Journal of Power Sources 196 (2011) 4418–4426

Contents lists available at ScienceDirect

Journal of Power Sources

journal homepage: www.elsevier.com/locate/jpowsour

Influence of wind turbine power curve and electrolyzer operating temperature on hydrogen production in wind–hydrogen systems

Fco. Javier Pino*, Luis Valverde, Felipe Rosa

Thermal Engineering Group, Energy Engineering Department, School of Engineering. Camino de los Descubrimientos s/n, 41092 Sevilla, Spain

ARTICLE INFO

Article history:
Received 30 July 2010
Received in revised form 18 October 2010
Accepted 20 October 2010
Available online 27 October 2010

Keywords:
Wind–hydrogen
Hydrogen production
Simulation
Experimental validation
Wind turbine

ABSTRACT

Current simulation tools used to analyze, design and size wind–hydrogen hybrid systems, have several common characteristics: all use manufacturer wind turbine power curve (obtained from UNE 61400-12) and always consider electrolyzer operating in nominal conditions (not taking into account the influence of thermal inertia and operating temperature in hydrogen production). This article analyzes the influence of these parameters. To do this, a mathematical wind turbine model, that represents the manufacturer power curve to the real behaviour of the equipment in a location, and a dynamic electrolyzer model are developed and validated. Additionally, hydrogen production in a wind–hydrogen system operating in "wind-balance" mode (adjusting electricity production and demand at every time step) is analyzed. Considering the input data used, it is demonstrated that current simulation tools present significant errors in calculations. When using the manufacturer wind turbine power curve: the electric energy produced by the wind turbine, and the annual hydrogen production in a wind–hydrogen system are overestimated by 25% and 33.6%, respectively, when they are compared with simulation results using mathematical models that better represent the real behaviour of the equipments. Besides, considering electrolyzer operating temperature constant and equal to nominal, hydrogen production is overestimated by 3%, when compared with the hydrogen production using a dynamic electrolyzer model.

1. Introduction

Currently, society and governments are interested in an energy supply based on renewable energy sources. This interest is reflected in various programs promoting renewable energies, for example: in Europe, plan 20/20/20; in Spain, National Renewable Energy Plan 2005–2010, or in Andalusia (Spanish region), the Andalusian Energy Sustainability Plan (PASSENER) 2007–2013.

In the last decade, one of the renewable technologies with a fastest growing was wind energy, with an average annual growth rate in the global electricity system (and also in Spanish system) of 28%. The electric power installed at the end of 2009 in Spain was 13366 MW, which accounts 19.2% of total installed capacity in the Spanish electricity system, surpassed only for combined cycle technology with a presence of 23.7% in the system. This presence in terms of power is not reflected in terms of energy, where wind technology contributed 13.4% to system demand in 2009. As shown in Fig. 1, the relationship between the power installed and the covered electricity demand has been maintained over last years [1].

One of the principal reasons of this level of penetration of wind energy in the electric system is the difference between profiles of electric production from wind farms and power demanded by the grid which are decoupled in time. Electric production profile is associated with wind conditions and demand profile is imposed by the consumption of users. One of the possible solutions to this problem would be the inclusion of hydrogen technology in wind farms that would: adjust electricity production and demand, increase penetration of wind energy in system, and improve the management of wind farms and general power system.

A wind turbine (or wind farm), along with a hydrogen storage system, form an integrated wind–hydrogen installation (Fig. 2), whose main elements are: wind turbine, electrolyzer, hydrogen storage system, fuel cells, electronics power conditioning, control system and auxiliary systems. Pino [2] carried out a state of the art of the experimental facilities that currently exist worldwide.

For analyzing, designing and sizing such systems, computer simulations tools are used [3–9]. Most of them are multi-objective and focusing on renewable energy integration with different storage technologies.Focusing on mathematical models of main equipment for hydrogen production in wind–hydrogen systems such as wind turbine and electrolyzer, several shortcomings are detected.

Considering the wind turbine, all simulation tools model it using the power curve provided by the manufacturer, which is calculated following the steps set out in norm UNE 61400-12. The Power curve relates the electrical power produced with respect of wind speed (Fig. 3). In this article it will be demonstrated that perform-

* Corresponding author. Tel.: +34 954486778; fax: +34 954487247.
E-mail address: fjp@us.es (Fco.J. Pino).

0378-7753/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.jpowsour.2010.10.060

Nomenclature

A	Active cell area (m^2)
DP	Power difference
f	Faraday efficiency experimental parameters
F	Faraday's constant (96500 C mol^{-1})
I	Intensity (A)
nc	cells number
P	Power (W)
Q	Heat (W)
r	experimental parameters
t	experimental parameters
T	Temperature (°C)
U	voltage (V)
UA	Global heat transfer coefficient (W $°C^{-1}$)
v	wind speed (m s^{-1})
z	electrons in electrochemical reaction (2)

Subscripts

AC	AC
cool	cooling
DC	DC
dem	demand
elec	electrolyzer
env	environmental
exc	excess
gen	generated
loss	losses
man	manufacturer
max	maximum
mod	model
rev	reversible

ing simulations with this curve produces overestimations of wind turbine electric production at a specific location. As a turbo machinery, the performance of the wind turbine when operating outside nominal conditions cannot be represented only by one parameter, in this case wind speed. It is necessary to take into account other parameters such as height of the site, air temperature, electrical and control system considerations, etc. in order to accurately calculate the electrical output of wind turbines.

