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H2RES2 simulator. A new solution for hydrogen hybridization with renewable energy sources-based systems

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ABSTRACT

This paper presents a new simulator for Hydrogen hybridization with Renewable Energy based Systems. The aim of this simulator is to provide a new solution for testing different energy management strategies of hydrogen hybridization based on renewable systems, in order to optimize them for implementation. The simulator uses the open architecture philosophy and has been developed in MATLAB®-SIMULINK environment. Its main feature is calculating technical and economical parameters for a deepened analysis of influences on energy management strategies. It considers each element of the hybrid system and the whole system function. A simulation case shows the proper functioning of the simulator.

Introduction

More and more companies and governments are committed to a change in energy policies, always oriented towards more energy efficient actions and more renewable energy use. Currently, there are many research groups encouraging and working on a change in the recent energy model, trying to integrate the use of renewable energy sources in our lives.

Thus renewable energy technologies cause high costs and a high dependence on climatic factors [1–3], the use of hybrid power systems is presented as an ideal solution to fill the gaps in the energy supply that the different renewable energy sources may provoke. Due to the fact that some of renewable energy sources are still not entirely developed, the costs for their utilization and lifetime depend largely on the used technology and the operating system. As a result, performance improvements in terms of life and cost reduction of this new energy generation technology, will allow better integration and acceptance in future applications [4,5].

To operate and interconnect different elements of a hybrid generation system, ensuring safe operation and fulfilling the objectives, it is necessary to sufficiently control the system to manage the energy supply by each source. A proper energy management strategy guarantees the load supply, increases the lifetime of each system element, reduces operating costs, and therefore maximizes system performance, providing a technical and economical feasible solution [6–8]. There are

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Nomenclature

PV	Photovoltaic source
WT	Wind Turbine
ELEC	Electrolyzer
FC	Fuel Cell
MH	Metal Hydride tank
BAT	Battery
DOD	Depth Of Discharge
SOC	State Of Charge
E_{GRID_IN}	Input energy from grid
E_{GRID_OUT}	Output energy to grid
E_{BAT}	Battery energy supplied
E_{FC}	Fuel cell generation
E_{ELEC}	Electrolyzer consumption
E_{LOAD}	Load consumption
$Loss_{CHA}$	Battery charging losses
$Loss_{FC}$	Fuel cell average losses per cell
FC_{CYCLE}	Fuel cell start/stop cycles
FC_{TIME}	Fuel cell operation time
$ELEC_{CYCLE}$	Electrolyzer start/stop cycles
$ELEC_{TIME}$	Electrolyzer operation time
BAY_{CYCLE}	Battery operation cycles
$ELEC_{H2}$	Produced hydrogen
CO&M	Operation and maintenance cost

many research works which propose different configurations of hybrid power systems based on renewable energy sources. These configurations have different energy management strategies, most of them focused on guaranteeing the demand [1–3,9,56], and are regardless of technical and economic optimization criteria, or problems associated with real equipment such as transients, stability, security, equipment degradation, hydrogen management, etc.

For all these reasons, the use of software tools is necessary. These tools allow us to perform simulations and previous analysis to enable an implementation, taking into account different management strategies, including genuine parameters for sensitivity analysis.

Recently, there exist plenty of simulators on the market (AEOLIUS, BALOMOREL, COMPOSE, E4CAST, EMCAS, EMINENT, EMPS, ENERGYPLAN, ENERGY PRO, GTMAX, INFORSE, INVERT, LEAP, MESAP, NEMOS, ORCED, PERSEUS, PRIMES, PRODRISK, RAMSES, SIVAEL, STREAM, UNISYD3.0, WASP or WILMAR), which are used to model different power generation systems and loads.

Most of these simulators allow the modeling of power generation systems connected to a grid, or a system integrated into microgrids, giving an optimal solution for economic and power management in the middle and long-term [10–13]. A reduced number of simulators include the ability to combine renewable energy generation equipment and their auxiliary systems. Additionally they permit the use of hydrogen as energy vector in all its phases: hydrogen production, storage and consumption (HOMER, RETSCREEN, HYBRID DESIGNER, HYBRID2, iHOGA, MATLAB or TRNSYS16) [10–13,47].

The above list of recent software tools can be basically divided into four categories according to their purpose [14,47].

Tools of the first tool category can be called *pre-feasibility* tools, which are tools for preliminary estimation, in order to study the feasibility of a project [14]. To this category belong tools like RETSCREEN or EXCELL (Really: Excel is a specialized spreadsheet that can be used for almost any application).

The second tool category refers to *sizing*. These tools' purpose is to generate a technical and economic long term study in order to obtain an optimum sizing [10,11,14]. These tools are very useful for economic viability studies, but they lack the possibility of studies of different energy management strategies, due to their closed software with little or no flexibility, as well as their use of very high integration periods. The most common ones to distinguish are the tools HYBRID DESIGNER and HOMER.

The third tool category includes *simulation*, that is intended to reproduce the behavior of a system based on fixed sizing and fixed operation parameters [10,11,14]. The main problem with this type of software tools is the low flexibility to modify simulation parameters, in order to carry out a study of different management strategies. Prominent examples of this type of software are HYBRID2 and iHOGA.

The fourth and last tool category unites open architecture software which offers better flexibility and is more suitable for analytical studies varying in the energy management strategy [14]. The main problem of this type of software is the high need of programming environment knowledge. TRNSYS16 and MATLAB are the most known software tools for this kind of applications.

Table 1 shows the principal drawbacks associated with the most used software tools.

Following the analysis of Table 1, we can deduce that simulation software tools with open architecture software would be the most useful for the study of different energy management strategies. Additionally, the fourth category of tools compiles software tools that could provide a solution capable of combining all the possibilities of analysis. Therefore, the developed simulator presented in this paper has been designed, according to the common characteristics of this category.

Regarding the software tools included in the last category, the main advantages of MATLAB over TRNSYS16 are its greater computational power and widely establishment [14]. In addition, MATLAB has the ability to be integrated into acquisition systems. This way it is possible to implement all the previously developed control logic into genuine future systems. However, MATLAB requires higher processing times (about 4 times) compared to other software tools based on different programming languages such as C, Fortran, Java, Julia or Phyton [53]. For this reason, a proper programming is necessary, to simplify the simulation tool and perform tests, resulting in more reasonable processing times.

In basis on all exposed above, this paper presents a simulator based on MATLAB-Simulink environment. The simulator allows modeling isolated or grid connected hybrid power systems. These systems allow the integration of hydrogen technology and renewable energy sources from different nature and energy storage systems. Additionally, the presented simulator offers the possibility of testing different energy management strategies, running simulations in the short-term time scale and improving sensitivity analysis attending

Table 1 – Simulators classification.

Software category	Software tool	Drawback
Pre-feasibility	RETSCREEN	Only for basic feasibility studies
	EXCELL	
Sizing tool	HOMER	Doesn't consider variations in bus voltage
		DOD is not considered, only in sensitive analysis
		Low and closed energy dispatching options
		Only minimize net present cost
	HYBRID DESIGNED	Focused on isolated applications
		Doesn't consider technical optimization
Simulation tool	HYBRID2	High learning time requirements
		Low and closed energy dispatching options
	iHOGA	Fixed optimization algorithm (GA)
		Difficult to extrapolate optimization algorithm to real implementation
		Complex models for elements
Open architecture software	TRNSYS16	Fortran knowledge is required
		For H_2 storage analysis, it needs HYDROGEMS tool
	MATLAB	C programming skills are required
		Structure programming notions are required

to cost and lifetime of the devices which integrate the hybrid power system. These features give benefit to the developed simulator, overtaking the main shortcomings that the authors have found in other software tools available in the scientific literature or in the market. All the developed functions are accessible and therefore adapting to user requirements.

In the next section, a detailed description of the proposed simulator is done. Section "Energy management study" presents the developed energy management strategy by authors and used in the simulator. In Section "technical and economic parameters" the technical and economical parameters considered by the simulator and needed for sensitive analysis are presented. In order to show the proper functioning of the simulator as well as its particular features, a simulation case of a practical system is carried out in Section "Simulation case". Finally, Conclusions and future works close the paper.

Simulator: architecture and interface description

The simulator proposed in this work has been developed under MATLAB-Simulink environment. It is a powerful tool, user friendly and very intuitive. It can be used already with very little training.

Regarding the software implementation, the simulator has been developed maintaining a modular structure in order to guarantee the highest level of scalability and flexibility.

The simulator provides default configuration and can be adapted to the user needs, allowing to update input data related to weather, load profile, base time, model used for each element as well as its size. The guiding thread the authors have followed in their development has been the possibility to perform realistic energy simulations of **H**ydrogen **H**ybridization with **R**enewable **E**nergy **S**ources-based **S**ystems (H2RES2). A general view of the simulator is shown in Fig. 1.

H2RES2 simulator architecture

The default hybrid system architecture (see in Fig. 2a a schematic representation) consists of two different sources of renewable energy as the primary energy source: photovoltaic panels and wind turbines. It is assuming a common hybrid power system supply of electric power to an electrical network. In case of isolated applications, the grid energy will define the energy deficit of the proposed energy management strategy and system sizing. This parameter indicates the difference between the generated and the consumed energy, providing the user a way to test the viability of his configuration.

In the hybrid system has to include different energy backup elements to ensure the load demand and grid stability in situations of energy deficit. In this case, a battery bank is used as the primary short- and middle-term energy backup. A modular fuel cell should be used secondary for a long-time energy backup. The use of a modular fuel cell (built out of single stacks) improves the performance of the whole configuration and guarantees the energy supply even in cases of stack failure [48]. However, the fuel cell configuration can be chosen by the user. It is possible to define one or more fuel cells built from one single stack. To guarantee an accurate fuel cell operation the use of hydrogen storage technology is required. For this target, in this topology there are metal hydrides tanks and high pressure tanks used. Finally, an electrolyzer is included to ensure a precise energy balance in situations of electrical overproduction and convert the overproduced electrical energy into chemical energy while producing hydrogen. In order to generate any consumption profile, we consider that the network has programmable AC and DC loads.

The H2RES2 simulator includes the ability to define different energy management strategies, as well as it includes auxiliary functions, state diagrams and truth tables that are derived from the established strategy, Fig. 2b.

Although MATLAB-Simulink is a powerful tool, the use of this program requires high computing times [53]. In order to mitigate this problem, all functions have been programmed with the aim of reducing the computation time. In this manner, the one-year simulation is performed in less than one and a half minutes, with a time step of seconds.

Besides, the H2RES2 simulator includes mathematical expressions to model the effect of the battery bank voltage and

Fig. 1 – H2RES2: General view.

charge efficiency, in order to calculate the energy losses associated with this process.

