INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 35 (2010) 7329–7336

Available at www.sciencedirect.com

ScienceDirect

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

Management of variable electricity loads in wind – Hydrogen systems: The case of a Spanish wind farm

F. Gutiérrez-Martín, D. Confente, I. Guerra*

EUITI, Universidad Politécnica de Madrid, Rda.Valencia 3, 28012 Madrid, Spain

ARTICLE INFO

Article history:
Received 6 November 2009
Received in revised form
30 April 2010
Accepted 30 April 2010
Available online 3 June 2010

Keywords:
Hydrogen production
Wind energy
Electrolysis
Surplus electricity
Energy management

ABSTRACT

The main obstacles of most renewable energies are their variability and availability; thus, we propose the 'hydrogen option' as a means of energy management, and we study its feasibility in a specific wind farm. The installation will be capable to store electrochemically the surplus energy and return the electricity to the grid during the peak hours. The solution was to connect the system, so that we store the energy as hydrogen when the wind generation exceeds a threshold; this is done by an electrolyzer set, with the appropriate nominal power, where, besides the electrical conversion devices, we have designed a control programme for tuning the voltage and current densities to the optimal operation of the cells. To utilize the hydrogen downstream the storage subsystem, we have selected a fuel-cell and the output is finally converted to the grid requirements.

The nominal power of the wind farm studied is 48.8 MW, and it generates 18.4% of surplus electricity which cannot be evacuated through the node during the off-peak hours; this is converted into nearly 13 GWh of hydrogen per year, which can be used to produce peak electricity (raising the power of the hybrid system to 12.3%). Thus, it presents many advantages, which could facilitate the penetration of the wind resource, leading to a cleaner energy production and moving one step forward to the 'hydrogen economy'.

1. Introduction

Hydrogen has attractive features for energy integration, primarily on account of its multi-functionality: it acts as a storable 'energy carrier' that can be either converted back into electricity – providing a balancing service to power generators and suppliers – or can be used as a 'zero emission' fuel for other applications, such as transport [1–3].

When wind power is added to an electrical grid it increases the system variability due to the wind fluctuations and results in a need for additional peak-load generators. In areas with growing wind penetration the intermittency of the source imposes additional requirements on the operation and management of the systems, the availability of reserve capacity, and costly network reinforcements. Moreover, sometimes wind generation exceeds the demand of electricity or the limit that the grid can absorb and then the wind farms have to be disconnected.

To absorb the excess power, sufficient balancing capabilities must be available. These can be acquired by different initiatives, like strengthening of transmission capacities, utilization of price demand elasticity and smart appliances in households, usage of electricity for vehicle battery charging or hydrogen production, etc. However, if energy storage is introduced in the system, power facilities can provide most of the peak requirements avoiding the need to build large generators and other limitations. The energy storage system could keep wind power excess so that the energy returns into the grid during low generation periods. In this way, the plant load factors would increase in relation to the power limit and its management would be similar to that of conventional generation plants.

* *Corresponding author*. Tel.: +34 913366887; fax: +34 913366836.
E-mail address: fernando.gutierrez@upm.es (F. Gutiérrez-Martín).
0360-3199/$ – see front matter
doi:10.1016/j.ijhydene.2010.04.181

For bulk storage of momentarily surplus grid electricity there are only a few methods of 'parking' the energy until it is needed. These have been reviewed extensively, including the strategies and limitations for storage in supply-demand matching on grids whose input power is provided by intermittent resources. In particular, the feasibility of joining hydrogen and renewables to ensure the energy supply in different systems has been studied by many authors, as well as the utilization of wind energy to generate hydrogen in parallel with the possibilities to use the hydrogen to enhance wind power competitiveness. The key idea is to convert hydrogen into electricity when the renewable energy is off (e.g., no wind); to have this fuel during high potential periods, the extra energy is converted by electrolysis leading to an important research work in the optimization and control of these installations, i.e., the renewable energy sources (RES), electrolyzers, hydrogen storage and fuel-cells [4–11].

In such systems, hydrogen production by grid connected electrolysis can be optimized by operating the electrolyzers part time (i.e., peak-shaving mode), while the above mentioned studies can be classified basically in two categories: models based upon their applicability for simulation purposes (input phenomena and components), and 'specific cases', conditioned by the location sceneries, seasonal variations and other aspects, which greatly affect the energy utilization analysis. It can be concluded that significant efforts have been made to study the major individual components of renewable hydrogen generation and utilization systems, including simulation and experimental research, though further efforts are needed to reduce generally the empirical nature of models and design methodologies need to explore the details of each specific overall system.

Thus, this paper deals with a selected 'wind case' in Spain, where the productivity of this technology accounts for more than 10% of its power consumption; although in occasional periods it exceeds the electricity demand in some areas, and there are times of energy curtailments when windmills are shutdown in order not to overload the power network. The study considers the problem of feasibility of a wind-hydrogen conversion and regeneration system to optimize the production of electrical energy by increasing the storage capacity: this process involves water electrolysis and compression of H_2 in a tank of finite capacity, and it includes adjusting the generation and demand curves and storing the energy when the production exceeds the power limit at the point of common-coupling (node); the last transformation process, involving fuel-cells, turns hydrogen into energy ready to be sold and distributed.

