First steps in Hydrogen production from wind energy in Greece

N. Lymberopoulos(1)(*), E. Varkaraki(1), M. Zoulias(1), P. Vionis(1),
P. Chaviaropoulos(1), D. Agoris(2)

(1)Centre for Renewable Energy Sources (CRES)
(2)High Voltage Laboratory, University of Patras

Greece

1. INTRODUCTION

It is widely acknowledged that Hydrogen and Electricity will be the prominent energy carriers of the future. In the medium term, Hydrogen will be produced from Hydrocarbons but in the long term it is foreseen that hydrogen will come from RES and nuclear power technologies. Hydrogen is the ideal medium for the storage of excess RES electricity through electrolysis with fuel cells used for re-electrification. Adequate hydrogen storage capacity would allow for the seasonal storage of this energy, which is most suitable for autonomous grids like for the case of islands. Hydrogen produced in this way can be used as a replacement of liquid fuels for heating and transportation purposes.

Over the last years, wind power has established itself as an economic grid-connected electricity generating technology, but its use in stand-alone power systems has been limited, because of the lack of suitable and economically viable energy storage technology. Hydrogen produced via water electrolysis could be such a storage medium in the near future, especially in isolated remote areas, where the cost of electricity is high. While a lot of research effort has concentrated on utilizing photovoltaic systems to generate hydrogen through water electrolysis, the possibility of connecting electrolysers to wind turbines has received less attention, since wind turbines deliver more irregular power compared to a solar photovoltaic power module. Nevertheless, a number of demonstration wind electrolysis units have already been installed.

Such a unit is the demonstration wind-powered hydrogen production plant in Italy. The wind hydrogen plant consisted of a wind turbine, an electrolyser, a DC-DC converter and a battery storage system. This project was concentrated on the production of hydrogen and not on the large scale storage or utilization, thus the product gases were being released to the atmosphere. The plant is schematically presented in Figure 1.

For the purposes of this project a 5,2 kW wind turbine was used. The electrolyser had the following main features: a nominal power of 2,25 kW, a nominal voltage of 50 V, and pressurized operation at 2 MPa. It also featured fully automatic operation (with the exception of an electric current limitation of less than 20 A during start-up, to be implemented separately). The step-down DC-DC converter comprised of three 0,8 kW units working in parallel and could supply a voltage linearly variable from

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* nlymber@cres.gr

7 to 50 V, which was controlled by a 0-10 V_{DC} signal. The battery storage unit comprised 54 series-connected lead-acid cells with a nominal voltage of 2 V each and a nominal capacity of 330 Ah, for a total nominal capacity of 35,6 kWh. It must be noted that the full extent on this large capacity was probably not completely available, due to battery aging.

During the wind hydrogen plant operation, specific problems were observed. Regarding the electrolysis unit, most of the problems were due to high impurity levels of hydrogen in oxygen during operation at low current levels and high impurity levels of oxygen in hydrogen after some hours of stand-by operation, both conditions lead to alarms and automatic plant shutdown. On the wind turbine side, it has been proved that a variable wind speed turbine, equipped with a synchronous generator, the decoupling provided by the AC-DC(/AC) interface removed the resonant mode of the direct grid coupling and the power fluctuations due to tower shadow and rotational sampling of wind shear over the turbine rotor. The power smoothing was typically effective on time scales of up to 20 seconds [1, 2].