A few references show detailed dynamic mathematical models of wind turbine [10,11]. They correctly represent the real behaviour

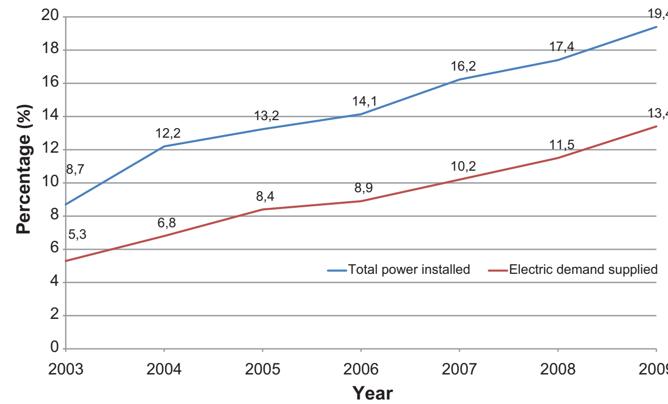

Fig. 1. Percentage of wind energy power installed in the Spanish electric system and energy provided to grid demand from 2003 to 2009.

of the equipment, but due to its complexity and the number of input data needed, such models are not practical for analyzing annual electricity production of such equipment. In addition, the inertial time constant of this equipment is of the order of seconds, a time period lower than electrolyzer time constant (of the order of minutes), so that the mathematical model developed for wind turbines is static.

Considering the existing detailed models and their applicability, it is necessary to develop a wind turbine model based on its manufacturer power curve in order to be easy to implement in simulation tool for the analysis of renewable energy systems. However, it must take into account the site and real operation characteristics. In the literature, no such a model was found with these features; the first mention is made in Pino [2].

Depending on the simulation tool used, the electrolyzer is modelled in different ways. Most of the models consider nominal operating conditions [3–7,9] without taking into account the operating temperature and thermal inertia of the equipment, which are parameters that affect to the hydrogen production. Hydrogems [12] consider electrolyzer dynamics, but have deficiencies in the modelling of heat losses to environment.

Thermal inertia is important when the electrolyzer is connected to renewable energy sources, such as wind energy, because operating temperature changes with time, and therefore hydrogen production.

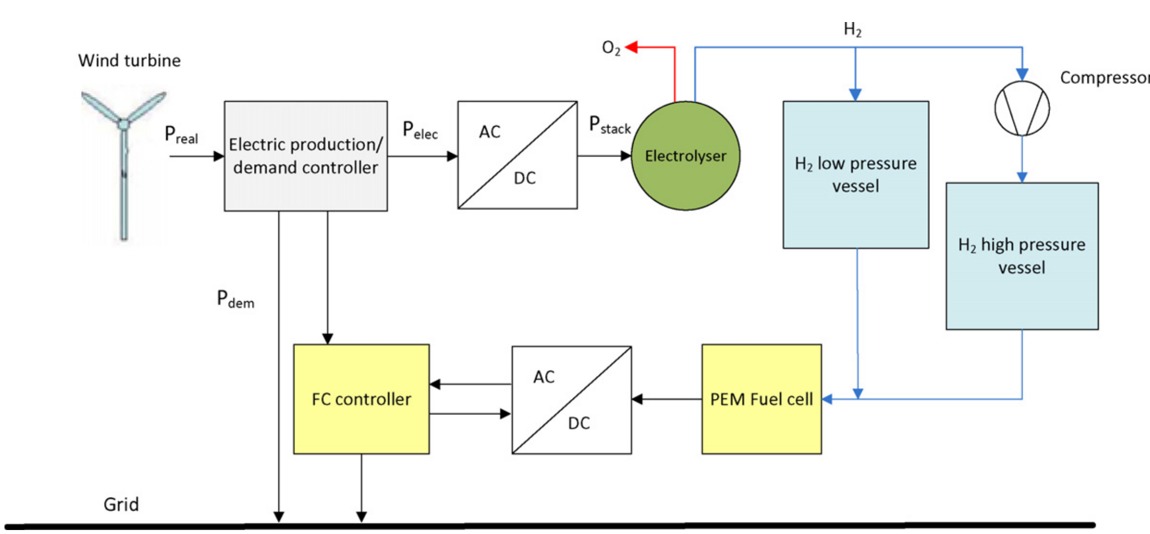

Fig. 2. Wind–hydrogen system.

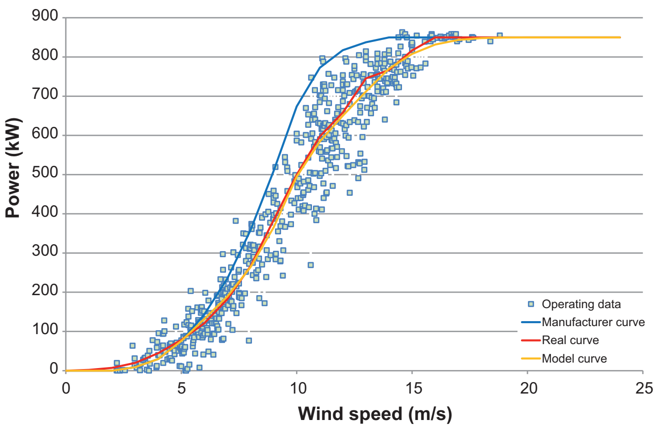

Fig. 3. Wind turbine power curves.

In addition, these simulation tools have not been validated with real operation data, and therefore the representativeness of the results is unknown.

This article analyzes the influence of the wind turbine power curve and the electrolyzer operating temperature, both in annual hydrogen production and in optimal electrolyzer size in a wind–hydrogen system.

For this purpose, a methodology and a mathematical model are developed in order to approximate the wind turbine power curve provided by manufacturer to the real operating conditions in a specific location. Additionally, the dynamic electrolyzer model proposed in Ref. [12] is improved in several areas (characteristic curve and thermal losses model in particular). These mathematical models will be validated with real operating data.

The article is divided in seven sections. In Section 2, the mathematical models are presented. Wind–hydrogen system is described in Section 3. The validation of the models is carried out in Section 4. Input data, simulation scenarios and system simulation results are presented in Section 5. Result discussion is carried out in Section 6. Finally, conclusions and future works are discussed in Section 7.