Seen in this perspective, emphases are not only to improve performance of existing technologies, but also to integrate them effectively with RES, whereas practically no real studies focus on the evacuation problems in the nodes or the variability of the wind phenomena in the macro-meteorological range, which affects the power management strategies and the design of the systems with finite storage capacities.

Finally, we analyze the wind-H_2 facility to determine its economical viability, where the increase of power density and energy efficiency at a competitive cost is a great challenge for the industrial implementation of these devices. This can be achieved through the research of new materials and components for the stack (as in other studies), but also by the optimization of the design and control of the whole system – the main objective in this case. Since the technology, manufacturing, and marketing of a great deal of the system components are still in early stages of development, the costs data are more uncertain, but this topic is addressed with price estimates as pointed out below. Additionally, the wind based hydrogen production system can offer some services to the grid to improve the quality of electricity supply and reduce the peak to average load ratios, as far as the new regulations for renewable energies make explicit references to predictability, stability and efficiency to guarantee the 'sustainability of energy systems' (i.e., equilibrium between manageable/variable generation and tariff gaps) [12].

2. Wind power penetration and energy storage

Since 2009, wind power in Spain (with near 17 000 MW) occupies a third place in their electricity generating systems – after combined cycle and hydropower installations – with a projection of 40 000 MW in 2020, which can greatly contribute to the 20% renewable target of the European Union for that year [13].

Focusing on the demand side, wind energy nearly covered 12% of the Spanish electricity consumption in 2008, which was above the large hydro production of the whole country; wind generation reached more than 27 000 GWh, covering more than 20% of the electricity demand for several consecutive days, with momentary supplies of 43%. This growing penetration level of wind energy is a remarkably strategic and environmental advantage for the country, but poses its electrical system in the forefront of novel and fascinating challenges [14].

Like many other renewable sources wind energy is intrinsically variable, and this represents a problem for electric load management as its contribution to the power mix increases. Daily average curves for wind production and energy demand do not typically follow the same patterns and wind peaks usually arise during night hours when electricity consumption is lower: e.g., during a real situation which arose on 2nd November 2008, the electric operator in Spain gave the order to stop more than 37% of wind production at this point to maintain the grid stability (Fig. 1). All this suggests that we need solutions to make the intermittent wind energy in a more manageable resource, which at the same time can overcome the technical limits to its deployment.

Pump hydro storage has been used to manage the surplus energy in these periods, but its yield is not very high and it is limited by hydrographic configurations; actually, there are plans to increase its capacity to 4000 MW in Spain [15], but it is difficult to go much further. Another form of energy coupling is to increase the demand during off-peak periods by means of price incentives to the consumers or new battery vehicles which are charged at night when electricity is cheaper.

Other storage means could be applied, like batteries, ultra capacitors, inertia, etc., but a more promising system seems to be hydrogen which can be used again for peak power generation, new vehicle fuels or other applications. There is such an

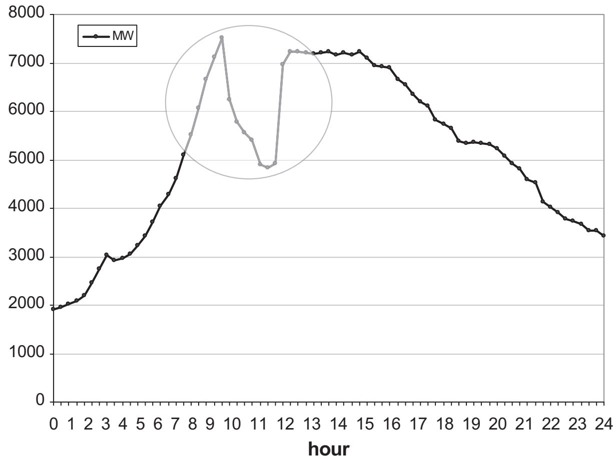

Fig. 1 – Restrictions for energy evacuation in Spain (as showed by the wind generation curve of 2/11/2008).

interest to exploit wind-hydrogen synergies, that the International Energy Agency (IEA) recently approved a Spanish proposal on hydrogen called Wind Energy and System Integration (Task 24) [16]. Today there are already some examples of such integrations, e.g., the first project to produce hydrogen in a Spanish wind site, built in Galicia (Sotavento), the wind-hydrogen demonstration system for remote areas launched in Norway (Utsira), while a hybrid industrial plant which combines wind, hydrogen and biogas is scheduled to start in Germany in 2010 (Uckermark).

Hydrogen is the most abundant element of the universe, though it is forming only practically compounds like water or hydrocarbons in our planet, meaning that it must be separated and stored (both requiring energy and technology). It can be produced basically by water reduction with carbon or electrolysis, with the advantage in the last case that if electricity is generated from renewables, hydrogen constitutes an energy carrier with nearly zero emissions [17]. The electrolysis process consists of the oxy-reduction of water molecules, promoted by a direct electric current (DC), that permits to obtain hydrogen with high purity: the voltage to be applied is the sum of the reversible potential, the polarization at the electrodes and the ohmic losses in the cell (which are proportional to the current density); thus, a greater intensity in the electrolyzer increases productivity, but at the same time the voltage becomes higher and this reduces process efficiency (leading to a delicate trade-off analysis to reach the optimal performance) [18]; a detailed discussion of such strategies in electrolyzer operations for managing surplus electricity loads can be found in our previous paper in this journal [19]. Finally, hydrogen can be used to produce energy in motors or gas turbines, but the best alternative is to use it directly in fuel-cells due to their higher expected efficiencies (min. 60%) [20].