Moreover, based on system parameters (like the battery State Of Charge, hydrogen tanks level, fuel cell and electrolyzer start–stop cycles, run times, SOC hysteresis-based operation mode, etc.), it is possible to perform a sensitivity analysis of the lifetime of the involved devices [15–18], comparing them after the implementation of different management strategies or configuration parameters.

Similarly, the H2RES2 simulator performs short-term time simulations, to tender the user detailed information of the system response with transients in a short time scale (seconds). Moreover it enables the user to study the system stability while accessing all electrical and physical parameters that are required for technical and economic analysis under different strategies and configurations. Additionally, this option allows the user to conclude causes of risks, damages or malfunction of all subsystems.

Results & graphical interface

Finally (see Fig. 2a), the simulator provides a graphical environment in which the user is able to choose any variable to be represented. This allows a fast location and simple definition of parameters or phenomena that may affect the proper functioning of the system as well as it compares the power generation of different sources and the amount of the produced, stored or consumed hydrogen.

In particular, the H2RES2 simulator has a graphical environment in which all system variables (physical, chemical and economical) can be represented (Fig. 3). Furthermore, it includes a summary window which shows global parameters (electrical and economic) obtained from the simulation (Fig. 4).

The results presented by the H2RES2 simulator include both, the power and energy associated with each element. They can be associated as well for electrolyzers, fuel cells, hydrogen storage tanks, the hydrogen production, the hydrogen consumption and hydrogen stocks. In case of fuel cells, battery banks and electrolyzers, the number of operation cycles can be displayed if necessary.

Particularly, the fuel cell deterioration, battery bank SOC, battery bank charge losses and real nominal capacity are represented in order to get enough information to develop various sensitivity analysis.

Finally, the overall operation and the maintenance costs are presented in the summary window.

Energy management study

The energy management strategy is responsible for solving the problem of the power balance as well as for the load demand at all time. Additionally, it must guarantee the hydrogen production, storage and consumption of each element; and all of this taking into account technical and economic optimization criteria with the aim of increasing the performance of the system.

Energy management criteria

Before a description of the different energy management strategies, we are going to define the parameters on which the proposed strategies are based. In case of the H2RES2 simulator, the control laws are established according to the priority of the elements, the power balance, the SOC hysteresis band-based operation mode and operation conditions.

Priority of the elements

Since the renewable energy hybrid system architecture of the H2RES2 simulator is composed of various generation and consumption subsystems, it is necessary to establish a hierarchical structure to determine the usage of them in different situations.

With this aim, the energy stored in the battery bank plays a special role [21]. In fact, it is the key given to define the energy management strategy. Remember this device should respond in situations of energy deficit and support with security and stability the transients both in the demand and the generation.

The use of primary generators of solar and wind energy is not causing any other certain requirements for the reason,

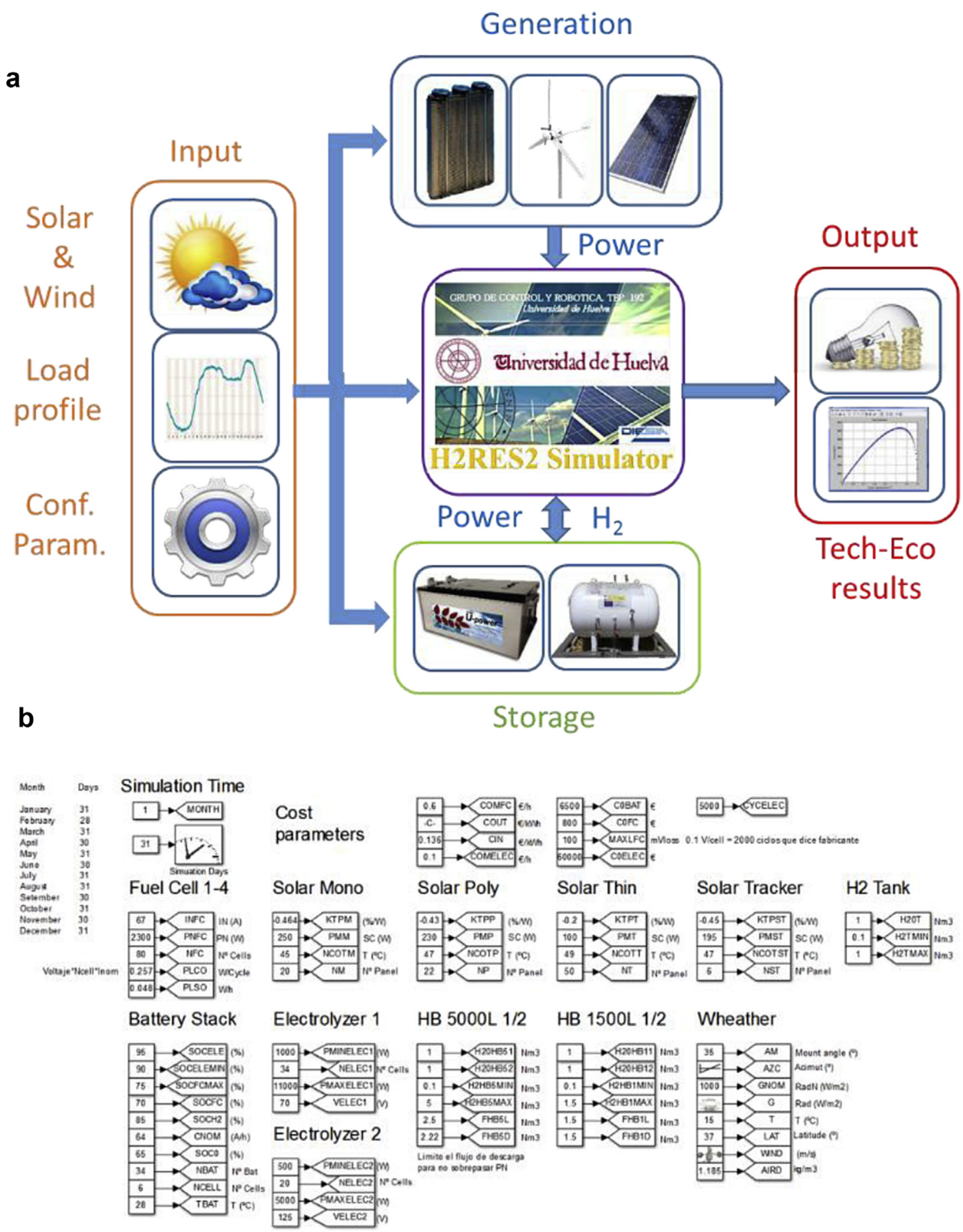

Fig. 2 – a. Default hybrid system schematic architecture, b. Simulator architecture implementation.

that these elements will supply energy whenever environmental resources are available.

The other elements of the hybrid system, like fuel cells and electrolyzers, have a secondary priority, due to their operation conditions that depend on the battery bank SOC level.

Power balance

The energy management strategy is based on the calculation of the power balance. The expression that models it is presented below Eq. (1):

$$P_{net} = P_{PV} + P_{WT} - P_{load} - P_{loss} \quad (1)$$

Where,

P_{net}: Hybrid system net power (W)
P_{PV}: Solar panels power (W)
P_{WT}: Wind turbine power (W)
P_{load}: Load power (W)
P_{loss}: Loss power (W)

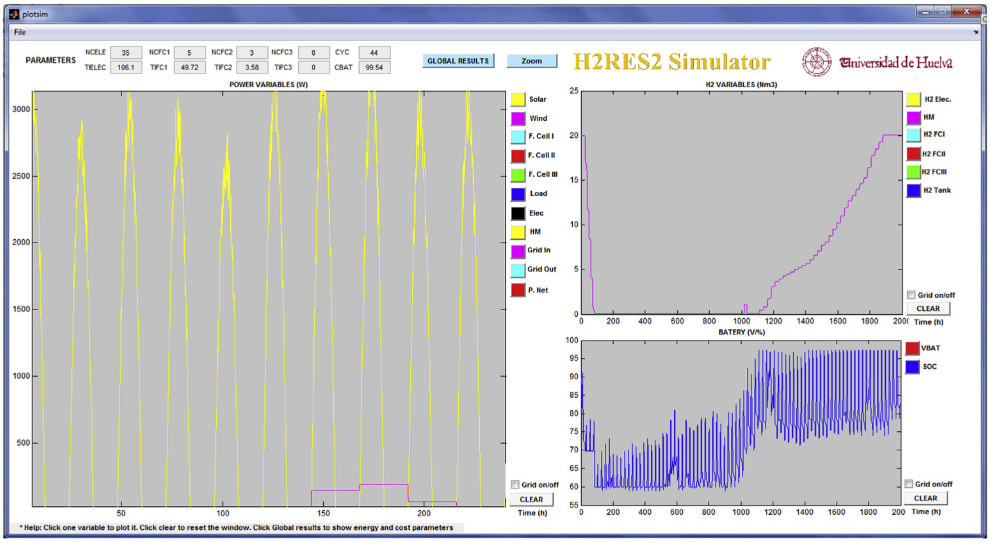

Fig. 3 – H2RES2 simulator: Simulation results window.

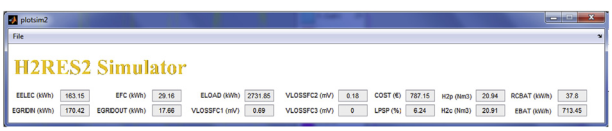

Fig. 4 – H2RES2 simulator: Summary window.

The sign and value of the power balance is determined system situations: deficit, balance or excess energy situation.

Hysteresis

In order to avoid a high degradation due to the number of operation cycles, the proposed strategy for electrolyzers and fuel cells is based on SOC hysteresis bandwidth.

This way the strategy consists on determining the start and stop conditions of fuel cells and electrolyzers in while using the battery bank SOC level [29–32].

The operation of the battery bank, the fuel cell and the electrolyzer inside the hysteresis band will be defined by the last element that was operating on the previous time step. The H2RES2 simulator facilitates the flexibility of modifying the hysteresis bandwidth values or even to removing them. In this last case, the user is given the chance to try other energy management strategy not based on the SOC hysteresis operation mode.

The values used in the definition of the hysteresis operation scheme are defined below (Fig. 5):

- **SOClow**: Allowed minimum SOC value. Below this level, the grid will supply demand and the fuel cell will be disconnected in order to save energy from the battery bank.
- **SOCmin**: Minimum SOC recommended to guarantee the lifetime of the battery bank. This value coincides with the start condition of the fuel cell.
- **SOCfcmax**: SOC value which indicates the stop condition of the fuel cell concerning the battery bank has enough stored energy to supply the load demand.
- **SOCH$_2$**: Minimum SOC value which indicates the stop condition for the hydrogen charging process from high pressure tanks towards the metal hydride tanks. This value is necessary for its absorption of energy in this charging process absorbs energy (please see Annex A, Section “Pressurized gas”) It will affect the remaining energy in situations of low SOC value.
- **SOCelemin**: SOC value below which the electrolyzer must be stopped.
- **SOCmax:** Maximum SOC value required for a reliable. This value matches the SOC value at which the electrolyzer should start, since this SOC value is the maximum allowed.

