Sánchez Díaz, C.; González, D. (2013). Experimental characterization of a grid-connected hydrogen energy buffer: Hydrogen production. International Journal of Hydrogen Energy. 38(23):9741-9754. doi:10.1016/j.ijhydene.2013.05.096.

Manuscript Number: HE-D-13-00572R1

Title: Experimental characterization of a grid-connected hydrogen energy buffer: hydrogen production.

Article Type: Full Length Article

Keywords: Hybrid system; Renewable energy; Energy Storage; Experimental Characterization; Grid connected; Data acquisition; Linux

Corresponding Author: Dr. Carlos Sanchez-Diaz, Ph.D.

Corresponding Author's Institution: Universitat Politècnica de València

First Author: Carlos Sanchez-Diaz, Ph.D.

Order of Authors: Carlos Sanchez-Diaz, Ph.D.; Domingo Gonzalez, MSc.

Abstract: Energy storage becomes a necessity when a high penetration of renewable energy sources is desirable. Variability in the energy production from these types of energy sources can make the utility grid unstable, if the percentage of production is important. In order to minimize this problem, the HiDRENER project was designed to study the effect of combining different renewable energy sources with energy storage on grid stability. The system has a wind generator, a gasifying biomass power plant with syngas storage, a solar photovoltaic plant, and a hydrogen energy buffer. Controlling the entire system is very complex. This paper shows the results of the grid-connected hydrogen energy buffer characterization, considering hydrogen production in this first stage. The objective is to know the complete behavior of the system, which could help us to define the energy buffer control. This control is oriented toward consuming excess energy produced by the other sources in real time. This means that the hydrogen buffer control has to negotiate how much energy can be stored, and act on the production system. Thus, actuation variables and dynamic behavior have to be discovered.

Dr. E.A. Veziroglu

Editor-in-Chief

International Journal of Hydrogen Energy

Corresponding autor:

Carlos Sánchez-Díaz

Phone Number: +34 653 953 003

Fax Number: +34 963 877 609

Email: csanched@eln.upv.es

Postal Address: Instituto de Ingeniería Energética, Universitat Politècnica de València, Camino de Vera s/n, 46022, Valencia, Spain.

Dear Dr. Veziroglu,

The article that I send to be considered for its inclusion in your publication presents the results of an experimental characterization study done to a grid connected hydrogen production system that is part of a complete project, named HiDRENER. The HiDRENER project was designed to study the effect of combining different renewable energy sources with energy storage on grid stability. The system has a wind generator, a gasifying biomass power plant with syngas storage, a solar photovoltaic plant, and a hydrogen energy buffer. The hydrogen production system takes part of the hydrogen energy buffer. The objective is to know the complete behavior of the system, which could help us to define the energy buffer control. This control is oriented toward consuming excess energy produced by the other sources in real time. Thus, before we designed the control system, we need to know the complete behavior of production system.

This work is the natural continuation of last papers that we published in your publication, titled *Wind park reliable energy production based on a hydrogen compensation system. Part I* and *II.* There, we showed the results of the system simulation. Now, we show first results of experimental implementation.

Thank you very much in advance for your time.

Sincerely yours

Carlos Sánchez-Díaz

Dear Dr. Muradov,

We want to thank the reviewers their comments that, we are sure, will improve the quality of the paper, even if they consider that it is not able to publication. Below we show their comments and we describe the modifications made to the original document we sent. If no modification is made, we justify why.

Reviewer #1:

This paper is generally well written, but another check is required: for example, figure 8, 9, 11, 13, 14, 15 present words in Spanish language that must be translated in English. Some other little errors can be found:
a) in the acknowledgments at the end: it lacks of the preposition "for"
b) in the sentence of Introduction "This variability forces the use of a type of energy storage with two characteristics" at 11th line: its form should be changed because it doesn't refers to the last sentence and, as a consequence, the adjective "this" is not suitable.

- Changes were made in the paper.
- Headings wrote in Spanish were changed by its translation to English.

However, my basic question does not concern the quality of English language or the calculations, which are fundamentally correct and correctly described, but some aspects of the whole analysis and system modelling:
a) I have not seen any comment about the produced energy: it should be a relevant aspect to be investigated in relation to the consumptions. Indeed, consumption and production analysed in real time determine the energy amount that reaches the electrolyser.

In our design, energy that electrolyser has to consume is the difference between produced energy and consumed energy. This consume can be considered just for the load contribution or it can be considered moreover the self-consume of systems. This last case is the case that we assumed in the paper.

We included a sentence showing the power that represents the electrolyzer auxiliary systems.

b) As a consequence, what about dimensioning of both electrolyser and storage system? Why did you choose this kind of storage system and pressure? Can dimensioning affect the obtained results? I have not seen any detailed comment about the hydrogen rate and compression of hydrogen from the electrolyser to the storage tanks.

A sentence at the end of Section 2 is included to explain the dimensioning of electrolyzer power.

This system is built in kW scale. If test results should be scaled to systems of hundred of kW, a storage method is necessary to select that could be used with this kind of systems. Current references [16] and [17] illustrate that if a big quantity of hydrogen is necessary to store, compressed hydrogen has to be used.

If we use 50 l. bottles, size of storage can be increased simply adding more bottles. In this first design, we use just one bottle. Future work will show if it is enough for a correct behavior of complete hydrogen buffer.

The equation that shows the relationship between hydrogen pressure and hydrogen flow is included in current page 8.

c) Which is the overall efficiency of the systems (sun/wind/biomass to electric energy generated by the fuel cell). This efficiency should be discussed and clearly stated in the paper.

A sentence at the end of Section 2 is included. It is stated that hydrogen buffer efficiency considering the systems operated separately is 21%.

d) Which is the most critical component in terms of cost/benefit analysis? Which are the chances to improve the efficiency or reduce the costs with current and future technologies? Is the fuel cell selected the best option or it has been chosen only because of commercial availability? How could the efficiency be improved with other types of fuel cells?

In this paper, we are just showing the experimental characterization of the hydrogen production of the hydrogen energy buffer. We hope that our future work give us the answers in experimental systems that reviewer ask to us. Now, we have not these answers.

In order to clarify where is placed our work inside the general project, a description of project stages is included in Section 2.

Related with the fuel cell technology, all the high temperature technologies (SOFC, MCFC, PAFC) show a very slow response to load changes, even efficiency of these technologies were higher than PEMFC. As an example, in Fuel Cells Science and Technology 2010 (Grove Fuel Cell Symposium) was presented an oral communication titled:

"Navantia´s fuel cell powered S-80 submarine programme" A F Mellinas, M F Burillo, Navantia S.A. Spain.

They needed 200 kW of fuel cell power and they used two stacks of PEMFC. In the paper, they presented the selection process giving advantages and disadvantages of each technology.

In the same Conference, another paper was presented:

"High temperature operation of a solid polymer electrolyte fuel cell stack based on a new ionomer membrane" A S Aricó, CNR-ITAE Messina, Italy

In the paper, a new PEM membrane was presented that could work at 200 ºC. Efficiency was increased because the higher temperature.

We think that the appropriate technology to scale our results is the PEMFC, but in the future we hope we could use this new technology for hundred of kW.

e) The authors speak about a grid-connected plant, but no investigation is carried out about the possible correlation with the energy feeding in to the grid: with this level of details, the analysis could be the same for a stand alone system. So, which differences? Indeed, storing renewable energy from wind, biomass and sun into hydrogen to use the hydrogen in a fuel cell is an idea that should be applied to stand alone plant: in such a plant, the overall efficiency of the system is heading towards zero, and it is actually a waste of renewable energy, which cannot be considered as free since the capital costs of such a system are unbearable if the production of electric energy is not sustained by excessively high feed-in tariffs.

Our work is related with microgrids. As it can be read in the Editorial of the Special issue on Power Electronics for microgrids (Guest editorial. Editorial special issue on power electronics for microgrids—Part I, IEEE Tans. On Power Electronics, Vol.25, No 12, December 2010), a microgrid can be defined as a part of the grid with elements of prime energy movers, power electronics converters, distributed energy storage systems, and locals loads that can operate autonomously but also interact with the main grid. The functionalities expected for these small local grids are black start operation, frequency and voltage stability, active and reactive power flow control, active power filter capabilities, and storage energy managements, among others. This way, the energy can be generated and stored near the consumptions points, increasing the reliability and reducing the losses produced by the large power lines. The proliferation of interconnected microgrids in one area can lead to the transformation of the distributed lines to tie lines for interchange relatively small amounts of power in order to achieve energy balance.

f) In Figures, there are different components, but it is not mentioned how they modeled, analyzed and obtained.

We do not understand this commentary. All the systems that appear in figures are real systems. We show a block diagram, but all the systems are experimental systems described in the section 2. Could you please tell us which figures are you referring to?

g) Introduction part is too general and there are not some recent publications especially regarding the grid connected storage plant. Please address the following paper in the introduction part:
C. Marino, A. Nucara, M. Pietrafesa, A. Pudano, An energy self-sufficient public building using integrated renewable sources and hydrogen storage, Energy (2013), article in press.

http://dx.doi.org/10.1016/j.energy.2013.01.053

Reference is addressed.

Reviewer #2:

Whilst the article covers quite an interesting field (storage of renewable energies in the form of hydrogen) I do not believe the article in its current form is suitable for publication.

1. you discuss a system and an approach for a control strategy, but the only outcome is that it does not work the way it should; the rather obvious conclusion, that the pressure levels are unsuitable for the dimensioning of the valve and thus the valve is dominated by the gas pressure, not its position, is not properly discussed - please re-work the article including the solution to properly control the system including experimental validation; the article will require a major revision if it is to be published

The following text has been included in Conclusion section.

“As we said in previous sections, the electrolyzer is a commercial model, which is designed for supplying the hydrogen flow demanded by the user. Thus, electrolyzer consumes the required electrical energy. In the electrolyzer, considered as a system, hydrogen flow is the input and consumed energy is the output. However, the operation mode of our hydrogen subsystem is the opposite. Input is the electrical energy that the subsystem must consume, while output is the hydrogen flow generated by the electrolyzer. Thus, a suitable algorithm must be developed in order to use the commercial electrolyzer in the conventional way (figure 17).

When wind subsystem produces an excess of energy which can be transformed into hydrogen, this value is sent to hydrogen subsystem. Input data is the excess of energy minus the electrical consumption of auxiliary components of subsystem. Hydrogen flow produced by electrolyzer can be calculated from electrical consumption of electrolyzer. This gas flow requires a certain number of piston cycle per minute (V_p), which can be obtained by a booster curves family. Next, required booster air pressure must be calculated, taking into account both V_p and bottle hydrogen pressure. Once air pressure has been obtained, gas booster can be regulated. The current manual air regulator of gas booster will be replaced with an automatic regulator commanded from the PLC, which will act over the regulator sending the suitable signal in order to apply the calculated air pressure. Thus, the gas booster will reach the required demand of hydrogen, and the electrolyzer will consume the amount of energy fixed as input. The described algorithm will be implemented into the PLC with the required control loops.”

And a new figure (Figure 17) has been included.

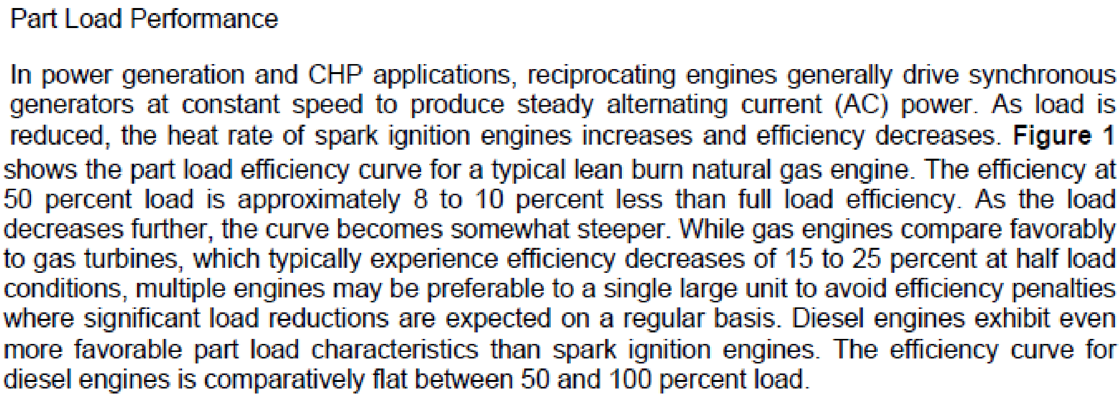
We showed in this work the experimental characterization of the hydrogen production that could help us to define de control system when we used it as a hydrogen buffer. This control system is currently developing. Therefore we have not experimental validation yet. In the included text we show our initial definition of control algorithm. Now, we are checking it in the system. In the next 6 months we will have experimental results.

