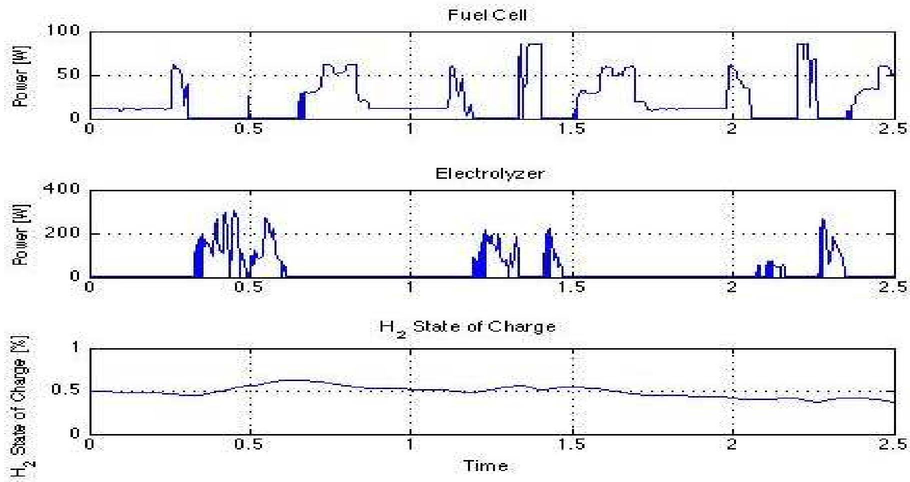

Fig. 12. RenH$_2$ electrolyser and fuel cell electrical power and H_2 state-of-charge

The control system implements the algorithm described above. It was developed in a VEE7.0 programming language implemented in the AGILENT data acquisition system. The program runs a continuous loop, considering a 5 second cycle. At each cycle, reads each channel and converts each signal (for quantities where this procedure is not automatic) for the physical quantity to be measured by means of programmed relations. The data is saved in two files that alternate cyclically, allowing access instantaneous values or 10 minutes average values. Afterwards it will decide how to act on the various systems' components. This is done by imposing conditions that implement the logical algorithm described above, comparing the instantaneous values of the physical system with the programmed references.

5. System Modelling

Obtaining the system model is essential for understanding and predicting systems' behaviour as well for specifying systems' components. In order to completely simulate the global system, sub-models for each system component were obtained. Each physical component was separately modelled as a Simulink block within the Matlab environment. The developed models, based on the fundamental physical, chemical and electromagnetic theories, were designed as general features that can be parameterized to match the real components characteristics. The structure of the simulation system is presented in Fig. 13.

