

Modeling and simulation of the integration of a Power-to-Gas plant in a power system network

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Abstract—Currently Colombian government is supporting more than ever the integration of renewable energy in the national electricity transmission system. Now, due to the variability of the solar and wind renewable electricity plants, the lack of cost-efficient in-situ storage at transmission level, and the need to balance demand and generation in real time, some of these renewable resources might be curtailed. Therefore, to fully exploit variable renewable resources one may use the process of converting electricity to a chemical vector, e.g., through electrolysis. However, to quantify the extend of the benefits and impact on the grid of such initiatives, a proper simulation environment must be set. This work presents the simulation of an advanced alkaline electrolyzer used for the production of hydrogen from curtailed solar photovoltaic renewable energy in a power system.

Keywords—Power-to-Gas, Electrolysis, Power System Operation, MATLAB/Simulink.

I. INTRODUCTION

Renewable energy is gaining thrust in national energy systems around the world, but, their integration rate is occurring faster than the modernization of the power electrical system. As a consequence, and because power system operator cannot jeopardize the security and reliability of the network, it is common to curtail renewable energy when surplus appear.

This is a clear inefficiency that must be corrected. On this regard, Power-to-Gas technologies, namely hydrogen electrolysis, seem to be promising. This is mainly because when producing hydrogen from curtailed renewable energy it is possible to obtain fuels (called “eFuels”) capable of replacing fossil fuels [1]. Among these fuels is methane, which could be used as a key component towards a practical sustainable energy transition [2].

Several European countries have assessed the potential of the hydrogen electrolysis as a technology to increase the amount of usable renewable energy. For example, in Spain [3] claims that 90% of the curtailed renewable energy could be recovered; on the other hand, in Germany, the high temperature electrolysis has been identified as an attractive

alternative because of its high efficiency (near 70%) and because it is capable of producing SynGas (which can be further transformed in methanol or methane), being the later a big selling point since this production can cope with a third of the energy demand (electricity and fuel combined) [4].

In general, any Power-to-Gas plant implementation needs an efficient and large-scale renewable energy sources to carry out hydrogen production. In Colombia, according to the Mines and Energy Ministry (MINMINAS), the daily radiation is above the world average, besides, wind speeds in “La Guajira” state are twice the world average. In addition, Colombia has an annual water availability almost 8 times higher than the world average, factors that allow the National Government to forecast a competitive position in the market for this fuel. The main limitation to carry out the integration of the Power-to-Gas plant in Colombia is the lack of the necessary technology to implement such a plant. Other limitations would be the location of these plants, since they are more financially viable in regions very far from urban centers, hence, the logistics involved could increase the implementation costs for this technology. To overcome all these challenges and due to the importance of studying the impact of hydrogen in the Colombian energy mix, MINMINAS has been working in a green hydrogen road map, for which the definitive version will be published in September 2021 [5].

In conclusion, there is sound evidence that indicates that green hydrogen could become a game changer in the energy landscape around the world. However, due to the complexity of power systems and electrolysis plants, it is not straight forward predict the behavior of this multi physics models, thus, the need of simulation tools able to quantify the power and hydrogen outputs for several scenarios. This work aims to show the resulting behavior and consequences of the integration of a Power-to-Gas plant integrated to a power transmission system.

This paper is structured as follows: In section 2, is given a brief introduction of the models used; In section 3, the scenario and simulation results are presented, while in section 4 are presented some concluding remarks.

II. MODELS AND PARAMETERS

An electrolyzer is a device able to separate the water molecules into oxygen and hydrogen atoms. Because chemical links in the water are very stable, some energy must be put in order to make the separation in a process called electrolysis.

According to the connection used, the electrolyzer can work in series or in parallel. Also, according to the technology employed the electrolyzer can be classified in one of three categories: alkaline electrolyzer, Proton Exchange Membrane (PEM) electrolyzer and Solid Oxide (SO) electrolyzer. Since alkaline electrolyzers are currently more commercial, it is important to understand its parameters and behavior. In this paper, an alkaline electrolyzer model is implemented using MatLab/Simulink and EES (Engineering Equation Solver) based on the theoretical description found in [6]. An schematic view of the simulated Power-to-Gas Plant (PTGP) is depicted in Figure 1.