3. Analysis of wind generation

As we have argued in the previous section, if wind power penetration becomes high in the Spanish electrical grid, then energy management will be necessary for some wind farms to adjust the generation curve to the demand curve. To analyze the feasibility of wind-hydrogen integration in a specific case study, we performed a statistical analysis of one year electricity generation in a Spanish wind farm, placed in the northwest region and named Park A to preserve the property's identity. The nominal power of this park is 48.8 MW and the total energy produced was 116.8 GWh/year (equivalent to 2390 h), but we used the hourly production data to calculate the "average day" which constitutes a first approach to the park generation patterns. As expected, the data show a great dispersion from average values, both hourly and seasonal, with a range between near zero and 28 MWh/h and higher production in autumn or spring. This analysis was carried out with the cooperation of the Spain's wind association (AEE) [21].

These data are considered as area representative of the wind resources in the zone, and thus, properly scaled, they were compared during off-peak hours (22.00–12.00 h in winter and their equivalent hours in summertime) with the evacuation limits in the electrical node (with a total connected wind power of 560 MW). The scale factor is 11.5, and for the statistical analysis of the hourly production data, these values were grouped and normalized in intervals of 0–560 MWh, whose frequency distribution and annual cumulative probabilities are shown in Fig. 2.

To verify the surplus generation of electricity during off-peak hours we must quantify this energy along the year and evaluate the node tolerances against wind production. Additionally, the operation of the system means that one cannot supply the power demand with wind solely, but we need an electrical mix composed of other generating plants to guarantee the stability of the grid. Thus, all the energy sources are faced to a reduction of their contributions to the demand, specially during off-peak periods, and this represents an evacuation limit of 200 MW for the wind farms connected to the node (according with the restrictions fixed by the Spanish grid operator – REE – in this location).

This is why, to evaluate when and how much this limit is exceeded by the wind supply in our case, we calculated the cumulative probabilities as shown in Fig. 2, which determine the occurrence of all the values below the indicated one: P (production) $\leq P_0$ (200 000 kW); one can see that this probability is 64%, i.e., 36% of the time windmills are generating on average more energy than the node could evacuate during

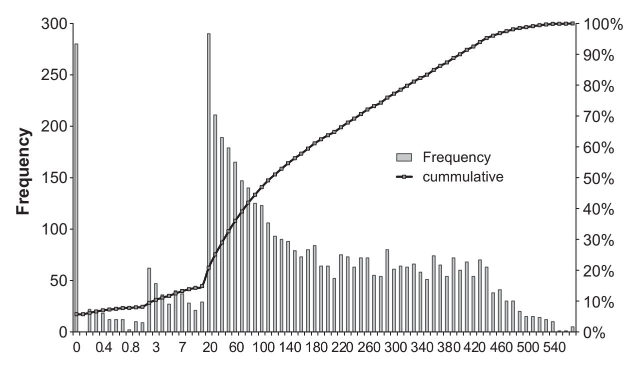

Fig. 2 – Histogram and cumulative probability of electricity production in the node during off-peak hours.

off-peak hours, and one could foresee the magnitude of this problem in the future, as well as for the whole electricity system of the country, as penetration of wind an other variable energy sources grow.

Clearly, we can reuse these surplus electricity loads – which otherwise will be wasted – in the form of hydrogen to reach a more efficient management of the wind resource. To estimate the amount of excess energy in the year, we subtract the evacuation capacity of the node during off-peak hours (i.e., 200 000 kWh) to the values of such energy range, and in this way we obtain a cumulative overproduction of 247.6 GWh/year; this is equivalent to 18.4% of the wind power produced along the year and can be translated to an economical value of 18.7 M€ at the regulated prices for wind electricity (7.5681 cent/kWh in 2008).

It can also be noticed that the surplus energy is much better distributed around specific values than the global wind production; now, the most usual figure of the excess electricity is 90 000 kWh, but a wide range of values between 20 000 and 230 000 kWh – which cannot be easily dumped to the grid – appear with nearly the same frequencies.

A partial solution to this problem could be to build new electricity lines for transporting the surplus energy to other consumption centers, located at longer distances from the production point. But these grid reinforcements are usually costly, require time and cause some energy losses and impacts; contrarily, in-situ devices which are capable to store the excess power, not only permit to increase the resource use but also facilitate the management of the system, as the stored energy can be supplied again to the grid and this can greatly improve the reliability of wind generation.

4. Wind-hydrogen system

The configuration of these systems to store and reuse the electrical energy in the form of hydrogen consist basically in a set of electrolyzers, pressurized deposits and conversion devices (like fuel-cells), all of which are interdependent.

4.1. *Water electrolysis*

The main difficulty for designing this component comes from the great variability of the excess energy throughout the year (Fig. 3). The relationship between the energy input and the hydrogen output is a nonlinear function (efficiency) which depends on the transformation device (electrolyzer); then, what is sought are equipments which are capable to convert the maximum available energy and to work most of the time with the highest efficiency.

