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# A NEW FUZZY LOGIC SOLUTION FOR ENERGY MANAGEMENT OF HYBRID PHOTOVOLTAIC/BATTERY/HYDROGEN SYSTEM

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**Key words: Energy management strategy, Fuzzy logic control, Photovoltaic, Fuel cell, Electrolyzer, Battery, Loss of power supply probability (LPSP).**

**In this paper, an intelligent energy management strategy of a hybrid system (HS) is proposed based on fuzzy logic. The HS consists of photovoltaic (PV) generator as a main energy source, whereas hydrogen subsystem and batteries are used for storing or supplying the balance energy. The HS components are sized using a probability method called power loss probability (PLP). It calculates the optimal number of PV panels and hydrogen storage elements meeting the load energy demand while optimizing the overall system price and its reliability. The fuzzy energy management strategy (FEMS) is established to manage the energy production according to the energy demand, the real-time production, the amount hydrogen consumed by fuel cell and generated from the electrolyser, the battery state of charge and by considering in addition component's lifetime and cost. Simulations are performed, using an experimental solar radiation database, to evaluate the effectiveness of the proposed FEMS over a one-year period. The results show the ability of the HS to meet the load requirements while extending the lifetime of the system components.**

## 1. INTRODUCTION

The world's energy demand for electricity continues to increase, with economic growth leading to higher energy consumption. This energy consumption has been and still is possible thanks to fossil fuel reserves, which to date remains the main source of electricity supply.

The use of renewable energy sources as a sustainable ecological solution is growing, particularly in electricity production. Among renewable energy sources, solar energy is now widely used because it is free, abundant, and non-polluting [1, 2].

The main problem with renewable energy production installations is their intermittency. The electricity produced can't be fully planned and generally doesn't coincide with the demand curve. To reduce the gap between the production and the demand curve, as well as the sudden variations in production, the possible measure to be taken is to store the surplus production. Conventional storage by batteries, remains expensive and cumbersome, many other solutions have been proposed. In stand-alone applications, hydrogen subsystems and batteries are associated with the objective of stabilization of the energy flow from renewable sources [3, 4]. In references [5, 6], a super capacitor and battery bank were used. This configuration improves the flexibility and dynamic response of the system, but its disadvantage is the energy storage capacity compared to hydrogen systems.

The energy challenge of hybrid storage systems is the ability to management power between different parts of the system, several works on the management of hybrid systems with hydrogen subsystems have been done [7–9] and several advanced management methods have been proposed [10–13]. These advanced management methods are complex, require precise knowledge of the system and a huge computation time, which led to choose fuzzy logic as the optimal management method [14–18]. In [17], the study presents a fuzzy supervisor used to manage energy flow for a photovoltaic pumping system and a fuel cell (FC) as backup source, this method is based on controlling the FC and the motor pump speed to meet the load. The cost function doesn't come into account in the management system. In [18], the author proposes a new method based on fuzzy controller and cost function, to satisfy the energy required by the load and optimize operating cost and lifetime of the hybrid system components. Its research focuses on the hydrogen flow control and the current variations in the dc bus, by the fuzzy controller while the electrolyzer (EZ) part isn't considered.

This paper focuses on the fuzzy energy management of a hybrid system in stand-alone operation, using a photovoltaic generator as the main energy source, and a hydrogen subsystem. This fuzzy supervisor controls the power of the FC and EZ by considering the difference between the generated and load energy, the stored battery energy, and the hydrogen level.

The paper is organized as follows: the mathematical models and the main equations determining the operation of the different components of the HS are briefly described in Section 2. The HS sizing using PLP is described in Section 3. Section 4 details the proposed FEMS. The simulation, results and discussion on the HS performances using the proposed FEMS are presented in Section 5. Finally, Section 6 outlines the conclusion.

## 2. MODEL DEVELOPMENT

The studied system is a domestic stand-alone HS with solar energy as the main source, battery bank and hydrogen subsystem consisting of (water electrolyzer, fuel cell and hydrogen tank) for storage and production of energy according to the load requirements as illustrated in Fig.1.