Operation conditions

The last criteria around that defines the energy management strategy is related to operations conditions of the fuel cell and the electrolyzer. H2RES2 simulator has the possibility to choose between fixed or variable power conditions for the fuel cell and the electrolyzer. This gives the possibility to perform an analytical study of the effect on the operation of these devices under the demand (Fig. 6).

Additionally, in case of the electrolyzer, a minimum power point from which the electrolysis reaction is produced is necessary. This also guarantees the minimum crossover effect [24,33].

Energy management strategy definition

The energy management strategy can be differentiated in the charging process (energy excess), the discharging process (energy deficit) and additionally the hydrogen storage strategy.

Charging strategy

During energy excess situations, the power balance of the system will be positive and as discussed above, the SOC value will determine which element is to operate. As a conclusion, it

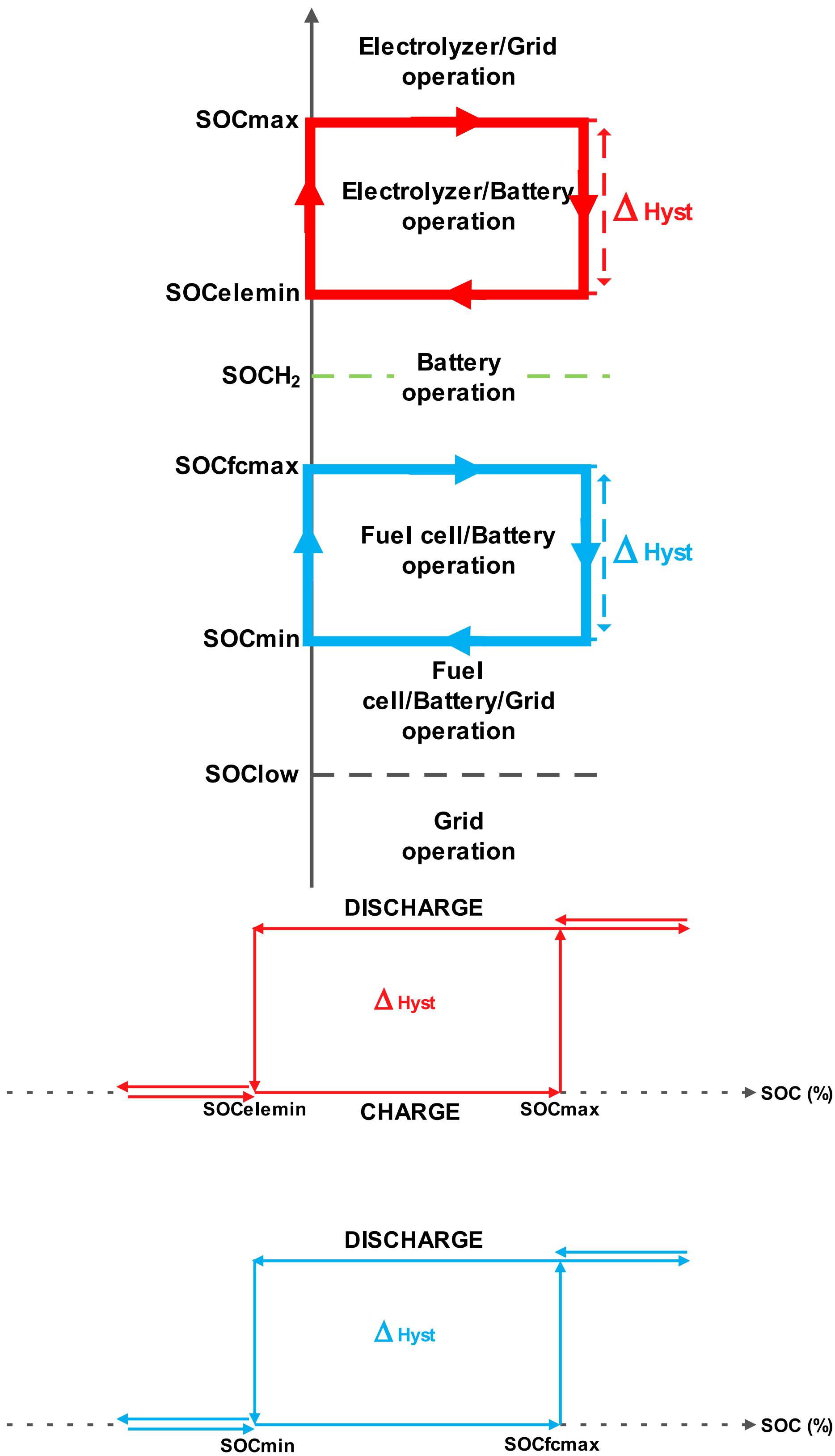

Fig. 5 – Hysteresis bandwidth-based operation diagram.

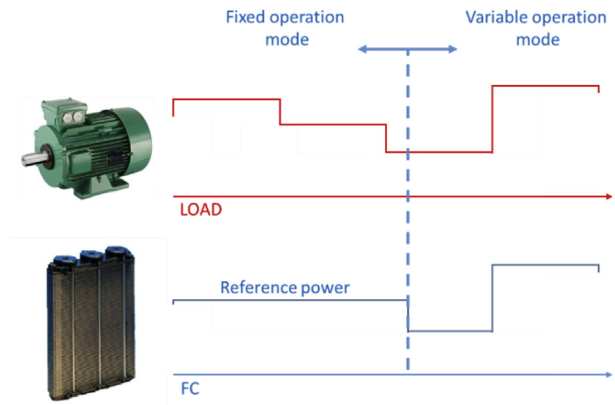

Fig. 6 – Fuel cell operation modes allowed by H2RES2 simulator.

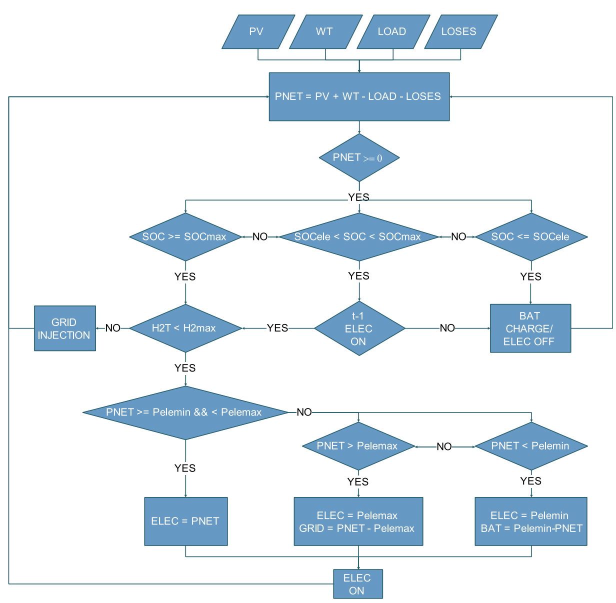

Fig. 7 – Energy management strategy: Charging process diagram.

is possible to distinguish between three possible situations (Fig. 7):

SOC ≤ SOCelemin

If the SOC is lower than for the electrolyzer start condition, all the excess of energy will be used to charge the battery bank, in order to have enough energy to provide energy in cases of an energy deficit.

SOC ≥ SOCmax

In this case, the battery bank is at its maximum charge capacity, so it should not admit more energy. The energy excess should be absorbed by other elements.

In the first instance, any energy excess is absorbed by the electrolyzer, taking advantage of it to produce hydrogen. If the energy excess is insufficient to guarantee the minimum power required by the electrolysis process, it is ensured at all times with the support of the battery bank.

In case the energy excess is higher than the electrolyzer rated power, or the hydrogen storage system is at its maximum capacity, the remaining energy is injected to the grid.

SOCelemin < SOC < SOCmax

During this situation the battery bank SOC is high enough and electrolyzer and battery bank will operate in basis on the hysteresis bandwidth strategy explained in Section "Hysteresis".

Discharging strategy

During an energy deficit situation, the SOC level will impose again the operation conditions of the rest of the elements of the system.

Since the battery bank is less expensive and more durable than the fuel cell, it reserves the use of the last one for cases in which the battery bank is not able to respond to the demand.

If the amount of hydrogen is enough negotiate the energy deficit, the fuel cell will supply the load demand until the SOC reaches the fuel cell's stop value. Conversely, if it is insufficient, the fuel cell will operate until the amount of hydrogen reaches its minimum value, then the battery bank or grid have to supply the demand. There are four operation zones distinguished, depending on the SOC value (Fig. 8):

SOC ≥ SOCfcmax

During this situation, the battery bank has enough charge capacity to keep the load demand under security conditions, therefore it is not necessary to use the fuel cell.

SOCmin < SOC < SOCfc

During this situation the SOC is low, the fuel cell and battery bank will operate based on the hysteresis strategy explained in Section "Hysteresis".

SOClow ≤ SOC ≤ SOCmin

This is case represents the limit situation of the system. On this occasion, the battery bank is at very low SOC. For this reason, all of the demand must be supplied by the fuel cell and/or an auxiliary grid (which can be, with the switching elements due, the same grid that is supplying the hybrid system; as long as it is not isolated).

SOC ≤ SOClow

This situation is given due to a lack of capacity of the fuel cell to supply the demand. All the demand is satisfied by the grid.

Hydrogen storage strategy

The hydrogen production will take place in situations of energy excess. The produced hydrogen must be stored in the

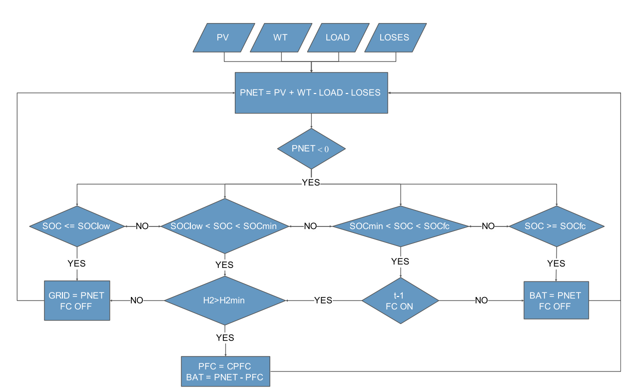

Fig. 8 – Energy management strategy: Discharging process diagram.