2. Page 4, 3. para: I do not agree that a downdraught gasifier (I believe this is the type considered) has a good behaviour in partial load, rather the contrary ... explain and reference; the dimensioning is badly explained - what does 'a third below its nominal capacity' mean? 67% of maximum rate? this is not really a 'partial load' as claimed earlier in the paragraph

An updraft or downdraft is the vertical movement of air as a weather related phenomenon. The more extended terminology to speak about this kind of gasifiers is “downdraft gasifier”, even considering that it is an American word.

Downdraft gasifier has a good behavior when syngas rate is not the 100% of gasifier capacity. Conversion efficiency is not affected by the syngas flow rate. It is not the case of fluidized bed gasifier, where air flow rate is important to maintain the bed fluidized. Thus, partial load affects negatively to syngas production.

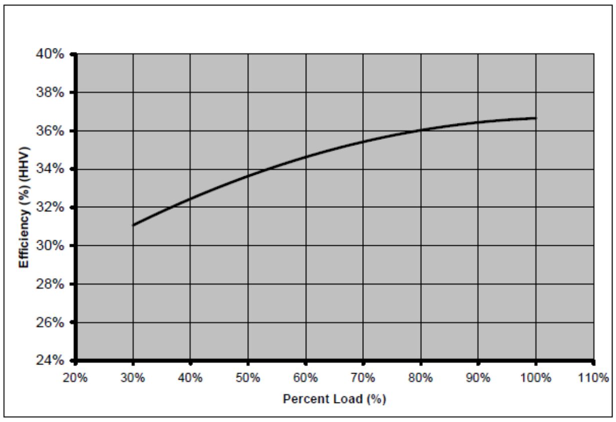
In our case, the efficiency decreasing is due to the gas engine. In the document: “Technology characterization: Reciprocating engines. Prepared for: Enironmental Protection Agency. Combined Heat and Power Partnership Program. Washington, DC. December 2008.”, page 11 it can be found the efficiency performance with part load. We reproduce a part of the text:



Part Load Performance

In power generation and CHP applications, reciprocating engines generally drive synchronous generators at constant speed to produce steady alternating current (AC) power. As load is reduced, the heat rate of spark ignition engines increases and efficiency decreases. **Figure 1** shows the part load efficiency curve for a typical lean burn natural gas engine. The efficiency at 50 percent load is approximately 8 to 10 percent less than full load efficiency. As the load decreases further, the curve becomes somewhat steeper. While gas engines compare favorably to gas turbines, which typically experience efficiency decreases of 15 to 25 percent at half load conditions, multiple engines may be preferable to a single large unit to avoid efficiency penalties where significant load reductions are expected on a regular basis. Diesel engines exhibit even more favorable part load characteristics than spark ignition engines. The efficiency curve for diesel engines is comparatively flat between 50 and 100 percent load.

Figure 1. Part Load Efficiency Performance



Source: Caterpillar, EEA/ICF

If biomass power plant is working at 70% of nominal capacity, efficiency changes from 36.5% to 35.5%. It represents around 3% less efficiency. Reference [17] (now, reference [19]) explains the dimensioning of biomass plant.

We modified the text in the article in order to clarify the explanation.

3. you continuously use the word 'deposit' in a wrong context (see http://en.wikipedia.org/wiki/Deposit) - you should use 'buffer storage', 'interim storage', 'gas storage', 'storage' etc. as appropriate - replace ALL mentions of 'deposit', please

- It is changed in nine cases. Thank you so much for the commentary.

4. Page 5 mentions PV panels but these are not shown anywhere and not mentioned anymore; delete

Reference to photovoltaic power plant is deleted. Even it is installed in our laboratory, system behavior is not affected by that, except in the amount of energy that it could be necessary to consume.

5. Page 5, last parag mentions an 'electro-valve'; this term does not exist, it is an 'electro-pneumatic valve' you are using (moved by compressed air)

- It is changed in thirteen cases. Thank you so much again for the commentary.

6. Page 6: electrolyser production rate is 1.33 cbm H2/h, the purification has a capacity of 6 cbm/h - this mismatch is not further explained

A sentence has been added to explain it:

"Difference between electrolyzer nominal hydrogen capacity and purifying system is due to the necessity to build this installation in kW scale. Commercial systems have been used."

7. page 6 bottom: refers to a 'deposit' (see above) - is a compressed air storage meant here? this is not properly indicated

- It is changed by tank.

8. Page 7: relationship between H2 flow and pressure should be validated by giving the equation

Equation that shows the relationship between hydrogen pressure and hydrogen flow is included in current page 8.

9. Page 7 bottom: manual reading of essential data input is not state of the art

We agree with the reviewer. But, when there is not founding possibilities, we have to use all that could help to research advance.

10. Page 8,top: term 'speed cycling' is very unusual - what do you really mean? 'dynamics'? 'variability'? 'frequency'?

"Speed cycling" is the name that hydrogen booster builder give to speed of piston knocks. We use it for this reason. In the article we changed it for "Swabbing speed". Please, tell us if it is clearest than the other name.

11. Discussion Page8/9: please check language - explanation is hampered by inadequate wording
Explanation is changed in order to clarify it.

12. Page 9, bottom: is it not rather obvious that using STP conditions will lead to wrong values since you disregard any non- STP-conditions of the pressurised H2? conservation of mass must apply,so your explanation does not seem very sound; there either are leaks or interim storage of H2 in the PSA is not taken into account

We agree with reviewer that explanation was not very clear. We modified the paragraph with the following text:

"Bottle charge is calculated by integration of instantaneous hydrogen flow values that are measuring from the electrolyzer. Due to purifying system processes, a pressure drop is caused in the output electrolyzer hydrogen pipeline. That causes a cell current increasing used to compensate this pressure drop in the intermediate electrolyzer hydrogen tank. This hydrogen will be in the bottle sometime in the future, but if booster is stopped, the real hydrogen flow inserted into the bottle is zero. Even if the gas booster is not running, the calculated bottle charge increases. Thus, the estimated bottle charge accumulates an error along the experiment, as it can be seen in the figure. For example the gas booster is stopped between marks M6 and M12, so any hydrogen is inserted into the bottle. However the calculated hydrogen pressure into the bottle increases due to internal flow showed above. A direct consequence is that we cannot use hydrogen flow from the electrolyzer to estimate bottle charge, because it is not a reliable measuring for instantaneous hydrogen flow."

13. Page 10: 'current cell' is the wrong term, you mean 'cell current'

- It is changed

14. Page 12: wording of previous section is repeated - shorten and change to avoid duplication

Following sentences were deleted in the article text.

"The purpose of this project is to technically demonstrate that it is possible to use different energy storage systems in combination with renewable energy sources to build an energy generation system that can handle the intrinsic variability of this kind of sources."

"consisting of an alkaline electrolyzer, a hydrogen purifying system, a compressed air system, a regulation electro-pneumatic valve and a hydrogen pressure booster"

15: Figures: various headings in Spanish have to be deleted or re-worded in English

Headings wrote in Spanish were changed by its translation to English.

Some of the references are not appropriate:
[4], [11], [15]do not seem to cover the topics that are claimed in the text
[5], [6] are papers by the authors - in case of major points to be referenced there should at least be proper references by other authors also
ref [16] is outdated, please find a more current one with correct % values (should be 3 to 6%)

Reference [4]:

Sudi Apak, Erhan Atay, Güngör Tuncer. Renewable hydrogen energy regulations, codes and standards: Challenges faced by an EU candidate country. Int. J Hydrogen Energy 2012; 37: 5481-97.

In the article text it is said:

“There are a large number of programs in the USA and the EU that promote the use of hydrogen for energy storage in stationary applications to produce electrical energy and in electrical vehicles as alternative fuel [4].”

In the reference we can find the following affirmations:

“- Although hydrogen offers advantages to society, it has not been perceived by the individual consumer yet. It is clear that hydrogen energy presents neither financial nor technological problems. The barriers to the hydrogen energy are not technical but the mindset, regulatory and political interferences are the source of the problems.

- Electric and hydrogen vehicles offer much more efficient fuel cycles, but their large-scale application is a long-run option. By benchmarking an ambitious shift to renewable energy and by fundinganaggressivehydrogenfuel cell technologyR&D program, the EU has taken the necessary steps on the way to a hydrogen economy. Setting a goal to become the first fully integrated hydrogen economy in the world is a grand idea which can be regarded as the next phase of European integration.

- Application Programs in USA:

EERE’s FreedomCAR and Vehicle Technologies (FCVT) Program. NREL’s work with alternative fuels programs, such as Clean Cities, the Advanced Vehicle Testing Activity and others has resulted in extensive knowledge and experience with the implementation of alternative fuels.

The American Honda Motor Company provides an example of the first solar-powered hydrogen production and fueling station. This is located in Torrance, California. It uses solar cells and has an electrolysis unit employing a high-efficiency ruthenium-based catalyst. An example in large - scale renewable hydrogen planning is the development of a 4000 MW wind farm on 350 square miles in North Dakota to produce hydrogen, to be delivered directly hundreds of miles away to Chicago via High Voltage Direct Current (HVDC) electricity lines or through a hydrogen pipeline.

- Application Programs in UE:

1. STORHY: Hydrogen storage systems for automotive application and network of excellence (Integrated Project),

2. HYSAFE: Safety of hydrogen as an energy carrier,

3. NESSHY: Novel efficient solid storage for hydrogen,

4. HYTRAIN: Hydrogen storage research training network (in EC; 6th Framework Program: Sustainable Energy Systems).”

And this table is showed in the reference.

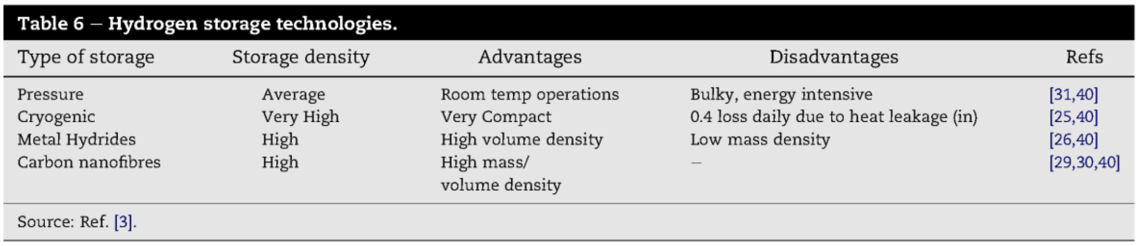


Table 6 – Hydrogen storage technologies.

Type of storage	Storage density	Advantages	Disadvantages	Refs
Pressure	Average	Room temp operations	Bulky, energy intensive	[31,40]
Cryogenic	Very High	Very Compact	0.4 loss daily due to heat leakage (in)	[25,40]
Metal Hydrides	High	High volume density	Low mass density	[26,40]
Carbon nanofibres	High	High mass/ volume density	–	[29,30,40]

Source: Ref. [3].

We think that reference is adequate to support our affirmation.

Reference [11]

M. Calderón, A.J. Calderón, A. Ramiro, J.F. González. Automatic management of energy flows of a stand-alone energy supply with hydrogen support. Int. J Hydrogen Energy 2010; 35: 2226-35.

In the article text it is said:

"Experimental studies demonstrate that it is possible to use this kind of energy storage in the scale of kW for residential application [10], [11]…"

In the reference we can find the following affirmations

"It comprises a photovoltaic generator, a wind-turbine generator, a battery set, an electrolyzer, a metal-hydride system for hydrogen storage, a fuel cell, and a supervisory control and data acquisition system. In the summer, solar energy is sufficient to supply the application, maintain a high state of charge of the batteries, and run the electrolyzer to produce hydrogen which is stored in the metal hydrides. In the winter, when the state of charge of the batteries is low, the fuel cell recharges the batteries avoiding any cut in electric power.

….