### 2.1 PHOTOVOLTAIC PANEL MODEL

The solar generator is the essential element of the studied HS. It consists of several series-parallel connected PV modules. A single diode model is chosen to model it. The generated photovoltaic power $P_{PV}$ is given as follow [5,19]:

$$P_{PV} = V_{PV} . i_{PV} = G.A_{PV} .\eta_{PV} , \quad (1)$$

where $V_{PV}$ (V) and $i_{PV}$ (A) are the voltage and output current of a PV generator, respectively, $\eta_{PV}$ represents PV modules and DC/DC converter efficiency, $A_{PV}$ is the PV module area (m²), $G(t)$ is the irradiance (kW/m²) [19].

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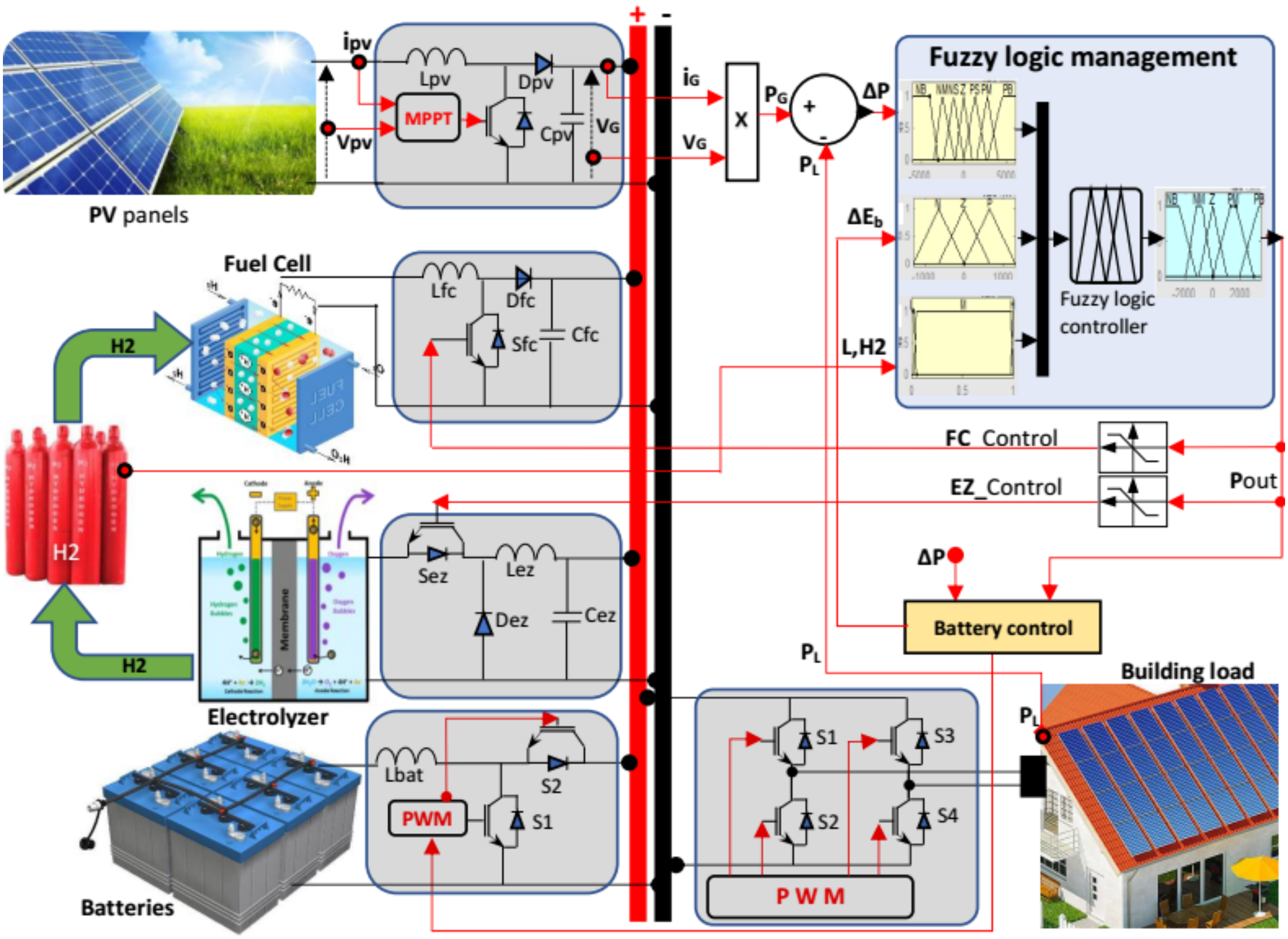


Fig. 1 – Block diagram of the proposed system.