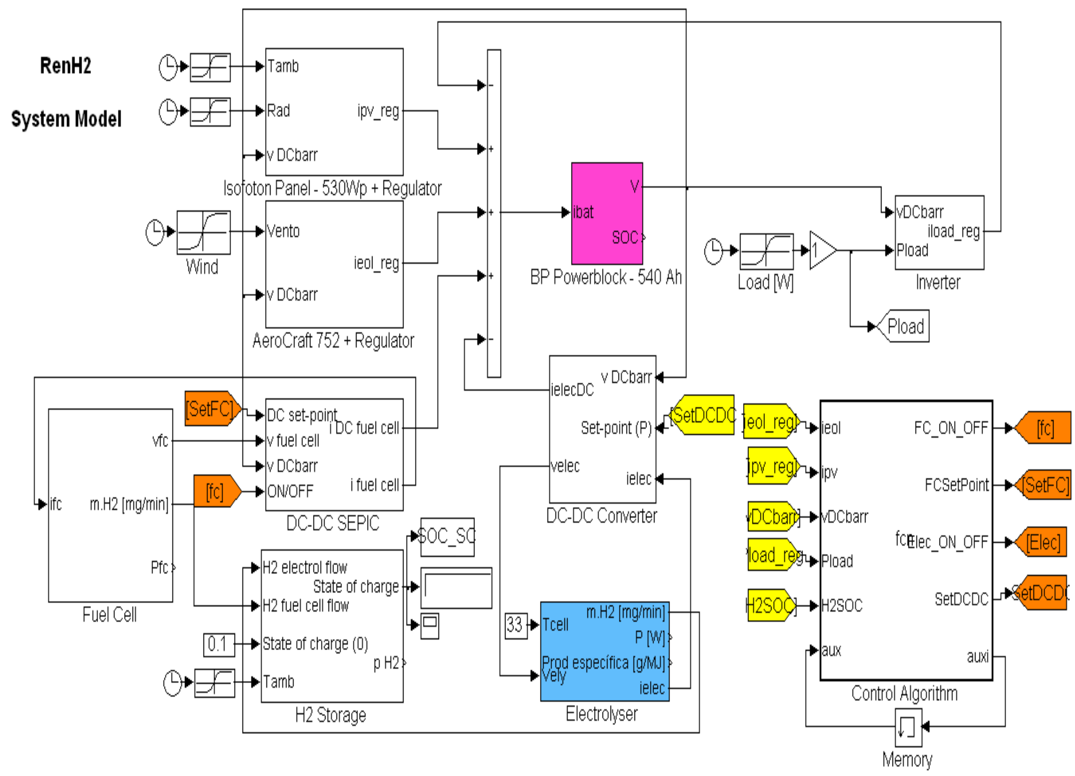

Fig. 13. Structure of the simulation system

The model of the PV modules uses a 5-parameter IV curve of the diode (3), where I_L denotes the current due to solar radiation exposure, I_0 the saturation current, q the electron charge, k the Boltzmann constant, T the temperature, R_s the series resistance, R_{sh} the shunt resistance, N_{cell} the number of cells in series per module and n the ideality factor ($n \in [1,2]$).

$$I = I_L - I_0\left[\exp\left(\frac{q(V + R_S I)}{nkTN_{cell}}\right) - 1\right] - \frac{V + R_S I}{R_{sh}} \quad (3)$$

The wind generator's Permanent Magnet Synchronous Machine is described in a classical dq axis model based on the evaluation of the fem and rotor speed, as in (Bose, 1996), being the stator transients neglected (4).

$$\begin{cases} v_q = R_s i_q + L_q \frac{di_q}{dt} + \omega_r L_d \frac{di_d}{dt} + L_{mq} \frac{di_{kq1}}{dt} + \\ \quad + L_{mq} \frac{di_{kq2}}{dt} + \omega_r L_{md} \frac{di_{fd}}{dt} + \omega_r L_{md} \frac{di_{kd}}{dt} \\ v_d = -\omega_r L_q \frac{di_q}{dt} + R_s i_d + L_d \frac{di_d}{dt} - \omega_r L_{mq} \frac{di_{kq1}}{dt} - \\ \quad - \omega_r L_{mq} \frac{di_{kq2}}{dt} + L_{md} \frac{di_{fd}}{dt} + L_{md} \frac{di_{kd}}{dt} \\ v_{kq1} = L_{mq} \frac{di_q}{dt} + R_{kq1} i_{kq1} + L_{kq1} \frac{di_{kq1}}{dt} \\ v_{kq2} = L_{mq} \frac{di_q}{dt} + R_{kq2} i_{kq2} + L_{kq2} \frac{di_{kq2}}{dt} \\ v_{fd} = L_{md} \frac{di_d}{dt} + R_{fd} i_{fd} + L_d \frac{di_{fd}}{dt} + L_{md} \frac{di_{kd}}{dt} \\ v_{kd} = L_{md} \frac{di_d}{dt} + L_{md} \frac{di_{fd}}{dt} + R_{kd} i_{kd} + L_{kd} \frac{di_{kd}}{dt} \end{cases} \tag{4}$$