A. Detailed models

1) Renewable energy input and power system model (A):

The electrical power system models for the simulation of a PTGP integrated to a power system are the ones found in MatLab/Simulink Simscape tool. A schematic of the simulation framework used is shown in Figure 2. The Photovoltaic Plant (PVP) is simulated simply as a power injection in one of the nodes of the system given a power profile. In contrast, the power consumption by the PTGP is computed from the power balance at the node where the plant is connected, then, the hydrogen production is calculated by a separate Simulink simulation which takes as input parameters the node voltage and the active power being withdraw from the network. With the above in mind, following subsections are focused on the modeling of the PTGP. For a more detailed development of the models and methods needed to simulate a PTGP, please refer to [6].

2) *Electrolyzer (B)*: Electrical behavior of the electrolyzer model was implemented according with the following equation:

$$U = U_{\text{rev}} + \frac{r}{A}I + s \log \left(\frac{t}{A}I + 1 \right) \quad [\text{V}] \quad (1)$$

Where, U is the voltage applied to the cell (V), U_{rev} is the reversible voltage (V), I is the current through the cell (V), s , t and r are the electrolyzer characteristic equation coefficients (V, m^2/A and Ωm^2 , respectively), and A is the electrode area for a electrolyzer cell (m^2). From here, the input power is computed following the following equation:

$$W_T = f_W W_S + (1 - f_W) W_{\text{nom.}} \quad [\text{W}] \quad (2)$$

Where, T sub-index denote the power consumed by the electrolyzer, S sub-index denote the total power input given to the PTGP, and nom. sub-index denote the nominal power of the electrolyzer. This equation is used to cap the maximum power through the electrolyzer. Thus, if $W_S > W_{\text{nom.}}$, f_W is chosen such that $W_T = W_{\text{nom.}}$. Electrolyzer voltage is

computed as W_T/NI , where N are the total number of cells in the electrolyzer (21 for the case study).

The reversible voltage is computed with the following expression:

$$U_{\text{rev}} = \frac{\Delta G_T(T, P)}{ZF} \quad [\text{V}] \quad (3)$$

Where, $\Delta G_T(T, P)$ is the increase in the Gibbs' free energy in a constant pressure (P) and temperature (T) process (J), Z is the number of electrons that are interchanged in the electrolysis (2 electrons for the case study), and F is the Faraday constant (96485.3383 C/mol). To account for the dynamic behavior of the electrolysis, the ΔG_T was computed using EES (Engineering Equation Solver) for a temperature range from 10° C to 209° C, and a pressure range from 1 to 10 bars. The link with Simulink was done through a lookup table imported from an Excel file.

Given the electrolyzer current, the hydrogen flow rate (\dot{m}_{H_2}) can be computed with the following equation:

$$\dot{m}_{\text{H}_2} = n_F \frac{NI}{ZF} \quad (4)$$

Where, n_F is the electrolyzer Faraday efficiency. In turn, this efficiency depends on the current density and the electrolyte temperature:

$$n_F = f_2(T) \frac{\rho^2}{\rho^2 + f_1(T)} = \frac{\dot{m}_{\text{H}_2}}{\dot{m}_{\text{H}_2}^{\text{ideal}}} \left[\frac{Nm^3}{h} \right] \quad (5)$$

Where $f_1(T)$ and $f_2(T)$ are cell parameters given for some experimental temperature points, therefore, any other operation point must be interpolated using a linear and a quadratic function.

3) *Heat exchanger (C)*: The resulting heat flow is computed using the following equation:

$$\dot{Q} = C_t \frac{dT}{dt} = W_T \left(1 - \frac{U_{tn}}{U} \right) - \dot{Q}_{\text{loss}} - \dot{Q}_{\text{cool}} \quad [\text{W}] \quad (6)$$

Where, C_t is the thermal capacity of the electrolyte (J/°C), T is the electrolyzer temperature, U_{tn} is the thermo-neutral voltage, \dot{Q}_{loss} are the heat losses and \dot{Q}_{cool} is the heat extracted by the automatic cooling system (see next subsection).

Similar to the reversible voltage, the thermo-neutral voltage is computed by solving:

$$U_{tn} = \frac{\Delta H_R(T, P)}{ZF} \quad [\text{V}] \quad (7)$$

Where, $\Delta H_R(T, P)$ is the increase in reaction enthalpy and it is computed using look up tables derived from EES software for the same temperature and pressure range that the Gibbs's free energy. For the heat loss only radiation and convection losses where taken into account.

Given all the terms in the right of equation 6, one can compute the electrolyte temperature by solving the resulting EDO. In Figure 3 is depicted the Simulink blocks used for this purpose.