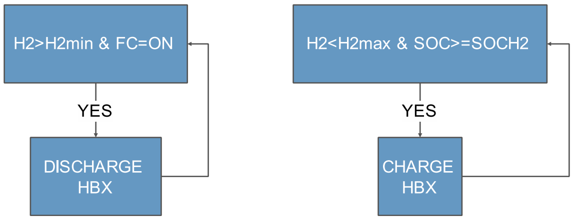

Fig. 9 – Hydrogen storage charging/discharging diagram.

hydrides metal tanks for its future use in situations of energy deficit.

The process of hydrogen storage only occurs in generation situations (energy excess) and for values of SOC > SOCH2, in order to guarantee the minimum charge level at all times. A States diagram that models the hydrogen storage strategy is presented in Fig. 9.

Technical and economic parameters

The H2RES2 simulator has been developed with the aim to test different energy management strategies, however, it also includes the possibility of a sensitivity analysis attending to lifetime and costs of the devices which are integrated in the hybrid power system. To conclude this section, technical and economic parameters calculated by H2RES2 are presented.

Technical parameters

As it happens to the entirely equipment, the useful lifetime of the elements that are integrated in the renewable energy hybrid system object of the H2RES2 simulator, depend on their use and work conditions [58].

Considering an expected lifetime by the whole hybrid system of typically 20–25 years, there are elements whose lifetime coincide with these values. In this case, for the cost analysis it is enough to assume the acquisition costs; this is the case in solar panels, wind turbines, and hydrogen storage equipment.

On the other hand, there are other elements whose useful lifetime depends on the number of working hours or operation cycles, for instance battery banks, fuel cells and electrolyzers. These elements' lifetime depends on the established management strategy.

Additionally, due to their extending acquisition costs, and to ensure the demanded supply as long as possible, a technical devise deterioration analysis is performed to increase the system performance.

Battery bank deterioration

According to scientific literature, operating temperature affects the battery lifetime [34–36]. High operating temperatures trigger a series of parasitic reactions which provoke the reduction of its nominal capacity (2):

$$Det_{BAT}\,(T) = Det_{BAT\_0}\,(T = 20^{\circ}C)*2^{\left(\frac{T-20}{10}\right)} \tag{2}$$

Where,

$Det_{BAT}\,(T)$: Battery deterioration associated with operation temperature (Ah)
$Det_{BAT\_0}\,(T = 20^{\circ}C)$: Battery deterioration at 20 °C operation temperature (Ah)
T: Battery operation temperature (°C)

From this expression, H2RES2 simulator estimates the nominal capacity degradation according to expressions (3) and (4):

$$Cnom(t) = Cnom(t-1),\ T \le 20^{\circ}C \tag{3}$$

$$Cnom(t) = Cnom(t-1) - 0.2*Cnom(t-1)* *2^{\left(\frac{T-20}{10}\right)}*\Delta t,\ T > 20^{\circ}C \tag{4}$$

Lead-acid batteries degradation can be modeled with complex models that accurately estimate the battery lifetime. As an example [49], presents a degradation model based on operating conditions during a discharge process with the use of the weight factor. This parameter represents the loss of degradation due to current rate, depth of discharge, acid stratification, corrosion, etc. This model was validated in Ref. [50], and it is used in iHOGA software.

A linear aging coefficient function is presented in Refs. [51,52], and was validated in Ref. [52]. The battery deterioration can be reflected over the nominal capacity deterioration with the use of the linear aging coefficient according to Eqs. (5) and (6). For lead acid battery technology, an aging coefficient value of $3*10^{-4}$ can be considered as a good approximation [52].

$$Cnom(t) = Cnom(t-1) - Cnom(0)*\alpha* *(SOC(t-1) - SOC(t),\ T \le 20^{\circ}C \tag{5}$$

$$Cnom(t) = Cnom(t-1) - Cnom(t=0)*\alpha* *2^{\left(\frac{T-20}{10}\right)}*(SOC(t-1) - SOC(t)),\ T > 20^{\circ}C \tag{6}$$

Where,

α: Estimated aging coefficient associated in the instantaneous discharging process.

Electrolyzer deterioration

The electrolyzer, mostly alkaline technology, is a high performance operation device which has an estimated lifetime of several years and even decades. The deterioration associated with the electrolysis process is minimal and therefore it can be considered negligible. At the end of the lifetime of an electrolyzer the deterioration is associated to the number of start–stop cycles [16,18].

To calculate the associated electrolyzer deterioration, the H2RES2 simulator uses the relationship between accumulated start.-stop cycles and the expected lifecycles (please see Section "Unitary cost function for each element"; expression (11)), given in typical electrolyzer technical handbooks/documents.

Fuel cell deterioration
Experimental studies on fuel cells agree that the most common processes, which have an influence on the fuel cell degradation, are related to start–stop cycles, the long operation time, and very fast demand variations [19,37,54]. The effect on the fuel cell is an increase of the kinetic losses due to the destruction of the catalytic layer and the reduction of the membrane thickness [38–40,54].

In practice, the deterioration results in a voltage drop which considered the effects commented above [41].

The assumptions used by the H2RES2 simulator to model the fuel cell voltage losses are presented in Eq. (7):

$$LOSS_{FC} = \Delta V_{CYCLE} * FC_{CYCLE} + \Delta V_{TIME} * FC_{TIME} \quad (7)$$

Where:

ΔV_{FC}: Overall fuel cell voltage losses (V/cell)
ΔV_{CYCLE}: Fuel cell voltage losses per operation cycle (V/operation cycle)
FC_{CYCLE}: Fuel cell operation cycles (operation cycles)
V_{TIME}: Fuel cell voltage losses per operation time (V/hr)
FC_{TIME}: Fuel cell operation time (hr)

The fuel cell net power results from the subtraction of the gross generated power minus and the power associated to the fuel cell (8):

$$P_{FC\_NET} = P_{FC\_GROSS} - LOSS_{FC} * I_{FC} \quad (8)$$

Where:

P_{FC_NET}: Fuel cell net power (W)
P_{FC_GROSS}: Gross power generated (W) by the fuel cell (please see Annex A)
I_{FC}: Fuel cell current (A)

Hybrid system reliability
Finally, the H2RES2 simulator offers the possibility to evaluate the system reliability. For this purpose the simulator includes the calculation of parameters called *Loss of Power Supply Probability* (LPSP).

The goal of any power generation system must be the demand satisfaction at all times. However, it is possible for autonomous systems or under operation failures, that the demand can not be guaranteed. Potentially, this results in non-continuous operations, that cause the destruction of elements and the economic detriment.

The simulator defines the LPSP index according to expression (9). This index allows it to compare the tested energy management strategies and decide over an optimal response. Furthermore, this index provides enough certainty to decide over the element sizing to form a proper hybrid system [42,43].

$$LPSP = \frac{\sum_{t=1}^{T} PDo}{\sum_{t=1}^{T} PD} * 100 \ (\%) \quad (9)$$

Where:

PDo: Power demand no supplied by the system (W)
PD: Total power demand (W)
T: Period of time

Economical parameters

Up to now we have described the energy management strategies based on the H2RES2 simulator, allowing the analysis of the operational feasibility. Additionally the technical parameters have been observed, to understand how the H2RES2 simulator processes information for and evaluates the lifetime of the whole hybrid system, foreseeing a necessary displacement of devices.

To increase feature advantages of the H2RES2 simulator and complete it with respect to the simulators reviewed in Section “Introduction”, a cost analysis is included. This allows the user to study the operational, technical and the economic viability of its project.

Nowadays, one of the drawbacks in renewable energy-based technologies is their high costs [1,2,9]. Nevertheless, possible changes in the legislation as well as new energy policies (in fact today all this is very different depending on the country concerned) increase the demand of auto consumption and distributed generation based on renewable energies presents to a remarkably boom in the upcoming decades. Moreover, in isolated applications, renewable energy sources-based hybrid systems are already economically justified.

To carry out an economic analysis of all the devices which integrate the hybrid system, the H2RES2 simulator involves the costs associated with each element as well as the lifetime of each, in order to compare the economic viability and the system behavior for different configurations.

Remembering the primary goal of the simulator, being a software tool to study different energy management strategies, the H2RES2 simulator takes those parameters into account, which vary during the operation and lifetime of the system. These parameters conclude the Operation & Maintenance and degradation costs.

Unitary cost function for each element
The H2RES2 simulator includes the expression that models the total costs of each element, according to Eq. (10). This unitary cost function, particularized by each element, reflects the contribution of the acquisition costs, its operation and maintenance costs, the expected lifetime and the expected lifetime of the whole hybrid system.

$$Cx(€) = Cox|_{L_X} + CO\&Mx * \left(\frac{i(1+i)^n}{(1+i)^n - 1}\right)$$
$$Cox|_{L_X} = \begin{cases} Cox, & if\ L_X \geq L_S \\ \sum_1^r Cox * \left(\frac{i(1+i)^{L_X * r}}{(1+i)^{L_X * r} - 1}\right), & if\ L_X < L_S \end{cases} \quad (10)$$
$$r = \frac{L_S}{L_X}$$

Where,

Cx: Unitary cost function for device x (€)
Cox: Acquisition cost of the device x (€)
$Cox|_{L_X}$: Actualized acquisition cost depending on lifetime (€)
L_{HS}: Lifetime of the hybrid system (years)

L_X: Lifetime of device x (years)
CO&Mx: Operation & Maintenance costs of the device x (€)
i: Annual interest rate (%)
n: Years
r: Number of expected replacement of device *x*

As it can be observed in Eq. (10), the effect of interest rates or inflation is considers the costs for each element, including the annual interest rate, the number of years and its lifetime. In case the user needs to change this relation, he can modify the interest rate expression by its own auxiliary function. Nevertheless, as has been mentioned before, the H2RES2 is not meant to provide an economic analysis software tool but its goal is to test different energy management strategies, evolving simulations in a one-year period.

Distinguishing the elements, of solar panels and wind turbines, their useful lifetime coincides practically with the expected lifetime of the whole hybrid system (20–25 years), so we just have to compute the acquisition costs at the beginning of the project.

Additionally, for those elements whose expected lifetime depends on operating conditions, such as the battery bank, the electrolyzer and the fuel cell, it is necessary to integrate the degradation expressions (please see Section "Technical parameters") into the expected lifetime model.