2. Component models

2.1. Wind turbine

The wind turbine model is based on a methodology developed to characterize its real behaviour in a specific location. The methodology is applied in three steps:

(1) Get the real power curve for the site, processing measured operating data by following the steps outlined in norm UNE 61400-12.The real power curve can be seen in Fig. 3.
(2) For each wind speed, calculate the normalized power difference points, according to Eq. (1), where the normalized power difference is equal to the difference of power according to manufacturer power curve and the real curve divided by the maximum power of the wind turbine. This calculation should be performed for several wind speeds within the operation range.

$$\mathrm{DP_{nom}} = \frac{(P_{\mathrm{wt,man}} - P_{\mathrm{wt,real}})}{P_{\mathrm{wt,\,max}}} \tag{1}$$

(3) Adjust the normalized power differences points of the previous step by means of a fitted curve (power difference curve). An equation for the curve, based on a 4-parameter Weibull (a, b, c and d) depending on the type of wind turbine, location and operating conditions, is proposed. The mathematical expression of the Weibull curve is shown in Eq. (2). The selected curve adjusts satisfactorily with experimental points (obtained in the previous step) and allows to be standardized for other wind turbines.

$$\mathrm{DP_{nom}} = a\left(\frac{d-1}{d}\right)^{1-d/d}\left(\left(\frac{v-b}{c}\right)+\left(\frac{d-1}{d}\right)^{1/d}\right)^{d-1}$$
$$\exp\left(-\left(\frac{v-b}{c}\right)+\left(\frac{d-1}{d}\right)^{1/d}\right)^{d}+\frac{d-1}{d} \tag{2}$$

A characterization of this type is not found in bibliography, because of the difficulty to access to real operating data of wind turbines. Real data are part of know-how of wind turbine manufacturers and wind farms operators, who not usually disclose this kind of information.

The Power generated by wind turbine, for each wind speed, is calculated, according to the proposed model ($P_{\mathrm{wt,mod}}$) as the difference between manufacturer power curve ($P_{\mathrm{wt,man}}$) and the maximum power ($P_{\mathrm{wt,max}}$) multiplied by the power difference curve ($\mathrm{DP_{nom}}$). Eq. (3) shows the curve for the proposed model curve:

$$P_{\mathrm{wt,nom}} = P_{\mathrm{wt,man}} - P_{\mathrm{wt,max}} \cdot \mathrm{DP_{nom}} \tag{3}$$

2.2. Electrolyzer

The electrolyzer model is composed of several modules [2] connected with each other as presented in Fig. 4. The main modules are in the electrical and thermal. These modules allow for the determination of the operating stack voltage, current and temperature. Globally, the electrolyzer model calculates the hydrogen production ($n_{\mathrm{H_2,prod}}$) from the electric power consumed ($P_{\mathrm{elec,AC}}$).

The electrical module is based on the electrolytic cell current–voltage characteristic curve. The equation proposed by Ulleberg [12] is modified in order to improve the adjustment between operating data and model results. A current–voltage curve equation is developed, and its dependence on electrolyzer temperature, has the following expression:

$$U = U_{\mathrm{rev}} + \frac{r_0 + r_1 T}{A} I + s \log\left(\frac{t_0 + t_1 T + t_2 T^2}{A} I + 1\right) \tag{4}$$

U_{rev} is the reversible voltage, calculated from the thermodynamic of the process. The parameters r_i and t_i are determined from measured experimental data, following the methodology indicated in Pino [2].

Hydrogen production is directly proportional to the current circulating in the cells, and it is calculated from Faraday's equation (Eq. (5)). Faraday's performance (Eq. (6)) depends on two parameters which are also determined from measured experimental data [12].

$$\dot{n}_{\mathrm{H_2}} = \varepsilon_F \frac{ncI}{zF} \tag{5}$$

$$\varepsilon_F = f_2 \frac{(I/A)^2}{(I/A)^2 + f_1} \tag{6}$$

The electrolyzer operation temperature is obtained from an energy balance on the device (Eq. (7)), where thermal inertia is equal to a generated heat flux (Q_{gen}) minus the cooling heat flux (Q_{cool}) and heat losses (Q_{loss}).

$$C_t \frac{dT}{dt} = Q_{\mathrm{gen}} - Q_{\mathrm{cool}} - Q_{\mathrm{loss}} \tag{7}$$

The generated heat flow is associated to thermodynamic irreversibilities in the process and it is defined in Ref. [13]. The cooling heat flux is considered when operating temperature is higher than

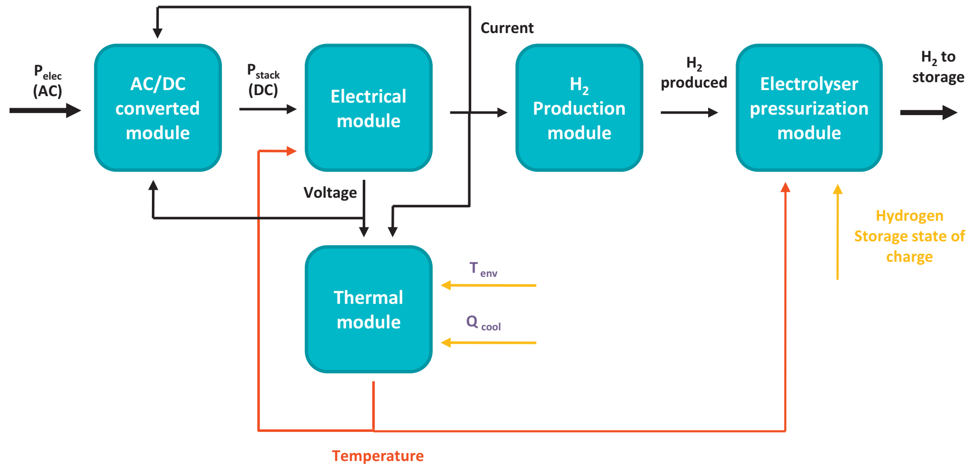

Fig. 4. Complete model electrolyzer.

nominal. Heat losses are quantified as the sum of convective losses and radiant losses to the environment, where the heat exchange area of the electrolyzer components (stack and gas separators) are taken into account [14]. Eq. (8) shows the mathematical model of thermal losses.

$$Q_{loss} = \sum_i UA_i(T_{elec} - T_{env}) \quad (8)$$

In the above equation, the same temperature difference between electrolyzer components and environment is used due to the constant temperature of the main components when the electrolyzer is operating [15].