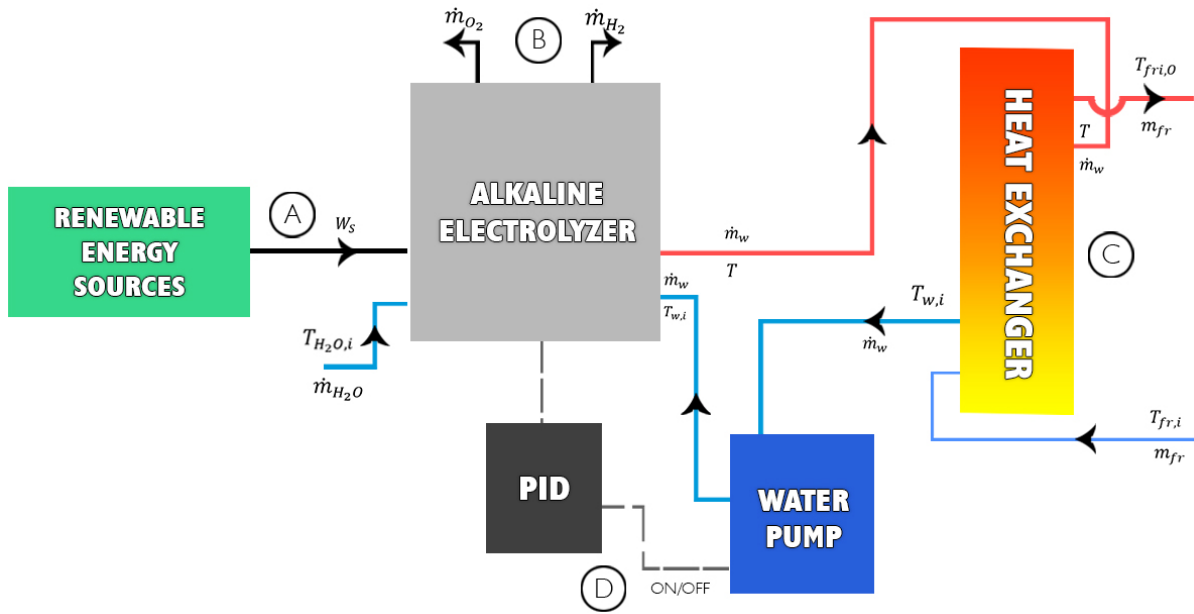


Fig. 1. Schematic of the simulated Power-to-Gas plant adapted from [6]. The process to be simulated start in (A) with the injection of renewable energy surplus from the power system. Then in (B) this energy is used to produce hydrogen with the electrolyzer, which need a heat exchanger (C) and a cooling system (D) to operate within secure operational limits. Source: N/A.

4) *Automatic cooling (D)*: For the automatic cooling a critical parameter is the maximum heat that can be transferred to the heat exchanger. This heat is computed as follows:

$$\dot{Q}_{\max} = C_{\min} \cdot (T - T_{fri,in}) \quad (8)$$

Where, C_{\min} is the minimum heat capacity and $T_{fri,in}$ is the temperature of the cooling water at the entrance of the heat exchanger. Given the maximum heat transfer, the cooling heat rate is computed by applying an efficiency parameter to \dot{Q}_{\max} :

$$\dot{Q}_{\text{cool}} = \varepsilon \dot{Q}_{\max}.$$

Where ε is the heat exchanger efficiency. This efficiency depends on the constructive parameters of the heat exchanger. For the case study was chosen a pure counter flow heat exchanger with a single step.

Given the cooling heat rate, the water temperature before the electrolyzer and the water temperature after the heat exchanger can be computed using equation 9:

$$T_y - T_\psi = -k \frac{\dot{Q}_{\text{cool}}}{\dot{m}_y C_{H_2O}} \quad (9)$$

Where, T_y is the water temperature before the electrolyzer ($T_{w,i}$) or after the heat exchanger ($T_{fri,out}$), \dot{m}_y is the water flow rate before the electrolyzer (\dot{m}_w) or after the heat exchanger (\dot{m}_{fr}), T_ψ is the water temperature after the electrolyzer (T) or before the heat exchanger ($T_{fri,in}$), respectively. On the other hand, C_{H_2O} is water specific heat capacity and $k = -1$ when computing the temperature through the heat

exchanger and $k = 1$ when computing the temperature through the electrolyzer.