The associated lifetime of the electrolyzer is depending on the number of operation cycles and the maximum expected operation cycles according to the following expression (11):

$$L_{ELEC} = \frac{ELEC_{CYCLE\_MAX}}{ELEC_{CYCLE}} * t\ (years) \tag{11}$$

Where,

L_{ELEC}: Electrolyzer expected lifetime (years)
$ELEC_{CYCLE\_MAX}$: Maximum expected start–stop cycles for the electrolyzer during its lifetime
$ELEC_{CYCLE}$: Accumulated start–stop cycles of the electrolyzer
t: Accumulated operating time (years)

On the other hand, in case of the fuel cell, the simulator includes the degradation costs depending on the maximum voltage losses of expression (12). The fuel cell degradation is determined by the operation cycles and operation time, as it was studied in Section "Fuel cell deterioration":

$$L_{FC} = \frac{LOSS_{FC\_MAX}}{LOSS_{FC}} * t\ (years) \tag{12}$$

Where,

L_{FC}: Fuel cell expected lifetime (years)
$LOSS_{FC\_MAX}$: Maximum voltage losses permitted for the fuel cell operation (V/cell)

And finally, in case of the battery bank, the H2RES2 simulator calculates two expressions for the lifetime parameter ((13) and (14)). The first one depends on the operation cycles, while the second one depends on the capacity losses respect to its initial value (please see Annex A. Lead-acid battery. State of charge estimation). Comparing results from both expressions, the one which provides the highest degradation value determines the lowest battery bank lifetime, and this one will be chosen by H2RES2 simulator for a conservative design.

$$L_{BAT} = \frac{BAT_{CYCLE\_MAX}}{BAT_{CYCLE}} * t \tag{13}$$

$$L_{BAT} = \frac{C_{NOM0} * 0.2}{\Delta C_{NOM}} * t \tag{14}$$

Where,

L_{BAT}: Battery expected lifetime (years)
BAT_{CYCLE_MAX}: Maximum expected battery operation cycles associated with DOD design
BAT_{CYCLE}: Accumulated battery operation cycles
C_{NOM0}: Initial nominal battery capacity
ΔC_{NOM}: Battery nominal capacity degradation
t: Accumulated operating time (years)

System cost function

The cost function of the whole system includes all the unitary cost functions calculated for each element. Additionally, in case of non-isolated systems, the H2RES2 simulator includes a term associated with the costs derived from the energy acquisition from the grid, or the benefits of energy injection in situations of energy excess. These factors can be decisive when choosing one or another energy management strategy. The cost function of the overall system is presented in Eq. (15).

$$C(€) = \sum Cx + C_{GRID} \tag{15}$$

Where,

C: Overall system cost (€)
C_{GRID}: Grid operation cost (€)

The grid operation cost is calculated as following:

$$C_{GRID} = E_{GRID\_IN} * C_{GRID\_IN} - E_{GRID\_OUT} * C_{GRID\_OUT} \tag{16}$$

Where,

E_{GRID_IN}: Input energy from the grid to the hybrid system (kWh)
C_{GRID_IN}: Cost to buy energy from grid (€/kWh)
E_{GRID_OUT}: Output energy from the hybrid system to the grid (kWh)
C_{GRID_OUT}: Cost to sell energy to grid (€/kWh)

Simulation case

Summarizing what has been presented up to now, a general description of the H2RES2 simulator has been done (description based on simulator structure, implementation and user interface) as well as a review of the energy management strategies that the H2RES2 simulator develops and the sensitivity analysis it offers according to studied technical and economic parameters.

Arriving at this point and in order to show the correct operation of the simulator as well as to know its genuine features, two simulation cases have been developed. For this purpose, authors have selected an energy management strategy based on hysteresis bandwidth, with a variable operating mode for the fuel cell and the electrolyzer. In the first simulation case, a detailed description of obtained results is presented attending to the power balance and technical and economic parameters. The second simulation case is proposed to show the sensitivity analysis allowed by the H2RES2 simulator.

Case I

For this case, the equipment characteristics like sizing, power rate, costs and degradation parameters of each element are shown in Table 2. There are 95% and 60% SOC values chosen for SOCmax and SOClow, in order to charge the batteries as much as possible and keep the maximum DOD under recommended values to keep a higher useful lifetime.

The system configuration, cost and degradation parameters as well as the weather and the load profile (Fig. 10), are based on a real prototype implementation developed by different authors [45,46].

In Fig. 11 the different results obtained for the simulation case are presented.

These results monitor the system behavior under energy excess and deficit situations, based on the hysteresis band strategy studied in Section "Hysteresis".

In Fig. 11 the battery bank SOC value is presented, which determines the charge state of the system. As it is presented, during the summer months the battery SOC is always remarkably high due to the high solar energy generation. During this period hydrogen is produced by electrolysis processes until the metal hydride tanks reach their maximum level (see Fig. 11, days 50–80) Then the energy excess is injected to the grid in order to keep the power balance at all time (Fig. 11, days 80–285).

Table 2 – Parameters selected for the simulation case I.

Sim. time: 1 year			
Element	**Resource**	**BAT SOC**	**%**
PV	7.5 kW	SOCmax	95
WT	2 kW	SOCelemin	90
MH	20 Nm^3	SOCH2	85
ELEC	5 kW, 1 Nm^3	SOCfcmax	75
FC	3.4 kW × 2	SOCmin	70
BAT	400 V, 100 Ah	SOClow	60
Equipment cost	**Units**		
CO&MFC	0.6 €/h		
CO&MELEC	0.1 €/h		
C_{GRID_IN}	0.136 €/kWh		
C_{GRID_OUT}	−0.03 €/kWh		
CoFC	8000 €		
CoELEC	75,000 €		
CoBAT	7650 €		
Degradation	**Units**		
V_{time}	9 μV/cell/h		
V_{cyc}	48 μV/cell/cyc		
ΔV_{FC_max}	150 mV/cell		
$N_{ELECcycmax}$	5000 cycles		

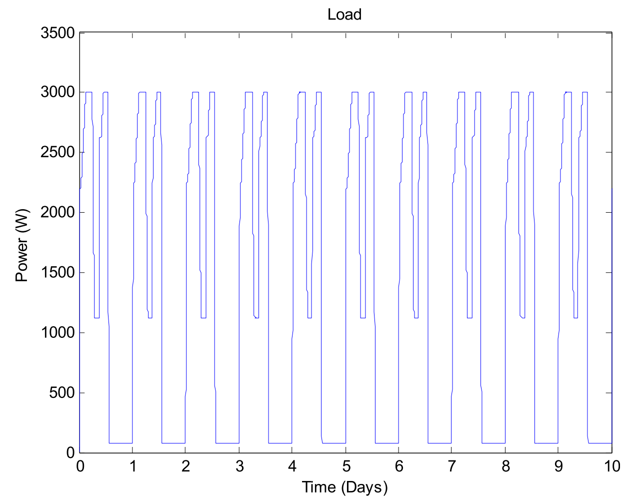

Fig. 10 – Load profile.

On the other hand, during winter months, the system experiences a constant energy deficit due to the low solar generation. During this period, the battery bank is more requested and therefore, the battery SOC is lower than the previous one.

In order to preserve the defined SOClow value, the fuel cell is used while the hydrogen resource is available. In the case that fuel cell generation is too low or zero, the grid (in an uninsulated configuration of course) will supply the necessary energy to guarantee the power balance and the minimum SOC value.

To detail the system behavior explained above, Figs. 12–17 show the SOC values, the hydrogen consumption and generation and the fuel cell, the electrolyzer and the grid power for different days and energy situations.

In the case of an energy deficit situation (days between 304 and 310), it is seen, how the battery reaches its minimum level, and the fuel cell operates in order to keep it. In this case, the fuel cell supplies the demand under variable operation mode. When there is enough energy to charge the battery, the fuel cell stops according to the hysteresis-band operation.

Finally, when the hydrogen stock is very low (from days 306–310), the fuel cell is not able to generate any energy, so it is the grid's responsibility to assure the demanded energy and keep the SOClow level balanced.

In the case of an energy excess situation (days 75–80), the battery SOC reaches its maximum value. The electrolyzer's start conditions are defined. The electrolyzer needs the extra energy of 1 kW of the minimum power operation condition (minimum power to start the electrolysis).

The overall simulation parameters are summarized in Table 3.

As we can extract from Table 3, the H2RES2 simulator provides all the electrical, technical and economic parameters necessary to perform a sensitivity analysis based on different energy management strategies.

Case II. Sensitivity analysis example

In order to show how to develop a sensitivity analysis with the H2RES2 simulator, a second case is simulated. In this case the

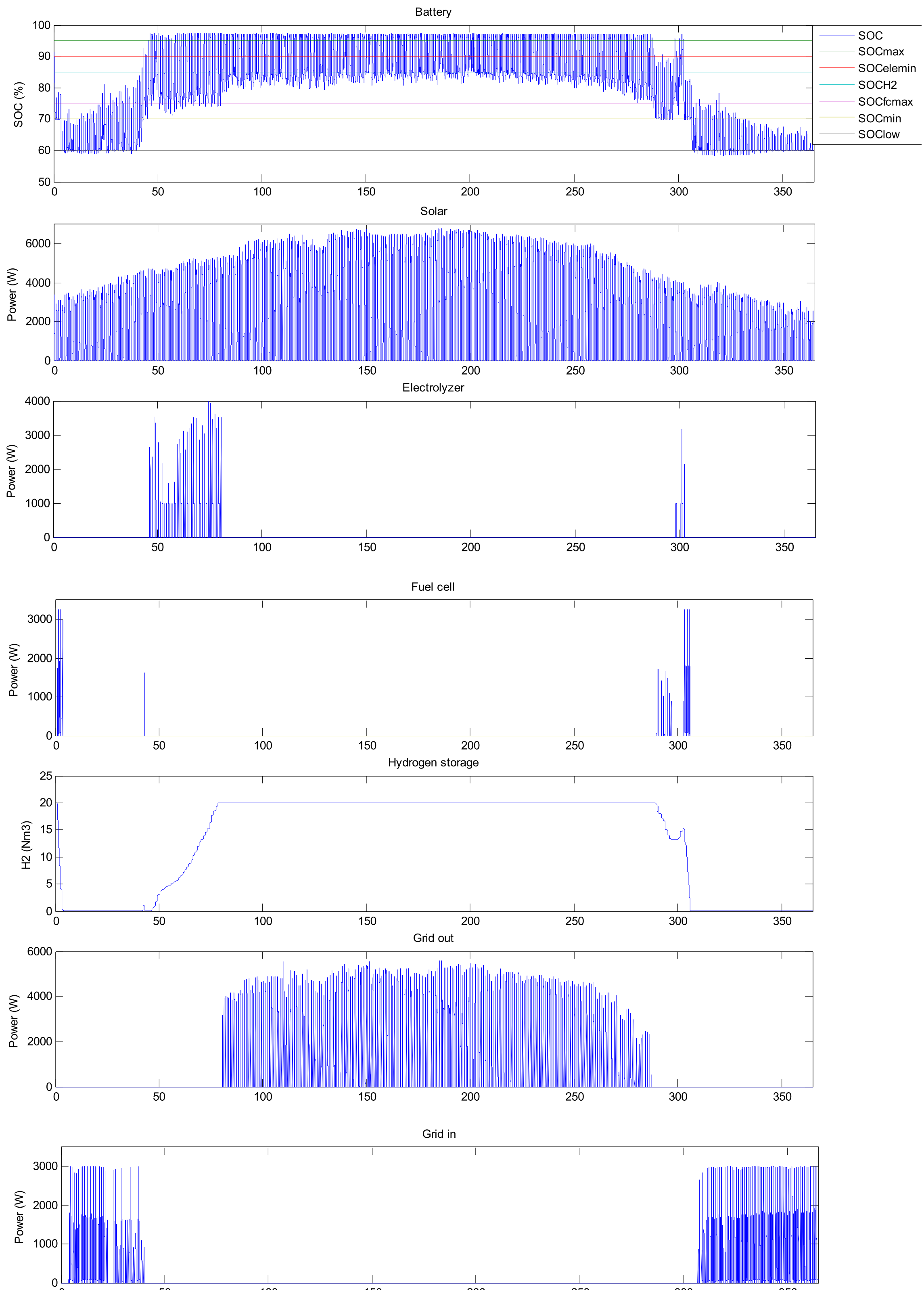

Fig. 11 – Overall system simulation results.

