# Pre-investigation of Water Electrolysis for Flexible Energy Storage at Large Scales: The Case of the Spanish Power System

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This report aims to analyze the basis of hydrogen and power integration strategies, by using water electrolysis processes as a means of flexible energy storage at large scales; we consider two main aspects: 1) the state-of-the-art & development for electrolyzer techniques, and 2) the potential for introduction in utility systems.

We focus in the Spanish system, holding a surplus capacity which means a poor utilization ratio of the technologies (≈ 30%), whereas the coverage with conventional utilities is near 50% over the peak demands. The load variations along the year make grid operations a challenging task to maintain the equilibrium in real time; this is complicated further by the geographic asymmetries of generation and demand, the penetration of renewable electricity and the limited interconnections. All of this means an inefficient use of infrastructures (both conventional and renewable), which suggests load leveling options to improve the efficiency based on more holistic energy approaches.

In this context, the production of hydrogen by electrolysis using the power grid mix is considered an option to increase flexibility and integration of renewable energy. Thus, we explore a novel aspect of the hydrogen economy which is based in the potentials of existing power systems and the properties of hydrogen as an energy carrier; the strategy is to control the power inputs, taking into account the efficiency and dynamics of electrolyzers, to show the benefits that can be reached by using surplus electricity at low prices, as well as the leveling effects on the energy balances of the plants.

## ELECTROLYZER PERFORMANCE

Several factors affect the performance of electrolyzers: namely, the water dissociation potential, the kinetic parameters, the cell resistance and the Faraday efficiency; then, the energy yield is obtained from the voltage, current and BOP efficiencies using the equations:

$$V = [J + 2K(J\cdot r + E_0) + (J^2 + 4K\cdot E_0 J)^{1/2}] / 2K \qquad \eta_F = f_1 \cdot J^2 / (f_2 + J^2) \qquad E = 26.8\cdot V / (\eta_F \cdot \eta_{BOP})$$

Focus is on alkaline water electrolyzers (AWE) which are the only currently available for large scales; fig. 1 show voltage, current and energy efficiency curves for AWE using representative parameters.

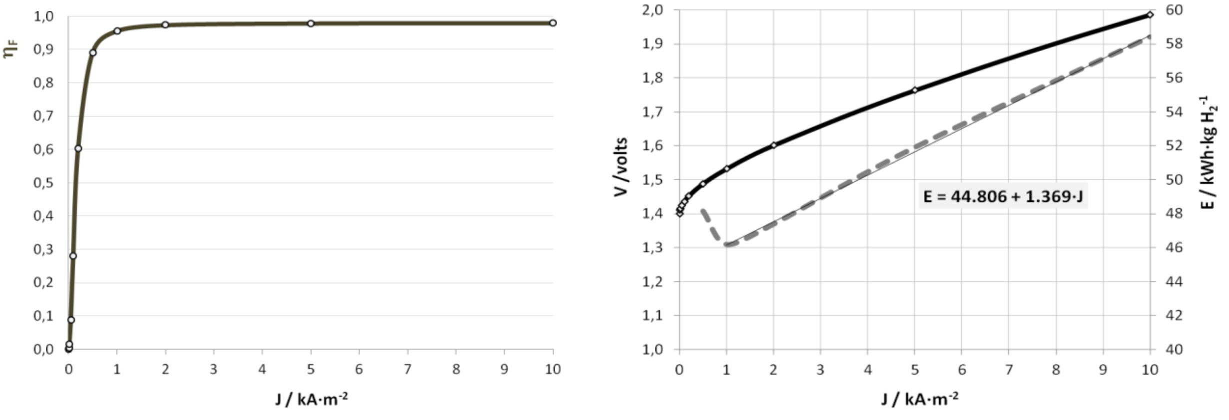

Fig. 1: Current-voltage and energy efficiency curves for an advanced alkaline water electrolyzer (AWE) with $E_0 = 1.4$ volt, $K = 120\ \mathrm{m}\Omega^{-1}\cdot\mathrm{m}^{-2}$ and $r = 0.020\ \mathrm{m}\Omega\cdot\mathrm{m}^2$, $f_1 = 0.98$ and $f_2 = 0.025\ \mathrm{kA}^2\cdot\mathrm{m}^{-4}$ (at 80ºC), and $\eta_{BOP} = 0.93$

Capital costs can be anticipated between 200-400 €/kW, for large electrolyzers at increased current densities; this excludes BOP cost (like electronics, purifiers or handling the hydrogen).

$$C_{EL}\,(€) = a \times Q_o\,(kg_{H2}/h)^{b} \times J_o\,(kA/m^2)^{-c}$$

The cost production of hydrogen is then estimated using expressions that include: the capital costs of electrolyzers+BOP (by a recovery factor and O&M rate), the inputs of electrolysis (from the power of the plants, their availability in h/year and the prices of electricity and water); the production of $H_2$ is the power input by the energy yield of electrolyzers.

