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Application of fuzzy logic for the management of electrical energy consumed by a heat pump for classroom heating

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Abstract

This paper presents a modeling of the energy management of a thermal energy system of a building equipped with a hybrid generation system with an energy storage unit, a heat pump and storage, heating equipment, and distribution of heat energy. However, the designed system provides heat energy to a classroom and is under a fuzzy controller managing the energy flows. The control strategy aims to manage the power flow through the heat pump based on its power demand and the storage bank's constraints. The proposed energy management algorithm is based on fuzzy logic. The implementation and simulation of the algorithm have been tested in the Matlab/Simulink environment. The results show that this approach is valid and can be a solution for future smart grid communication between buildings and public networks and contribute to a better balance between production and consumption and future energy management.

Keywords — *Fuzzy logic, management, heating, building, heat pump*

I. INTRODUCTION

A building is an artificial construction used to accommodate people or activities to ensure comfort in the face of climatic severity. Its external envelope surrounds the building and gives it a role as a thermal filter to recreate an indoor microclimate independently of external climatic hazards. The shape, orientation, and composition of the constituent elements determine the characteristics of this filter. The latter minimizes heat exchange, protects the human body against climatic aggressions. In its role of shelter, a building marks a physical separation of the man's habitat between inside and outside. But alas, this separation does not always give place to interior environments that fully meet the occupants' comfort requirements. For this purpose, the building's response is corrected by air conditioning or heating devices acting as controlled sources of heat or cold and sometimes affecting the humidity level. This quest for comfort, which, moreover, is the satisfaction expressed concerning the thermal environment of the surrounding environment, causes a significant consumption of energy, inducing air pollution, global warming, etc. On the other hand, with this situation, several solutions are emerging to reduce energy consumption, including the optimal management of energy sources. Thus, a review of the scientific literature reveals several energy management methods, from the simplest to the most complicated, through the most intelligent close to human reasoning, namely fuzzy logic. Considering the advantages of fuzzy logic, this method is chosen in this article because of its proximity to human reasoning, its simplicity in programming, its flexibility in implementing and managing complex systems.

Formalized in the United States by Professor Lofti Zadeh in1965, fuzzy logic is a mathematical theory of fuzzy sets representing an extension of the theory of classical sets to imprecisely defined sets. It finds its applications in many different and varied fields, including electrification and intelligent micro-grids [1][2][3], in agriculture, in this case, the pumping of water [4][5][6], residential use [7][8], etc. Most of these applications are used in power generation optimization using the Perturb and Observe algorithm or any other [6]. Concerning the fuzzy management of a multi-source system, in general, the input variables considered are the SOC and the photovoltaic power. The decision variables used can be wind, sunshine, and SOC [3]. In pumping, we often use the SOC, the photovoltaic power produced, and the water level of the storage tank as input variables in the management algorithm [4] or, we always associate in the context of pumping of water, input variables such as sunshine, temperature, error, and SOC [5]. In our studied case of the autonomous domestic heating system, the decision input variables are the SOC, the photovoltaic power P_{pv}, the wind power Pw and the load's PL profile, in this case, that of the heat pump.

This article has the particularity of devoting itself to the intelligent management of a hybrid energy source with storage batteries consumed by a heat