From the power overproduction data discussed in the previous section, if we limit the electrolyzers size to 250 MW, we found values in excess to this capacity during only 11% of the surplus periods; this represents 194 h of the 1771 off-peak hours with excess electricity per year (or 22.3% of the energy), but with a limiter of the power input to the equipment we make only not use of: $247\,600 \times 0.223 - 250 \times 194 = 6700$ MWh (i.e., 2.7% of annual surplus energy).

Obviously there are not units of this size, but one could think in technical arrangements in parallel which have the additional advantages of admitting a wider range of input energy values and a more flexible operation by means of a controller which incorporate them depending on the available energy. It has been seen in all demonstrations that the intermittent renewable energy and the electrolyzer dynamic behavior are closely correlated, and this responds rapidly to the varying electricity yields from wind converters [22].

4.2. *Hydrogen storage*

To approach the design of this component we took into account the characteristics of the wind phenomena in the macro-meteorological range, which can show aleatory peaks in typical time intervals of 12 h, 4 days or even monthly (see the left side of Fig. 4).

From this analysis, it follows that if we are running across a semi-diurnal overproduction peak during the night hours, we could easily evacuate the stored energy during the next peak demand period; but with a four days peak we cannot probably

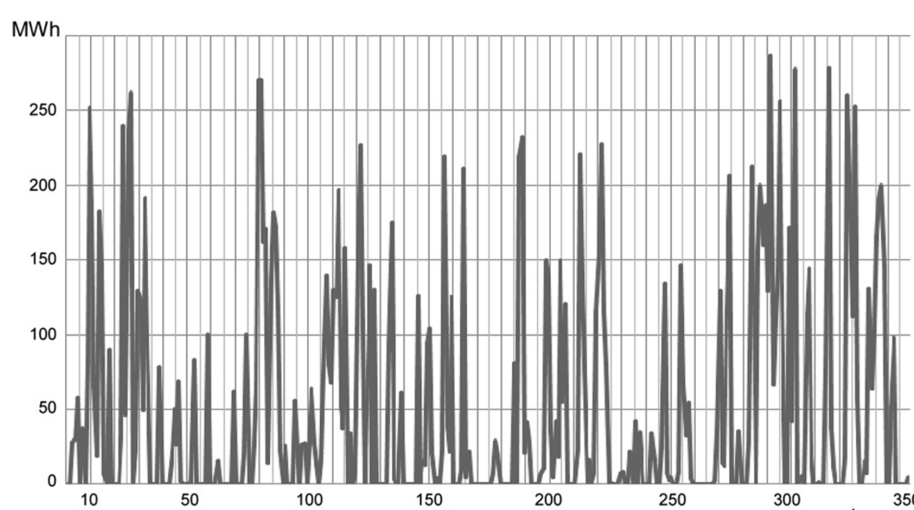

Fig. 3 – Daily average surplus of energy in the node during the off-peak periods of electricity demand.

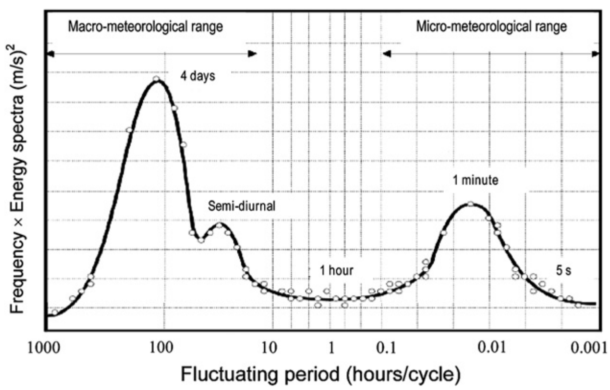

Fig. 4 – Typical spectra of wind fluctuations in all ranges.

consume the surplus electricity – stored as hydrogen – during the next daytimes of excess wind generation. A mathematical description of this problem is depicted by:

$$E_p + E_v \times \eta < U \quad (1)$$

where, E_p: electricity produced during peak hours, E_v: excess electricity during off-peak hours, η: global efficiency of the energy conversion system, U: evacuation limit in the node during peak hours.

Thus, if the above condition is not satisfied we need to increase the storage capacities for a better utilization of the surplus electricity: e.g., if we size the deposit to fit the daily average excess energy multiplied by typical electrolyzer efficiencies (21 900 kg of hydrogen), we will have 30 days where it is not possible to return to the grid the energy in excess from the night before and the system is not capable to utilize the one of the following day (this amount in our case 15 700 MWh or 1.19 M€ at the regulated prices); but this scenery changes if we store the energy corresponding to the average production of two days, because the thirty critical days are minimized when doubling the size of the deposit, as we have more reserves to distribute the surplus energy in a greater number of days and this matches better with the production planning.

4.3. *Fuel-cells*

All the above elements need to be combined with hydrogen-to-electricity devices, i.e., capable to convert the stored energy, which could limit the performance of the whole system if they are not properly sized; its nominal power is a key point of the installation because it determines the capacity to supply regenerated energy to the grid, at the same time that its economy is one of the most sensible items of the project (around 700 €/kW).

We have focused in fuel-cells instead of conventional motors by the great difference of efficiencies (70% vs. 30%), though the former constitute a new technology, with short learning curves and where the priority is to reduce costs.