The wind turbine model and the electrolyzer model have been implemented in Matlab Simulink, and they are part of a simulation tool which allows the analysis of the integration of renewable energies with hydrogen technology [9]. This tool is currently under development.

3. Wind–hydrogen system description

The wind–hydrogen system lay-out is shown in Fig. 2. Among the possible operation modes of system, wind-balance is selected. This mode seeks to couple the wind turbine electric power produced with the electric power demanded by the grid at each instant of time. The operation mode is explained in detail in Ref. [2].

The system operation is divided into two possibilities for each time step:

- If the power produced by the wind turbine (P_{real}) is higher than demanded by the grid (P_{dem}), power excess (P_{exc}) is sent to the electrolyzer in order to produce hydrogen. Depending on the size of the electrolyzer and the state of charge of the hydrogen storage system, not all power excess could be used.
- If the power produced is less than demanded, the necessary power is supplied by the fuel cell. Again, not all the necessary power might be supplied, depending on the size of the fuel cell and the state of charge of the storage system.

The power produced is calculated by the simulation tool using the profile of real wind speed (measured) at the site and the power curve of the wind turbine. The power demanded is calculated using the forecasted wind profile (in this case 24 h in advance) and the power curve of the wind turbine. Forecasted wind profile is obtained using wind forecasting tools. In this case, data provided by the tool CASSANDRA [16] are used.

The sizes of hydrogen technology equipments will be determined by the level of mismatch accuracy between the forecasted and real wind speed values in the wind farm. If the mismatch is greater, the size of the electrolyzer, fuel cell and hydrogen storage system will be larger.

To optimize the absorption of power excess by hydrogen technology is necessary to optimize the electrolyzer size. This will produce a larger economic benefit of the wind farm because wind–hydrogen system will better cover the grid electric demand. The sizing process is accomplished by using a methodology that is applied prior to the complete system simulation. The steps of the methodology are:

(1) Determine the power excess at each time step, calculated according to Eq. (9).

$$P_{exc} = P_{real} - P_{dem} \quad (9)$$

(2) Select a nominal power of electrolyzer ($P_{elec,rated}$) and its operation range. In this case, commercial electrolyzer is considered whose operation range is between 20% and 100% of its nominal power.

(3) Calculate the power absorbed by the electrolyzer (P_{elec}).There might be three possibilities at each time step:
   (a) If $P_{exc} > 0{,}2P_{elec,rated}$, the power absorbed by electrolyzer (P_{elec}) is zero and all power excess is sent to the grid. In this situation, the wind farm will have financial penalties due to the fact that it puts more power into the grid than demanded, which it creates instabilities.
   (b) If $0{,}2P_{elec,rated} < P_{exc} < P_{elec,rated}$, the power absorbed correspond to the total power excess.
   (c) If $P_{exc} > P_{elec,rated}$, the power absorbed is the nominal power of the electrolyzer, and the remaining power excess is sent to the grid (again the wind farm will have financial penalties).

(4) Once all time steps are analyzed, the power absorbed by the electrolyzer is integrated over the year. It is necessary to obtain a curve that yearly relates the electric energy absorbed by electrolyzer with its nominal power.

(5) Steps 3 and 4 are repeated for different sizes of the electrolyzer.

Once the optimal size of the electrolyzer is obtained, the complete simulation of the system is performed.

4. Models validation

4.1. Wind turbine

The model validation is realized with an 850 kW wind turbine.

Table 1
850 kW wind turbine data for 10 operation days.

Day	E_{real} (MJ)	Manufacturer curve		Real curve		Model curve	
		E_{calc} (MJ)	Error (%)	E_{calc} (MJ)	Error (%)	E_{calc} (MJ)	Error (%)
14/02/2007	14769.2	18567.5	25.7	14747.1	0.1	15211.1	3.0
19/02/2007	17211.6	21259.0	23.5	16693.6	3.0	16532.6	3.9
03/03/2007	12484.2	15103.8	21.0	12347.7	1.1	12603.0	1.0
13/04/2007	16039.6	20332.4	26.8	16036.4	0.0	16089.6	0.3
27/06/2007	6429.8	7036.9	9.4	6634.6	3.2	6481.9	0.8
23/07/2007	8261.3	9217.4	11.6	8456.6	2.4	8308.8	0.6
05/10/2007	19502.2	25826.7	32.4	19829.4	1.7	19980.6	2.5
17/11/2007	14829.5	19411.3	30.9	15413.2	3.9	15431.9	4.1
27/11/2007	14257.0	19362.3	35.8	15271.0	7.1	15312.1	7.4
16/12/2007	24280.4	32909.5	35.5	24554.8	1.1	24672.9	1.6

Fig. 3 shows the power curves of wind turbine (manufacturer, real and calculated using the proposed model). The real measured operation data obtained during ten days of operation are presented as well. The real power curve is obtained from the operating data, as explained in the model description (step 1). As observed, there are considerable differences between the manufacturer power curve and the real power curve, whereas the real curve is below of the manufacturer curve for most of the wind speed range. The figure also demonstrates a satisfactory fit between the proposed model power curve and the real curve in this particular location, so that the power difference curve provides a good fit of experimental data.

For the wind turbine considered, parameters of the power difference curve are: $a = 0.22$, $b = 10.78$, $c = 6.60$ and $d = 2.86$ (coefficient of determination is $r^2 = 0.97$)

Table 1 shows summarized data of ten days of wind turbine operation. For each day, the electricity produced by the wind turbine measured in the field, electricity calculated using power curve (manufacturer, real and proposed model). For each power curve, the relative error between measured and calculated data is represented.