## 2.2 FUEL CELL MODELLING

Today the fuel cell (FC) has evolved a lot. Several types of FC exist in the literature, and many research works used proton exchange membrane fuel cell (PEMFC) [20–22]. A brief presentation of the PEMFC model used in this work is given. A single FC voltage $V_{FC}$ is given in eq. (2):

$$\mathrm{V_{FC}} = E_{Nernst} - V_{ohm} - V_{act}, \qquad (2)$$

where $E_{Nernst}$ is the Nernst's instantaneous voltage, $V_{ohm}$ and $V_{act}$ are Ohmic voltage drop and activation over voltage respectively [20, 21].

The amount of the hydrogen consumed by the fuel cells $M_{FC}$ (mol/s) can be calculated by eq. (3) and eq. (4),

$$M_{FC} = \frac{i_{FC}}{2.F} \cdot \frac{1}{\mu_{FC}} .3600, \qquad (3)$$

$$\mu_{FC} = \frac{m_{H2,th}}{m_{H2,act}}, \qquad (4)$$

where $F$ is the Faraday constant (96 485 C/mol), $m_{H2,act}$ and $m_{H2,th}$ are the actual and theoretical hydrogen flow rates through the fuel cells, respectively.

In this work, it is considered that the output performance of the fuel cell module degrades at a rate of 1.1 mV/cycle. The fuel cell is replaced when it loses 33 % of its rated voltage. The number of FCs required $N_{FC}$, can be calculated by eq. (5).

$$N_{FC} = \mathrm{Roundup}\left(Life_{HS} . Life_{FC}^{pu,year} / T_{FC}^{Life}\right), \qquad (5)$$

where $Life_{HS}$ is the HS life, $T_{FC}^{Life}$ is the lifetime FC period, and $Life_{FC}^{pu,year}$ is the unit FC life at the end of the last year and *Roundup* represents the rounded-up value.

## 2.3 ELECTROLYZER MODELLING

The hydrogen produced in the EZ, $M_{EZ}$ (mol/s) is calculated using eq. (6) [22, 23].

$$M_{EZ} = \frac{\eta_F . n_c . i_e}{2.F}, \qquad (6)$$

$$\eta_F = 96.5 \exp\left(\frac{0.09}{i_e} - \frac{75.5}{i_e^2}\right). \qquad (7)$$

where $n_c$ is the number of series cells composed the EZ, and $i_e$ (A) is the EZ current.

The nominal EZ efficiency is depending on the number of working hours, according to eq. (8).

$$\eta_{EZ} = \frac{\eta_{EZ,0}}{1 + N_{h,EZ} . R_{EZ}}, \qquad (8)$$

where $\eta_{EZ,0}$, $N_{h,EZ}$ and $R_{EZ}$ are respectively the nominal efficiency of the EZ at the beginning of use, the operation hours of the EZ and the rate degradation of the EZ.

## 2.4 HYDROGEN STORAGE TANK MODELLING

A hydrogen storage tank (HST) stores the produced hydrogen via a compressor, the mathematical model of the HST and the system dynamics can be expressed by the eq. (9) [21].

$$P_{tk} \hat{=} P_{init} = z\frac{N_{H_2}.R.T_{tk}}{M_{H_2}.V_{tk}}, \quad (9)$$

where $P_{tank}$, $P_{init}$ are pressure of the storage tank and its initial value in Pascal, respectively, $z$ is the compressibility factor that depends on the pressure. $N_{H2}$, $M_{H2}$ are the hydrogen moles per second (kmol/s) and hydrogen Molar mass (kg/kmol) respectively. $T_{tank}$ is the HST temperature (°K) and $R$ is the gas constant (8.314 J/mol/K).

### 2.5 BATTERY MODELLING

The battery is an essential element and acts as an energy regulator in renewable electricity generators. In this work, the battery is used as an auxiliary element to improve the flexibility, speed, and lifetime of the PEMFC. The amount of energy stored in the battery $E_b$ can be calculated by the following equation [23].

$$E_b = \int (P_{b.ch} . \eta_b - P_{b.dis}) \mathrm{d}t, \quad (10)$$

where $P_{b.charg}$, $P_{b.discharg}$ are respectively the battery power in the case of charging and discharging, and $\eta_b$ is the battery efficiency.