The detailed model of the fuel-cell considers the fundamental anode/cathode equations with temperature effects. The relationship between the gas molar flow through the valve and its partial pressure inside the channel can be expressed as (5) p_{H2} denotes the hydrogen partial pressure, R the universal gas constant, T the temperature and V_{an} the anode voltage.

$$\frac{d}{dt} p_{H_2} = \frac{RT}{V_{an}} \left(q_{H_2}^{in} - q_{H_2}^{out} - q_{H_2}^{r} \right) \tag{5}$$

Assuming constant temperature and oxygen concentration, the fuel cell output voltage can be expressed as (6). E denotes the Nernst instantaneous voltage (7), V_{act} the activation voltage losses (8), V_{ohmic} the resistive voltage losses (9), $V_{concentration}$ the voltage losses due to the mass transport losses (10), N_0 the number of cells in series, E_0 the open circuit output voltage, T the stack temperature, F the Faraday's constant, $p_{H2}/p_{O2}/p_{H20}$ denote respectively the hydrogen/oxygen/water partial pressure, R_{FC} the electrical resistance, I_{dc} the fuel cell stack current, α the electrodes' charge transfer coefficient, I_{Lim} the limiting current of the fuel stack and I_0 is the exchange current.

$$V_{dc} = E - V_{ohmic} - V_{activation} - V_{concentration} \tag{6}$$

$$E = N_0 \left[E_0 + \frac{RT}{2F} \log \left(\frac{p_{H_2} \sqrt{p_{O_2}}}{p_{H_2O}} \right) \right] \tag{7}$$

$$V_{ohmic} = R_{FC} I_{dc} \tag{8}$$

$$V_{activation} = N_0 \left(\frac{RT}{2\alpha F} \right) \ln\left(\frac{I_{dc}}{I_0}\right) \tag{9}$$

$$V_{concentration} = -\frac{RT}{2F} \ln\left(1 - \frac{I_{dc}}{I_{Lim}} \right) \tag{10}$$

Experimental polarization and power curves for the fuel cell stack are shown in Fig. 14 evidencing how the fuel cell responds to load.

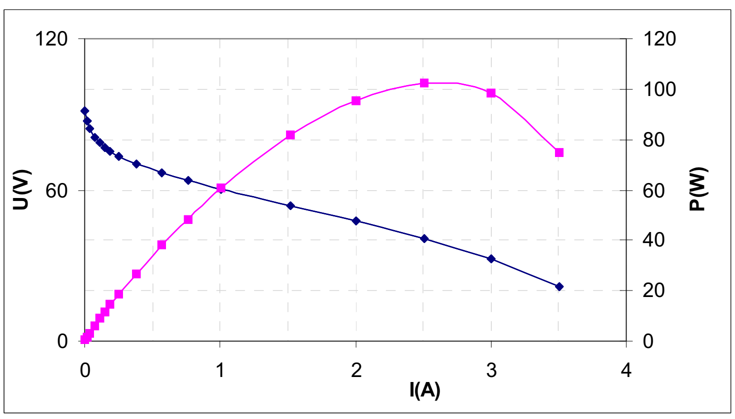

Fig. 14. Polarization and power curves for the 100 W fuel cell stack used in this work.

The electrolyser was modelled with experimentally obtained V(I) curves, presented in Fig. 15, and considering Faraday's law for optimal performance comparison.