As observed, using the manufacturer power curve leads to considerable errors in electrical energy produced by the wind turbine, on average 25%, whereas real curve and proposed model curve lead to lower errors, on average 2.3% and 2.7%, respectively.

So, it is therefore demonstrated that it is important to correct the manufacturer power curve.

Pino [2], performed the same analysis for a 230 kW wind turbine in other location, where similar errors were obtained for the manufacturer power curve.

4.2. Electrolyzer

The electrolyzer model is validated using operation data of a 25 kW alkaline electrolyzer, whose principal characteristics are shown in Table 2.

From the measured operation data of voltage and current, following steps described in Ref. [2], parameters r, s and t (and their dependence with temperature) of the cell current–voltage curve (Eq. (4)) are calculated. Table 3 shows the value of these parameters.

Table 2
25 kW electrolyzer technical information.

Manufacturer	CASSALE CHEMICALS
Rated power	25 kW
Operation range	20–100%
Voltage operation range	0–110 V (DC)
Intensity operation range	0–275 A
Rated pressure	20 bar
Rated H_2 production (at 80 °C)	5 $Nm^3 h^{-1}$ (0.45 $kg h^{-1}$)
Electrolyte	KOH 30%
Rated operation temperature	80 °C
Cells numbers	48
Active cell area	0.06 m^2

Table 3
Electrolyzer mathematical model parameters.

Parameter	Value
r_0	$1.127 \cdot 10^{-4}$ V A^{-1} m^{-2}
r_1	$-1.269 \cdot 10^{-6}$ V A^{-1} °C^{-1} m^{-2}
s	0.2982 V
t_0	0.173 A^{-1} m^{-2}
t_1	$4.24 \cdot 10^{-3}$ A^{-1} °C^{-1} m^{-2}
t_2	$-3.6 \cdot 10^{-5}$ A^{-1} °C^{-2} m^{-2}
f_1	20000 A^2 m^{-4}
f_2	0.93
C_T	320 kJ kg^{-1}

Fig. 5 shows the real cell operation points at temperatures between 30 and 80 °C, and characteristic curves for each temperature obtained with the proposed model. As observed, experimental data and curves obtained with model fit satisfactorily.

Heat capacity ($C_T = 320$ kJ °C^{-1}) is obtained by analyzing the heating process of the electrolyzer using temperature measured in experiments. Overall heat losses coefficient is calculated from the geometry of the main electrolyzer components (stack and gas separators).

In order to validate the model, simulation results are compared with data from an experiment where the electrolyzer operates at variable load along time. Fig. 6 shows the variation of the intensity, voltage, power and operation temperature measured.

Using the measured current, the model calculates the electrolyzer voltage, power and operation temperature (also represented in Fig. 6). It is observed that the fitting between experimental data and simulation results is appropriate with a relative error between parameters below 2%.

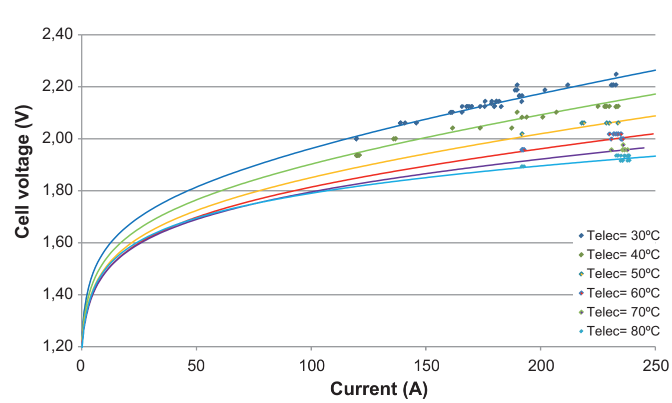

Fig. 5. Characteristic electrolyzer cell current–voltage curve considering different operating temperatures.