$$C_H = (C_{CC}+C_{O\&M}+C_E+C_W)/Q_H$$

$$C_{CC}+C_{O\&M} = (F+OM)\cdot C_{EL+BOP} \qquad C_E+C_W = 8760\cdot P\cdot u\cdot C_{AE} + 9\cdot Q_H\cdot C_{AW} \qquad Q_H = 8760\cdot P\cdot u / E$$

With this model we analyze electrolytic production, e.g. for big capacity plants, running part periods at increased current densities and using low priced power: the results are large installations with high hydrogen production, diminished efficiency (due to the high intensities) and reduced costs of energy. We simulated four parameters by a 2nd order design, where the regression shows significant effects of the utilization ratios and electricity prices, with relevant interactions of $P/u$, $J_o/u$, $J_o/C_{AE}$; concluding that the cost of hydrogen can be reduced using low priced electricity in long enough surplus periods, with larger capacities as $u$ decreases, and rising the current densities as $C_{AE}$ , $u$ , $P$ become lower.

Summing up, reducing the voltage reduces the cost of energy, while increasing the intensity reduces investment costs; however, cell voltage increases with current density: in new advanced electrolyzers this conflict of interest is being optimized by new catalysts, new cell configurations and increasing the conductivity of electrolytes, till a point that there are not strong reasons to await for much more efficient processes to start business development; the relative high cost of equipment is still a barrier, but developing cheaper units (e.g. large plants for energy use) is just an engineering matter and not a feasibility question.

## BALANCING THE GRID LOADS

An interesting system aspect of electrolytic processes is the possibility of power management; in this case, the choice of equipment has influence on the control capabilities of the system (range & times); The proposed model requires a holistic approach to the generating systems, the demand profiles, and their variations in space and time, together with an evaluation of electrolysis technologies that are applicable for managing the grid loads at large scales.

For the analysis, several power generation scenarios are superimposed to the load curves to estimate the $H_2$ producible in the *valleys* and the $H_2$ consumable in the *peak* hours; looking at the maximum surplus power values, we calculate the number/size of the plants, and using the electrolyzer model and parameters we approximate the production of hydrogen by:

$$Q_p = \Sigma P_t / E_t = \Sigma u_t P_0 / (k_0 + k_1\cdot J_t)$$

where we regulate current densities according to the utilization ratios in each period (within a defined range): $J_t = u_t\cdot J_0 \quad u_t = P_t / P_0 \; (0.10 \le u_t \le 1.20)$

The hydrogen for power regenerators (e.g. fuel-cells) is estimated from the peak imbalances, using a typical energy efficiency ($\eta = 0.60$): $Q_c = P_c / (\eta\cdot LHV)$

Finally, the hydrogen available for other uses is obtained as: $Q_a = Q_p - Q_c$

The analysis illustrates how variation of generation scenarios serves the purpose to get a balance of the efficiency, economy and easiness of operations; the capacity of the installations and the power consumption determine the costs, whereas there are returns by selling energies and savings in fuel utilities. Such approach is completed with the whole analyses of the loading curves and the hydrogen operations annually, fixing a base-load power that is added to the production of the non-manageable resources and compared with the actual energy demands: the `net surpluses´ represent the electricity theoretically available for other uses (fig. 2a). If this energy is utilized in relation with the hydrogen technologies for electric grid load balancing, the model has to include: the maximum power surplus, which determines the capacity and utilization of electrolyzers (we use a limiting value); the hydrogen production, by taking into account the inputs, the efficiency and dynamic range of electrolyzers; and the deficits of electricity, due to the power imbalances and electrolyzers' operation, that account for the hydrogen consumed by e.g. fuel-cells (fig. 2b).