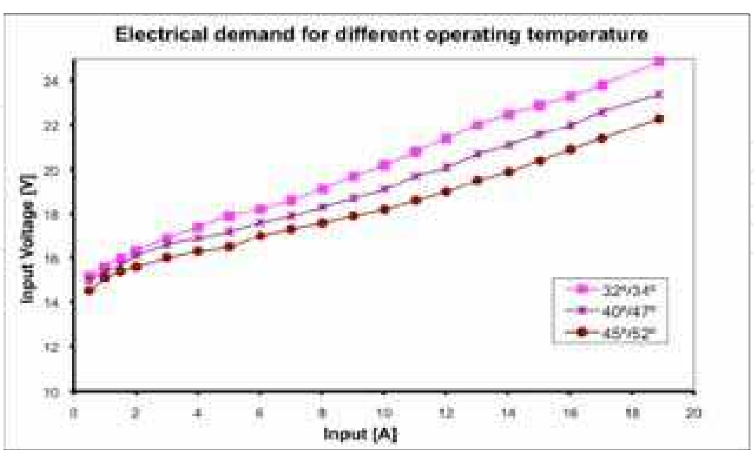

Fig. 15. Electrolyser experimental V(I) curves

Regarding the storage option, it is demonstrated that the metal hydride is able to supply hydrogen at the flows demanded by the fuel cell. A device was built incorporating a water circuit for cooling and heating of the metal hydride reactor during the charge and discharge of hydrogen respectively, allowing the fuel cell to be fed with fuel in a secure, fast and simple way, see Fig. 16. Using a pressure controller, inserted in the hydrogen circuit of the device, allows activation of the water circuit when the pressure of hydrogen is less than 2 Bar.

Fig. 17 presents the hydrogen absorption rate, during the charging process, of alloy LaNi4.7Al0.3. The alloy showed a high absorption kinetics, achieving total loading of the reactor storage in ~ 30 min, for a cooling water temperature of 22 º C.

The pressure of the reactor containing metal hydrides during discharge for different hydrogen flow-out is presented in Fig. 18. A full loading with partial discharging was used for 1 and 3 $Lmin^{-1}$ and a partial loading (30%) with total discharging was used for 2 $Lmin^{-1}$. It was possible to observe a rapid decrease in pressure in the initial download time, reaching a level close to 2 bar. This rapid decrease in pressure is explained by the fact that, until the pressure of the programmed controller is reached (2 bar), there is no water flow within the reactor. This leads to a decrease in temperature of the reactor and the consequent decrease of the hydrogen desorbed.

It is to be noticed that for a hydrogen demand of 1 $Lmin^{-1}$, it is possible to keep the discharge at 2 bar as required in this case; for 3 $Lmin^{-1}$, the plateau at 2 Bar was only managed in the first 60 minutes of the discharge, being lower for the rest of the discharge, (it is suggested that the rate of desorption of the alloy is lower than the required flow).

Data presented for discharge at 2 $Lmin^{-1}$ correspond to partial loading of the hydride, which may account for a situation where more than 70% of the hydrogen has been consumed. Results show that it is possible to proceed up to the total discharge of the alloy at a constant pressure of 2 bar.

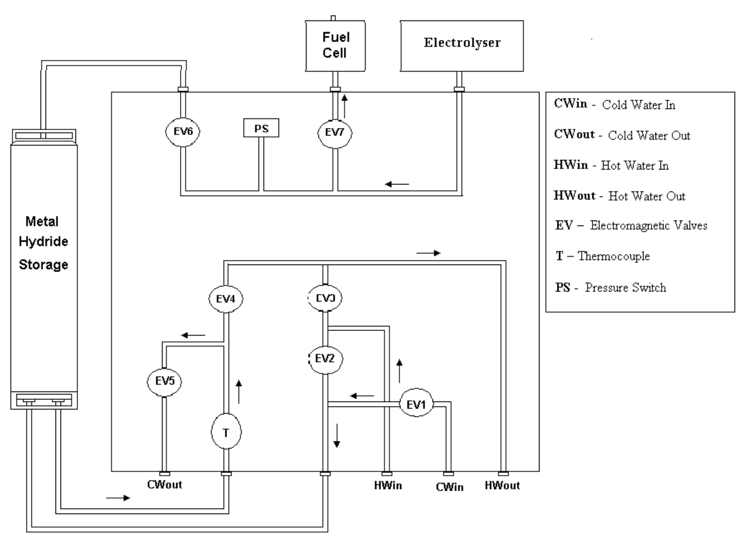

Fig. 16. Schematic drawing of the device implemented for the charging and discharging of metallic hydride hydrogen storage of 1500 NL feed a fuel cell.