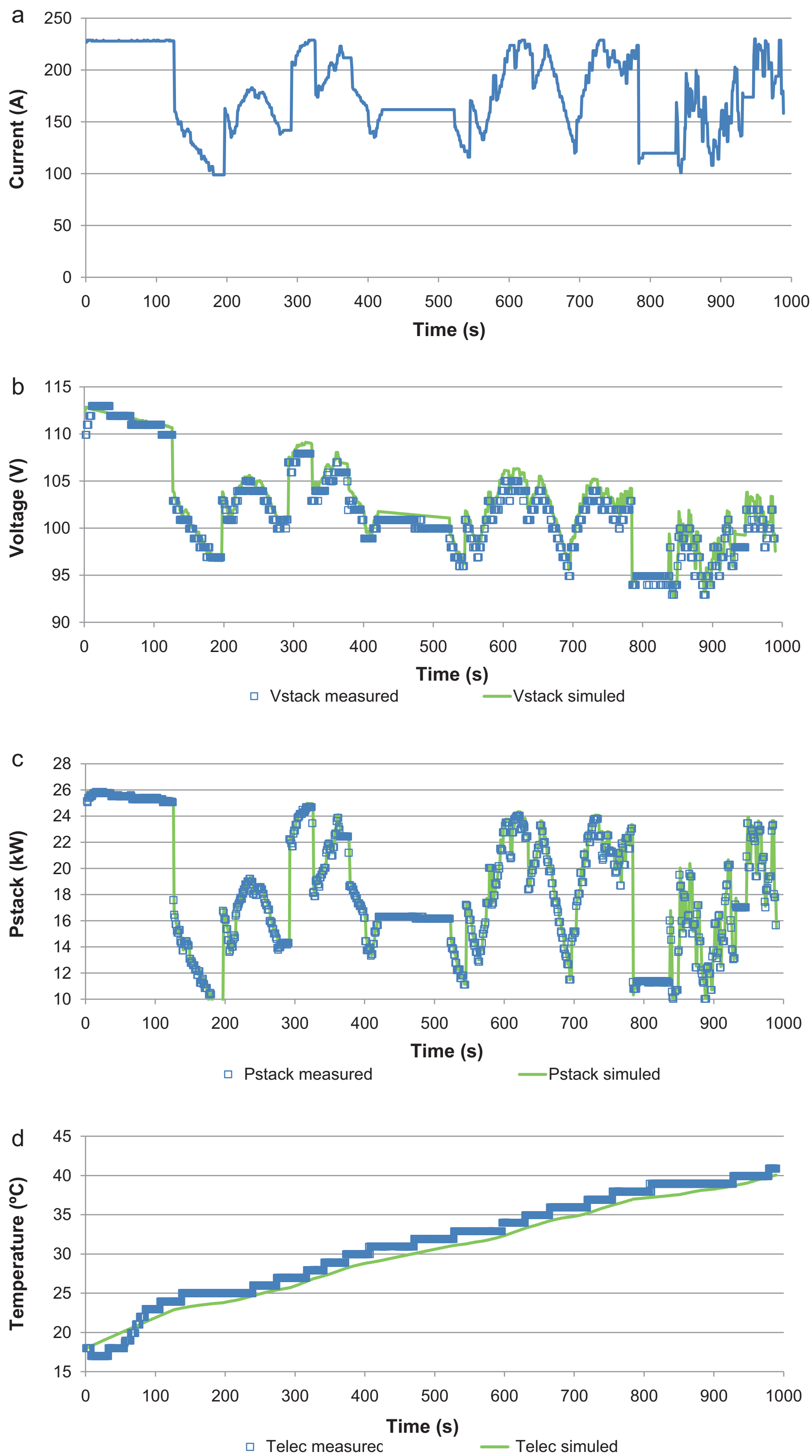

Fig. 6. Electrolyzer model validation (a) current, (b) voltage, (c) power consumed by stack, (d) operating temperature.

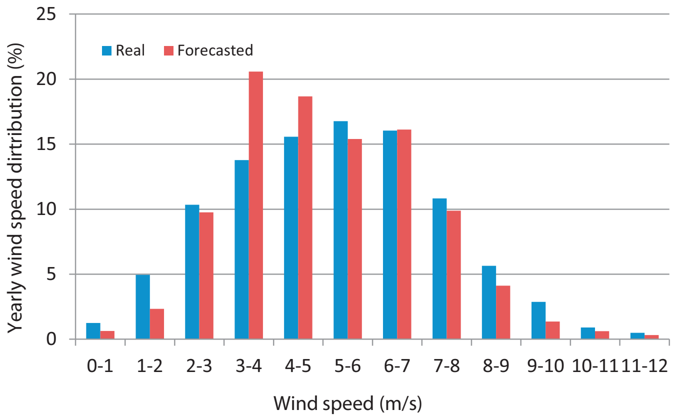

Fig. 7. Real and forecasted wind speed distribution.

Pino [13] compares the results of the model to other operation curves of electrolyzer also obtaining low errors between simulation results and operation data.

5. Simulation results

This section is divided into the following sub-sections:

- First, definition of input data for the system simulation and simulation scenarios.
- Next, the optimal electrolyzer size is determined.
- Finally, full system simulation results are shown.

5.1. Input data

In order to simulate the system, real and forecasted wind speed profile for a year in time intervals of 10 min is known. Fig. 7 shows the wind speed distribution, real and forecasted, indicating the percentage of total time for each speed range. It is observed that for each wind speed interval there are differences between both wind speeds, although the qualitative form of both distributions is similar. This means that there are differences between electricity produced and demanded, which in turn motivates the presence of an energy storage system.

The simulation is performed considering one 850 kW wind turbine, whose power curves are shown in Fig. 3. The real curve and proposed model curve were obtained from wind turbine operating data on the location where the wind–hydrogen system is analyzed.

The electrolyzer cell current–voltage characteristic curve is known. In the simulation current–voltage curve obtained in the model validation is used (Section 4.2). The electrolyzer size is optimized in the next section. The system simulation is dynamic, so the influence of electrolyzer operating temperature in hydrogen production is taken into account.

The performance of the AC/DC converter (which connects electrolyzer to wind turbine) is assumed constant and equal to 0.9.

The hydrogen storage system is assumed infinite for not limiting the hydrogen production of the electrolyzer.

The system simulation time step is 10 min, as this is the interval of wind speed information available.

Three simulation scenarios are defined, and they are based on the level of information that it could be available:

- In scenario 1, wind turbine operation data are available, so for system simulation, real power curve is used.
- In scenario 2, there is no real operation information of the wind turbine on the site, so the wind turbine is simulated in this scenario with manufacturer power curve.
- In scenario 3, no operation data are available for the wind turbine operating at the site, but the power difference curve is known. In this scenario, the model power curve obtained from Eq. (3) is used.

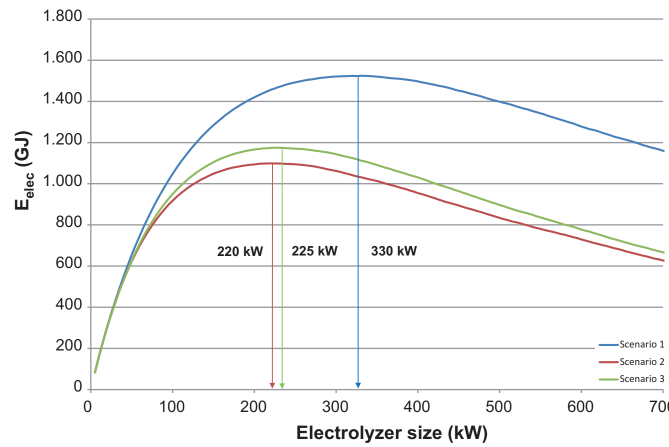

Fig. 8. Absorbed electric energy as a function of electrolyzer size in the three scenarios simulated.