5. Description of the installation

As shown in Fig. 5 the installation connects with the medium voltage (MT) output of the park – in parallel with the medium/high voltage (MT/AT) transformer to the grid – by means of a converter in series which receives a three-phase input from the aerogenerators (AG) at a lower voltage (BT 400 V) and turns it into DC for the electrolysis. After this converter, there is an electronic controller for tuning voltages and current densities to the electrolyzers.

In approaching an optimal size for the equivalent electrolyzer, there is always a cost-benefit balance which depends on variables like prices of electricity, times of operation and the power of installations (as shown in other papers); but in this case the total power of electrolyzers can be scaled to a limit value of 21.3 MW (for the park A), which has the potential to convert more than 97% of the surplus energy in the node (this is discussed in Section 7). Then, we have chosen to connect 10 units in parallel (2.13 MW), which were the biggest and the best performance atmospheric models found in the market, and for this reason the controller must be able to manage the starting of the electrolyzer lines according with the energy available in each moment and always at the maximal efficiency.

Each electrolyzer consists of 230 cells (0.60 m^2) and operates with 5.15 kA at the maximum power, so that the current density is 8.6 kA/m^2 and the potential between electrodes 1.8 V, with a hydrogen production efficiency of 62% [23]. It is necessary to provide water for electrolysis by means of a tank of enough capacity (i.e., about 1 L per $Nm^3_{H_2}$), though we can reuse a great part of it from the fuel-cell. Downstream of the electrolyzers we need a compressor for increasing the exit pressure to 135 atm, and storing two average days of hydrogen (3800 kg) in a spherical deposit of 9.55 m diameter (340 m^3).

The last important element of the set is the hydrogen fuel-cell, the size of which could be established by multiplying the nominal power and the efficiency of the electrolyzers – as this is the maximum hourly energy available in the form of hydrogen – and finally by the output efficiency of the fuel-cell (i.e., approx. $21.3 \times 0.62 \times 0.70 = 9.2$ MW); but this leads to oversize the cell, as this flow is only available at the maximum electrolyzer capacity and we never produce the hydrogen at the same time as we return it into electricity.

Thus, if we consider the problem globally, it results more relevant to build an adequate deposit than a hydrogen-cell of the maximum power, provided that it do not create a bottleneck for the rest of the installation, as well as the costs impel to look for the minimum sizes of this equipment; after evaluating all these criteria, we have selected a fuel-cell of 6 MW,

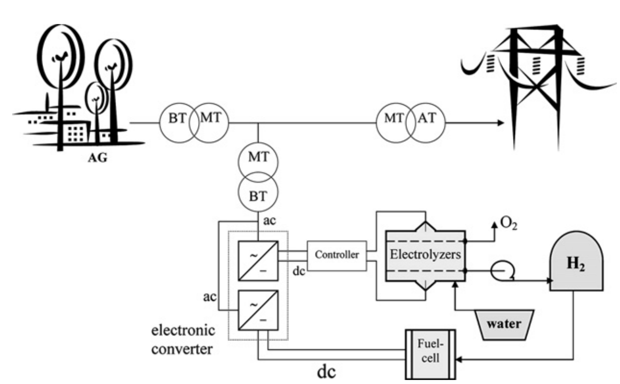

Fig. 5 – Scheme of the installation of aerogenerators connected to the hydrogen storage and conversion system.

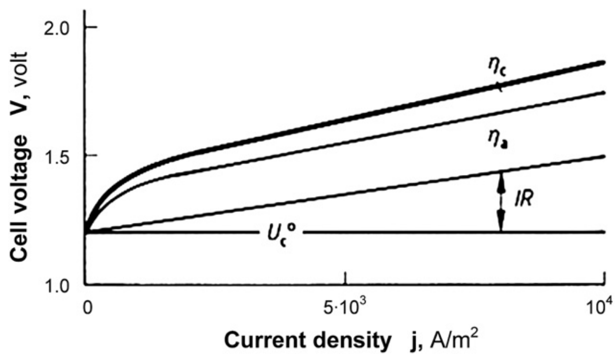

Fig. 6 – Current–voltage curves for advanced alkaline electrolysis.

which still permit to supply a considerable peak energy and to face eventual turnings of production away; the hydrogen power system can also offer other services to the grid (like stable active and reactive supplies, voltage and frequency regulation, etc.) becoming an active wind energy conversion system [24].

Finally, the DC output of the cell is rectified in the second block of the converter at 400 V, so that the resulting AC output can be turned to 20 kV (MT) by using the same transformer which served to derivate the surplus electricity of the park; this means that the current intensity could reach 15 kA (6 MW/400 V) and it must be taken into account for sizing the electrical circuit, the insulations, switches, etc.

6. Control of the electrolyzers

The management of electrolyzers is done by an electronic controller which decides how many and which units are in operation, ordering the corresponding starts or shutdowns, at the same time that determines their set points (V & I). The voltage comes from the Tafel curve (Fig. 6), which is the sum of the Gibbs potential (U_c°), the ohmic losses (IR), and the electrode effects (η), and must be multiplied by the number of cells [25]. These barriers are proportional to the current densities (j), changing the voltage in function of the applied intensity and modifying the efficiency of the electrolysis process ($\eta_e = 1.23/V$).