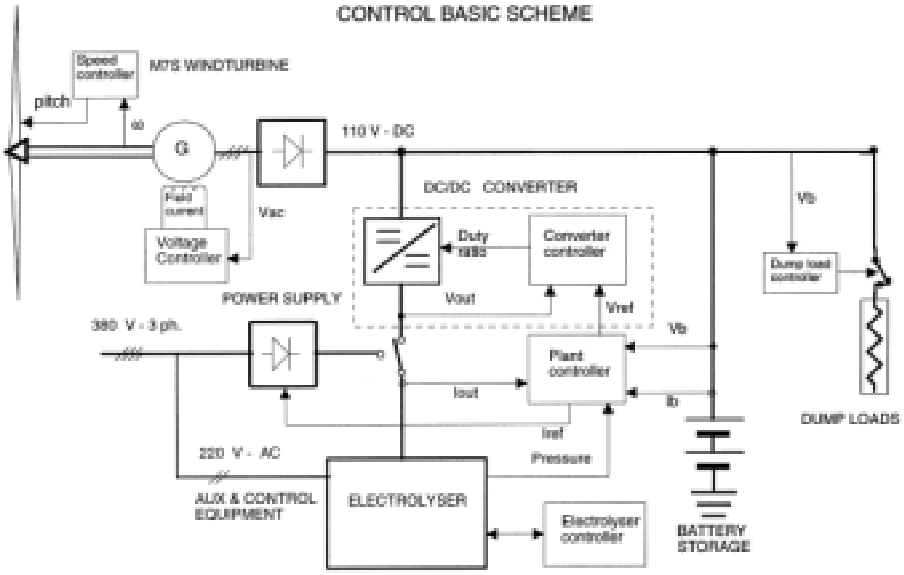

Figure 1. Basic scheme for demonstration wind-powered hydrogen generation plant, [2].

Another wind-hydrogen system has been installed in Canada. This system really operated in stand-alone mode [3]. The system consisted of the following components:

- A wind turbine that was able to deliver a maximum output power of 10 kW. The wind turbine was coupled to a PV array with a maximum output power of 1 kW. The voltage produced by these sources was regulated and converted to a 48 V on a DC bus. A set of batteries connected in a series/parallel configuration acted as a buffer between the load and the power sources.
- A 5 kW electrolyser which was able to deliver up to 1 m^3/h of hydrogen, subsequently purified, dried and compressed at 0,7 MPa (a).
- The hydrogen was further compressed to 1 MPa, and directed to a storage tank with a capacity of 3,8 m^3 (water capacity).
- A 5 kW-24 V_{DC} proton exchange membrane fuel cell stack, with an effective voltage output of 19-35V.
- 48 V deep-discharge batteries for voltage stabilization, of 42.24 kWh storage capacity
- A 12 kW water cooler.
- A DC bus controller including the batteries for energy transfer.
- A DC-AC inverter, which was able to deliver a constant 60 Hz 115 V output to the load.

According to Agbossou et al [3], the electrolyser efficiencies without compressor are 65% at ambient temperature around 23 ^{o}C and 71% at 55 ^{o}C. There is a decrease of 5% in these efficiencies when hydrogen is compressed. Assessing the experimental results, it was estimated that for an average wind speed at the test site of 6 m/s which translates in an average wind turbine power of approximately 2 kW, the hydrogen production rate was about 0,4 Nm^3/h.

The load-leveling electrical system is composed of the 5 kW fuel cell system connected to the DC bus, through a regulated DC-DC converter (24/48 V). The specific fuel cell consists of a total of 35 cells connected in series. Each cell has a surface area of 225 cm^2. The reactant gases (hydrogen and air) are humidified within the stack. The hydrogen is recirculated at the anode and the air is directed to the cathode. The DC-DC converter has an efficiency that exceeds 95%. The efficiency of the fuel cell system in converting hydrogen into electricity is approximately 45% when delivering a power of 4 kW. Therefore, the overall efficiency of the load-leveling electrical system is about 42%. This system is proposed for providing stabilized electrical power for communication stations.

Another interesting wind-electrolysis system has been studied in Germany [4]. The wind turbine is a two-speed asynchronous generator with a nominal power output of 100 kW. The alkaline electrolyser delivers hydrogen at up to 2,5 MPa and a hydrogen compressor can be used to increase the pressure up to 30 MPa. Upon exiting the electrolyser, the hydrogen is purified and dried. The hydrogen storage tank has a geometrical volume of 8 m^3 and contains 200 Nm^3 H_2 at 2,5 MPa. It is filled in 50 hours at nominal electrolyser capacity (4 Nm^3/h H_2).

For steady state operation, the nominal current is set to 120 A. Initially, when the system is at ambient temperature and pressure, the control system applies a current limitation until the pressure in the system attains 1,3 MPa. At this point, the hydrogen delivery can start. Upon reaching the 1,3 MPa, the initial current limitation is switched off and the actual current is only limited by the temperature. It takes circa 45 minutes for the electrolyser to achieve the operating temperature of 75ºC and therefore the nominal current of 120 A. The reported efficiency of the electrolyser is very low (approximately 56%) [4]. The electrolyser has also been tested under a controlled operating regime, probably through a simulator of variable power input. According to the related publications [4,5], there has been no direct connection between the wind turbine and the electrolyser.