The battery state of charge ($SOC$) is a function on the maximum capacity ($Q$ (Ah)) and battery current $i_b$, given by eq. (11), [24].

$$SOC(\%) = 100\left(1 - \frac{\int i_b \, \mathrm{d}t}{Q}\right). \quad (11)$$

The battery lifetime is related to the charge and discharge number of cycles and the discharge depth of each cycle. The nominal lifetime of the battery used in this work is 2500 cycles according to the datasheet [24]. The needed number of batteries, $N_B$, can be calculated in eq. (12).

$$N_B = \text{Roundup}\left(Life_{HS}.Life_B^{pu,year} / T_B^{Life}\right), \quad (12)$$

where $Life_B^{pu,year}$ is the unit life of the battery at the end of the last year, and $T_B^{Life}$ is the period since the last battery was replaced until the beginning of the current year.

## 3. HYBRID SYSTEM SIZING WITH PLP METHOD

The calculation of the amount of HST is inspired by the PLP method used for sizing a classical PV/battery system presented in [1, 4]. The method consists of computing the optimal amount of HST/PV modules needed to meet the load energy demand, with a given probability of energy loss while considering the criterion minimizing the overall cost of the system. The PLP algorithm's implementation process to give the number of PV module and HST is depicted in the flowchart shown in Fig. 2.

There are two possible cases regarding the stored energy in the HST [4]:

- If the generated PV power ($P_G$ (t)) is greater than the power load requirement ($P_L$ (t)) then the HST is supplied (calculated as an equivalent kWh) by considering the charging efficiency $\eta_{EZ}$,

$$E_{stor}(t) = E_{stor}(t-1) + \left(P_G(t) - \frac{P_L(t)}{\eta_{inv}}\right)\eta_{EZ}. \quad (13)$$

- When the power load requirement is greater than the available PV energy, then The $E_{st}$ ($t$) can be calculated

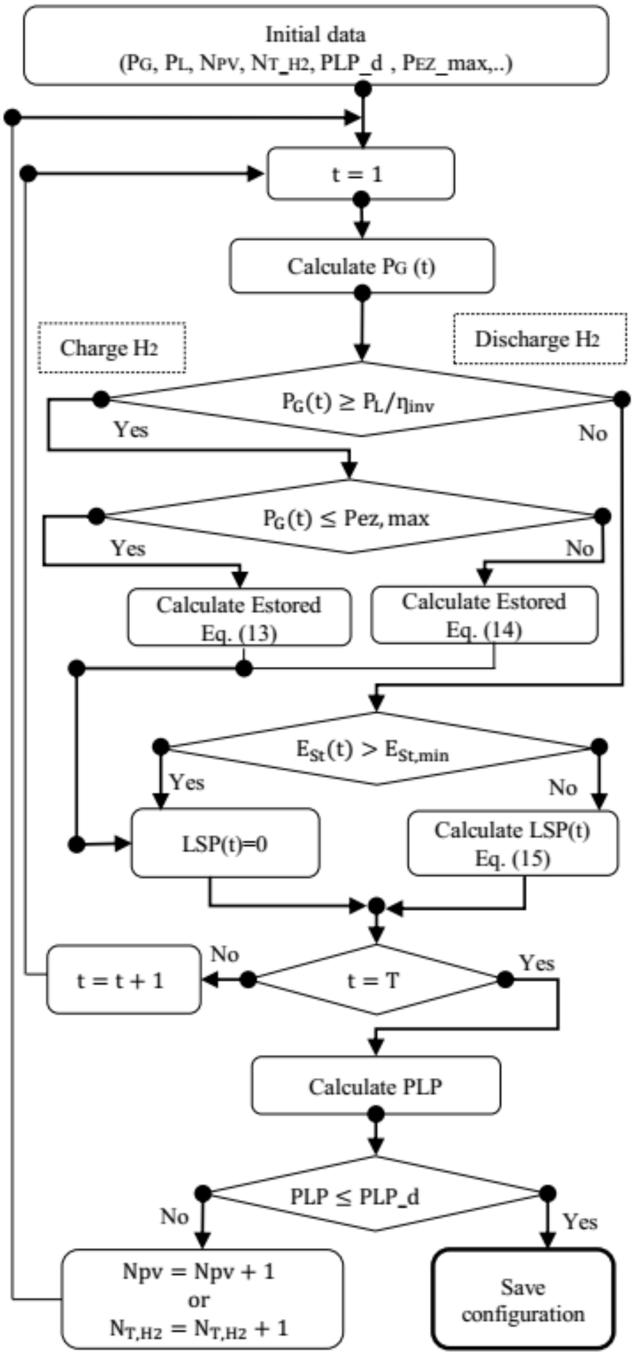


Fig. 2 – Flowchart of PLP method.