To quantify the instantaneous power input to the installation the controller measures the intensity only, as the voltage from the rectifier is constant: $P_e\,(kW) = i\,(A) \cdot 400\,(volt)$; then, its distribution between the electrolyzer set is done by fixing the optimal values of the intensity and voltage for the different condition of operation, in the linear range of high current densities which are of interest:

$$V(\text{volt}) = 1.44 + 4.2 \times 10^{-5} \cdot j(\text{A/m}^2) \tag{2}$$

The electrolyzers operate in a range from 20 to 100% of the nominal intensity, meaning that they can start running at 1030 A, which correspond to 1.51 V, and thus we require 358 kW to activate the equipment (230 cells); this means that the electrolyzer system is capable to operate from an input equivalent to 1.7% of the nominal power (21.3 MW).

Thus, operatively, the controller measures continuously the energy input and starts the electrolyzers in such a way that only one unit is working at the least energy values; then, once the available energy doubles the limit for running one electrolyzer, it starts the next unit to maintain the minimum intensity in each equipment; and the same applies to the rest of the installation, as the maximal efficiency depends on maintaining the lowest current densities; when all units are running ($n = 10$), the energy is distributed in parallel, i.e., with the same voltages and intensities (V_n, i_n), so that, if the power input changes, they move over the Tafel's line as with the previous sequence (Eq. (2)).

Table 1 summarizes the control programme, which has been designed to ensure the maximal efficiency for all power inputs to the system, as far as it lets each electrolyzer to operate at the minimum current densities, optimizing their productivities.

7. Hydrogen production and economic analysis

To calculate the electrolytic production, we need to filter the surplus energy data from those values out of the range of operation, i.e., lower than 358 kWh (the minimum hourly energy to the electrolyzers), or higher than the nominal power of the installation (which are then substituted by the maximum capacity of the electrolyzer set: 21 300 kWh). The result of this correction is that the energy wasted represents only 3% of the total available off-peak electricity.

The efficiency of converting electricity-to-hydrogen varies with the hourly power inputs, due to the performance of electrolyzers; thus we can group the data in the different sequences of operation, as explained above, and evaluate the production of hydrogen with:

$$\text{Prod}_{H_2}(\text{kg}) = P_n \bullet \eta_{\text{energ}} \bullet \frac{0.03\text{kg}_{H_2}}{kWh} \tag{3}$$

Then, for any number of electrolyzers in operation (from 1 to 10) Eq. (3) can be expressed generically using the expression:

Table 1 – Control programme of the electrolyzers.

$L < P_e < 2L \Rightarrow$ running $n = 1$	$P_1 = P_e$	P_e: Instantaneous power input to the system (kW)
$2L < P_e < 3L \Rightarrow$ running $n = 1 + 2$	$V_1 = 347$ volts	L: Activation value (358 kW)
	$P_2 = P_e - L$	n: Electrolyzer branch in parallel (1,2,3,…n…10)
… … …		P_n: Instantaneous power through electrolyzer n
$10L < P_e < P_{max}$	$P_n = P_e/10$	V_n: Regulated voltage to electrolyzer n
$P_n = V_n \cdot i_n = (4.2 \times 10^{-5} \cdot j + 1.44) \cdot i_n$		i_n: Electric intensityin electrolyzer n
		j_n: Regulated voltage to electrolyzer n
		j: Current density (i_n/0.60)
		P_{max}: Curtailment power (21.3 MW)

$$\text{Prod}_{H_2}(\text{kg}) = P_n \bullet \eta_{\text{energ}} \bullet \frac{0.03\text{kg}_{H_2}}{kWh} + (n-1) \bullet L \bullet \eta_L \bullet \frac{0.03\text{kg}_{H_2}}{kWh} \quad (4)$$

Finally, after starting the 10th unit:

$$\text{Prod}_{H_2}(\text{kg}) = 10 \cdot P_n \cdot \eta_{\text{energ}} \cdot \frac{0.03\text{kg}_{H_2}}{kWh} \quad (5)$$

As shown in Fig. 7, which summarizes the system performance vs. the variable power to the electrolyzers, the process efficiency varies globally in a nonlinear form: the first intervals reflect the production of hydrogen during the initial sequences before running all the electrolyzers, while the longer part of the curve represents the ten units working at one time (the average yield is approximately 0.62 kWh of hydrogen per kWh of electrical energy input to the cells).

We present a summary of data with the values of the energy profitable, its relation with the energy available (97%), and the energy stored as hydrogen (62%):

– Total energy profitable (Park A): (247 600/11.5) × 0.97 = 20 900 MWh
– Energy stored as hydrogen: 20 900 × 0.62 = 13 000 MWh

The park studied has a nominal power of 48.8 MW, but thanks to the hydrogen management devices this power could rise 12.3% to reach 54.8 MW, which permits to sell peak electricity in the market and avoid turnings of production away: when the park generates energy in excess, it can be stored as hydrogen, or otherwise, if the balance is negative we can make use of the parallel generation of the fuel-cell (which runs only during peak hours, when the price of electricity is higher and the payback times become lower); other advantages are that the fuel-cell output is regulated electronically to the reactive energy requirements of the electrical grid, and in the case of curtailments or failures of the park we could easily start it up again by means of the energy storage and conversion system.