The objective of this paper is to give a briefing about the first steps in Hydrogen production from wind energy in Greece. The main features of a major installation related to hydrogen production from wind energy that is being erected in Greece by CRES, the Greek National co-ordination centre for Renewables and Rational Use of Energy will be described with reference to the previously mentioned similar installations. This, new installation is related to the production of "green" Hydrogen from wind energy, as a potential alternative product to electricity and is being developed in the context of an EC co-funded project. Potential applications of similar wind-hydrogen systems on Greek islands are also discussed.

2. SYSTEM OUTLINE

The wind-hydrogen system under development at a wind park in Lavrion, Greece consists of a pressurised electrolyser with a 25 kW / 5 Nm^3/hr production capacity operating at 1,5 MPa that is connected to a commercial variable speed pitch-regulated wind turbine powering the whole plant. Through appropriate control strategies, major power fluctuations are fed to the electrolyser and the remaining "more uniform" energy is fed to the electricity grid. Hydrogen is stored in a metal hydride tank (50 Nm^3 capacity) and is compressed in cylinders at 20 MPa pressure. The produced high purity (99.999%) Hydrogen will be fed to the existing Greek Hydrogen market that is non-energy related, as a way to investigate alternative commercial paths for wind park developers. The wind turbine used is grid connected.

3. SYSTEM DESIGN

The water electrolysis unit is connected to the 400 V line of a 500 kW gearless, synchronous, multipole wind turbine. The hydrogen produced by electrolysis is purified flows into a small, conventional buffer tank. From the buffer tank, there are two different pathways available for the hydrogen. One is to flow into a metal hydride tank of 50 Nm^3 H_2 capacity and the other is to flow to a compressor and subsequently to a filling station, to fill hydrogen cylinders at 20-22 MPa. When the electrolyser is not in operation, the hydrogen stored in the metal hydride tank can be used to supply the compressor and fill the cylinders.

The materials of construction for the piping and all the vessels must not be subject to hydrogen embrittlement. The materials suitable for hydrogen service are stainless steel, carbon steel, aluminum and copper. A process flowsheet of the plant is presented in Figure 2.

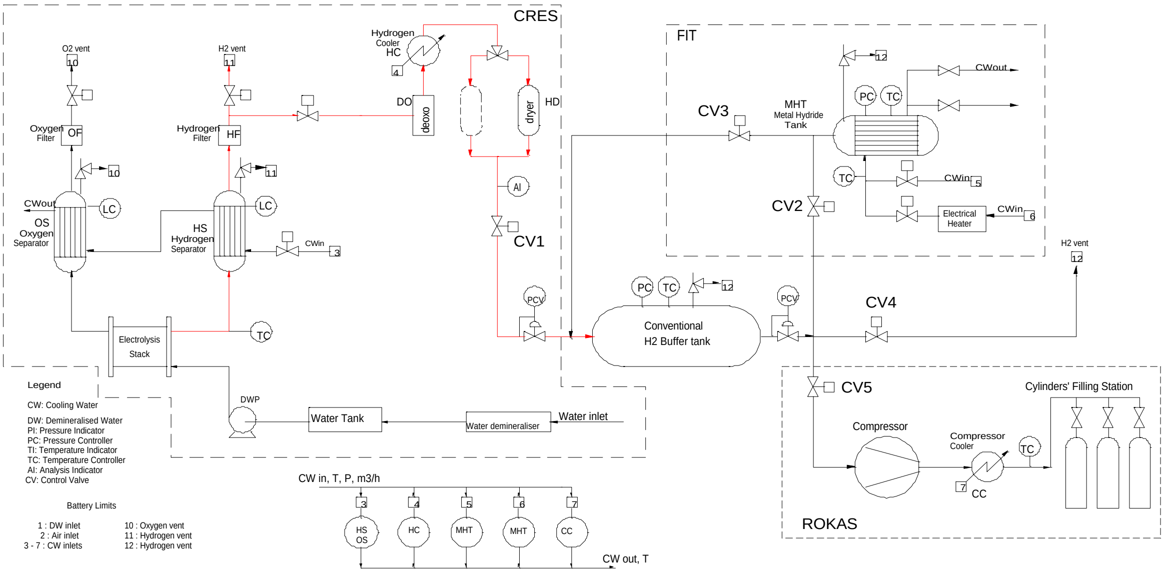

Figure 2. Preliminary process flowsheet of the hydrogen plant at the wind-park of CRES

4. COMPONENTS OF THE HYDROGEN PRODUCTION PLANT

The hydrogen production plant comprises a water electrolyser with a hydrogen purification unit, a compressed hydrogen buffer tank, a metal hydride tank, a hydrogen compressor, a cylinder filling station and a control and power conditioning unit. The operational characteristics of each component are described below.