by considering the charging efficiency $\eta_{FC}$:

$$E_{stor}(t) = E_{stor}(t-1) + \left(\frac{P_L(t)}{\eta_{inv}} - P_G(t)\right) \Big/ \eta_{FC}, \quad (14)$$

where $\eta_{inv}$ is the inverter efficiency, $E_{st}$ ($t$) and $E_{st}$ ($t$–1) are the stored energy in the HST at time ($t$) and ($t-1$), respectively.

- When the stored energy in HST and the generated PV power are insufficient to satisfy the load energy demand for hour t, the standalone HS will run out of energy, this deficit is called loss of power supply (LPS) for hour t, it can be calculated as follow:

$$LSP(t) = P_L(t) - \left(P_G(t) + E_{stor}(t-1)\eta_{FC}\right)\eta_{inv}. \quad (15)$$

The final $PLP$ for a given time period T is calculated as follows in eq. (16) [6]:

$$PLP = \sum_{t=1}^{T} LSP(t) \Big/ \sum_{t=1}^{T} P_L(t). \quad (16)$$

The most relevant factor in determining the number of PV and hydrogen tank is the cost function, it is described as follows:

$$C = a.N_{PV} + b.N_{T,H2} + C_0 , \qquad (17)$$

where $a$ and $b$ are respectively the unit cost of PV module and hydrogen tank, $C$ and $C_0$ are respectively the HS total cost and installation cost.

After determining the different combinations ($N_{T,H2}$ , $N_{PV}$) satisfying a desired PLP (PLP_d), a nonlinear function is obtained $N_{PV}(N_{T,H2})$. The optimal solution of this function is obtained by its intersection with the curve of equation (17) given by the following relation [1]:

$$\frac{\partial N_{PV}}{\partial N_{T,H2}} = -\frac{b}{a} \cdot \qquad (18)$$

## 4. FUZZY ENERGY MANAGEMENT SYSTEM

The main objective of the energy management algorithm of HS is to satisfy energy demand while taking into account the lifetime of the hybrid system elements.

### 4.1 ENERGY EVOLUTION

The energy evolution along a period $\Delta t$ can be defined by eq. (19),

$$\Delta E_i(t) = \int_t^{t+\Delta t} P_i(t)\,\mathrm{d}t \cdot \qquad (19)$$

If we consider the integration and sampling periods equal, then:

$$\Delta E_i(n.\Delta t) = \int_{(n-1)\Delta t}^{n.\Delta t} P_i(t)\,\mathrm{d}t . \qquad (20)$$

FC and EZ system lifetime preservation can be optimized if the number of working hours and voltage current constraints is minimized.

The use of a fuzzy controller allowed us to adapt the FC and EZ current, according to the intermittent source and the load energy demand.

### 4.2 FUZZY ENERGY MANAGEMENT SYSTEM DESIGN

The supervisor system based on fuzzy logic (Fig. 3), takes into account the net power variation (ΔP), battery energy ($\Delta E_b$) and hydrogen level (L,H2) and controls the power of the EZ and the FC. Table. 1 shows the FEMS rule table.

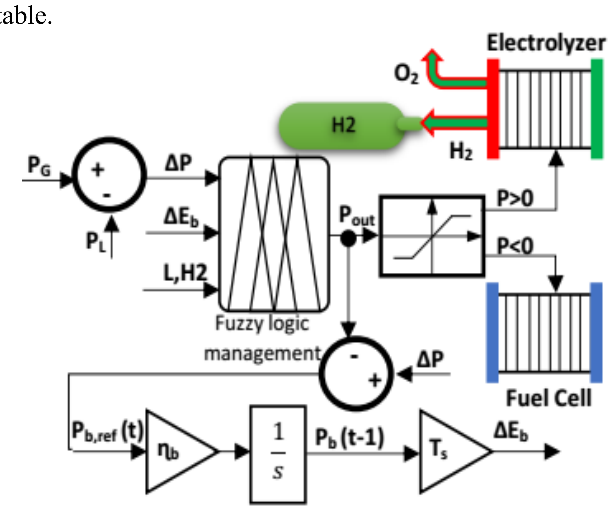


Fig. 3 – Supervisor and controlled system.