To achieve adequate performance from such a complex system, one requires appropriate components and a well-designed control system in order to achieve the system's autonomous operation and energy management."

In System description section of reference it is given the size of installed elements. All of them are in the watts scale (two 45 Wp photovoltaic modules, a 90 W wind turbine). But objective of the paper is to demonstrate that designed control works perfectly when it is used in islanding systems. Reference conclusions were:

"The automatic management of the energy flows of a standalone renewable energy source with hydrogen support has been implemented using a PLC. The control system was successfully tested for autonomous operation and energy management of the installation. The system behaves as an effective test-bed for testing control strategies and optimization algorithms based on data acquired by the monitoring and supervisory system."

We used this reference as an example that there is a lot of work made in isolated systems using hydrogen as energy storage. We think that reference is adequate to support our affirmation in the text.

Reference [15]

Mahmood Farzaneh-Gord, Mahdi Deymi-Dashtebayaz, Hamid Reza Rahbari. Effects of storage types and conditions on compressed hydrogen fueling stations performance. Int. J Hydrogen Energy 2012; 37: 3500-9

In the article text it is said:

"Hydrogen production from electricity produced by wind energy will be the best source of energy [14], but for high volumes of production, high pressure storage is needed. In some studies, the storage method is metal hydride, but in all cases the power considered is low. When large quantities of energy must be stored, compressed storage is chosen [15]."

Reference shows the results of a study made to determine the best way to store hydrogen in hydrogen fuelling stations. When large quantities of hydrogen must be stored, as in the case of this kind of installations, compressed hydrogen method is used. We used this reference as an example of this situation, because our system is built in the kW scale but future results will be scalable to hundreds of kW. In this case, compressed hydrogen is the best storage method.

However, a new reference is addressed:

Mandhapati Raju, Siddhartha Kumar Khaitan. System simulation of compressed hydrogen storage based residential wind hybrid power systems. J Power Sources 2012; 210: 303-20.

In this paper, a revision of compressed hydrogen storage is made and it is simulated a hybrid wind system in order to study the overall behavior.

Reference [5] [6]

An additional reference, where a technical and economic study is presented, has been included.

[10] C. Marino, A. Nucara, M. Pietrafesa, A. Pudano. An energy self-sufficient public building using integrated renewable sources an hydrogen storage. Energy 2013; (Article in Press): 1-11. ***http://dx.doi.org/10.1016/j.energy.2013.01.053***

Reference [16]

Reference

I. Segura et al. Technical requirements for economical viability of electricity generation in stabilized wind parks. Int. J Hydrogen Energy 2007; 32: 3811-9.

Has been changed by the following

Federico Cassola, Massimiliano Burlando. Wind speed and wind energy forecast through Kalman filtering of Numerical Weather Prediction model output. Applied Energy 2012; 99: 154-66.

And percentages were changed in the text. A brief additional sentence is included.

There are a number of language issues:
1. Introduction:
'eternal' should be 'long-term'
- It is changed.

Section 2:
title is unclear, should it be 'Characteristics of the project'?
- Title was changed.

Page 4,top:
delete 'several', 'represented should be 'contributed'

- It is deleted and changed.

Page 4, 4th line
'assumed' should be 'balanced', 'regulation' should be 'regulating' (also in other places in the text)
- It is changed

various mentions of 'gasifiying' should be 'gasifying'

- It is corrected in two cases.

***Highlights (for review)**

- An experimental characterization of a grid connected hydrogen production system was made.
- Characterization will help us to design the electronic control of the system.
- Control system is complex because excess energy from other renewable sources has to be consumed.
- Energy consumption will be made in real time.
- Influence of control parameters in the system behavior is shown.

Experimental characterization of a grid-connected hydrogen energy buffer: hydrogen production.

Carlos Sánchez, Domingo González

Institute for Energy Engineering, Universitat Politècnica de València, Camino de Vera s/n,
46022 Valencia, Spain

csanched@eln.upv.es; dgn@iicv.es

Corresponding author:

Carlos Sánchez

Phone Number: +34 653 953 003

Fax Number: +34 963 877 609

Email: csanched@eln.upv.es

Postal Address: Instituto de Ingeniería Energética, Universidad Politécnica de Valencia, Camino de Vera s/n, 46022, Valencia, Spain.

Abstract

Energy storage becomes a necessity when a high penetration of renewable energy sources is desirable. Variability in the energy production from these types of energy sources can make the utility grid unstable, if the percentage of production is important. In order to minimize this problem, the HiDRENER project was designed to study the effect of combining different renewable energy sources with energy storage on grid stability. The system has a wind generator, a gasifying biomass power plant with syngas storage, a solar photovoltaic plant, and a hydrogen energy buffer. Controlling the entire system is very complex. This paper shows the results of the grid-connected hydrogen energy buffer characterization, considering hydrogen production in this first stage. The objective is to know the complete behavior of the system, which could help us to define the energy buffer control. This control is oriented toward consuming excess energy produced by the other sources in real time. This means that the hydrogen buffer control has to negotiate how much energy can be stored, and act on the production system. Thus, actuation variables and dynamic behavior have to be discovered.

Keywords

Hybrid system; Renewable energy; Energy Storage; Experimental Characterization;
Grid connected; Data acquisition; Linux;

1. Introduction.

In the current economic situation, when the global crisis is on everyone's mind, new ways to supply the energy demand become necessary. Renewable energy sources (RES) can help to implement a solution in areas where this demand cannot be met with fossil fuel production (e.g. the European Union, which is the world's largest importer of fossil fuels). One of the main inconveniences of this kind of sources is that they are usually diffused and not fully accessible, some are even intermittent, and they vary widely among regions. In order to promote the development of competitive systems, the European Council approved a set of strategic energy policy goals, based on the fact that about one-third of the electricity demand in 2020 could be supplied by RES [1]. Variability of RES energy production forces the use of a type of energy storage with two characteristics: it should be "long term", that is, the energy stored should be available months after it was saved, with no losses due to self-discharging phenomena, and it should be able to store large quantities of energy. Hydrogen is a good candidate to be used for this purpose [2], [3]. There are a large number of programs in the USA and the EU that promote the use of hydrogen for energy storage in stationary applications to produce electrical energy and in electrical vehicles as alternative fuel [4]. The use of hydrogen is considered a strategic policy in energy matters. Moreover, a lot of studies have been published about hydrogen as an energetic vector using renewable energy sources. Simulation studies have demonstrated the technical and economic viability of the use of hydrogen in wind farm compensation combined with a biomass gasification plant [5], [6], or in stand-alone systems for residential areas [7], [8], [9] combining wind energy production with solar photovoltaic and hydrogen storage [10]. Experimental studies demonstrate that it is possible to use this kind of energy storage in the scale of kW for residential application [11], [12] or even in extreme environmental conditions. An example would be the system presented in [13], where a hydrogen storage system is combined with two wind turbines and a battery bank, in order to supply the energy demand of the Argentine Esperanza Station, in Hope Bay, Antarctica. Data from two years of this experience are provided in the paper, and the results were very positive, due to the good acceptance of hydrogen technologies among residents and the fact that Antarctica is a protected area where the use of fossil fuels is restricted in order to prevent any external contamination. This last argument justifies the use of hydrogen as energy storage, because what is good for Antarctica's ecosystem might be good for the rest of the world.

At the present time, hydrogen is used successfully in stand-alone systems. Now it is necessary to demonstrate that it could be a very good solution in grid-connected systems. Hydrogen generation and storage as an energetic vector makes a double contribution to the current energy problem. On the one hand, energy storage makes it possible to decouple energy production and demand, so that energy production can be achieved from energy sources where there is no control over the production moments. This situation facilitates the increase in the use of this kind of sources because hydrogen can provide regulating capacity. On the other hand, thanks to its electrochemical properties, hydrogen can be an alternative in energy transport, by means of pipelined infrastructures.

Some studies [14] state that storage helps to reduce backup energy demand by averaging intermittent power generation in space and time. This paper shows a systematic study of the interdependence between two technologies, transmission and storage, varying the two degrees of freedom separately over a wide range of values. The results depend on the storage technology considered. Low efficiency storages like H2 render it important to reduce fluctuations before storage and, thus, require a well-extended grid. Therefore, choosing H2 storage as the major storage option leads to the largest grid and the largest storage market.

Hydrogen production from electricity produced by wind energy will be the best source of energy [15], but for high volumes of production, high pressure storage is needed. In some studies, the storage method is metal hydride, but in all cases the power considered is low. When large quantities of energy must be stored, compressed storage is chosen [16], [17].

Taking into account the state of the art, it is justifiable to consider an energy production system based on the aggregation of different renewable energy sources with a hydrogen storage system. This system, connected to a grid, could help to reduce backup energy installed power and improve grid behavior (reducing transport losses) [14]. In order to achieve this objective, a hybrid system is proposed. The system is composed of a wind farm, a biomass gasification plant, a photovoltaic plant, a battery bank, a hydrogen production system with high pressure storage, and a fuel cell to produce electrical energy from stored hydrogen. All of this is connected to a micro-grid, making up a whole system called the HiDRENER project. In the following sections, we will describe the characteristics of each sub-system. The aim of this paper is to present the hydrogen buffer characterization, considering hydrogen generation, which will help us to design the electronic control of the system, in order to provide effective energy storing and production when needed.

In Section 2, we will present the characteristics of the general project. The description of the hydrogen production and data acquisition system is provided in Section 3. In Section 4, we will show the results of the hydrogen production system tests and discussion about them.

2. Characteristics of the HiDRENER project.

It is commonly accepted that the introduction of renewable energy sources in the electric generation system is a viable and economical solution to substitute nuclear and fossil fuels, allowing an important reduction in CO2 emissions. Wind energy is one of the renewable sources that makes the greatest contribution to this objective. In Spain, in particular weather conditions, it has contributed up to 50% of the electric consumption. But its non manageable nature presents a problem when it is necessary to maintain a balance between generated energy and consumed energy in the electric system. Differences between these magnitudes are balanced by regulating power plants that provide a fast response. But these kinds of power plants often use fossil fuels to operate, which could lead to an even greater problem. Although new complex wind prediction systems have been developed, error in energy forecasts could reach values of between 2.4 to 6% depending on the wind speed and time considered [18]. This deviation complicates trying to maintain a balance between production and consumption. When production exceeds consumption, it is possible to disconnect some turbines in the wind farm, with the energy waste that this action implies. But when the situation is the opposite, the electrical system has to use regulating power plants.

In this context, the HiDRENER project is proposed. The project's aim is to technically demonstrate that it is possible to use different energy storage systems in combination with renewable energy sources to build an energy generation system that can handle the intrinsic variability of these kinds of sources. Figure 1 shows a block diagram that summarizes the global project. A wind farm is compensated with a biomass power plant and a hydrogen production system that can produce electrical energy by means of a fuel cell system. Project is mainly organized in three stages. In the first stage the hybrid system is defined, modeled and simulated, in order to study its correct working. In the second stage, a scale prototype plant is designed and built. Each physical subsystem is operated and tested individually in order to obtain its behavior. At this point, the work described in this article concerns the hydrogen production system characterization. This characterization will allow us to develop the system control and its integration into the complete hybrid system. The last step of the second stage will be integration of all subsystems using a distributed control system. A communication network is also designed and implemented, which is used for establishing communication between subsystem components and between all subsystems. In the third stage, technical and economic viability of a real scale system will be done.

Gasification biomass power plants are considered adequate to work with a wind farm due to good behavior with partial loads and, combining it with a syngas storage tank, due to fast response to variations in demand. In our design, the gasifier and the engine are over-dimensioned with respect to the biomass power plant base electrical generation. Excess syngas is stored in a tank and can be used when wind farm compensation is needed. Current gasifier technology allows it to operate correctly at 70% of nominal capacity [19]. Therefore, this is the percentage of gasifier over-dimensioning. The biomass power plant is continuously generating a base electrical energy using syngas produced by the base gasifier, and it increases production when required, consuming gas from the tank. Thus, the change in production is very fast and limited exclusively by the electrical generation engine. Changes in gasifier point operation are slower, and so that over-dimensioning is used to fill the tank.

When the wind farm produces excess energy, it is used to produce hydrogen by means of an electrolysis system. Hydrogen is stored and can be used if additional compensation is needed by means a fuel cell system. Moreover, oxygen, which is a byproduct, could be used to increase the efficiency of the gasification process. Syngas, produced using oxygen directly or by enriching the needed air, has a higher quality, and more energy is obtained from the generator engine.