4.1. Water electrolyser

The water electrolyser is a key element for the wind-hydrogen plant, because its technical characteristics and delivery conditions have an important impact on the following subsystems. Two different electrolyser technologies have been investigated as possible options within the available budget. The first option is to install a conventional alkaline electrolyser of 10 Nm^3/h H_2 capacity, consuming approximately 55 kW of electrical power and delivering hydrogen at 0,5 MPa(g) pressure. The second option is to install an advanced alkaline electrolyser of 5 Nm^3/h H_2 capacity, consuming approximately 25 kW of power and delivering hydrogen at minimum 1 MPa(g) pressure. In both cases, the oxygen produced will be vented, because no use of oxygen has been foreseen.

The detailed analysis of these two options showed that the choice of an advanced alkaline electrolyser presents several advantages. Advanced, pressurized electrolysers are safer, more reliable and more efficient than conventional electrolysers. In addition, the delivery of hydrogen at higher pressures (1-2 MPa(g)) adds a precious versatility to the global plant.

Conventional electrolysers are cheaper, so they offer the advantage of installing a unit of higher capacity for the same budget, but they have never been tested in intermittent operation, and they are not designed for part load operation, as advanced electrolysers do.

The purity of the hydrogen coming out of an alkaline electrolyser varies from 99.5% for a conventional one to 99.9% for advanced ones. This purity is generally attained at full load operation and decreases upon part load operation. The electrolytically produced hydrogen contains small quantities of oxygen, which is dissolved in the electrolyte at the operating temperature and diffuses from the oxygen to the hydrogen compartment. In addition, the hydrogen flow is saturated with water vapour at the delivery pressure and temperature.

The hydrogen coming out of the electrolyser must be purified to circa 99.999% vol., because such a high purity is generally required for the metal hydride tanks. Hydrogen containing large quantities of water vapour may also cause water condensation problems inside the hydrogen compressor. Thus, a hydrogen purification unit must be added to the system.

4.2. Hydrogen buffer tank

A small hydrogen buffer tank is necessary after the electrolyser and purification section, in order for the plant to operate smoothly. The role of the buffer is to absorb the eventual pressure variations at the outlet of the electrolysis and purification section. In addition, if the electrolyser is tripped out for any reason (absence of wind, emergency shut-down), the buffer tank gives to the system more time for a regular shutdown.

4.3. Metal hydride tank

Hydrogen will be mainly stored in a metal hydride tank. Some AB_5-type materials, with the compositions $La_{1-x}R_xNi_{5-y}M_y$, where R= Nd, M=Co, Fe, Cu and x=0-0.2, y=0-1 and the AB_2-type materials, with the compositions $Zr_{0.8}Ti_{0.2}(Ni_xMn_{0.9-x}V_{0.1})_2$, x=0.4, 0.5, 0.6, 0.7, 0.8, have been homogenised and characterised in terms of phases present and hydrogen absorption. New alloys with compositions $LaNi_{5-x}Al_x$, where x=0-0.25 have also been prepared for studying. The goal of achieving hydrogen capacities of more that 0,1 m^3/kg of material has been achieved easily. Most of the materials tested show a capacity of more that 0,150 m^3/kg at room temperature and low pressures (<1 MPa). A 5 Nm^3 hydrogen storage prototype has been designed and constructed. Preliminary results indicate very good hydrogen response characteristics which go beyond the desired one (5 Nm^3/h). The response characteristics of the 5 Nm^3 hydrogen storage prototype will be further investigated at different temperatures.

The capacity of the metal hydride tank will be 50 Nm^3 H_2, for a charging pressure of 0,5 MPa and a discharging pressure of 0,3-0,5 MPa. The above mentioned pressure conditions may be modified according to the characteristics of the electrolysis unit. The response time of the storage system is actually under study. At this stage, considering a discharge rate of 5 Nm^3/h H_2, the start-up and shut-down time of the metal hydride tank is approximately 5 minutes each.