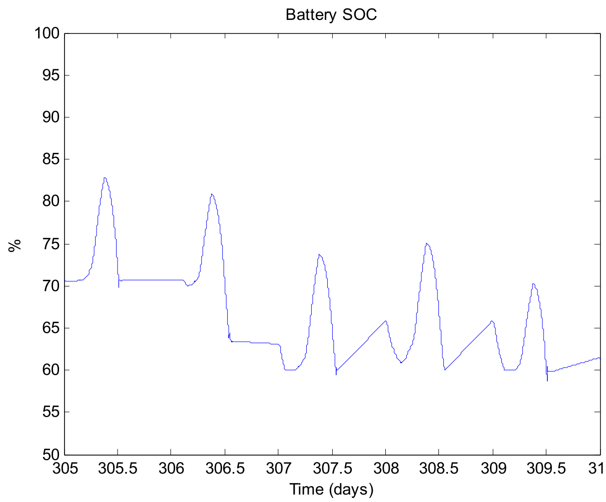

Fig. 12 – Battery SOC under energy deficit situation.

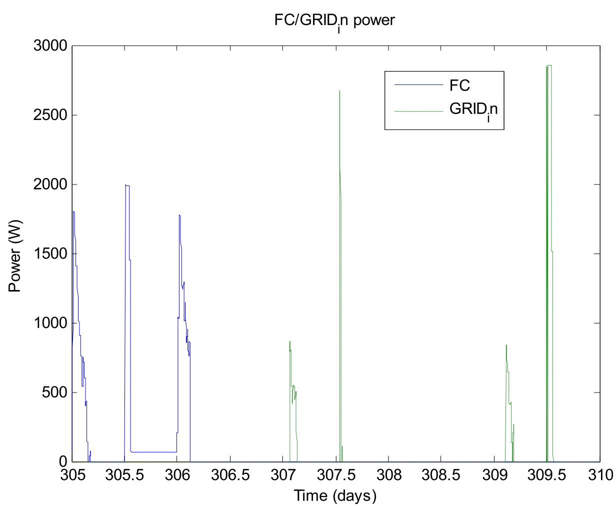

Fig. 13 – Fuel cell and grid power during energy deficit situation.

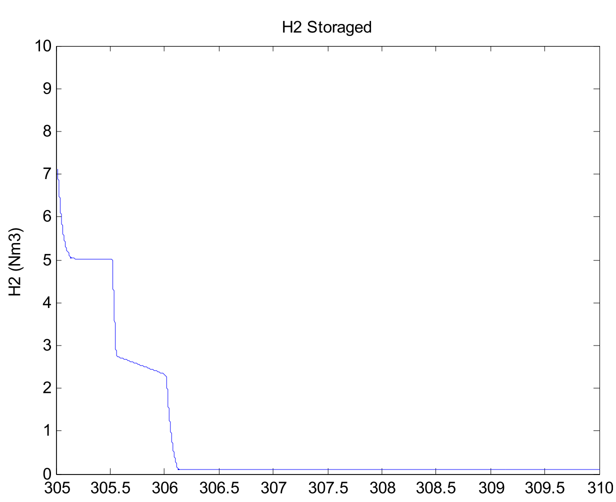

Fig. 14 – Hydrogen level in metal hydride tanks.

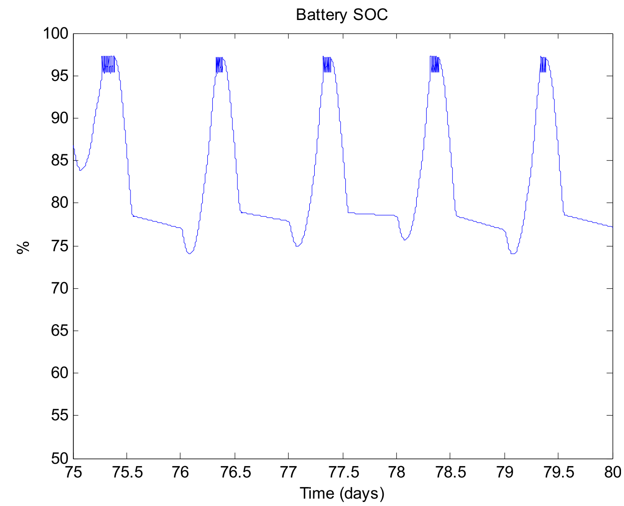

Fig. 15 – Battery bank SOC under energy excess situation.

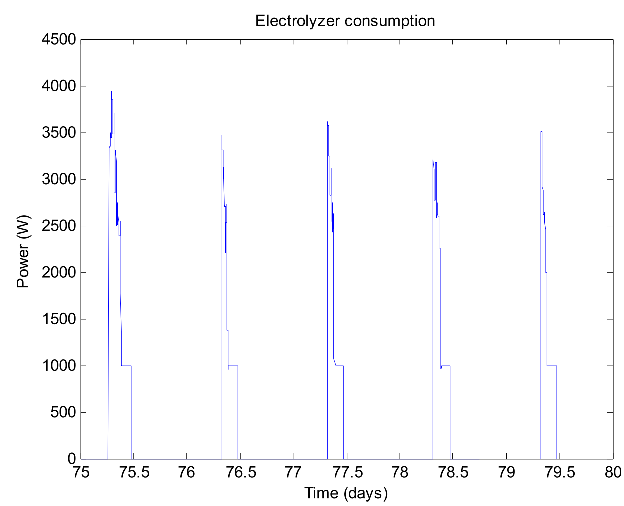

Fig. 16 – Electrolyzer power during energy excess situation.

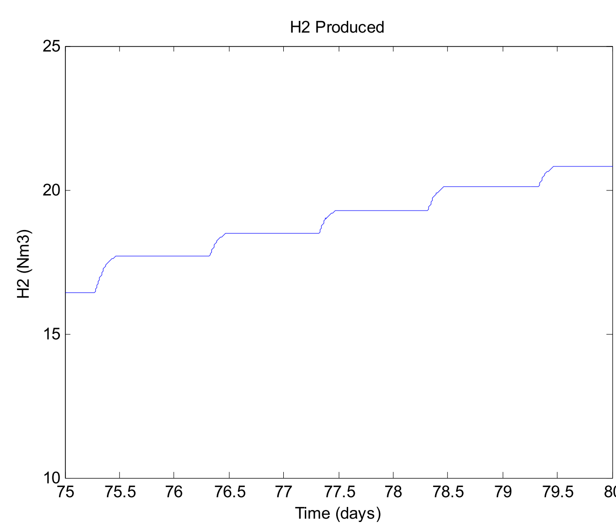

Fig. 17 – H_2 production during energy excess situation.

Table 3 – Summary of technical–economical parameters.

E_{GRID_IN} (kWh)	710.47
E_{GRID_OUT} (kWh)	2908.397
E_{ELEC} (kWh)	180.33
E_{FC} (kWh)	64.35
E_{BAT} (kWh)	2635.58
E_{LOAD} (kWh)	11,967.03
$LOSS_{CHA}$ (kWh)	209.54
$ELEC_{H_2}$ (Nm^3)	23.15
$ELEC_{CYCLE}$	39
$ELEC_{TIME}$ (h)	117.37
$FCI_{CYCLE}/FCII_{CYCLE}$	17/6
$FCI_{TIME}/FCII_{TIME}$ (h)	165.58/6.08
$\Delta V_{FCI}/\Delta V_{FCII}$ (mV/cell)	2.31/0.34
$N_{BATCcyc}$	68
ΔC_{NOM} (%)	2.12
LPSP (%)	5.94
CO&Mx (€)	1247.76

Table 5 – Summary of technical and economical parameters.

E_{GRID_IN} (kWh)	709.69
E_{GRID_OUT} (kWh)	2908.97
E_{ELEC} (kWh)	180.28
E_{FC} (kWh)	65.08
E_{BAT} (kWh)	2635.57
E_{LOAD} (kWh)	11,967.03
$LOSS_{CHA}$ (kWh)	209.54
$ELEC_{H2}$ (Nm^3)	23.14
$ELEC_{CYCLE}$	39
$ELEC_{TIME}$ (h)	117.32
$FCI_{CYCLE}/FCII_{CYCLE}$	31/15
$FCI_{TIME}/FCII_{TIME}$ (h)	128.97/6.3
$\Delta V_{FCI}/\Delta V_{FCII}$ (mV/cell)	2.65/0.78
$N_{BATCcyc}$	67
ΔC_{NOM} (%)	2.12
LPSP (%)	5.93
CO&Mx (€)	1263.81

different authors have eliminated the hysteresis bandwidth of the fuel cell operation (Table 4), maintaining the same SOCmin value and the rest of the simulation parameters similar to Case I.

According to the results obtained from Case I and Case II, Tables 3 and 5 respectively, we can state that the use of the hysteresis band mode can reduce the start–stop cycles of the fuel cell [45,46]. Besides, it requires higher operation time to reach the SOCfcmax value [45,46]. Depending on the hydrogen storage capacity, the difference between the fuel cell degradation of both strategies can be determined by one of the previous parameters.

In both cases, the hydrogen storage capacity is too low considering the demand. All the hydrogen resource is consumed and the fuel cell energy production is practically the same. However, the overall fuel cell degradation is higher in Case II due to the higher number of start–stop cycles. All of this causes a low increase in the fuel cell's costs (C_{FC}), and therefore an increase in the overall system costs.

Thanks to this sensitivity analysis, the user can propose different solutions for its simulation cases in order to minimize the equipment deterioration and the system costs. As an example, in the simulation case studied by various/the authors a possible solution increases the hydrogen storage capacity and allows a longer operating time of the fuel cell without start–stop cycles. This option reduces the degradation associated with operation time respect to the Case I.

Table 4 – Parameters defined for the simulation case II.