A global system needs effective control if energy generation should maintain stability. A distributed control is proposed, based on the energy measurement in each system (wind farm, biomass gasifying plant and hydrogen buffer) and a network implemented using Modbus TCP/IP protocol. Each subsystem has a dedicated control that is autonomous in decisions related to its work. The communication network is used to negotiate with other subsystems about conditions of the system's global work (i.e. how much energy is necessary to deliver through what subsystem, biomass power plant or hydrogen buffer, or how much energy can be stored in hydrogen).

In order to implement all the subsystems, a new laboratory was built (Distributed Energy Resources Laboratory, LABDER) at the Universitat Politècnica de València. This laboratory has a 6 kW wind turbine, a 5 kW downdraft gasifying power plant, an 1.33 Nm3/h alkaline hydrogen generator with high pressure hydrogen storage, connected to a 1.2 kW PEM fuel cell. Hydrogen flow rate of electrolyzer was selected attending to electrical power needed to obtain it, 7 kW. This system has to be able to consume all energy generated by the wind generator. Commercial system with the nearest power was the selected system. Attending to the behavior of hydrogen production system and fuel cell system operated separately, the hydrogen buffer efficiency will be 21%. When the buffer control was completed, tests will be made and this efficiency should be validated. A communication network is designed to decide the operation point of each subsystem. It is composed of two redundant physical networks (wired and wireless) with Modbus TCP/IP logical protocol. The network connects Programmable Logic Controllers (PLC) that control each subsystem with the energy measure subsystems. A SCADA is developed to run on a computer that serves as an interface between the human power plant operator and the system (Human Machine Interface, HMI). The design of the communication network is shown in figure 2.

3. System Description.

The previous section briefly described the hydrogen production system as a part of a complete project. If effective control of the hydrogen system is needed, the first step is to characterize the behavior of the hydrogen production. In this section, we will describe the hydrogen production system, the data acquisition system developed, and the methodology used in the tests to obtain all the information.

Hydrogen production is done by means of an alkaline electrolyzer Erre Due G2.0 from distilled and deionized water. Products of electrolysis are hydrogen and oxygen. Currently, oxygen is not used, but in the future it will be used to increase the efficiency of syngas production in the biomass power plant. Hydrogen is pipelined to a purifying system, Erre Due DPSH-6, that can increase its purity to 99.995% (needed to use this hydrogen in a PEM fuel cell). This process requires a refrigeration system, provided by a Euro Cold ACW-LP 25 refrigerator, and compressed air, provided by an industrial PUSKA SIL NH 700-300 compressor.

This system is an industrial process designed to provide as much hydrogen as needed to the end consumer. An electro-pneumatic valve is connected in the process of hydrogen production, in order to control how much hydrogen is generated and, consequently, how much energy is consumed by the electrolyzer. This energy is the excess from the wind farm, so it is necessary to control the consumption of the same quantity of energy. In our first design, the mission of the electro-pneumatic valve was to regulate hydrogen flow, but in section 4 we will show what the real effect on the system was. The electro-pneumatic valve is controlled by an electrical signal (4-20 mA), but it is piloted by 6 bar compressed air.

Generated hydrogen is stored in a 50 liter gas bottle. Maximum pressure in this bottle can reach 200 bar. It is necessary to use a Haskell AGT/7-30 booster to store hydrogen at this pressure. This compressor is operated with compressed air in order not to contaminate the hydrogen with any components that would be necessary to operate a conventional compressor (i.e. oil).

Figure 3 shows a block diagram of the complete hydrogen generation system, where the energy measurement system implemented by a Siemens SENTRON PAC installed in the electrical connection of the hydrogen generator and compressor can be seen. This device can be easily accessed by means a TCP/IP network, and it provides information about main energy consumed by the system. This information could be used in the system controller unit.

The electrolyzer G2.0 requires a three-phase electric supply with a nominal power of 7.2 kW. The nominal current is 14 A, and in these conditions, nominal hydrogen production is 1.33 Nm^3/h at 2.5 bar of outlet pressure. Electrolyzer auxiliary systems represent a constant power of 500 W. Hydrogen purity is between 99.3 and 99.8 %. In our system, outlet pressure is set to 4 bar. Maximum water consumption is 1.2 l/h, and the electrolysis medium is a sodium hydroxide (NaOH) solution with 1.2 g/ml density. The entire electrolysis process is controlled by a Programmable Logic Controller (PLC) ABB 07KT97. This device is connected to the tactile screen that serves as the interface with the user, and provides information about energy consumed, hydrogen and oxygen flow, electrolysis cell current, pressure and temperature, and other information related to the process. This PLC has a serial port that makes it possible to consult all these parameters from an external device by means of a RS232 serial communication with Modbus RTU protocol.

After hydrogen production, it is necessary to purify it by extracting residual oxygen, humidity and electrolytic solution from the hydrogen flow. Purifying system DPSH6 is based on a Pressure Swing Adsorption (PSA) process. It consists of three filters (activated carbon, aluminum oxide and hygroscopic salts), and requires a minimum of 6 bar of compressed air flow supplied by the PUSKA compressor. Nominal capacity of the purifying system is 6 Nm^3/h. Difference between electrolyzer hydrogen nominal capacity and purifying system is due to the necessity to build this installation in kW scale. Commercial systems have been used. Input hydrogen purity has to be more than 99%, and output purity is 99.995%. Water steam is eliminated by condensation. This process uses two heat exchangers, one internal with an air radiator, and one external. The external unit is a Euro Cold ACW-LP 25, with a nominal frigorific power of 3460 W. Figure 4 shows an electrolyzer and purifying system image.

The compressor has a 4 kW electric motor that can suck a nominal air flow of 700 liters per minute at 7 bar. The tank has a capacity of 300 liters, and the working set point is defined at between 6.5 and 9 bar. Compressed air is used in the purifying system and needed in the electro-pneumatic valve and in the booster. The electro-pneumatic valve (a SAMSON 240 Series with a pneumatic drive type 3277) is controlled by a 4 – 20 mA signal, but constant air pressure of 6 bar allows the movement of the piston rod. A Phoenix Contact MCR-SL-U-I-4 module enables the transformation of a variable voltage between 0 to 10 V into a 4 – 20 mA signal. The booster uses the variable compressed air pressure to compress hydrogen, depending on the inlet hydrogen pressure and the bottle hydrogen pressure. Both systems have a manual regulator to control inlet air pressure.

The Haskel AGT-7/30 Booster is a two-stage compressor that compresses hydrogen up to a maximum pressure of 200 bar. The compressor is composed of an air section with a central pneumatic cylinder, and a gas section with two compression cylinders, the first with a compression rate of 7 and the second with a compression rate of 30. Refrigeration of the compressor is done with the exhaust air by means of a heat exchanger, so no electrical supply is required. Pressure in the outlet pipeline is related to hydrogen inlet pressure and compressed air pressure, since this pressure depends on the diameter relation between air cylinder and the corresponding hydrogen cylinder in each stage. Figure 5 shows a scheme that includes the two phases: suction and compression. The first stage sucks hydrogen from the inlet pipeline and compresses it at high pressure in the outlet pipeline. Output pressure depends on the relationship between sections of two pistons (air and output hydrogen) and on the difference between air pressure and output pressure. The second stage transfers hydrogen from the low pressure to high pressure hydrogen cylinder. Again, there is a relationship between hydrogen inlet pressure, air pressure and diameters of air and low pressure hydrogen cylinder. The final expression that relates all these variables is presented in equation 1.

$$P_o = 30 \cdot P_{ab} + 4.2 \cdot P_s \tag{1}$$

where P_o is output hydrogen pressure, P_{ab} is compressed air pressure, and P_s is hydrogen supply pressure.

Focusing on this expression, the only parameter that can be modified independently is compressed air pressure. In our system, this can be achieved by using a manual pressure regulator. The hydrogen flow that a booster can compress is a function of air flow, which determines the number of piston cycles, and the volumetric efficiency, which depends on the bottle pressure. Hydrogen flow through gas booster is calculated by equation 2.

$$F_h = \frac{\frac{V_p}{100} \cdot V_e \cdot D_b \cdot (P_s + 1.013)}{1.013} \qquad (2)$$

where F_h is hydrogen flow, V_p is the number of piston cycles per minute, V_e is the volumetric efficiency, D_b is geometrical volume of gas piston and P_s is hydrogen supply pressure. Again, the parameter that can be changed is air pressure, which is related to air flow. Thus, there is a relationship between output hydrogen pressure and hydrogen flow.

In order to read all the necessary data to allow us to characterize the hydrogen production system's behavior, a data acquisition system is built. The particularity of the data format and the acquisition medium in each device made it impossible to use a commercial system. Moreover, not all the data could be read automatically. Table 1 shows automatic data collection and the medium used to acquire them. Table 2 shows manual data collection and how they are read.

As can be seen in these tables, a complex communication network had to be implemented. A PC acts as the host for acquiring software. Graphical versatility and data processing ease recommended its use. The acquisition software was implemented using Python language [20] [21] running over a Linux platform. Free software has a lot of advantages, and Linux is a very stable operating system [22]. Regarding communication networks, on the one hand, two Modbus TCP Clients were created to read data from the Sentron module (electrical information) and from the Phoenix ILC 150 ETH PLC (swabbing speed). A physical net was implemented using a standard switch Repotec RP-1708I with Ethernet cable. On the other hand, a Modbus RTU Client was created in order to read information from the electrolyzer control unit. Physical connection was achieved with a RS232-USB converter, using a USB port in the computer as the input port. Figure 6 shows a schematic representation of the communication network. A second computer is needed to program the Phoenix ILC 150 ETH because this software (PcWorx, from Phoenix Contact) runs over a Windows platform. The same switch can be used to connect both systems.

The structure of the data acquisition software can be defined in two main modules. The first one is dedicated to starting communication with the corresponding system and collecting data (called SAD module), and the second one is dedicated to generating the data structure and graphics interface (called the PLOT module). Parallel to the first module, the user can run other software that allows him/her to fix temporary marks (called MARK module). This software is used to indicate in the data file and output graph when a parameter change occurs (i.e. a change in the booster piloting compressed air) or when an interesting event happens (i.e. a system failure). Figure 7 shows a diagram that summarizes the working procedure.

The test procedure always has the same structure. First, the hydrogen generation system starts. Second, the SAD and MARK modules are running. The experiment progresses by making the parameter changes related to the previous experiment design. When the experiment ends, both software modules are closed, and the PLOT module starts. A set of graphs is produced for all the data collection, including user marks (vertical lines in the example graph shown in figure 7).

4. Results and discussion.

The purpose of the characterization of a hydrogen generation system is to know its behavior in order to control it. This control should make the hydrogen production system consume the excess energy produced by the other renewable sources connected to the micro-grid. Control will read the consumed energy by means of the Sentron system, and it will act on the system to modify the operation point until the energy objective is achieved. In the initial design, this mission was assigned to the electro-pneumatic valve. Experiments demonstrated that this was not a correct decision.

In this first design, the hydrogen flow reading from the electrolyzer was considered enough to know how much hydrogen is stored in the bottle, taking into account that hydrogen is in a closed pipelined circuit. First experiments were conducted to explain it. Figure 8 shows the results of the hydrogen production system, with and without connection to the DPSH6 purifying system. The electro-pneumatic valve was completely closed. When the hydrogen system starts, the first step is to pressurize the intermediate hydrogen and oxygen tanks until reaching a set pressure (4 barg in our system). This operation requires a power consumption that can be seen in figure 8 in the first change in total power graph. When the set up pressure is reached, if there is no hydrogen consumed, power drops to a pressure maintenance state. In the second start (mark M2 in figure 8), DPSH6 is connected. The purification process forces electrolyzer to work with variable electrical consumption cycles. This is due to pressure variations in the purifying system that acts in the electrolyzer as temporary hydrogen flow demands.

Figure 9 shows the pressure and current electrolysis cell after the M2 mark in the same experiment. The working procedure of the electrolyzer can be seen. When pressure drops, the cell current is increasing in order to produce more hydrogen. That increases hydrogen pressure. When pressure is increasing, the current is decreasing at the same speed, until the maintenance current is reached. Variations in pressure are due to periodic demands made on the purifying system. This situation poses a problem when precise adjustments are required in regulating system parameters. It has been demonstrated that this perturbation is less important when the electrolyzer is in a high production state. However, when storage bottle pressure is increasing, hydrogen flow decreases, representing a serious impediment to a precise characterization of the system.