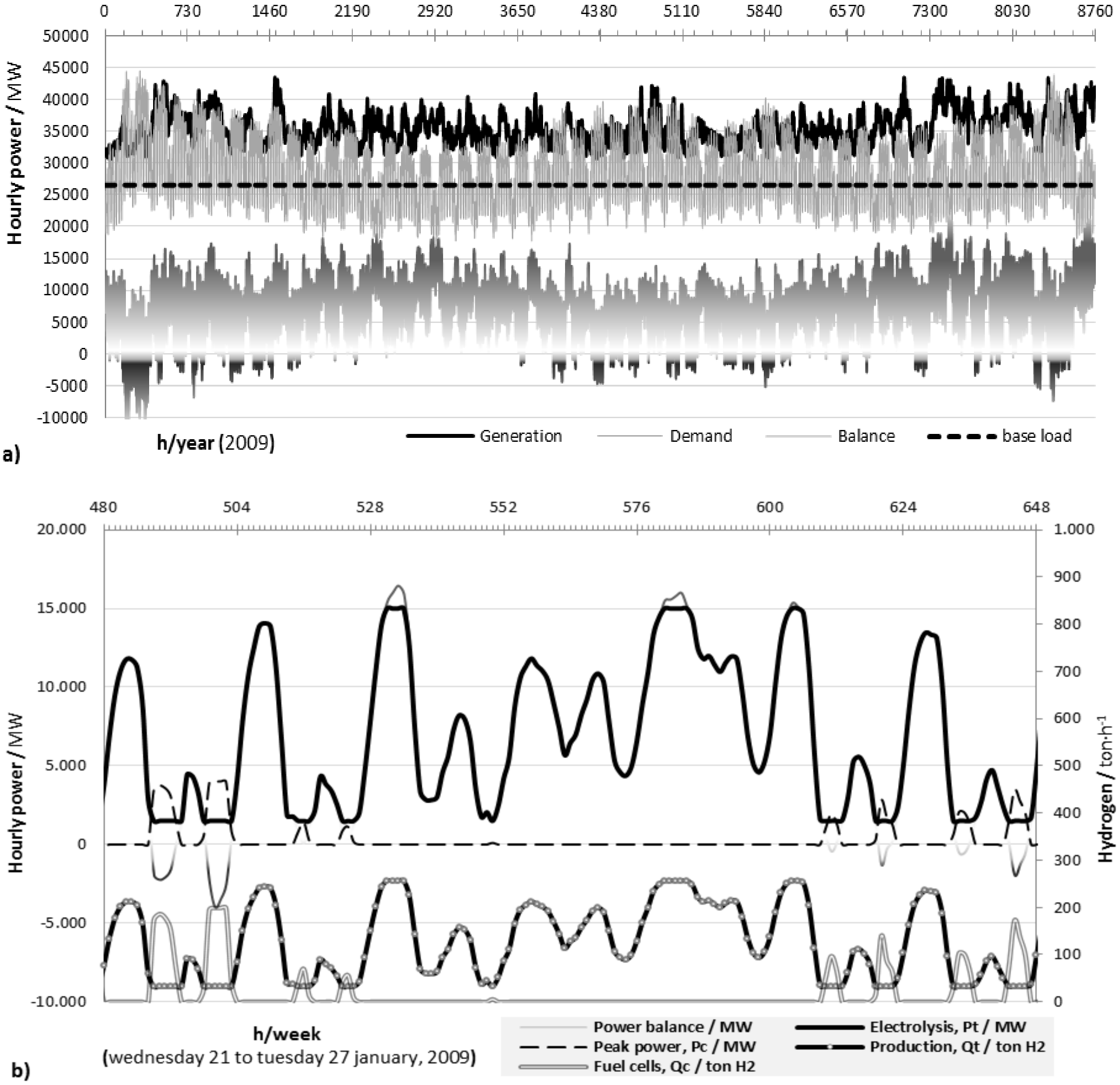

Fig. 2: a) Power generation scenario and load curves with a disaggregation of hours (Spain, 2009)
b) Weekly balance of electricity and hydrogen using the electrolyzer and fuel-cell system

Finally, we simulate distinct scenarios -using all the model variables- to analyze their sensibility on the size, operation and economy of `electricity and hydrogen processes´: most significant factors are related to the efficiency and cost of electrolysis, power to electrolyzers and fuel-cells, but particularly electricity and hydrogen prices which are the only capable to render the systems cost effective within the ranges of values studied.

As we focus in the `Spanish case´, this is a good example for planning the transition from a power system holding large reserve capacity, high renewable energy and limited interconnections, to a more sustainable energy system being capable to optimize the size, the regulation modes, utilization ratios and impacts of the installations. Barriers for implementation can arise from political willingness, economical priorities or technical limitations; but whether this option is more feasible, when enough power surplus or grid constraints exist, as an alternative to other operating procedures or exporting the electricity, is the prime question we are trying to answer in this report.

## CONCLUSSIONS

- The electricity systems in many countries hold an excess of capacity that show the failures of the current liberalized energy markets to appoint resources efficiently.
- The power industry is in probably a unique position, if the economy converts to hydrogen, to increase energy efficiency and avoid pollution.
- Hydrogen production by electrolysis using the power grid mix could be an option, depending of the prices of energy in the different periods, if sufficient electrolyzer efficiencies and cost reductions are achieved.
- The analyses show the effects of all factors relevant, and feasible results can be anticipated in some scenarios, e.g. for base load with power surplus at low price, running large electrolyzers in dynamic-range mode.
- As concluding remark, with a large fraction of renewable in future power systems electrolysis is probably unavoidable even technology is not perfect; we can discuss efficiency, costs, etc., however a more fundamental question could be: what is the alternative, if business as usual is not an option?

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