4.4. Hydrogen compressor

Centrifugal compressors are suitable for very high capacities. For the capacity range envisaged here, only reciprocating compressors are suitable. There are two types of reciprocating compressors, namely piston compressors and diaphragm (or membrane) compressors. The cheapest piston compressors are oil-lubricated, but the compressed hydrogen is contaminated with oil, so the more expensive non-lubricated piston compressors should be preferred. Diaphragm or membrane compressors are even more expensive, but they prevent contamination of the compressed gas and are more suitable for hydrogen service. Metal hydride compressors are an interesting alternative, but they are still in their R&D phase and actually, they are more expensive than diaphragm compressors. In addition, for similar larger systems, the cost of the metal hydride compressors does not decline much with increasing capacity, as is the case for conventional compressors.

Basic design considerations imply that the capacity of the compressor should be smaller or equal to the capacity of the electrolyser, because there is no reason for compressing hydrogen at a rate higher than its production. The input pressure of the compressor also depends on the delivery pressure of the electrolyser and the minimum storage pressure in the buffer tank.

The compressor module is basically composed of 6 major pieces or groups of equipment: the compressor, the motor, the terminal box and panel, the control cabinet, the sensors and controls and the aftercooler. Interstage cooling with a condensate separator after the cooling stage may also be required, but will be decided later during the design of the compressor. Purging with an inert gas (i.e. nitrogen) is generally foreseen and strongly recommended. A frequency controlled motor may be used, in order to be able to vary the input power to the compressor. The operation with a frequency controller is generally limited to the range 50-100% of capacity.

Following the preliminary design of the plant, the hydrogen compressor should have a capacity of 5-10 Nm^3/h, for a suction pressure of 0,3-0,7 MPa and a delivery pressure of 22 MPa. The final pressure in the cylinders would be 20 MPa at the ambient temperature of 25ºC, assuming that the temperature of the hydrogen compressed at 22 MPa at the outlet of the aftercooler would be circa 60ºC.

4.5 Cylinder filling station

Cylinders represent a convenient supply source for applications with gas requirements up to 5000 m^3 per month. The cylinders may be made of aluminum, steel, light alloy or composite materials. They can be supplied individually or in sets of 9 or 18 bundled together and emptied as a unit.

The filling station that will be constructed at the wind park of CRES will probably be designed so as to be able to fill two or three 9-cylinder bundles simultaneously. Assuming a cylinder capacity of 0,050 m^3, the storage volume at the filling station with two bundles can be estimated around 0,900 m^3, which corresponds to a capacity of circa 165 Nm^3 H_2 at 20 MPa and 25ºC. The filling station should be placed at least 6-10 metres away from the compressor and preferably separated by a short wall.

4.6. Control and Power Conditioning unit

The Power Conditioning Unit (PCU) is mainly a power distribution board, taking power from the wind turbine and distributing to the various users. It is schematically presented in Figure 3, with the potential electricity users. The power characteristics of the main electricity users, namely the electrolyser, compressor, electrical heater for the metal hydride tank, water refrigerating and pumping unit, are 400 V, 50 Hz, 3 phase. The power characteristics of the Central Control Unit have not yet been defined.

When the plant is operating, the PCU must supply the necessary power to the appropriate users. According to the possible modes of operation of the plant, not all the electricity users may operate simultaneously. The simultaneous operation of the electrolyser, compressor and metal hydride tank heater is excluded. However, the Central Control and Cooling Water units will always need some power when the system is operating. The maximum total power consumption of the plant in operation is approximately 40 kW.

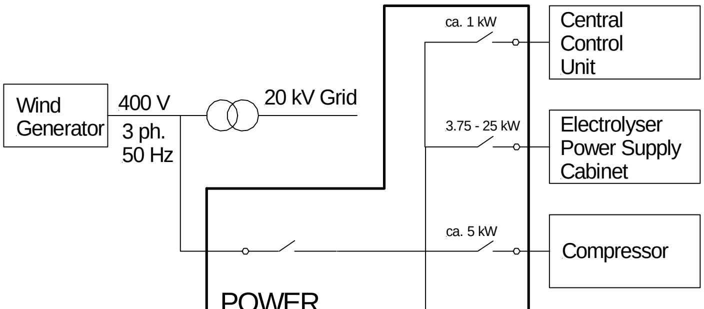

Figure 3. A simplified scheme of the Power Conditioning Unit

The main characteristics of the different electricity users are presented in Table I, and some more detailed explanations are given hereafter.