One of the objectives of the initial system design was not to use a hydrogen pressure measuring system in the storage bottle, because we can find out, by means of the hydrogen flow reading, how much hydrogen is stored if we know the initial conditions of the bottle. Pressure in the bottle can be calculated by equation 3 [23].

$$P_b = P_{bi} + \frac{Z(P)\cdot n\cdot R\cdot T_{amb}}{V} \quad (3)$$

where P_b is bottle pressure, P_{bi} is initial bottle pressure, Z(P) is the hydrogen compressibility factor (which varies between 1 at 0 bar and 1.132 at 200 bar, 20 ºC), n is the mol number, R is the perfect gases constant, T_{amb} is the ambient temperature, and V is hydrogen volume.

The mol number can be calculated from reading the hydrogen flow, as expressed in equation 4.

$$n = \int_0^{t1} Fh(t)\cdot dt \quad (4)$$

where Fh(t) is the instantaneous hydrogen flow. Considering a hydrogen density of 0.08376 kg/m^3 (which corresponds to 1 bar, 20 ºC), and using hydrogen flow data from the electrolyzer, theoretical bottle pressure was calculated and compared with real bottle pressure (reading it directly from the bottle manometer). Results are shown in figure 10. It can be observed that there is a considerable difference between the two magnitudes. Again, this discrepancy is due to perturbation introduced by the purifying system.

Bottle charge is calculated by integration of instantaneous hydrogen flow values that are measuring from the electrolyzer. Due to purifying system processes, a pressure drop is caused in the output electrolyzer hydrogen pipeline. That causes a cell current increasing used to compensate this pressure drop in the intermediate electrolyzer hydrogen tank. This hydrogen will be in the bottle sometime in the future, but if booster is stopped, the real hydrogen flow inserted into the bottle is zero. Even if the gas booster is not running, the calculated bottle charge increases. Thus, the estimated bottle charge accumulates an error along the experiment, as it can be seen in the figure. For example the gas booster is stopped between marks M6 and M12, so any hydrogen is inserted into the bottle. However the calculated hydrogen pressure into the bottle increases due to internal flow showed above. A direct consequence is that we cannot use hydrogen flow from the electrolyzer to estimate bottle charge, because it is not a reliable measuring for instantaneous hydrogen flow.

Future control of hydrogen production systems will need to know how much hydrogen can be stored, based on current stored hydrogen and the capacity of the storage tank.

Therefore, it is necessary to know the quantity of hydrogen that can be produced relative to the electrolysis cell current rate (in other words, electrical power rate). Figure 11 shows the relationship between current cell and hydrogen flow. Between 10 and 40 A, there is less hydrogen flow than expected. One of the parameters that affect electrochemical conversion is temperature. A specific experiment was defined in order to find out whether temperature affects it. Figure 12 shows the temperature evolution and cell current. It can be seen that the maximum working cell temperature was 57 ºC, and the tendency is to stabilize it at 55 ºC. The relationship between current cell and hydrogen flow had the same behavior as what is reflected in figure 11. A possible explanation for this behavior was that, normally, high current rates occur when hydrogen intermediate tanks show low pressure. It is necessary to produce much more hydrogen in order to increase pressure. When intermediate hydrogen tank pressure reaches its maximum, the current decreases (as shown in figure 9). Thus, low current rates are achieved with high pressure.

The more complex element in the system is the pressure booster. As described in section 3, high hydrogen pressure is achieved by means of the action of compressed air pressure in a central cavity (air section) that compresses the hydrogen in the cavities at each side (gas section), as shown in figure 5. Air consumed is the addition of exhausted air in each of the displacements. In [24] it is described how to calculate air flow consumed by a single stage booster. The calculation was adapted in this study to a double stage compressor. Simply applying the Boyle-Mariotte law to phases a) and b) in figure 5 makes it possible to calculate air flow with equation 5.

$$Q_a = 2 \cdot St \cdot (A - a_0) \cdot \frac{P_{ab}}{P_{at}} \cdot V_p \qquad (5)$$

where Q_a is the air flow, St is the stroke length, A is the piston area, a_0 is the axis section, P_{ab} is the air pressure, P_{at} is the atmospheric pressure and V_p is the swabbing speed in cycles per minute.

In our system, maximum air flow provided by the air compressor, maintaining 6.5 bar as minimum pressure, was 610 l/min (experimentally validated). Using this air flow and taking into account geometrical parameters of the booster, a graph is constructed to find the valid range of operation for air pressure versus swabbing speed (figure 13). This is an important parameter because an air pressure of below 6 bar brings the purifying system to a standstill, stopping hydrogen production.

And why is the booster a complex element in the system? Because with parameter air pressure (P_{ab}), hydrogen flow is regulate and, therefore, electrical consumption, which is the objective of the control. Figure 14 shows the high correlation existing between swabbing speed and hydrogen flow (without taking into account perturbation introduced by the purifying system). However, the necessary air pressure to maintain constant swabbing speed depends on the hydrogen bottle pressure (considering practically constant hydrogen supply pressure, because it varies between 3 and 3.9 bar, depending on the flow rate). This relationship is shown in figure 14, where air pressure is maintaining constant swabbing speed, for example, in intervals of between 7100 to 9000 seconds.

In our first design, an electro-pneumatic valve was connected in the hydrogen pipeline to regulate hydrogen flow. In order to characterize the effect of the valve opening, an experiment was designed for a high hydrogen production rate, which means high and constant booster swabbing speed, eliminating purifying system perturbations. Figure 15 shows the results of the experiment. When hydrogen flow was stabilized (after 350 seconds), the valve opening was periodically increased from an initial 20% opening to a 100% opening in 510 seconds (indicated by vertical lines in figure 15). The effect on hydrogen flow was practically non-existent due to the booster working. Compressed air causes the displacement of the piston booster, that is, moving a gas volume through it. The booster is located in the electro-pneumatic valve output, so that it forces gas flow through the electro-pneumatic valve, independently of the valve opening. Therefore, the booster air drive becomes the only factor for regulating hydrogen flow. How can the control system correctly run with only one regulating parameter? The control system works with two operational parameters, one internal and one external to the system. The external parameter is the electrical energy that the system must consume, a value that is given by the global system. Energy value can be easily converted to hydrogen flow. The internal parameter is the bottle charge state. It determines the minimum required hydrogen pressure to introduce it into the gas bottle. Therefore, the system operation space is defined by the required hydrogen flow and bottle charge.

The compressor booster can generate an output gas pressure by means of air drive pressure (equation 1) and a speed cycle value that is also created through the air drive. Thus, the booster could operate at any work point defined by hydrogen flow and output gas pressure, using only air drive pressure as the regulating parameter. However, the system cannot work in all operation spaces due to the output gas pressure and hydrogen flow relationship, as well as some technical restrictions. For example, maximum generated air flow from the air compressor delimits the air consumed by the booster (equation 4) and, consequently, the operation space (figure 13). In this way, it is necessary to modify the expected control system.

In order to validate the relationship between hydrogen flow and booster cycling speed, a statistical analysis was performed. Figure 16 shows that there is a positive relationship between the cycling speed of the booster compressor and the measured hydrogen flow (generated from the electrolyzer), according to the final results. However, as can be seen in the figure, there is a strong data dispersion due to the effect of the DPSH6 purifying system. In zero-speed conditions, when the booster compressor is stopped, there are several hydrogen flow measures with a non zero value. This data dispersion makes it more complicated to obtain an accurate relationship between the desired parameters. A Pearson product-moment correlation coefficient was calculated in order to measure the strength of the association between swabbing speed and hydrogen flow. Results indicate that booster swabbing speed explains 35% of the hydrogen flow value, with 95%

confidence. This value is very low, and it confirms the detrimental effect of the purifying process in the electrolyzer-booster control model. Therefore, it is necessary to measure hydrogen flow in some other way.

The only possible effect when the valve is near to be closed is a hydrogen pressure drop in the input of the booster that would slightly reduce swabbing speed and, consequently, hydrogen flow. Thus, in this system, the electro-pneumatic valve will be used as a security element in the case of hydrogen flow cut-off.

Conclusion.

This paper presented the characterization of the hydrogen production system that is part of the energy buffer implemented in the HiDRENER project. One of the components of this project is the hydrogen energy buffer. In order to control the energy consumed by this system when there is an excess of the other renewable sources, a control system is necessary. Defining the control parameters requires knowing all the behaviors of the subsystem. In order to extract this information from the system, a specific data acquisition system was built, and a set of experiments was designed. The most relevant results from these experiments are shown and some conclusions are presented.

In the first design, the electro-pneumatic valve was the basic regulating element of hydrogen flow that made it possible to control the energy consumed by the electrolyzer. Results demonstrated that this element has no influence on hydrogen flow variation. This task is done by the hydrogen pressure booster, and the study has shown that this element can adjust the operation point of the entire system: produced hydrogen flow and bottle charge rate. This one element needs just one control parameter, piloting compressed air. The control system works with two operational parameters, one internal and one external to the system. The external parameter is the excess electrical energy (that is, hydrogen flow), and the internal parameter is the bottle charge (that is, minimum required hydrogen pressure). System operation space is defined by both parameters. Both work parameters can be achieved by means of air drive pressure, although with some technical restrictions.

However, hydrogen flow regulating is not an easy task, because hydrogen flow is related to booster swabbing speed, which is related to piloting compressed air pressure and hydrogen bottle pressure, and hydrogen bottle pressure is related to hydrogen flow. Therefore, a complex control system is needed to maintain the consumed energy constant. This complexity increases in a real system where the hydrogen flow that it must regulate continuously changes. Thus, this control must continuously modify the system operation point according to the excess energy and the bottle hydrogen charge. As we said in previous sections, the electrolyzer is a commercial model, which is designed for supplying the hydrogen flow demanded by the user. Thus, electrolyzer consumes the required electrical energy. In the electrolyzer, considered as a system, hydrogen flow is the input and consumed energy is the output. However, the operation mode of our hydrogen subsystem is the opposite. Input is the electrical energy that the subsystem must consume, while output is the hydrogen flow generated by the electrolyzer. Thus, a suitable algorithm must be developed in order to use the commercial electrolyzer in the conventional way (figure 17).

When wind subsystem produces an excess of energy which can be transformed into hydrogen, this value is sent to hydrogen subsystem. Input data is the excess of energy minus the electrical consumption of auxiliary components of subsystem. Hydrogen flow produced by electrolyzer can be calculated from electrical consumption of electrolyzer. This gas flow requires a certain number of piston cycle per minute (V_p), which can be obtained by a booster curves family. Next, required booster air pressure must be calculated, taking into account both V_p and bottle hydrogen pressure. Once air pressure has been obtained, gas booster can be regulated. The current manual air regulator of gas booster will be replaced with an automatic regulator commanded from the PLC, which will act over the regulator sending the suitable signal in order to apply the calculated air pressure. Thus, the gas booster will reach the required demand of hydrogen, and the electrolyzer will consume the amount of energy fixed as input. The described algorithm will be implemented into the PLC with the required control loops.

The hydrogen purifying system, due to an internal process, introduces perturbations in the hydrogen flow measured in the electrolyzer. Measuring hydrogen at this point as an input parameter in the control system is not a good idea. A direct hydrogen flow measure after the purifying system is needed.

The capacity of the air compressor is not enough to operate the system in a wide range, because these limitations affect the purifying system and maximum booster swabbing speed. As the installation design was made using static characteristics of each element, a new design procedure is necessary when dynamic behavior is considered.

The data acquisition system designed for this application is flexible and can easily be extended to other hosts, such as, for example, the ILC 150 ETH from Phoenix Contact, which will be the core of the hydrogen production control system. To implement this control, results suggest some changes in the installation. The first change is the use of a hydrogen bottle pressure meter with digital communications, as well as the substitution of the manual air pressure regulator in the booster input by an automatic regulator with digital communications. Second, if precise control is required, it is advisable to install a hydrogen pressure meter in the booster hydrogen input and a flow meter in the booster hydrogen output.