Figure. 4 shows the membership functions of the input/output fuzzy energy management system. Seven membership functions are selected in the case of the $\Delta P$, noted as NB NM, NS, Z, PS, PM and PB. $\Delta E_b$ and L, H2 inputs are divided into three linguistic variables, defined according to Fig. 4. (B) notation is used for big, (M) for medium, (S) for small, (N) for negative, (P) for positive, (Z) for zero (L) for large and (H) for high.

The inference method uses the Mamdani's procedure based on a min-max decision [19].

*Table 1*

Control rule base

| $\Delta P$ | | NB | NM | NS | Z | PS | PM | PB |
|---|---|---|---|---|---|---|---|---|
| $\Delta E_b$ | L,H2 | | | | | | | |
| N | L | Z | Z | Z | Z | Z | PM | PB |
| | M | NB | NB | NB | Z | Z | Z | PB |
| | H | NB | NB | NB | Z | Z | Z | Z |
| Z | L | Z | Z | Z | Z | PM | PM | PB |
| | M | NB | NB | NM | Z | Z | PM | PB |
| | H | NB | NB | NM | Z | Z | Z | Z |
| P | L | Z | Z | Z | Z | PM | Z | PB |
| | M | Z | Z | Z | Z | PM | Z | PB |
| | H | Z | Z | Z | Z | Z | Z | Z |

## 5. SIMULATION RESULTS AND DISCUSSION

### 5.1 RESOURCE AND CONSUMPTION DATA

Using the solar radiation data registered by meteorological station located in Algerian Renewable Energy Development Center (CDER), the hourly, daily and monthly generated energy are calculated [1], (Fig. 5). In this study, the load represents a typical day's consumption of a few houses, with a peak electrical load of 31 kWh and a yearly load of 11 MWh shown in Fig. 6.

### 5.2 SIMULATION RESULTS

MATLAB Simulink is used to simulate the studied HS with the supervision using FEMS method. In our application, the desired power loss probability is considered (PLP_d $\leq$ 0.1). Using the flowchart described in the previous section, an optimal number of hydrogen tank /PV modules are computed according to the fixed PLP_d and the load energy requirement.

The obtained results are demonstrated in Fig. 7, which correspond to an optimal couple of 155 PV (110 W polycrystalline) modules and 70 HST (9.09 gr or 300 W). The battery sizing is based on the instantaneous current and powers exchanged between the elements of the hybrid system, for an EZ of 5.5 kW, PEMFC of 3 kW and four batteries (12 V, 54 Ah).

The fuzzy management system provides power references via a FEMS, these power references are used to control the battery and EZ current via a dc/dc converter.

The storage level of hydrogen tanks during the four seasons of the year is shown in Fig. 8. A total discharge of the hydrogen tank is allowed, as the hydrogen level and the number of cycles does not influence the life of the tank. It is clear that the demand is widely satisfied, in summer and spring, the hydrogen level in most cases exceeds 40 %. However, in winter and autumn, there are days when the tank is empty.

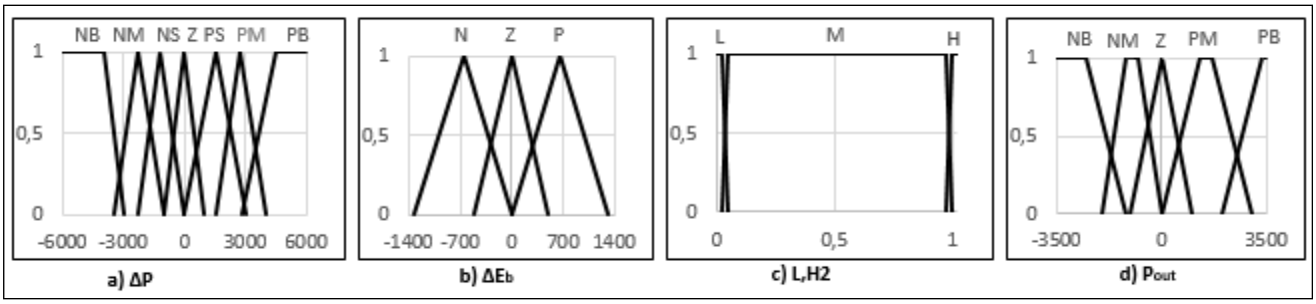


Fig. 4 – Membership functions of inputs and output.