5.2. Optimal electrolyzer size

Using wind data, the methodology described in Section 3 to determine the optimal electrolyzer size of the electrolyzer is applied for each scenario defined before.

Fig. 8 shows the variation of the electrical energy absorbed by the electrolyzer based on its nominal power in the three scenarios. As shown, the curves present a maximum, which corresponds to the optimal size of the equipment (which allows it to absorb the maximum excess of energy). It can be observed that the optimum power varies depending on scenario. Optimal size is 220 kW, 330 kW and 225 kW for scenario 1, 2 and 3, respectively.

5.3. Complete system simulation results

To analyze only the influence of the wind turbine power curve in the hydrogen production of the system, it is considered a fixed electrolyzer size of 220 kW (optimal size of scenario 1, which is the nearest to the wind–hydrogen real system behaviour).

A 220 kW alkaline electrolyzer are composed by 423 electrolytic cells with the same properties and geometry as the electrolyzer described in Section 4.2. Geometry, thermal capacity and heat transfer area increase proportionally to cells number. In this case, heat capacity is 2816 kJ $^{\circ}C^{-1}$.

Annual simulation results for the three scenarios are shown in Table 4. The values represented are real electricity produced by the wind turbine, demanded electricity to the wind–hydrogen system, electricity excess, electrical energy absorbed by the electrolyzer and consumed by its stack, and hydrogen production. All of them are summarized annual values.

Table 4
Annual simulation results.

	Scenario 1	Scenario 2	Scenario 3
E_{real} (MJ)	3948684	4739436	3808161
E_{dem} (MJ)	3409580	3977496	3242786
E_{exc} (MJ)	1386876	1890265	1438470
E_{elec} (MJ)	1127884	1513180	1203258
E_{stack} (MJ)	1015096	1361862	1082932
H_2 production (kg)	5046.3	6742.8	5385.3

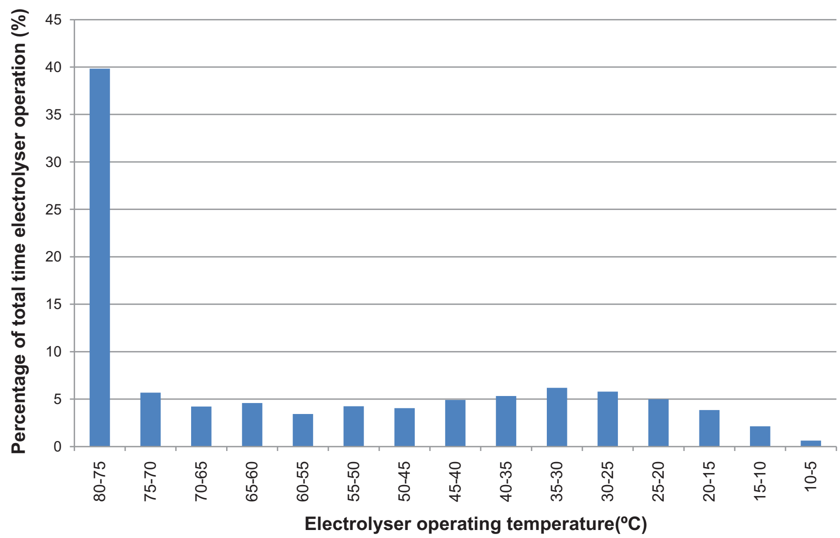

Fig. 9. Electrolyzer operating temperature distribution.

Annual hydrogen production for scenarios 1, 2 and 3 is respectively: 5046.3 kg, 6742.8 kg and 5385.3 kg.

6. Discussions

6.1. Optimal electrolyzer size

For the input data considered, the optimal electrolyzer size is a function of wind resource, and it depends on the wind turbine power curve. Considering the manufacturer power curve (scenario 2), it leads to significant error. The size obtained, 330 kW, is 50% higher than obtained simulating the wind turbine with real power curve on the location (scenario 1, closer to real behaviour).

Current simulation tools use manufacturer power curve, so all commit errors when calculate optimal electrolyzer size from a energy standpoint. This wrong size leads to a higher equipment cost and affects to hydrogen storage system (hydrogen production will be less in reality).

Moreover, as observed in Fig. 8, 330 kW electrolyzer operating in reality (scenario 1) would absorb less energy than the smaller optimal electrolyzer in this scenario (220 kW), because the minimum operation threshold in 330 kW electrolyzer (66 kW) is larger than 220 kW (44 kW). The consequence is that the power excess will be below than the minimum threshold in many time steps during year simulation.

New electrolyzer developments are necessary in order to reduce the minimum operation threshold. With this improvement, electrolyzers will operate more hours when connected to renewable energy sources like wind energy.

Using the proposed wind turbine model, the optimal electrolyzer size obtained is 225 kW, 2% above optimal in reality. So the benefits of applying the difference power curve to manufacturer curve in the wind turbine model are demonstrated.

6.2. Hydrogen production

Hydrogen production is influenced by the wind turbine power curve selected when performing simulations of the wind–hydrogen system. As presented in Table 4, simulating the system with the manufacturer power curve (scenario 2) leads to an overproduction of hydrogen, for this case 33,6% when compared to the real production (scenario 1). Hydrogen overproduction is associated with a greater electric excess throughout year simulated.

These results show again that current simulation tools lead to significant errors when hydrogen production is calculated, due to the use of manufacturer power curve. Hydrogen overproduction affects the calculation of economic benefits of the wind farm when it includes an energy storage system, because the sales of electricity from the hydrogen produced will be lower.

With the proposed wind turbine model (scenario 3) results of hydrogen production are closer to reality. The overproduction is 6%.