Future work is oriented toward implementing these changes in the installation and design of the complete hydrogen buffer control, which includes three aspects: hydrogen generation control; energy generation control from this hydrogen by means of a 1.2 kW Nexa PEM Fuel Cell and its corresponding grid connected inverter; and coordination with the other elements in the HiDRENER project (wind farm measuring system and gasification biomass plant).

Acknowledgements

The authors thank the Ministerio de Educación y Ciencia of Spain for the financial support of this research through Proyectos de Infraestructura Cientifico-tecnológica program.

References.

[1] A. Tolón-Becerra, X. Lastra-Bravo, F. Bienvenido-Bárcena. Proposal for a territorial distribution of the EU 2020 political renewable energy goal. Renew. Energy 2011; 36: 2067-77.

[2] M. Calderón, A.J. Calderón, A. Ramiro, J.F. González. Automatic management of energy flows of a stand-alone energy supply with hydrogen support. Int. J Hydrogen Energy 2010; 35: 2226-35.

[3] E. Bocci, F. Zuccari, A. Dell'Era. Renewable and hydrogen energy integrated house. Int. J Hydrogen Energy 2011; 36: 7963-8.

[4] Sudi Apak, Erhan Atay, Güngör Tuncer. Renewable hydrogen energy regulations, codes and standards: Challenges faced by an EU candidate country. Int. J Hydrogen Energy 2012; 37: 5481-97.

[5] Carlos Sánchez, Belén Abad, Stefan Hübner, David Alfonso, Isidoro Segura. Wind park reliable energy production based on a hydrogen compensation system. Part I: Technical viability. Int. J Hydrogen Energy 2011; 36: 15548-60.

[6] Carlos Sánchez, Stefan Hübner, Belén Abad, David Alfonso, Isidoro Segura. Wind park reliable energy production based on a hydrogen compensation system. Part II: Economic study. Int. J Hydrogen Energy 2012; 37: 3088-97.

[7] Mandhapati Raju, Siddhartha Kumar Kaitan. System simulation of compressed hydrogen storage based residential wind hybrid power systems. J Power Sources 2012; 210: 303-20.

[8] Chrysovalantou Ziogou et al. Automation infrastructure and operation control strategy in a stand-alone power system based on renewable energy sources. J Power Sources 2011; 196: 9488-99.

[9] Prabodh Bajpai, Vaishalee Dash. Hybrid renewable energy systems for power generation in stand-alone applications: A review. Renew. Sustain. Energy Rev. 2012; 16: 2926-39.

[10] C. Marino, A. Nucara, M. Pietrafesa, A. Pudano. An energy self-sufficient public building using integrated renewable sources an hydrogen storage. Energy 2013; (Article in Press): 1-11. ***http://dx.doi.org/10.1016/j.energy.2013.01.053***

[11] A. Bergen, L. Pitt, A. Rowe, P. Wild, N. Djilali. Experimental assessment of a residential scale renewable-regenerative energy system. J Power Sources 2009; 186: 158-66.

[12] M. Calderón, A.J. Calderón, A. Ramiro, J.F. González. Automatic management of energy flows of a stand-alone energy supply with hydrogen support. Int. J Hydrogen Energy 2010; 35: 2226-35.

[13] José Luis Aprea. Two years experience in hydrogen production and use in Hope Bay, Antarctica. Int. J Hydrogen Energy 2012; 37: 14773-80.

[14] Florian Steinke, Philipp Wolfrum, Clemens Hoffman. Grid vs. storage in a 100% renewable Europe. Renew. Energy 2013; 50: 826-32.

[15] Duu-Hwa Lee. Toward the clean production of hydrogen: Competition among renewable energy sources and nuclear power. Int. J Hydrogen Energy 2012; 37: 15726-35.

[16] Mahmood Farzaneh-Gord, Mahdi Deymi-Dashtebayaz, Hamid Reza Rahbari. Effects of storage types and conditions on compressed hydrogen fueling stations performance. Int. J Hydrogen Energy 2012; 37: 3500-9.

[17] Mandhapati Raju, Siddhartha Kumar Khaitan. System simulation of compressed hydrogen storage based residential wind hybrid power systems. J Power Sources 2012; 210: 303-20.

[18] Federico Cassola, Massimiliano Burlando. Wind speed and wind energy forecast through Kalman filtering of Numerical Weather Prediction model output. Applied Energy 2012; 99: 154-66.

[19] A. Pérez-Navarro et al. Hybrid biomass-wind power plant for reliable energy generation. Renew. Energy 2010; 35: 1436-43.

[20] H.P. Langtangen. A primer on scientific programming with Python (Texts in computational science and engineering). Springer. 2009.

[21] J. Kiusalaas. Numerical Methods in Engineering with Python. Cambridge University Press. 2010.

[22] B.G. Penaflor, J.R. Ferron, D.A. Piglowski, R.D. Johnson, M.L. Walker. Real-time data acquisition and feedback control using Linux Intel computers. Fusion Eng. and Des. 2006; 81: 1923-6.

[23] O. Ulleberg. Modeling of advanced alkaline electrolyzers: a system simulation approach. Int. J of Hydrogen Energy 2003; 28: 21-33.

[24] H. Wang, W. Xiong, X. Wang. Research on the static characteristics of air driven gas booster. Proc. of the 7th JFPS Int. Symp. on Fluid Power, TOYAMA 2008, September 15-18. 22-23.

Table 1. Automatic data collection.

Variable	Subsystem	Medium to acquire
- Line and phase voltages. - Line current. - Active, reactive and apparent power. - Power factor. - Current Total Harmonic Distortion.	SENTRON PAC Grid Analyzer	Modbus TCP/IP communication
- Hydrogen and oxygen flow. - Hydrogen pressure. - Current electrolysis cell. - Temperature electrolysis cell.	G2.0 electrolyzer control unit	Modbus RTU by means of a serial communication
- Speed cycling	Booster AGT-7/30	Specific sensor by means of PLC ILC 150 ETH and Modbus TPC/IP communication.

Table 2. Manual data collection.

Variable	**Subsystem**	**Reading way**
- Air header pressure.	PUSKA SIL NH 700-300	Inside manometer.
- Electro-valve opening rate	SAMSON 240 Electro-valve	Voltage programmed in control power source.
- Booster piloting air pressure.	Booster AGT-7/30	Manual regulator manometer.
- Hydrogen bottle pressure.	Storage bottle	Manometer.
- Ambient temperature.	---	Temperature measuring system.

Figure 1

Figure 1. Block diagram of HiDRENER Project.

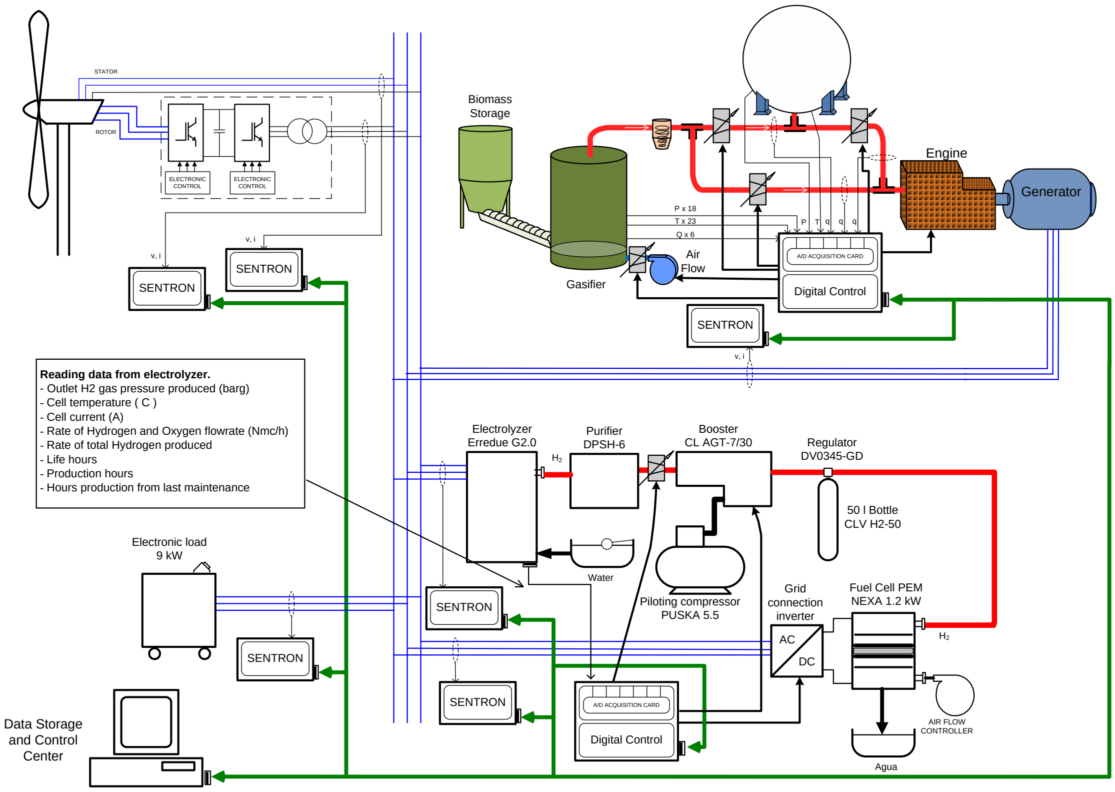


Figure 2

Figure 2. Redundant communication network designed in HiDRENER Project.

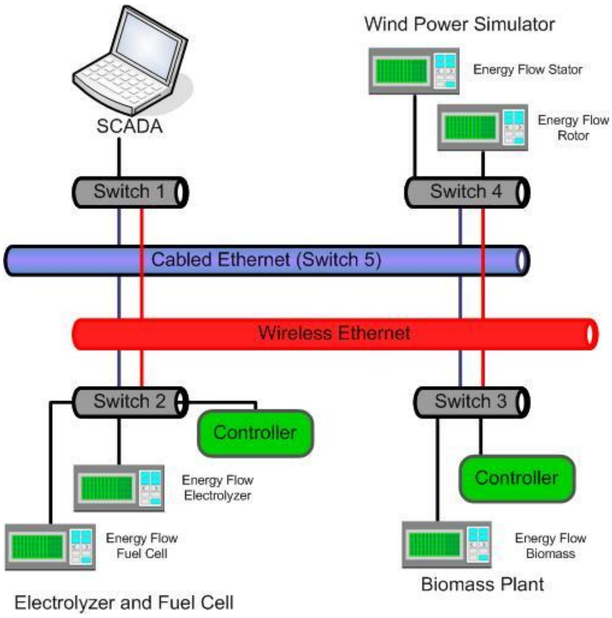


Figure 3

Figure 3. Block diagram of complete hydrogen generation system.

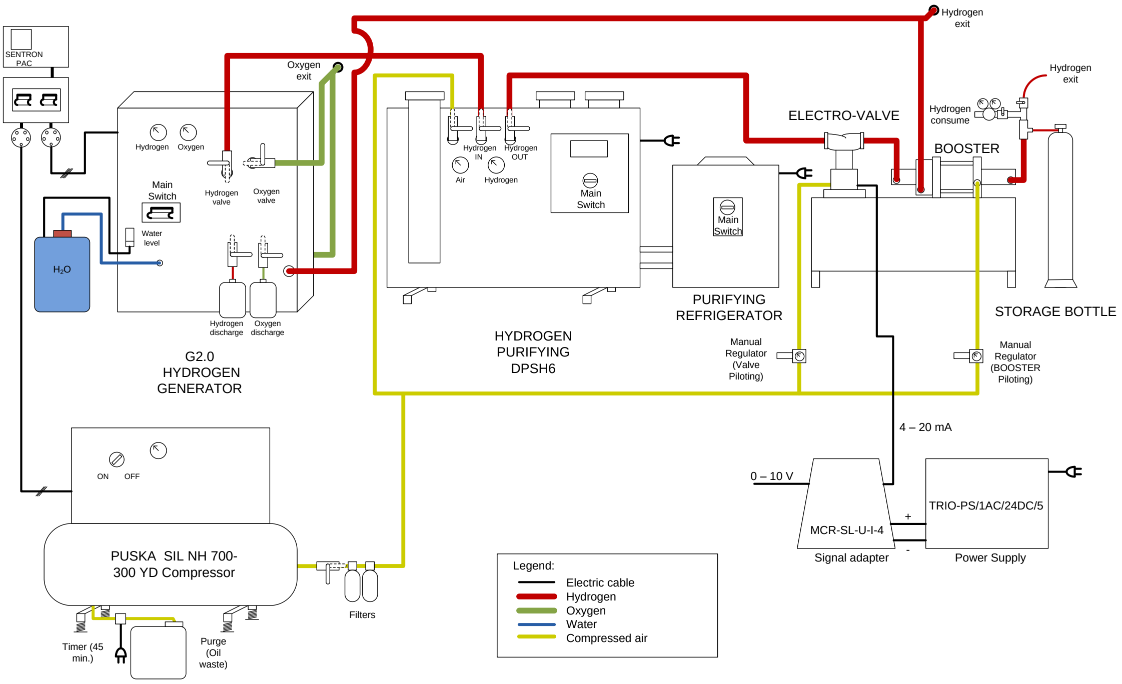


Figure 4

Figure 4. Images of G2.0 hydrogen generator (left) and DPSH6 purifying system (right).