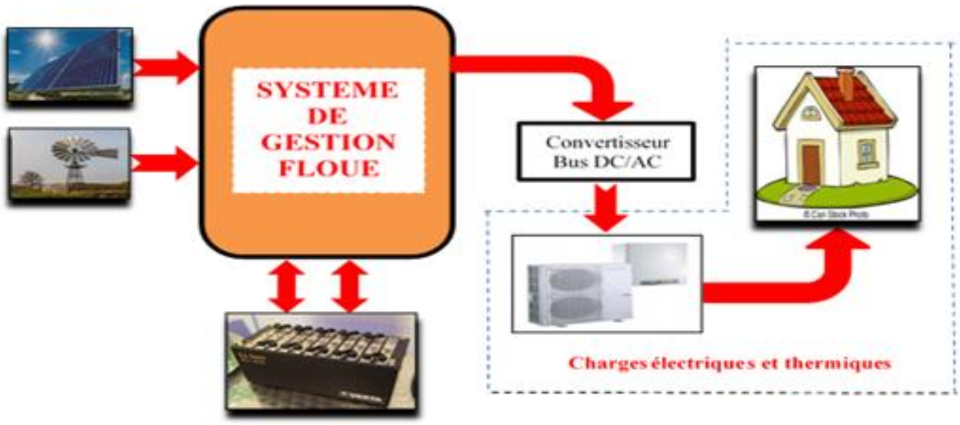


Fig.1: Architecture of the studied system

Pump. A fuzzy, simple, and easy controller allows the first party to determine the different operating variants of the energy generation system according to the meteorological conditions. The second part maintains the state of charge of the batteries to prevent a breakdown and prolong the battery discharge time. The model is implemented under Matlab/Simulink. The application is made for an isolated building powered by a hybrid system with a battery storage unit. In addition to this fuzzy controller, a discrete control system is used to control the heat pump according to the temperature difference between the set temperature and the temperature measured in the building. To achieve the organization of this paper presents the modeling of the system's different components, the fuzzy management algorithm strategy, the results of the simulations, and finally a conclusion.

II. MODELING OF SYSTEM

Our energy system's global architecture includes a building, a local renewable energy generation system (photovoltaic generator, wind generator and storage batteries), a heating system, and a digital controller. The electric generators and the storage bench primarily supply the heat pump for heating needs in winter, then the current functional loads. To develop the management algorithm, models of system components are required.

A. Model of building

The thermal modeling of a building is interested in the representation of the temperatures of the latter. Despite its thermal inertia, it suffers the external environment's impact because of the circulation of air and heat exchange with the walls and facades. The thermal model is intended to predetermine the thermal behavior of a building. The literature review follows that a second-order RC model is largely sufficient to predict a building's behavior during heating. Two temperature knots are considered, namely, the indoor air temperature of the building and the walls' temperature. It is thus the application of the Kirchoff law to each node makes it possible to obtain a system with two equations with two unknowns, which is written in the form defining the model used:

$$[C]\frac{d[T]}{dt}=[A].[T]+[B].[U] \quad (1)$$

Where [T] vector of temperatures, [U] vector of solicitations, [C] matrix of capacitances, [A] matrix of conductances et [B] matrix of control.

L = 10m of length, l = 6.5m of the width and h = 3m the height under ceiling, the studied building is a classroom of the capacity of reception of 31persons. Its occupation profile is supposed to be that of the students' moment of presence, from 8h to 13h and from 14h to 18h. The rest of the time, she is unoccupied. Twelve luminous ceiling boxes provide the lighting with four fluorescent lamps of 18W per box.

B. Heat pump model

The heat pump acts as heating equipment. It is a thermal machine whose thermodynamic system allows the transfer of heat from a medium to a lower temperature where the heat is taken (cold source) to a medium at a higher temperature where it is rejected (hot source). For this study, the model of a heat pump used is the model developed by Jong et al. [9][10].

$$\begin{cases} COP=k_1\dfrac{0,5T_{co,e}+0,5T_{co,s}+273,13}{\left(0,5T_{co,e}+0,5T_{co,s}\right)-\left(0,5T_{ev,e}+0,5T_{ev,s}\right)} \\ C_{co}\dfrac{dT_{co,s}}{dt}=m_{co,e}Cp\left(T_{co,e}-T_{co,s}\right)+COP.Ehp \\ C_{ev}\dfrac{dT_{ev,s}}{dt}=m_{ev,e}Cp\left(T_{ev,e}-T_{ev,s}\right)-\left(COP-1\right).Ehp \end{cases} \quad (2)$$

Where, k_1 heat pump performance determined from measurements at the test site (K_1 = 0.4), C_p (J/K) specific heat capacity of water, C_{co}, C_{ev} (J/K) respective thermal capacities of the condenser and the evaporator, $T_{co,e}$, $T_{co,s}$ (°C) respective temperatures of the inlet and the outlet of the condenser, $T_{ev,e}$, $T_{ev,s}$ (°C) respective temperatures of the inlet and outlet of the evaporator and Ehp (W) electrical power of the heat pump.