Sim. time: 1 year			
Element	**Resource**	**BAT SOC**	**%**
PV	7.5 kW	SOCmax	95
WT	2 kW	SOCelemin	90
MH	20 Nm^3	SOCH2	85
ELEC	5 kW, 1 Nm^3	SOCfcmax	70
FC	3.4 kW × 2	SOCmin	70
BAT	400 V, 100 Ah	SOClow	60
Equipment cost	**Units**		
CO&MFC	0.6 €/h		
CO&MELEC	0.1 €/h		
C_{GRID_IN}	0.136 €/kWh		
C_{GRID_OUT}	−0.03 €/kWh		
CoFC	8000 €		
CoELEC	75,000 €		
CoBAT	7650 €		
Degradation	**Units**		
V_{time}	9 μV/cell/h		
V_{cyc}	48 μV/cell/cyc		
ΔV_{FC_max}	150 mV/cell		
$N_{ELECcycmax}$	5000 cycles		

Conclusions

There is an increasing commitment of governments and companies to change their energy policies, orienting them towards higher energy efficiencies and renewable energy sources. This leads to the need of a control system required by hybrid renewable energy-based systems to manage the energy supplied by each source ensuring safe operation and fulfilling the objectives. This control system must be based on a proper energy management strategy which guarantees the load supply, increases the lifetime of the elements, reduces the operating costs, and therefore maximizes the system performance and providing a technical and economical feasible solution. For this purpose the use of software tools which allow us to perform simulations and previous analysis before the real implementation is necessary.

The software tools found in the scientific literature include some restrictions, so that the development of new simulators is necessary. The H2RES2 simulator presented in this paper overtakes these restrictions and it allows the testing of different energy management strategies, providing simulations in the short-term time scale. Additionally it offers a sensitivity analysis attending to costs and lifetimes of the devices which are integrated in the hybrid power system. The presented simulator allows the user to choose a configuration and management strategy using a user-friendly interface, providing a useful tool which offers detailed information for technical and economic data analysis, that is needed before any genuine implementation is possible. Additionally, the H2RES2 simulator has been developed in MATLAB Simulink environment adding helpful computing power and security.

Simulation cases studied in the last section demonstrate a proper H2RES2 performance and show its features: energy management strategy selection as well as a technical and economic study.

Future work

The H2RES2 is in a constant evolution process in order to expand its architecture (generators, elements backups and kind of loads) and integrate new tools and functions to improve it.

New economic functions are developed in order to test the effect of interest rates of inflation over the economical results for long term simulations.

As a future task, H2RES2 simulator may also be used as a SCADA (Supervisory Control And Data Acquisition) system, taking advantage of all the previous studies performed under simulation conditions. This involves the integration of sensors replacing the previous simulation variables and communication protocols of electronics and the PC hosting the SCADA system. Finally, new kinds of elements and different nature elements are going to be added in order to increase the applications range of H2RES2.

Annex A. Simulator. Hybrid system models

Since the H2RES2 Simulator is intended to be a tool for testing different energy management strategies, it is not necessary to use excessively complex models that require a tedious programming. The models used for the generators and auxiliary elements have been widely studied; they are based on empirical curves and parameters obtained from technical documentation, so they represent faithfully the behavior of different elements of the real systems.

Renewable resources and demand

Renewable resources

Solar radiation will be an input parameter to H2RES2 simulator so it can be adapted to different weather resources of different locations. The radiation series is considered to be a file data with radiation data of every 10 min expressed in W/m^2.

Solar radiation and wind speed are other possible input parameters for the H2RES2 simulator, that are used to estimate the production of the wind turbine. Wind speed series is a file with speed data every 10 min expressed in m/s.

Demand

H2RES2 allows to define different load profiles. The goal is a simulator with the possibility to simulate both, typical demand profiles and extreme conditions, in order to analyze the system response. The demand load profile must have at least involved data of every 10 min expressed in watts.

Photovoltaic panels

Photovoltaic (PV) panels are arrays of serial and parallel connections. The model used to represent them is based on the empirical behavior of the panel current and voltage regarding the radiation and operating temperature. According to Figs. A1 and A2, in a PV panel the behavior of the short circuit current regarding the incident irradiance is almost linear. Conversely, the open circuit voltage hardly suffers variations with irradiance, so it can be assumed as practically independent of it [20].

In the same way, the short circuit current is maintained virtually invariant with respect to the cell temperature. The open circuit voltage behaves similar to a linear function with a negative slope [20].

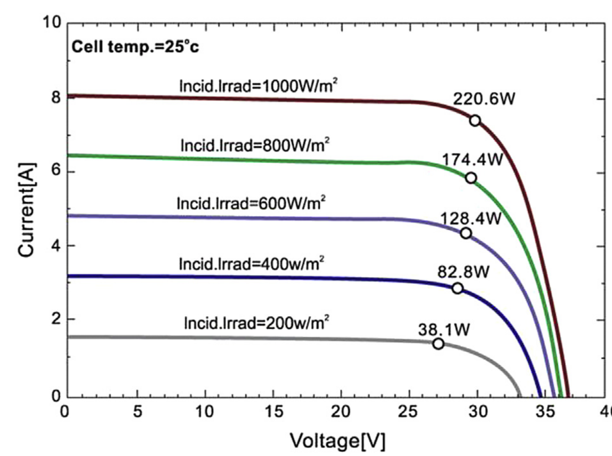

Fig. A1 – PV (60 cells) polarization curves dependency with irradiance.

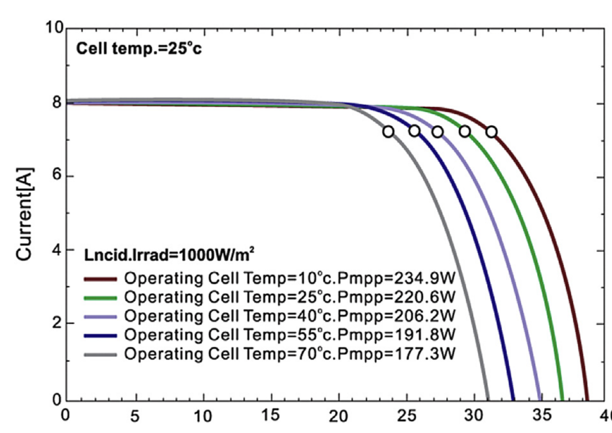

Fig. A2 – PV (60 cells) polarization curves dependency with cell temperature.

Based on the above, the equations that model the behavior of a PV panel regarding the irradiance (G) and temperature (T) can be written with a good approximation as:

$$Isc(G,T) = Isc_{ref}*G/G_{ref} \quad (1)$$

$$Voc(G,T) = V_{OCref}*(1 - kv*T_{cell}) \quad (2)$$

Where,

I_{SC} : PV panel short circuit current (A)
Isc_{ref}: PV panel short circuit current (A) at reference irradiance
V_{OC} : PV panel open circuit voltage (V)
V_{OCref} : PV panel open circuit voltage at reference temperature (V)
G_{ref} : Reference irradiance (W/m^2)
G : Incident Irradiance (W/m^2)
T_{cell}: Cell temperature (°C)
kv: Voltage temperature coefficient (V/°C)

To calculate the generated power at any irradiance, it is common to use the NOCT (Nominal operating cell temperature) conditions as reference, because it determines real power, voltage and current under nominal cell temperature operation. Then the generated power dependence with irradiance follows expression (3):

$$P(G) = P_{NOCT}*G/G_{NOCT} \quad (3)$$

Where,

P_{NOCT} : Generated power at NOCT condition (W)

After this, for given conditions of irradiance and cell temperature, the real generated power by the PV panel can be calculated from Eq. (4):

$$P(G,T) = P(G)*(1 - K_{PT}*T_{cell}) \quad (4)$$

Where,

K_{PT} : Thermal power variation coefficient (W/°C)

Finally, to calculate the cell temperature (°C) we can use Eq. (5) [20]:

$$T_{cell} = T_{amb} + \frac{T_{NOCT} - 20}{G_{NOCT}}*G \quad (5)$$

Wind turbines

The wind turbine model used in H2RES2 is based on the power curve relating the generated power with the wind speed and referring to electrical and mechanical losses.

According to Ref. [22], we can define the following areas in a wind turbine power curve (Fig. A3):

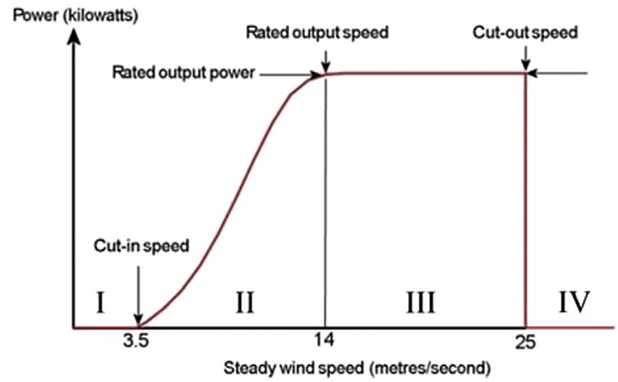

Fig. A3 – Wind turbine power curve.

Zone I: This zone corresponds to the area between a null and the cut-in wind speed.

Zone II or partial cargo area: This area is defined by the cut-in speed and the operation rated speed of the machine. In this area, the generated power is lower than the nominal power and it follows a cubic function with respect to the wind speed.

Zone III or full load area: In this area the wind speed is higher than the rated speed. To avoid any damage in the wind turbine, it is common to use a power control technique whose aim is to keep the machine running at rated power.

Zone IV: This area is defined by wind speeds higher than the cut-out speed. In order to protect the wind turbine, mechanical breaking techniques are used to cut down the generation.

Expression (6) shows the relation of generated power regarding wind speed, differencing each above described zones.

$$P_{WT} = \begin{cases} 0; \ v \le v_{cut-in} \\ \eta_m \eta_e Cp \frac{1}{2} \rho A v^3; \ v_{cut-in} < v < v_{rated} \\ \eta_m \eta_e P_N; \quad v_{rated} \le v \le v_{cut-out} \\ 0; \ v_{cut-out} < v \end{cases} \quad (6)$$

Where,

η_m: Mechanical efficiency of the wind turbine
η_e: Electrical efficiency of the wind turbine
Cp: Power coefficient
ρ: Air density (kg/m^3)
A: Rotor area (m^2)
v: Wind speed (m/s)
P_N: Nominal power of the wind turbine

Lead-acid battery

For the needs of the H2RES2 simulator, the energy that the battery is able to absorb and the transfer during the charging/discharging cycles is modeled. It is necessary to model the battery state of charge (SOC) as well, due to the fact, that it represents a fundamental decision parameter in every energy management strategy. It determines start–stop conditions of other elements of the system.

Battery electrical model

The battery electrical model is obtained from its Thevenin simplification (Fig. A4). From here we can propose the battery current dependence on the net power (Eq. (7)) and consequently the battery voltage, (Eqs. (8) and (9)) according to Ref. [23].