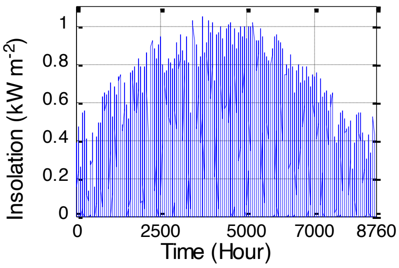


Fig. 5 – Hourly irradiation profile.

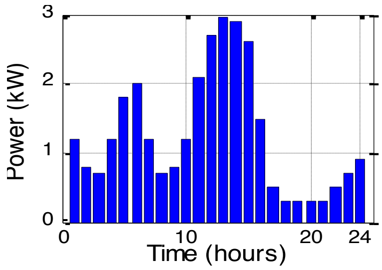


Fig. 6 – Profile of consumption.

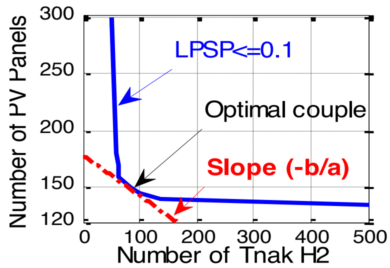


Fig. 7 – Results of LPSP simulation.

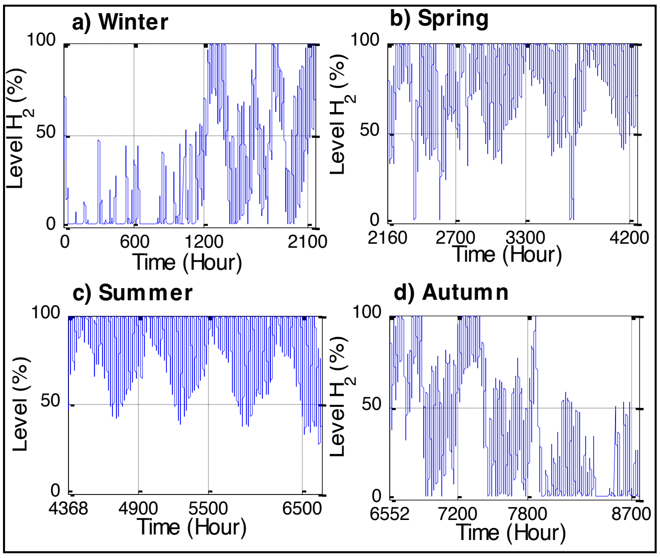


Fig. 8 – Storage level of hydrogen tanks.

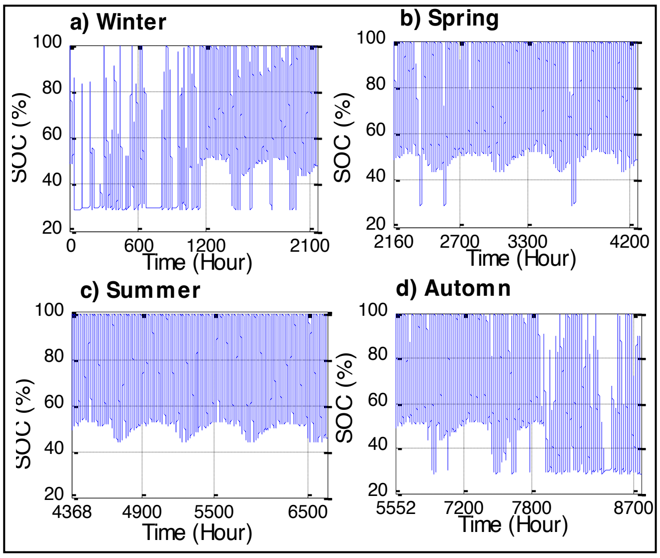


Fig. 9 – Storage level of batteries.