Table I. Main power characteristics of the different plant units

Item	Main Power Characteristics
1. Electrolyser Power Supply Cabinet	The electrolyser cabinet includes the AC/DC converter to supply the electrolysis stack with the appropriate DC power. The operating range of the electrolyser is 3.75 – 25 kW, corresponding to a hydrogen production of 0.75 – 5 Nm^3/h. A full-range power variation is possible within 1 second. The corresponding power necessary for cooling the water and pumping it into the system varies in the range 0 – 4 kW, but not in a linear manner.
2. Compressor	The power input to the compressor will be circa 5 – 7.5 kW, to be precisely defined by the manufacturer (not chosen yet). It must remain rather constant, but an eventual variation range must be checked with the manufacturer. At full power, the compressor should need approximately 4 kW for cooling water and recirculation pumping.
3. MHT heater	During hydrogen delivery, the Metal Hydride Tank must be heated. At nominal discharge rate, i.e. 5 Nm^3/h H_2, approximately 2 kW power are needed. During hydrogen absorption, the Metal Hydride Tank may need cooling, with approximately 2 kW cooling required at the absorption rate of 5 Nm^3/h. The heating and cooling power may vary as a function of the absorption and desorption pressure and temperature.
4. Cooling water refrigerating & pumping unit	During normal operation, the maximum quantity of cooling water may be needed during the simultaneous operation of the electrolyser and compressor. It corresponds to 8 kW cooling energy. So, the energy for the refrigeration of the cooling water will vary in the range 0 – 8 kW.
5. Central Control Unit	The CCU needs some power, in order to receive signals, treat them and send other signals to the different control elements of the plant. The data monitoring is also included in the CCU. CCU power consumption is estimated around 1 kW.

The PCU will be installed in a non hazardous zone of the plant. A minimum distance of 5 meters is foreseen from the zones with possible presence of inflammable gases, according to the available codes of practice.

5. FUTURE APPLICATIONS FOR SIMILAR WIND-HYDROGEN SYSTEMS

The concept of using hydrogen as a medium for the storage of excess wind energy through water electrolysis with fuel cells used for re-electrification is considered ideal for most of the non-interconnected Greek islands. Adequate hydrogen storage capacity would allow for the seasonal storage of this energy, which is most suitable for autonomous grids like for the case of islands. Hydrogen produced in this way can be used as a replacement of liquid fuels for heating and transportation purposes. A pre-feasibility study related to the introduction of a wind-hydrogen energy system in the island of Kythnos is briefly presented. It must be noted that the proposed system design and dimensioning was performed with the TRNSYS simulation tool where the HYDROGEMS library of modules has been incorporated [6].

Kythnos island in Greece has a peak power demand of approximately 2.5 MW and is electrified mainly by diesel generators sets. A wind turbine with a nominal power of 500 kW and a photovoltaic system of around 100 kW have also been installed on the island. The main problem related to the wind turbine operation is that it is currently connected and is shedding power to 500 kW of electrical resistances in order to ensure the stability of the autonomous electricity grid of Kythnos. The introduction of a hydrogen system to the existing energy system of the island would significantly reduce the shedding of power to the electrical resistances and increase the penetration of Renewable Energy Sources.

The existing 500 kW wind turbine is proposed to be connected to a hydrogen production, storage and re-electrification plant. A 100 kW electrolyser operating at a pressure of 1,5 MPa connected to the wind turbine can be used for hydrogen production. Hydrogen storage in conventional pressure tanks able to store up to 4,800 Nm^3 of hydrogen is indicated. PEM fuel cells (with a nominal power of approximately 25 kW) should also be installed for re-electrification purposes. Hence, the electrolysis unit can be used rather than the electrical resistances as the load-levelling device, by sending to the electrolyser major power fluctuations (up to 120% of the nominal capacity of the electrolyser, any excess energy to this would still go to the resistances). Stored energy in the form of hydrogen can be fed back to the grid through the fuel cells demonstrating that a RES installation that has been hybridised with hydrogen technologies can provide a minimum guarantied level of power, equal to the nominal capacity of the fuel cells. It is estimated that 120.000 kWh that would have otherwise been lost could be fed to the local grid per annum.

Wind energy based systems that incorporate appropriate hydrogen storage and re-electrification technologies could thus be “promoted” from stochastic sources of electrical energy to dispatchable power plants.

6. ACKNOWLEDGEMENTS

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