In order to analyze the influence of the electrolyzer operating temperature in hydrogen production, the three scenarios are simulated again, imposing in the electrolyzer model an operating temperature constant and equal to nominal (80° C). The hydrogen production obtained from the system simulation are:

- Scenario 1: 5197 kg.
- Scenario 2: 6907 kg.
- Scenario 3: 5542 kg

Comparing these results with the ones obtained from the dynamic simulation of the scenarios (Section 5.3), hydrogen overproduction is close to 3% on average.

As the electrolyzer temperature increases, hydrogen production increases (keeping constant other operating conditions), so this result indicates that considering a dynamic system simulation of the electrolyzer, the average operating temperature is close to the nominal temperature. Fig. 9 shows the distribution of electrolyzer operating temperature, indicating percentages of the total electrolyzer operating hours for each temperature interval in scenario 1. As observed, during 40% of the operation time, the electrolyzer is working at a temperature between 75 and 80 °C (closer to nominal).

So for the input data considered, the hydrogen production is less influenced by the electrolyzer operating temperature than by the wind turbine power curve.

7. Conclusions

In the present study, the influence of wind turbine power curve and electrolyzer operating temperature in the hydrogen production has been analyzed, when the wind–hydrogen system is operating in wind-balance mode. To perform the analysis two mathematical models of the equipment have been developed: a wind turbine "black box" model, that can approximate manufacturer power curve to the wind turbine real behaviour in a specific site, and a dynamic electrolyzer model. Also, a methodology to determine the optimal electrolyzer size has been proposed. Most relevant conclusions of the study are:

- The manufacturer power curve does not fit well with real the behaviour of the equipment in a particular site, overestimating electricity production. By using a power difference curve (proposed) the electrical production calculated is close to measured values.
- The manufacturer power curve is used in current simulation tools for analyzing and sizing hybrid systems based on renewable energy sources and storage systems, so that results offered by these tools are presenting large errors. For the input data considered, errors between electricity calculated with respect to measured values are in average 25%.
- Optimal electrolyzer size is influenced by wind turbine power curve in wind–hydrogen systems. The manufacturer power curve overestimates the optimum electrolyzer size, in comparison with the size obtained with the real curve of the wind turbine in location. This overestimation increases the system costs.
- The manufacturer curve also has an influence in the annual hydrogen production. Considering input data, it overestimates hydrogen production in 33% when it is compared with the hydrogen production of the system considering real wind turbine power curve in the location.
- The wind turbine model developed uses a power difference curve that can be included in any simulation tool. It will allow obtaining optimum electrolyzer size and hydrogen production closer to reality, in wind–hydrogen systems.
- Electrolyzer operating temperature has a lower influence in hydrogen production. The differences obtained from a static and dynamic simulation of the electrolyzer is 3%.
- Technically, the development of electrolyzers with a lower minimum operation threshold is necessary, as it will allow greater power absorption when the electrolyzer is connected to renewable energy sources.

The wind turbine power difference curve is useful, because in most cases the wind turbine is not implemented in the location when the system is analyzed, so a real power curve cannot be obtained. Current work is focused on giving a physical meaning to parameters *a*, *b*, *c* and *d* of the power difference curve, in order to establish a relationship between parameters and type of wind turbine, location and operating conditions, so that the difference curve can be applied in any situation.

Acknowledgements

This work has been carried out with the financing of Andalusia Energy Agency (Spain) and the provision of operating data fromx the Canarias Technologic Institute (ITC) of Spain and the National Renewable Energy Centre (CRES) of Greece.

References

[1] REE, El sistema eléctrico español 2009, REE, Madrid, 2010.
[2] F.J. Pino, Analysis of Hydrogen Production in Integrated Wind–Hydrogen Systems. Contributions to Dynamic System Modelling PhD, University of Seville, Seville, 2010.
[3] http://homerenergy.com/.
[4] http://www.unizar.es/rdufo/hoga.htm.
[5] M. Aguado, E. Ayerbe, C. Azcárate, R. Blanco, R. Garde, F. Mallo, M. Rivas, International Journal of Hydrogen Energy 34 (2009) 2845–2854.
[6] http://www.tyndall.ac.uk/content/hydrogen-energy-economy-its-long-term-role-greenhouse-gas-reduction.
[7] G. Kravacic, N. Duic, M. Graça, International Journal of Hydrogen Energy 34 (2009) 7015–7026.
[8] O. Ulleberg, T. Nakken, A. Eté, International Journal of Hydrogen Energy 35 (2010) 1841–1852.
[9] M.C. Arco, F.J. Pino, M. Martín, F. Rosa, Herramienta de simulación de sistemas basados en energías renovables, I Congreso Nacional de Pilas de Combustible (2004), San Sebastián (Spain), pp. 72–73.
[10] J. Sánchez, C. Veganzones, S. Martínez, F. Blázquez, N. Herrero, J. Wilhelmi, Renewable Energy (2009) 1186–1198.
[11] M. Martins, A. Perdana, P. Ledesma, E. Agneholm, O. Carlson, Renewable Energy 32 (2007) 1301–1316.
[12] O. Ulleberg, International Journal of Hydrogen Energy (2003) 21–33.
[13] F.J. Pino, F. Rosa, J.R. López, L. Valverde, A. Iranzo, Respuesta de un electrolizador alcalino a diferentes ciclos de operación. Comparación de datos experimentales con un modelo matemático dinámico, IV Congreso Nacional De Pilas De Combustible (2010), Sevilla (Spain), pp. 369–372.
[14] F.P. Incropera, D.P. DeWitt, Fundamentals of Heat and Mass Transfer, Prentice Hall, Mexico, 1996.
[15] P. Diéguez, A. Ursúa, P. Sanchis, C. Sopena, E. Guelbenzu, L. Gandía, International Journal of Hydrogen Energy 33 (2008) 7338–7354.
[16] C. Gallardo, M. Gaertner, C. Tejada, N. Martínez, S. Calabria, N. Martínez, The Casandra Project: First Results of a New Wind Power Operating Forecasting System in Spain, Proceedings of European wind energy conference, Madrid, 2003.