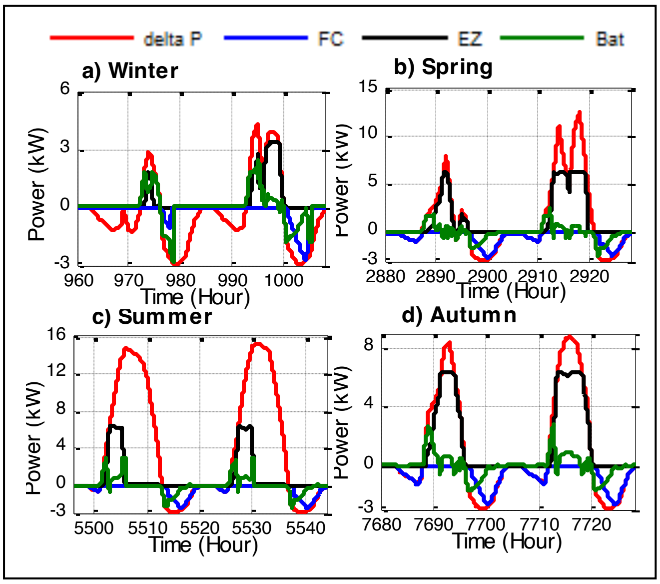


Fig. 10 – Power split between the power sources to meet the load.

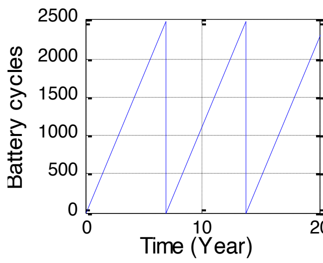


Fig. 11 – Unit life of the battery.

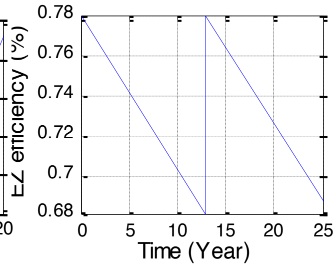


Fig. 12 – Unit life of the electrolyzer.

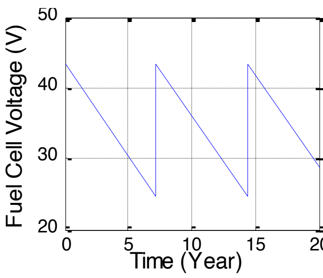


Fig. 13 – Unit life of the fuel cell.

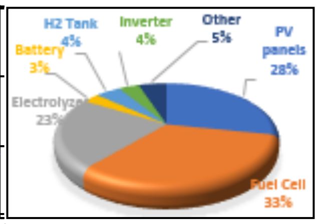


Fig. 14 – Summary cost.

The evolution of the battery SOC during the year is represented in Fig. 9. It is maintained in the range of 50 % in the most cases, and drops to 30 % in cases of very low sunlight (at the beginning and the end of the year). Figure 10 shows the evolution of the powers over 48 hours over the four seasons of the year of $\Delta P$ (difference between the generated PV and required load power), the power supplied to the EZ, the battery power and the energy generated by the fuel cells. The battery plays the role of energy damper during peak production, and it is allowed to reduce the peak currents supposed sent to EZ. On the other hand, this battery plays the role of energy compensator during strong demands and allows sharing most of the charging power with the PEMFC. The lifetime of the battery is shown in Fig. 11 which is directly dependent on the number of charge and discharge cycles and the depth of discharge. The EZ and PEMFC unit lifetime is shown in Figs. 12 and 13, respectively. When the PEMFC reaches a nominal voltage below 18 % of the nominal voltage at the start of use, the element is replaced. For the EZ, it will be replaced when it reaches a nominal efficiency of 68 %. The costs of the different components of the studied HS are summarized in Fig. 14.

## 6. **CONCLUSION**

The paper proposes a Fuzzy energy management system FEMS for an HS including PV generator, fuel cell, electrolyzer and battery bank. The HS sizing is ensured by a proposed PLP methodology, which calculates the optimal size of the HST and the PV modules for a given load and reliability level. FEMS allows intelligent control of battery and EZ currents, and then increases system life by limiting high current stress and meeting load requirements even during PV source fluctuations. Local controls are used to extract maximum power from the PV generator, satisfy load requirements via inverter and control the battery charge and discharge. The simulation results showed load requirement satisfaction by respecting the lifetime/cost ratio of each component, which allows the reduction of HS system total cost. Over a lifetime of 20 years, which corresponds to the lifetime of the PV generator, the fuel cells will be changed twice, while the EZ and the battery bank need to be changed three times. The flexibility and the robustness of the FEMS makes the hydrogen system more reliable and competitive.

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