For an economical analysis of the project, we performed cost estimations by using the average prices of equipments and other installations (as shown in Table 2). We can appreciate that the investment is quite high, but it could supply the electrical grid with 6 MW during peak hours at a cost of 2.45 € per each watt of additional power; though this could be reduced to 1.34 €/W if a new wind farm and hydrogen-electricity systems were built *ex-novo*, with a cost of the installed wind power of 1.20 €/W.

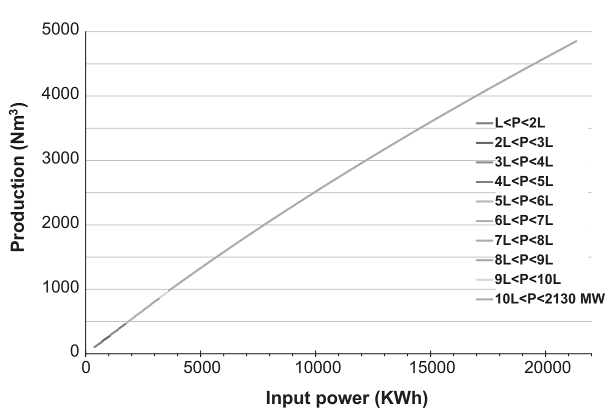

Fig. 7 – Production of hydrogen vs. energy input to the electrolyzers in all the power range.

Table 2 – Investment prices of equipments for cost estimations of the installation.

Equipment	Prices (€/MW)	Nominal power (MW)	Cost (€)
Transformer	15,000	22.0	330,000
Electrolyzers	280,000	21.3	5,9670,000
Deposit and compressor	8,500	125.7	1,070,000
Fuel-cell	700,000	6.0	4,200,000
Frequency converter	50,000	22.0	1,100,000
Construction and installation (10%)			1,270,000
Engineering and general expenses (6%)			760,000
Total			14,690,000

Concerning the profitability of the project, the result of multiplying the hydrogen production and energy conversion efficiencies gives 9.1 GWh per year, which amounts to 1.1 M€ at the price of the electricity generated by fuel-cells (12.1533 cent/kWh) [26]; from all these data, together with the maintenance cost and interest rates, we estimated the return of investment in less than 20 years, with a net present value near to 700 000 € and return rates of 3%.

We could add other favorable factors to this analysis, like the cost reductions which are expected from technology learning, savings in conventional power generation and new electrical lines, bonus for a better regulation of the grid, the deployment of renewable energy sources, as well as environmental benefits of all kind.

8. Conclusions

Wind energy contributes to the Spanish generation system by supplying more than 10% of the electricity demand, while its growth pattern is foreseeing a much faster penetration level in near future; e.g., 43% of new power capacity installed in the European Union in 2008 was wind generation, well above gas, coal and nuclear technologies [27]. Thus, it becomes critical to profit at maximum these power resources for a better management of electrical grids, as well as for a more rational utilization of the energy and their environmental benefits.

We used historical data of the hourly renewable energy available for one year period in a real emplacement, where the maximum power that can be generated is 48.8 MW and the power limit is 17.4 MW during off-peak periods; comparing the annual available wind power to its capacity in the farm case, we obtain a wind capacity factor of 27%, and 36% of the time the windmills are generating more off-peak electricity than we could evacuate in the node.

Thus, the operation of an electricity powered hydrogen production system was analyzed and optimized, revealing its role in managing this surplus energy; the simulation of the intermittent operation shows the benefits which could be achieved by using low prized electricity during off-peak periods of electricity demand, as well as the leveling effect on the energy balances of the park.

The proposed scheme includes the use of the excess energy to run a water electrolysis process, where the hydrogen produced is an ideal fuel for the highly efficient new electrochemical cells.

Once proved that it was not possible to evacuate all yearly generated electricity which is connected to the electrical node, we have designed the installation to manage this overload: the electrolyzer capacity is 21.3 MW and the expected efficiency is 62%, while the selected operation has resulted very versatile, as electrolyzers are able to run into a range from 1.7 to 100% of the maximum power, by using of an adequate control.

Downstream of the electrolyzers, the system includes water and hydrogen storages, as well as one stationary fuel-cell to supply the electrical grid: the hydrogen tank was sized for 3800 kg, and the maximum capacity of the recovery system is 6.0 MW, with an efficiency of 70%. Considering the average efficiencies of the equivalent electrolyzer, the electrical devices, the compression-storage losses and the fuel-cell, the projected system has still a global yield of about 40%, which represents the percentage of excess generation from wind that we are capable to reintegrate in the grid if it were wasted in any circumstance.

The continuous improvement in relevant hydrogen technologies were decisive for selecting this alternative of energy storage and wind management, though they need longer learning periods for a better performances and lower costs; but even using the current economies, the wind-hydrogen installations could attain a payback into their lifetimes. We should consider more detailed geographical evaluations of the grid for planning the installations or operating the devices at optimal performance, taking into account the balances between the supply and the demand at large scales. Studies for wide source availability and variability across the country are in progress, including the load sequences to operate the electrolyzers and avoid the negative impact of dynamic cycles [28,29]; thus, they will be the objective of further research where we plan to analyze how renewables need hydrogen to facilitate their contribution to the electricity trade, since so far all utilization of no storable energies is restricted mainly to local applications.