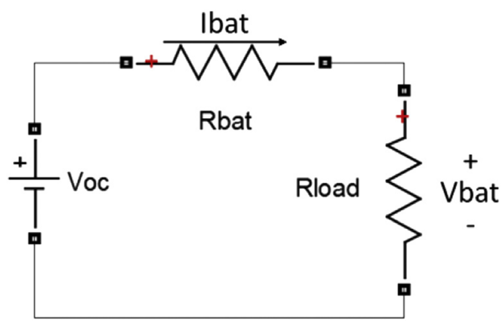

Fig. A4 – Battery simplified model.

$$I_{BAT} = \frac{P_{net}}{V_{BAT}} \tag{7}$$

$$V_{BAT} = V_{oc} - I_{BAT} * R_{BAT} \tag{8}$$

$$R_{BAT} \cong \left(\frac{1.89}{SOC} - 0.0150\right) \tag{9}$$

Where,

P_{net} : Net battery power (W)
I_{BAT}: Battery current (A)
V_{BAT}: Battery terminal voltage (V)
V_{oc}: Battery open circuit voltage (V)
R_{BAT}: Battery internal resistance (Ω)

State of charge estimation

In H2RES2 simulator *Coulomb counting method* has been used as SOC estimator.

SOC estimator algorithm. The Coulomb counting method calculates the capacity balance during charging and discharging processes. To improve the algorithm accuracy, it is necessary to use short time samples and high accuracy sensors. However, this method is an open loop estimator, so external correction after a certain period of time is required [23,55].

The equation that models the Coulomb algorithm is presented in Eq. (10):

$$SOC(t) = SOC(0) \pm \int_0^t \frac{I_{BAT}(t) * \eta_C\ (t)\ dt}{Cap(t)} \tag{10}$$

Where:

SOC(0): Initial battery SOC value (%)
$I_{BAT}(t)$: Battery current (A)
η_C (t): Coulomb efficiency (%)
Cap(t): Battery current capacity (Ah)

Equation (10) can be solved using numerical integration (11):

$$SOC\ (t) = SOC(t-1) \pm \frac{\eta_C\ (t) * I_{BAT}(t) * \ \Delta t}{Cap\ (t)} \tag{11}$$

These expressions can be separated for charging process:

$\eta_C < 100$ %

$Cap(t) = Cnom(t)$

Where Cnom is the nominal capacity of the battery.

And discharging process, according to Peuckert' law:

$\eta_C \cong 100$ %

$$Cap(t) = \frac{Cnom(t) * I^{1-n}}{Inom^{1-n}}$$

Where Cnom integrates the deterioration associated with the different charging/discharging processes.

Electrolyzer

There are several electrolyzer technologies in the market, while alkaline electrolysis is the most widely used, due to its price and demonstrated performance [24,25]. Reactions occurring within an electrolytic cell regardless of the technology are:

$$\text{Anode}: \ 2OH\ aq \rightarrow 1/O_2\ g\ +\ H_2O\ \ +\ 2e^- \tag{12}$$

$$\text{Cathode}: \ H_2O\ +\ \ 2e^-\ \rightarrow 1/2H_2 +\ 2\ OH\ aq \tag{13}$$

Hydrogen production

As opposed to what happens with photovoltaic panels and wind turbines as electrolyzers, it is not very common to find power-hydrogen generation curves in its technical characteristics. For this reason authors have opted for using a model based on Faraday's law, which relates the amount of input current regarding the produced hydrogen [26,57].

$$\text{mols } H_2 = \frac{\eta_F * I_{ELEC} * t}{F * z} \tag{14}$$

Where,

η_F: Faraday's efficiency
I_{ELEC}: Electrolysis current (A)
t: Time (s)
F: Faraday's constant (96,485 C/mol)
z: Number of electrons which play in the reaction ($z = 2$)

According to the electrical power definition and considering the nominal operation voltage, a relationship between input power and hydrogen production is easily found (15):

$$P_{ELEC} = V_{ELEC} * I_{ELEC} \Rightarrow \text{mols } H_2 = \frac{\eta_F * P_{ELEC} * t}{F * z * V_{ELEC}} \tag{15}$$

In a real system this expression needs to be corrected to take into account the auxiliary loads consumption (P_{aux}). Auxiliary loads usually represent 10–20% of the total consumed power, and mainly used to feed the refrigeration system, and the control and operation electronics. Finally, expression (16) allows the calculation of the hydrogen production based on the supplied power and the auxiliary loads consumption:

$$\text{mol } H_2 = \frac{\eta_F * (P_{ELEC} - P_{aux}) * t}{F * z * V_{ELEC}} \tag{16}$$

Fuel cell

In a fuel cell, the processes of oxidation and reduction of hydrogen and oxygen at the anode and cathode respectively follow the equations:

$$\text{Anode}: 2H_2 \rightarrow 4H^+ + 4e^- \tag{17}$$

$$\text{Cathode}: \ O_2 + 4e^- + 4H^+ \rightarrow 2H_2O \tag{18}$$

Fuel cell power curve model
In the case of fuel cells, polarization and power curves in technical documentation are commonly provided by manufacturers. Taking advantage of this, the model used by the H2RES2 simulator corresponds to the least squares method of the voltage versus current curve provided by the manufacturer (19). The greater number of points that are used is, the better the accuracy achieved. Fig. A5 shows the real performance of a fuel cell developed by authors and based on the stack FC1020 from Ballard® [44].

$$V_{FC} = a * I_{FC}^3 + b * I_{FC}^2 + c * I_{FC} + d \tag{19}$$

$$P_{FC\_gross} = V_{FC} * I_{FC} \tag{20}$$

Where,

V_{FC}: Fuel cell voltage (V)
I_{FC}: Fuel cell current (A)
P_{FC_gross}: Gross power generated (W) by the fuel cell

Fuel cell consumption model
Similar to what was done in electrolyzer modeling, the Faraday's law will be used again to calculate the hydrogen consumption based on the fuel cell operating point [27,28]. Knowing the operation point of the fuel cell, the hydrogen consumption can be determined.

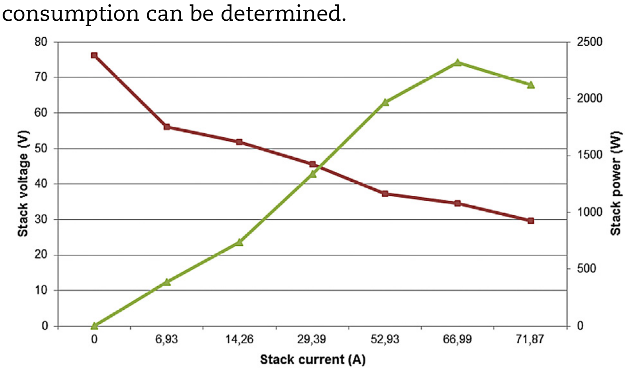

Fig. A5 – V–I, P–I curve for FC1020 from Ballard®.

$$\text{mol } H_2 = \frac{I_{FC} * t}{F * z * Eff} \tag{21}$$

Where,

mol H_2: Produced hydrogen (mol)
Eff: Fuel cell efficiency (%)

The efficiency is calculated from the quotient between the electrical power produced by the fuel cell and the hydrogen heat power, expression (22):

$$Eff = \left(\frac{P_{FC_{gross}}}{P_{H_2}}\right) = \frac{V_{FC} * I_{FC}}{\text{mol } H_2 * LHV * I_{FC}} \tag{22}$$

Where,

$P_{FC_{gross}}$: Fuel cell output power (W)
P_{H_2}: Chemical power associated to determined hydrogen consumption (W)
LHV: Hydrogen lower heating value

Hydrogen storage

Regarding hydrogen storage, H2RES2 simulator implements the two most widely used hydrogen storage technologies currently: pressurized gas and metal hydrides.

Pressurized gas
The considered parameters regarding pressurized hydrogen in a tank are the hydrogen input (Nm^3) (this hydrogen has been generated by the electrolyzer), consumed hydrogen by the fuel cell, initial level of the hydrogen tank (H_{2_0}), as well as the maximum and minimum levels which guarantee the proper tank operation. Since the input and output flow rate capacity is higher than metal hydrides tanks can support, it can be assumed, that the flow rate is imposed by the maximum capacity of hydrogen absorption of metal hydrides tanks.

The hydrogen balance inside the tank is given at every moment by the amount of hydrogen input and hydrogen output, adding the initial hydrogen stock.

$$H_2(Nm^3) = H_{2\_in} - H_{2\_out} + H_{2\_0} \tag{23}$$

Metal hydrides tank
Unlike high pressure tanks, metal hydrides tanks need a power supply to stabilize the temperature of the cooling water during the hydrogen charge and discharge processes. This means that the power consumption by hydride metals can be considered as another load with respect to the power balance. The metal hydrides model includes the hydrogen balance, similar to the one for high-pressure tanks, and a model that reflects the power consumption of the cooling system.

The power consumption of the cooling system can be obtained from the manufacturer's data, and in general it is given as a function of the input/output hydrogen flow rate. Given a particular operation flow rate, it is possible to calculate the metal hydride tanks power consumption according to expression (24):

$$P_{HM} = FR_{H_2} * P_{cool}\ (H_2) \tag{24}$$

Where,

P_{HM}: Metal hydride tank power consumption (W)
FR_{H_2}: Inlet/outlet hydrogen flow rate (Nm^3/h)
P_{cool} (H_2): Cooler/heater power consumption per Nm^3/h (W)

To distinguish the charging and discharging process of the metal hydride tanks, the model includes a way to check the derivative of the hydrogen balance. If the derivative is not zero, the metal hydride tank is charging or discharging and the derivative sign will define it.

The hydrogen balance model is similar to the high pressure tank model. The model takes considers the hydrogen input (from high pressure tank), the hydrogen output (towards the fuel cell), the initial hydrogen level and the maximum and minimum limits which ensure the safe operation of the system.

Grid

As it has been mentioned above, H2RES2 allows modeling isolated or grid connected hybrid power systems.

In case of grid connected systems, the grid is represented by a model that is recommended to solve two different situations (deficit and overproduction). In energy deficit situations, the grid behaves as an additional generator that injects the needed power to guarantee the power balance of the system.

On the other hand, when the system provide an over production, the grid is supposed to behave as a variable charge that consumes as much power as needed to achieve the power balance.

Finally, in case of isolated applications, the *grid* concept which appears in the simulator defines and allows quantifying the energy deficit or energy overproduction of the studied hybrid system. This parameter indicates the difference between the generated and the consumed energy, providing the user an opportunity to test the viability of his configurations. Based on the obtained results, the user is enabled to look over the proposed energy management strategy and the system sizing.

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