C. Model of the photovoltaic generator

In this study, we are interested in a simple photovoltaic generator model to calculate only the power Ppv (kW) produced by the photovoltaic system. It is expressed as a function of the area of the A_{pv} system (m^2), its efficiency η_{pv} and incident solar radiation G_T (W/m^2) [11]:

$$P_{pv} = \eta_{pv} A_{pv} G_T \tag{3}$$

Where Apv (m^2) represents the area of the photovoltaic generator, G_T (W/m^2) is the illumination and ηpv represents the overall efficiency of the latter, and it is given by [11]:

$$\eta_{pv} = \eta_r \eta_{pc} \left[1 - \beta \left(T_c - T_{cref} \right) \right] \tag{4}$$

Where η_r is the PV module's reference efficiency, it is chosen equal to 13% for polycrystalline silicon modules. η_{pc} represents the efficiency characterizing the influence of the load (degradation factor). Here it will be equal to 0.9 [14]. β is the coefficient of the influence of the photovoltaic cells' temperature on the efficiency of the generator between 0.004 and 0.006 per degree Celsius. T_c is the temperature of the cell, T_a (°C) is the ambient temperature, T_{anoct} (°C) represents the cell temperature under Normal Operating Cell Temperature (NOCT) conditions. T_{cref} is the reference temperature between 40 and 50°C.

D. Model of wind generator

Several models of wind generators exist in the literature. The model chosen is a very simple model of the wind generator characterized by its electrical output power governed by equation (4) below [13]:

$$P_e = \frac{1}{2} C_p \eta_g \eta_m \rho A_w v^3 \tag{5}$$

Where η_g and η_m are the conversion efficiency of the generator, the conversion efficiency of the turbine, C_p is the nominal power factor of the turbine, A_w (m^2) is the total area swept by the rotor, the density of the turbine air and wind speed.

E. Model of storage batteries

The batteries are used to meet the load demand in times of unavailability or insufficient energy in the renewable energy production system. The dynamics of battery operation are characterized by the charging and discharging cycle. When photovoltaic generators' production is greater than the load demand, the capacity of the bank of batteries available at time t is charged. On the other hand, when the demand for the charges is greater than the available energy generated, the bank of batteries is in a state of discharge. Therefore, the storage bank is characterized by the parameter called charge rate or State of Charge (SOC) and is determined by the expression:

$$SOC(t) = SOC_0 + \int_{t0}^{t} \frac{I_{bat}(t)\,dt}{Q_{bat}} \tag{6}$$

Where SOC is the state of charge of the batteries (%), SOC_0, the initial state of charge of the battery (%), Q_{bat} is the maximum capacity of the batteries (Wh). In this system, the battery is modeled according to deep-cycle lead-acid batteries' characteristics, with discharge efficiency assumed to be 95%.

III. ALGORITHM FOR GLOBAL MANAGEMENT OF THE SYSTEM

A. Management strategy

The autonomous local source management strategy meets the energy demand of the load under varying weather conditions and manages the power flow while ensuring efficient system operation and constant DC bus voltage maintenance. This strategy relies on using the powers generated and stored in the batteries to meet the load demand. For better functionality of the production and storage systems, a supervision and management system based on fuzzy logic has been designed. A fuzzy multi-input/output intelligent controller is developed in the Matlab/Simulink software environment. It includes four inputs and four outputs, providing signals to electronic switches to the load and storage batteries. The controller is configured to establish rules as determined by all possible modes of operation of the system with constraints initially fixed to the system, as the photovoltaic is the priority source to power the heat pump and that when the sunshine is strong, photovoltaic power powers the heat pump and other loads.

B. Fuzzy management algorithm

The powers produced by renewable sources, the power consumed by the heat pump, and the state of charge SOC batteries constitute our fuzzy algorithm's input variables. Its implementation is based on four main elements: the knowledge base, fuzzification, rules of inference, and defuzzification.