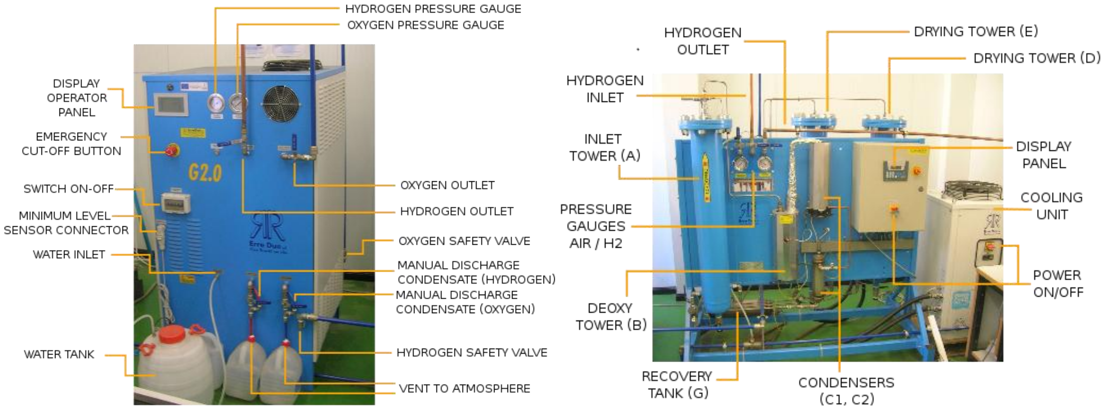
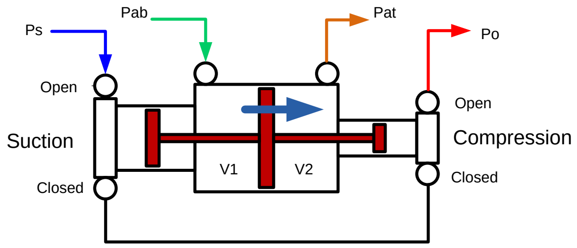
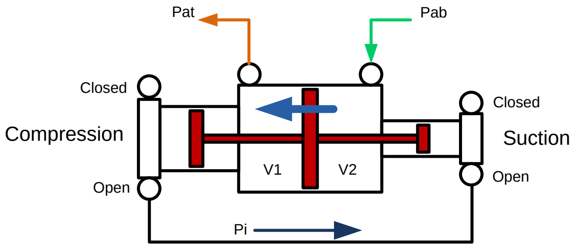


Figure 5

Figure 5. Block diagram of booster working procedure. a) Suction stroke, b) Compression stroke. *Legend: Ps, hydrogen supply pressure; Po, hydrogen output pressure; Pi, hydrogen internal pressure; Pab, compressed air piloting pressure; Pat, atmospheric pressure; V1, V2, corresponding air cavity volume.*



a) Suction stroke



b) Compression stroke

Figure 6

Figure 6. Schematic representation of data acquisition system communication network.

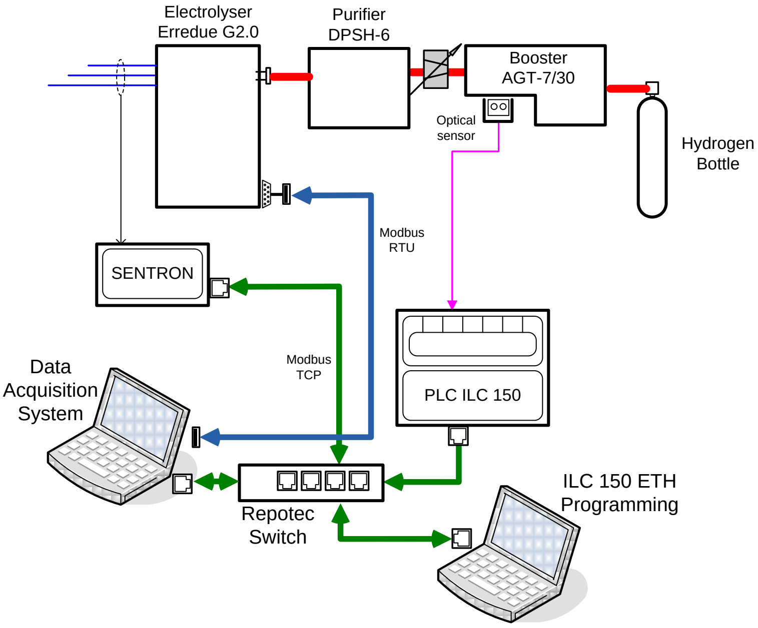


Figure 7

Figure 7. Data acquisition system procedure diagram.

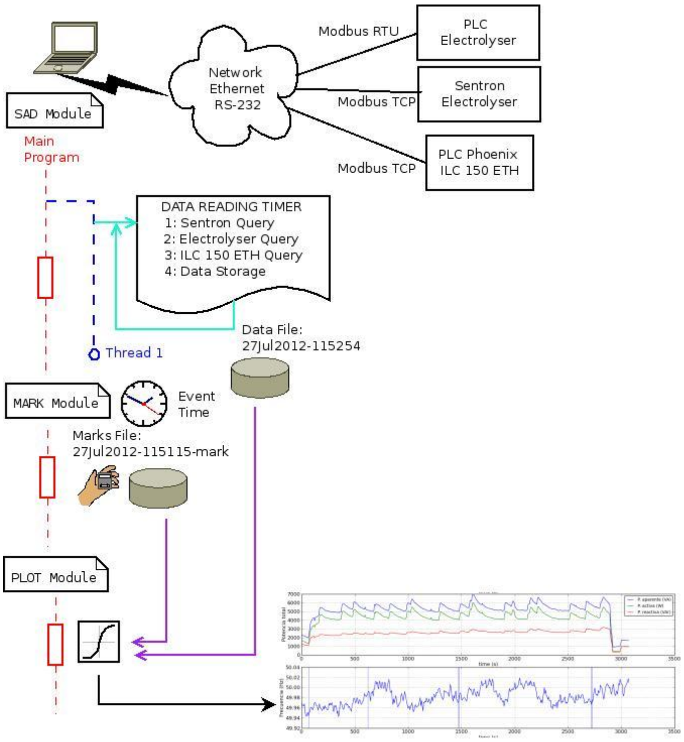
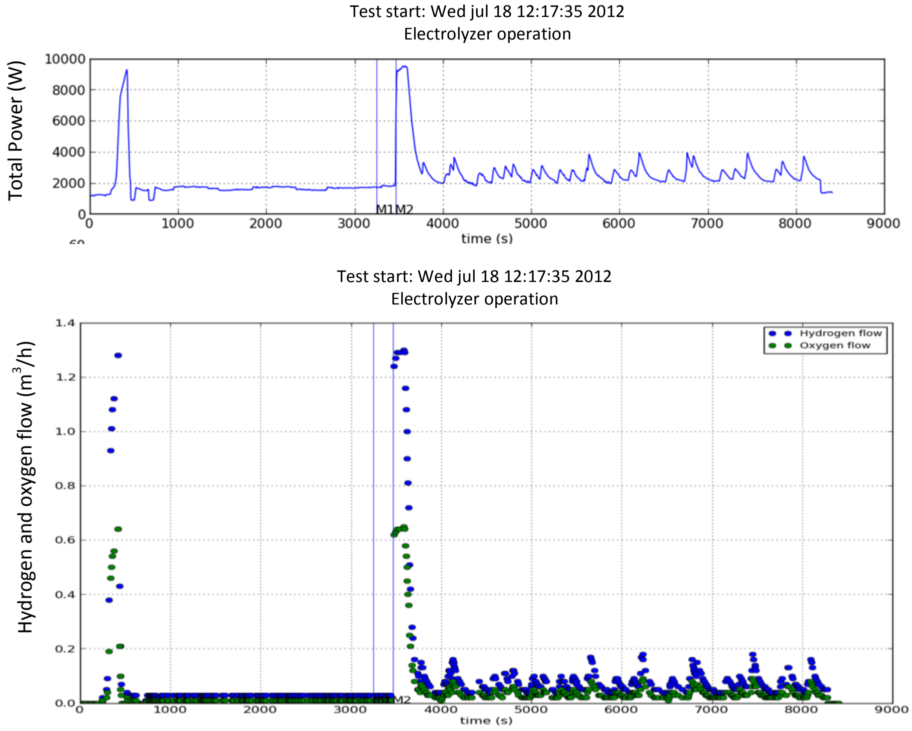


Figure 8

Figure 8. Hydrogen production system start, without and with DPSH6 purifying system. a) Electrical power consumed, b) Instantaneous hydrogen and oxygen flow.



b)

Figure 9

Figure 9. Electrolysis cell pressure and current of hydrogen production system.

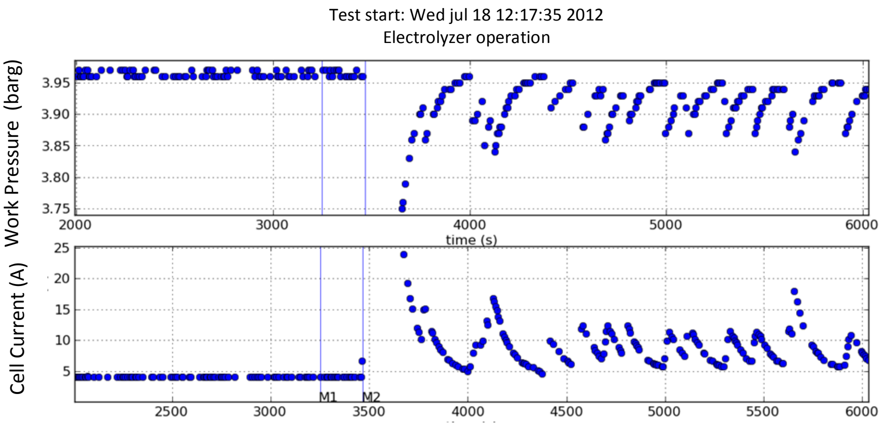


Figure 10

Figure 10. Hydrogen flow and real (crosses) and estimated (dashed line) bottle pressure.

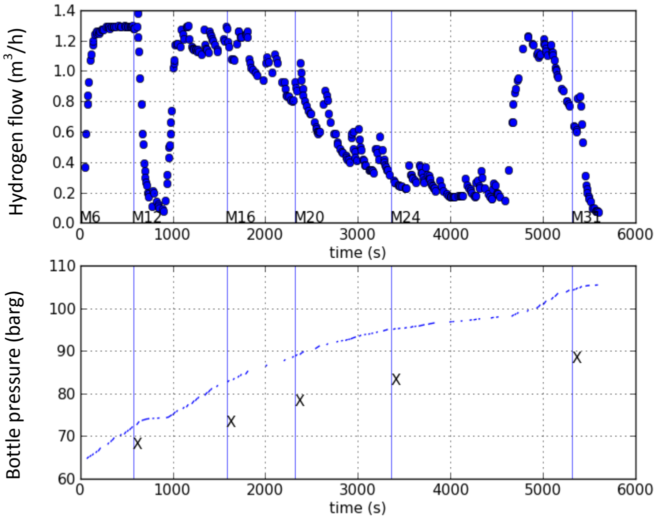


Figure 11

Figure 11. Relationship between electrolysis cell current and hydrogen flow.