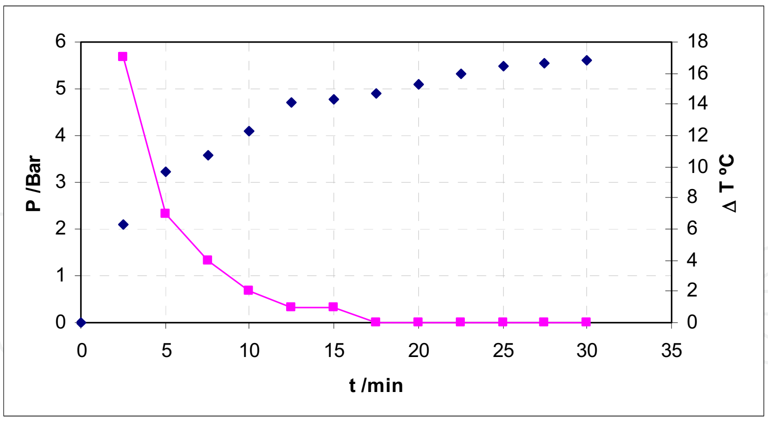

Fig. 17. Pressure of the reactor as a function of charging time, obtained in the process of charging with hydrogen of alloy LaNi4.7Al0.3. Represented also is the temperature variation as function of time during the charging process. The cooling water initial temperature was 22° C.

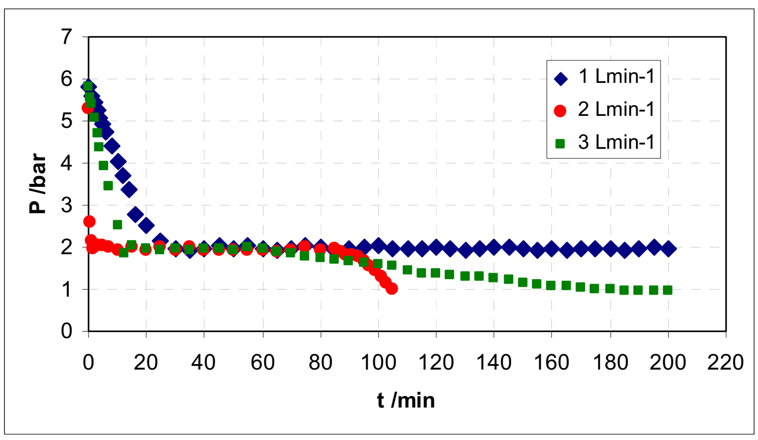

Fig. 18. Discharge curve of alloy LaNi4.7Al0.3 for flow rates between 1 and 3 Lmin-1. Water temperature and delivery pressure were programmed to ~70°C and to 2 bar respectively.

The process of hydrogen absorption/desorption is best illustrated by pressure-composition-temperature profiles, denoted as PCT curves, the pressure at a given H-content increases with temperature and is a direct consequence of the thermodynamics associated with the hydriding reaction (1).

$$M + x/2\, H_2 \Leftrightarrow M\text{-}Hx \quad (1)$$

Since the metal hydride is able to supply hydrogen at the demanded flows, the metal hydride component is modelled using the state of charge (SOCMH) in a simplified manner, described by equation (1), where $N_{MH,initial}$ is the initial hydrogen content; $N_{MH,total}$ is the total capacity of hydrogen in the metal hydride, $m_{EL,H2}$ is the hydrogen flow from the electrolyser and $m_{FC,H2}$ is the hydrogen flow demanded by the fuel cell. In this way the model considers a simple and effective hydrogen mass balance.

$$SOC_{MH} = \frac{N_{MH,\ initial} + \int \dot{m}_{EL,H_2} dt - \int \dot{m}_{FC,H_2} dt}{N_{MH,\ total}} \quad (11)$$

The global system has several topologies of power electronics converters: AC/DC (wind generator), DC/DC (Pv system, fuel cell), DC/AC (load). The complete modelling of all of these components strongly slows down the computation time. Several methods have been proposed in order to reduce computation times, however simple ON/OFF switches and average values models were used in the simplified model. Fig. 19 presents the DC busbar voltage for both models. The gray line refers to the detailed model while the black line refers to the simplified model.