Acknowledgements

We are gratefully acknowledged to the Spanish wind association (AEE) for providing all the real data necessary for this study, and to Victoria Machuca at EUITI for the whole revision of the manuscript.

REFERENCES

[1] Balat M. Potential importance of hydrogen as a future solution to environmental and transportation problems. Int J Hydrogen Energy 2008;33:4013–29.

[2] Moriarty P, Honnery D. Intermittent renewable energy: the only future source of hydrogen? Int J Hydrogen Energy 2007;32:1616–24.

[3] Marbán G, Valdés-Solís T. Towards the hydrogen economy? Int J Hydrogen Energy 2007;32:1625–37.

[4] Sherif SA, Barbir F, Veziroglu TN. Wind energy and the hydrogen economy – review of the technology. Solar Energy 2005;78:647–60.

[5] Deshmukh SS, Boehm RF. Review of modeling details related to renewably powered hydrogen systems. Renew Sustain Energ Rev 2008;12:2301–30.

[6] Pickard WF, Shen AQ, Hansing NJ. Parking the power: strategies and physical limitations for bulk energy storage in supply-demand matching on a grid whose input power is provided by intermittent sources. Renew Sustain Energ Rev 2009;13:1934–45.

[7] González A, McKeogh E, Gallachóir BÓ. The role of hydrogen in high wind energy penetration electricity systems: the Irish case. Renew Energ 2004;29:471–89.

[8] Hajimiragha A, Fowler MW, Cañizares CA. Hydrogen economy transition in Ontario – Canada considering the electricity grid constraints. Int J Hydrogen Energy 2009;34:5275–93.

[9] Lebbal ME, Lecœuche S. Identification and monitoring of a PEM electrolyser based on dynamical modeling. Int J Hydrogen Energy 2009;34:5992–9.

[10] Aguado M, Eyerbe E, Azcárate C, Blanco R, Garde R, Mallor F, et al. Economical assessment of a wind-hydrogen energy system using WindHyGen® software. Int J Hydrogen Energy 2009;34:2845–54.

[11] Jørgensen C, Ropenus S. Production price of hydrogen from grid connected electrolysis in a power market with high wind penetration. Int J Hydrogen Energy 2008;33:5335–44.

[12] Eurobserv'er. The state of renewable energies in Europe – edition, http://www.energies-renouvelables.org/observ-er/sig.asp; 2008.

[13] European Commission, http://ec.europa.eu/environment/climat/climate_action.htm [last accessed 01.11.09].

[14] Red Eléctrica de España (REE), http://www.ree.es/https://demanda.ree.es/eolica.html [accessed 03.11.09].

[15] Energía & empresa N, http://www.energiayempresa.com/indexing.asp; 31 April 2008 [accessed 31.10.09].

[16] Asob I. Energía eólica e hidrógeno, una iniciativa y necesidad internacional. Energética 2009;21:118–9.

[17] Qadrdan M, Saboohi Y, Shayegan J. A model for investigation of optimal hydrogen pathway, and evaluation of environmental impacts of hydrogen supply system. Int J Hydrogen Energy 2008;33:7314–25.

[18] US-DOE Hydrogen Program (DE-FG02–04ER83968), http://www.docstoc.com/docs/919615/Novel-Low-Cost-Solid-Membrane-Water-Electrolyzer-(Phase-II-Project).

[19] Gutiérrez-Martín F, García-de María JM, Baïri A, Laraqi N. Management strategies for surplus electricity loads using electrolytic hydrogen. Int J Hydrogen Energy 2009;34:8468–75.

[20] Albadalejo J, Gegundez J. Situación actual de las pilas de combustible. Ingeniería Química 1997;333:97–104.

[21] Asociación Empresarial Eólica (AEE), http://www.aeeolica.es/galicia.php [last accessed 04.11.09].

[22] Winter CJ. Hydrogen energy – abundant, efficient, clean: a debate over the energy-system-of-change. Int J Hydrogen Energy 2009;34(14):S1–52.

[23] Norsk Hydro Electrolysers AS, http://www.nortech.es/productos/Atmospheric%20Electrolysers-es.pdf.

[24] Zhou T, Francois B. Modeling and control design of hydrogen production process for an active hydrogen/wind hybrid power system. Int J Hydrogen Energy 2009;34:21–30.

[25] Electrochemistry. In: Ullmanńs encyclopedia of industrial chemistry. Wiley-VCH Verlag GMBH; 2001.

[26] Bernal-Agustín JL, Dufo-López R. Hourly energy management for grid-connected wind–hydrogen systems. Int J Hydrogen Energy 2008;33:6401–13.

[27] European Wind Energy Association (EWEA), http://www.ewea.org/ [last accessed 22.09.09].

[28] Idae, Gobierno de España, Atlas Eólico de España. Mapas de Viento, http://atlaseolico.idae.es/CENER, http://www.cener.com/es/energia-eolica/mapas-viento.asp.

[29] Bergen A, Pitt L, Rowe A, Wild P, Djilali N. Transient electrolyser response in a renewable-regenerative energy system. Int J Hydrogen Energy 2009;34:64–70.