1) Base of knowledge

The knowledge base is generated on the specification analysis base:

- State of charge of the batteries SOC

It consists of three fuzzy sets that cover the interval S = [0, SOC_{max}] at Low, Medium, and High production levels, respectively, and verify:

(7)

$$\forall s \in S, \quad \mu_{sL}(s)+\mu_{sM}(s)+\mu_{sH}(s)=1$$

Where $\mu_{sL}(s)$, $\mu_{sM}(s)$, and $\mu_{sH}(s)$ are respectively the Low, Medium, and High membership functions of the SOCs.

- Photovoltaic power P_{pv}

The generated photovoltaic power is periodically measured and partitioned into two fuzzy sets, respectively, covering the interval X = [0, Ppvmax] at the low and high generation levels.

$$\forall x \in X, \quad \mu_{xL}(x)+\mu_{xH}(x)=1 \tag{8}$$

Where, $\mu_{xL}(x)$ et $\mu_{xH}(x)$ are respectively membership functions Low and High P_{pv} x.

- Wind power P_w

The generated wind power and photovoltaic power are subdivided into two fuzzy sets that cover the interval Y = [0, Pwmax] at the low and high generation levels.

$$\forall y \in Y, \quad \mu_{yL}(y)+\mu_{yH}(y)=1 \tag{9}$$

Where $\mu_{yL}(y)$ et $\mu_{yH}(y)$ are membership functions Low and High P_w y.

- Load power P_L

The load power is partitioned into two fuzzy sets covering the Z = [0, PLmax] interval at the Small and Big generation levels, respectively.

$$\forall z \in Z, \quad \mu_{zS}(z)+\mu_{zB}(z)=1 \tag{10}$$

Where $\mu_{zS}(z)$ et $\mu_{zB}(z)$ are membership functions Small and Big P_L z.

- Relay

To decide on switching the relays K_{b0}, K_{b1}, K_{pv} and K_w according to the fuzzy variables s and x, two fuzzy sets are provided O = (On, Off). They cover the domain O = [0, 1] and verify whatever the element o belonging to the set O:

$$\begin{aligned} &\mu_{off\,K_{b0}}(o)+\mu_{on\,K_{b0}}(o)=1 \\ &\mu_{off\,K_{b1}}(o)+\mu_{on\,K_{b1}}(o)=1 \\ &\mu_{off\,K_{PV}}(o)+\mu_{on\,K_{PV}}(o)=1 \\ &\mu_{off\,K_{W}}(o)+\mu_{on\,K_{W}}(o)=1 \end{aligned} \tag{11}$$

The switching commands given to the relays are provided by the membership functions corresponding respectively to K_{b0}, K_{b1}, $K_{pv,}$ and K_w evaluated in o.

2) ***Fuzzification***

- State of charge of the batterie SOC

The membership functions of $\mu_{sL}(s_{ok})$, $\mu_{sM}(s_{ok})$ et $\mu_{sH}(s_{ok})$ corresponding to SOC are expressed:

$$\mu_{sL}(s_{ok}) = \begin{cases} 1 & \text{if } 0 < s < s_{sBmin} \\ \dfrac{s_{ok}-s}{\varepsilon_{ok}} & \text{if } s_{sBmin} < s < s_{sBmax} \\ 0 & \text{otherwise} \end{cases} \tag{12}$$

$$\mu_{sM}(s_{ok}) = \begin{cases} \dfrac{s-s_{ok}}{\varepsilon_{s_{ok}}} & \text{if } s_{sMmin1} < s < s_{sMmin2} \\ 1 & \text{if } s_{sMmin2} < s < s_{sMmax1} \\ \dfrac{s_{ok}-s}{\varepsilon_{s_{ok}}} & \text{if } s_{sMmax1} < s < s_{sMmax2} \\ 0 & \text{otherwise} \end{cases} \tag{13}$$

$$\mu_{sH}(s_{ok}) = \begin{cases} 1 & \text{if } s > s_{sHmax} \\ \dfrac{s-s_{ok}}{\varepsilon_{ok}} & \text{if } s_{sHmin} < s < s_{sHmax} \\ 0 & \text{otherwise} \end{cases} \tag{14}$$