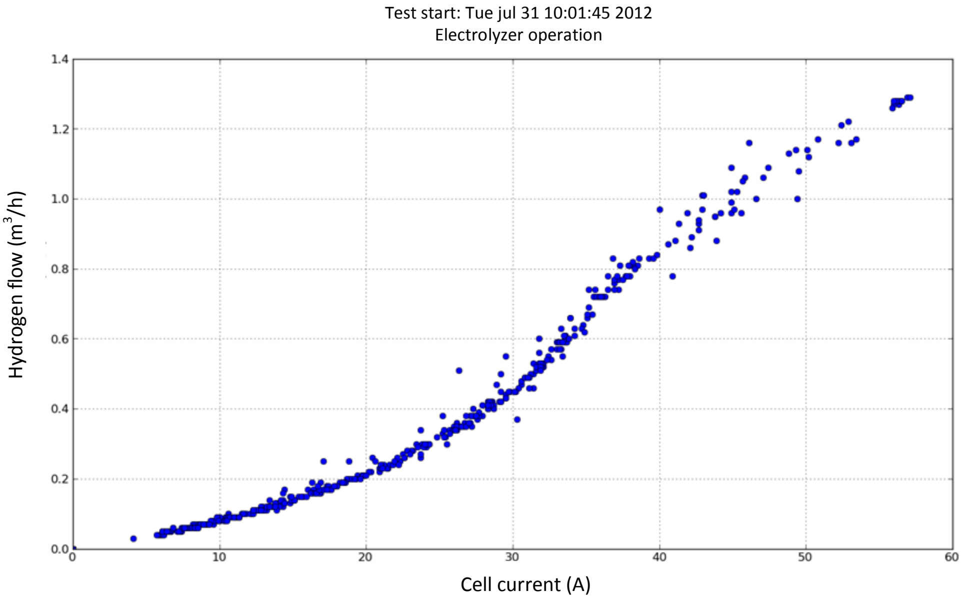


Figure 12

Figure 12. Electrolysis cell temperature and current cell for a specific production situation.

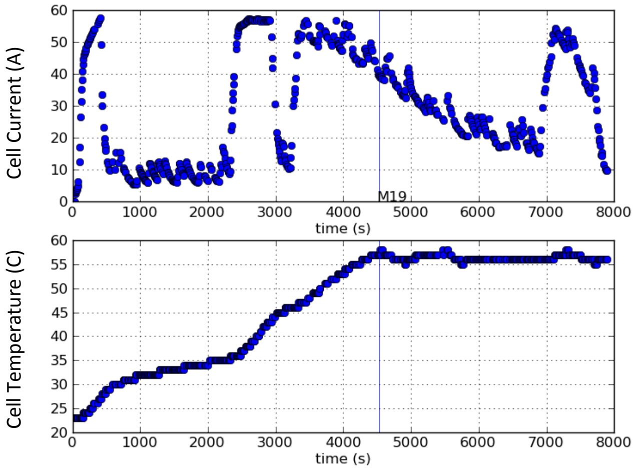


Figure 13. Piloting air pressure versus speed cycling safe working area (under the line) to guarantee enough air pressure in the system, considering a maximum air flow of 610 l/min.

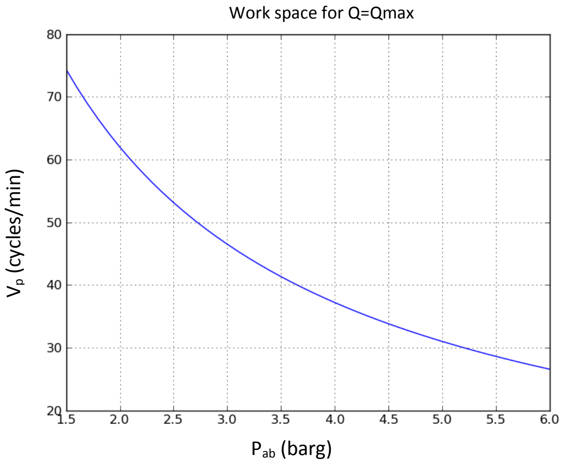


Figure 14

Figure 14. Booster speed cycling (V_p) and hydrogen flow in different working situations.

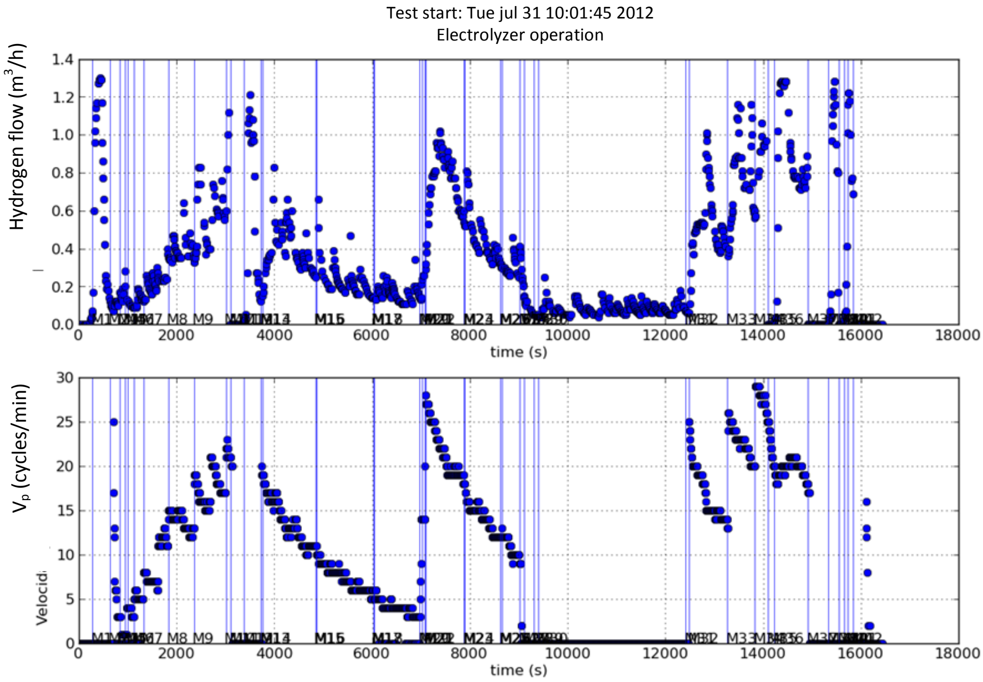


Figure 15

Figure 15. Electro-pneumatic valve opening effect on hydrogen flow with booster speed cycling constant in a high rate of hydrogen flow (changes in the opening made after 350 seconds).

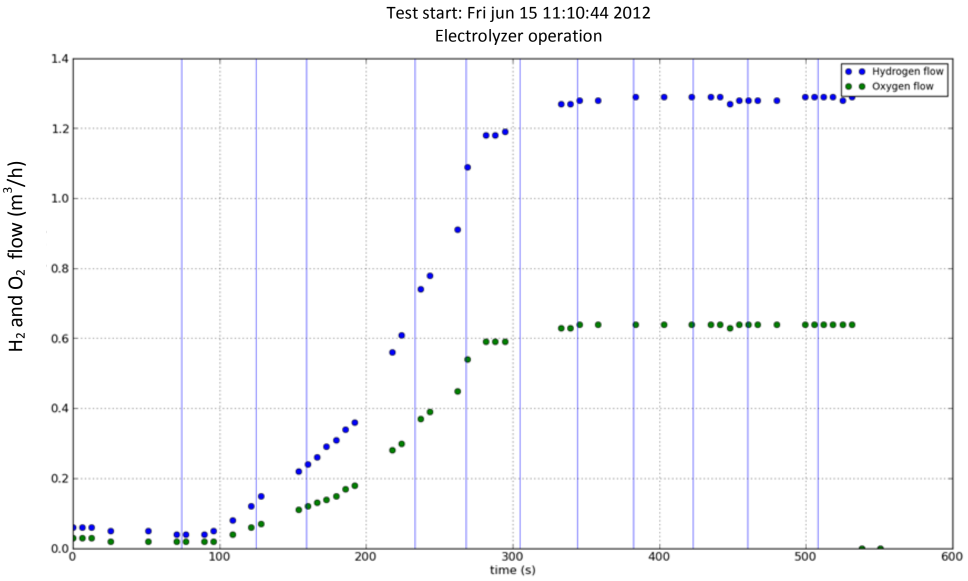


Figure 16

Figure 16. Relationship between hydrogen flow (V37) and booster swabbing speed (V39). Linear and no-linear adjusted curves are also drawn.

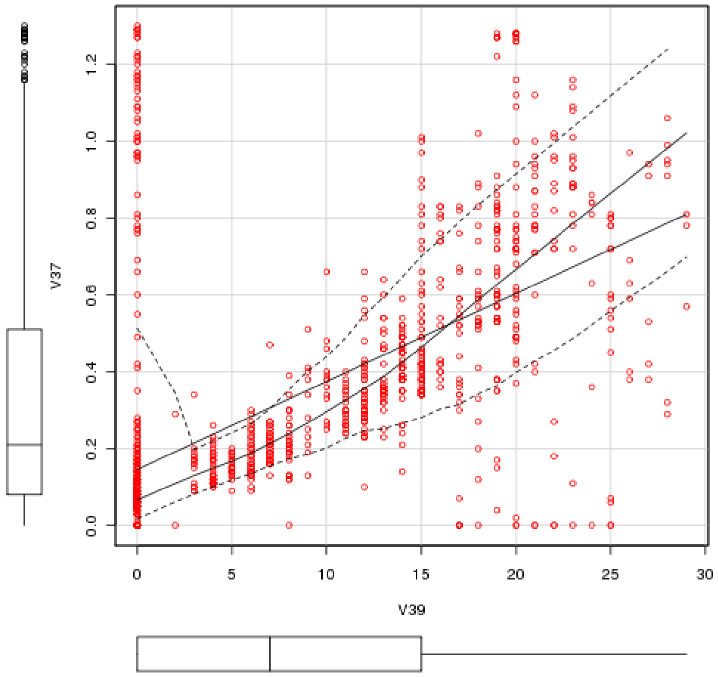
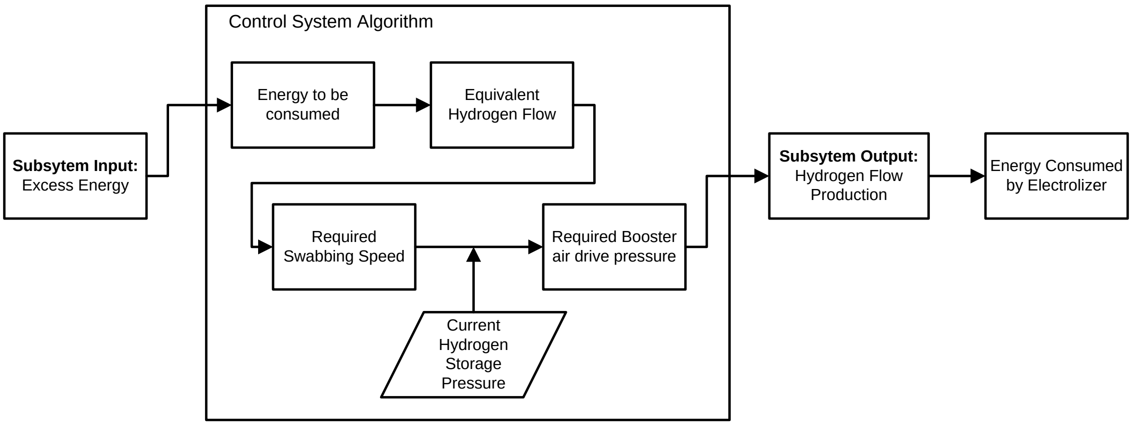


Figure 17

Figure 17. Block diagram of the suggest control system algorithm.



***Suggested Reviewers**

Reviewer number 1:

Name: Maria del Pilar Argumosa
Filiation: INTA (Instituto Nacional de Técnica Aeroespacial), Spain.
Email: argumosa@inta.es

Reviewer number 2:

Name: Andreas Miege
Filiation: Institute of Renewable Energy Sources at University of Applied Sciences Stralsund, Germany.
Email: andreas.miege@fh-stralsund.de

Reviewer number 3:

Name: Jan Michalski
Filiation: Technische Universität München, Lehrstuhl für Betriebswirtschaftslehre – Controlling, Germany.
Email: Jan.Michalski@wi.tum.de