B. Parameters

The PTGP parameters used for this model from the PHOEBUS plant located in Julich, Germany, as described in Table I; all electrolyzer constructive parameters are from [6]; whereas the power system parameters are described in Table II.

III. RESULTS

Three simulations are presented in this section: First, the simulation of the electrolyzer, then the simulation of the power system with the PVP, and finally the simulation of the power system with a PTGP and a PVP.

A. Electrolyzer

A test power profile for one day of operation window was injected to the electrolyzer model to check its behavior. In Figure 4 are depicted the resulting current and hydrogen flow rate with respect the maximum observed value for each variable. Note that because of the unitary power factor, the shape of the power consumed by the electrolyzer is proportional to the current. In contrast, the hydrogen flow rate is proportional to the electrolyzer current only when operating under nominal conditions.

For the sake of the device health, the maximum power of the PTGP is capped at nominal capacity, then, in case of an injection surplus (e.g., for period 10, 12 and 14) the power is being held constant. Under such circumstances, the automatic cooling system is critical, since it allows handling such high power inputs without stressing the electrolyzer

TABLE II
POWER SYSTEM PARAMETERS

Bus	B1 PALOS 115 kV	
	B2 CONUCOS 34.5 kV	
	B3 CANEYES 34.5 kV	
	B4 CABECERA 13.8 kV	
	B5 BUCARICA 34.5 kV	
Transmission lines	L1 34.5 kV / 150 A / 3 km	R: 0.23 Ω /km
	L2 34.5 kV / 207 A / 3 km	L: 1.33 m Ω /km
	L3 34.5 kV / 130 A / 1 km	C: 9.78 nF/km
Power transformer	T1 115/34.5 kV / 20 MVA	L _{1,2} = 0.3p.u.
	T2 34.5 kV/13.8 kV / 2 MVA	
Load	D1 15 MW / 1 MVar	
	D2 1.5 MW / 0.1 MVar	
Generation	115 kV / 20 MW	

Source: N/A.

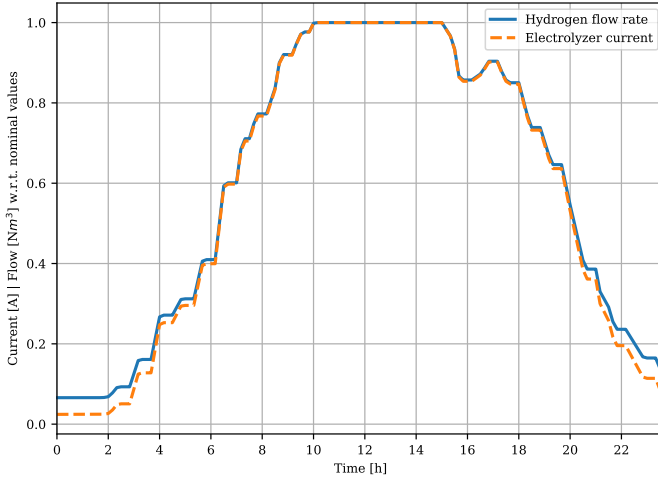


Fig. 4. Current and hydrogen flow as a fraction of its nominal values. When both curves are equal current and hydrogen production are proportional. Source: N/A.

B. Power-to-Gas integration

In Table III are presented the normal operation loading of the power system and the loading including the PVP. As can be seen, without renewable energy all line thermal limits are satisfied. However, by integrating a PVP of 4.6070 MW of installed capacity, near at noon, the power through Line 3 is above the maximum line capacity. This is quite interesting since, as shown in Figure 7, overall the impact of the PVP is to decrease the total network active power imports and loading in the other two lines.

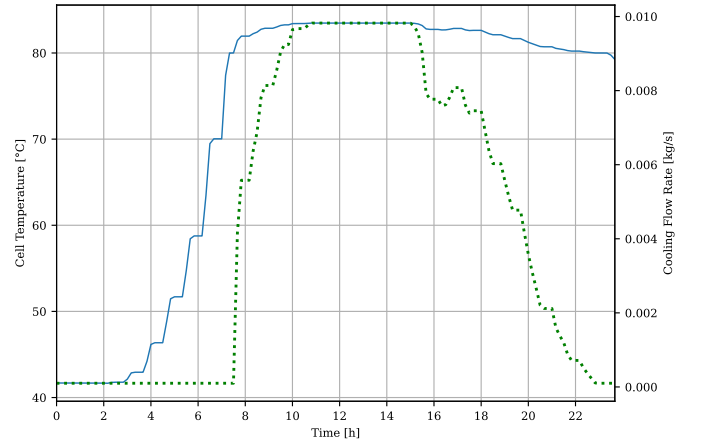


Fig. 5. Cell temperature (continuous line) and cooling system water flow rate (dotted line) operation profile of the PTGP. Source: N/A.