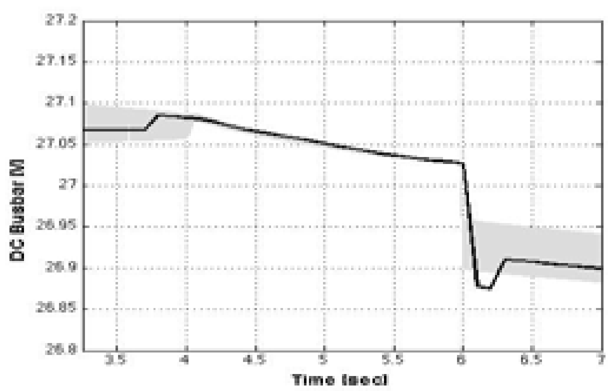

Fig. 19. DC busbar voltage for the detailed and simplified model

6. Conclusions and Remarks

The main goal of $RenH_2$ project is the full study of low power stand-alone totally renewable power supply systems. Thus, the main idea behind this project was the development of a fully autonomous system, where every component is based upon renewable energies. The project comprises model development and prototype implementation with full integration of the different components, namely: Photovoltaic cells, Wind turbine, Electrolyser system, Fuel Cell, Hydrogen storage, Power electronics converters and Control system.

The paper also describes the optimization and integration of production modules, storage and energy conversion within fuel cells, photovoltaic cells and wind turbines to achieve the production of hydrogen. Each component was separately modelled, in order to test the overall control strategy. Key feature in the modelling process was the correct choice of input/output variables, in order to perfectly establish the sensor array that should be used in the experimental prototype. Two distinct models were considered: a detailed one and a simplified one. While each component was accurately detailed modelled for the overall system, due to its complexity, a simplified model was assumed. Each modelling was experimentally validated.

The obtained system is a suitable choice regarding the actual stand-alone systems, based upon diesel generators and lead-acid batteries energy storage. It meets the sustainability and environmental respect criteria regarding the energetic solutions of the future – zero emitting either on production or consumption. Conceived to meet the energetic needs of a rural facility, this system considers the energy storage within hydrogen fuel cells and the connection to several energy sources, which may be placed where the receptive resource is by far more abundant.

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Renewable Energy

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Renewable Energy is energy generated from natural resources-such as sunlight, wind, rain, tides and geothermal heat-which are naturally replenished. In 2008, about 18% of global final energy consumption came from renewables, with 13% coming from traditional biomass, such as wood burning. Hydroelectricity was the next largest renewable source, providing 3% (15% of global electricity generation), followed by solar hot water/heating, which contributed with 1.3%. Modern technologies, such as geothermal energy, wind power, solar power, and ocean energy together provided some 0.8% of final energy consumption. The book provides a forum for dissemination and exchange of up-to-date scientific information on theoretical, generic and applied areas of knowledge. The topics deal with new devices and circuits for energy systems, photovoltaic and solar thermal, wind energy systems, tidal and wave energy, fuel cell systems, bio energy and geo-energy, sustainable energy resources and systems, energy storage systems, energy market management and economics, off-grid isolated energy systems, energy in transportation systems, energy resources for portable electronics, intelligent energy power transmission, distribution and inter-connectors, energy efficient utilization, environmental issues, energy harvesting, nanotechnology in energy, policy issues on renewable energy, building design, power electronics in energy conversion, new materials for energy resources, and RF and magnetic field energy devices.

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