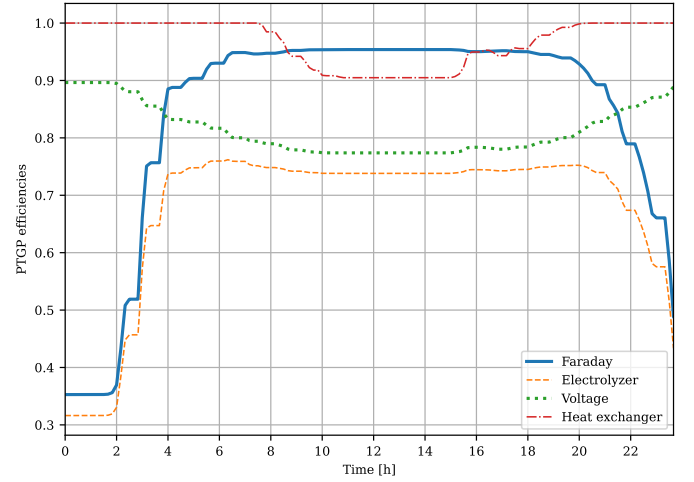


Fig. 6. PTGP Faraday, Electrolyzer, Voltage and Heat exchanger efficiencies for the operation profile. Source: N/A.

In a real application this condition would demand a curtailment of renewable energy in the network if there is no way to store electrical energy *in-situ*. Another way to avoid this energy inefficiency in the system is to transform the surplus to another energy vector, in this case, hydrogen. After some testing, it was found that a PTGP of 14 kW can remove the line 3 thermal limit violation, thus, supporting the security and reliable operation of the power systems as well as avoiding energy inefficiencies.

IV. CONCLUSIONS

A simulation tool based in Matlab/Simulink and EES to quantify the power and hydrogen outputs for a PTGP connected to the power transmission system was successfully implemented and tested. A case study to show the impact on the network secure operation of PVP was presented, as well as a solution based on the integration of a PTGP. From the simulations it is clear the importance of the electrolyzer tem-

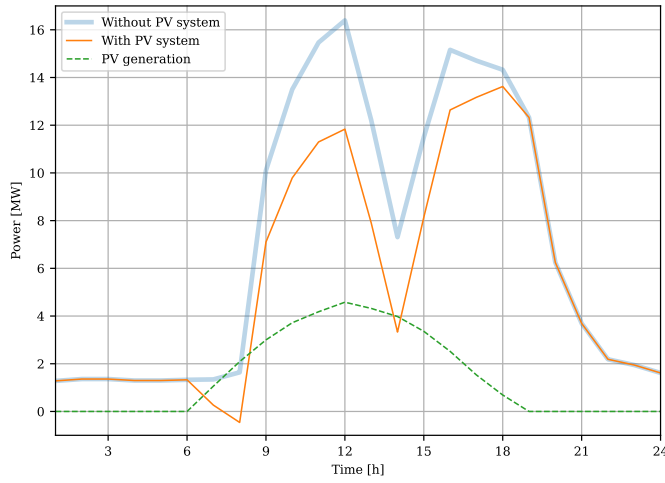


Fig. 7. Active power profile at slack bus and PVP generation. Source: N/A.

TABLE III
LINE LOADING WITH AND WITHOUT PVP AT 11:00 A.M.

Line	Loading [%]		
	without PVP	with PVP	with PVP and PTG
L1 (150 A)	81.36	65.54	65.63
L2 (207 A)	74.54	63.27	63.32
L3 (130 A)	76.50	100.06	99.99

Source: N/A.

perature and current to maintain maximum efficiency. Besides, MatLab/Simulink has been presented as a capable framework to predict the behavior of this kind of energy systems. The current model handle the changes in input power with a quasi-dynamic approach, however, experimental studies are needed to understand the errors and limitation of this kind of modeling when predicting the electrolyzer dynamics. Also, as a future work, it is important to study the power electronic interface controls and architectures to improve PTGP efficiency and increase the device life-time even under a variable input power profile.

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