- Photovoltaic power P_{pv}

The membership functions of $\mu_{xL}(x)$ et $\mu_{xH}(x)$ corresponding to P_{pv} are expressed as follows:

$$\mu_{xL}(x_{ol}) = \begin{cases} 1 & \text{if } 0 < x < x_{xFamin} \\ \dfrac{x_{ol}-x}{\varepsilon_{ol}} & \text{if } x_{xFamin} < x < x_{xFamax} \\ 0 & \text{otherwise} \end{cases} \tag{15}$$

$$\mu_{xH}(x_{ol}) = \begin{cases} 1 & \text{if } x > x_{xFomax} \\ \dfrac{x-x_{ol}}{\varepsilon_{ol}} & \text{if } x_{xFomin} < x < x_{xFomax} \\ 0 & \text{otherwise} \end{cases} \tag{16}$$

- Wind power P_w

The membership functions of $\mu_{yL}(y)$ et $\mu_{yH}(y)$ corresponding to P_w are expressed as follows:

$$\mu_{yL}(y_{om}) = \begin{cases} 1 & \text{if } 0 < y < y_{yFamin} \\ \dfrac{y_{om}-y}{\varepsilon_{om}} & \text{if } y_{yFamin} < y < y_{yFamax} \\ 0 & \text{otherwise} \end{cases} \tag{17}$$

$$\mu_{yH}\left(y_{om}\right)=\begin{cases}1 & \text{if } y>y_{yFomax}\\ \dfrac{y-y_{om}}{\varepsilon_{om}} & \text{if } y_{yFomin}<y<y_{yFomax}\\ 0 & \text{otherwise}\end{cases} \quad (18)$$

- Load power P_L

The membership functions of $\mu_{zS}(z)$ et $\mu_{zB}(z)$ corresponding to P_L are expressed as follows:

$$\mu_{zS}\left(z_{on}\right)=\begin{cases}1 & \text{if } 0<z<z_{zPmin}\\ \dfrac{z_{on}-z}{\varepsilon_{on}} & \text{if } z_{zPmin}<z<z_{zPmax}\\ 0 & \text{otherwise}\end{cases} \quad (19)$$

$$\mu_{zB}\left(z_{on}\right)=\begin{cases}1 & \text{if } z>z_{zGmax}\\ \dfrac{z-z_{on}}{\varepsilon_{on}} & \text{if } z_{zGmin}<z<z_{zGmax}\\ 0 & \text{otherwise}\end{cases} \quad (20)$$

- Relay switching control

The membership functions of $\mu_{off\ Kbo,\ Kb1,\ Kpv,\ Kw}(0oz)$ et $\mu_{on\ Kbo,\ Kb1,\ Kpv,\ Kw}(0oz)$ relay corresponding to the relays K_{b0}, K_{b1}, K_{pv} et K_w are expressed as follows:

$$\mu_{off\,K_j}\left(o_{oz}\right)=\begin{cases}1 & \text{if } 0<o<o_{offmin}\\ \dfrac{o_{oz}-o}{\varepsilon_{ooz}} & \text{if } o_{offmin}<o<o_{offmin}\\ 0 & \text{otherwise}\end{cases} \quad (21)$$

$$\mu_{on\,K_j}\left(o_{oz}\right)=\begin{cases}1 & \text{if } o>o_{onmax}\\ \dfrac{o-o_{oz}}{\varepsilon_{o0z}} & \text{if } o_{onmin}<o<o_{onmax}\\ 0 & \text{otherwise}\end{cases} \quad (22)$$

Avec $K_j = K_{b0}, K_{b1}, K_{pv}$ ou K_w

3) Rules of inference

Based on fuzzified inputs, the rule set is used to determine the relay switching control derived from the modes previously explained. The relay control signals are given below:

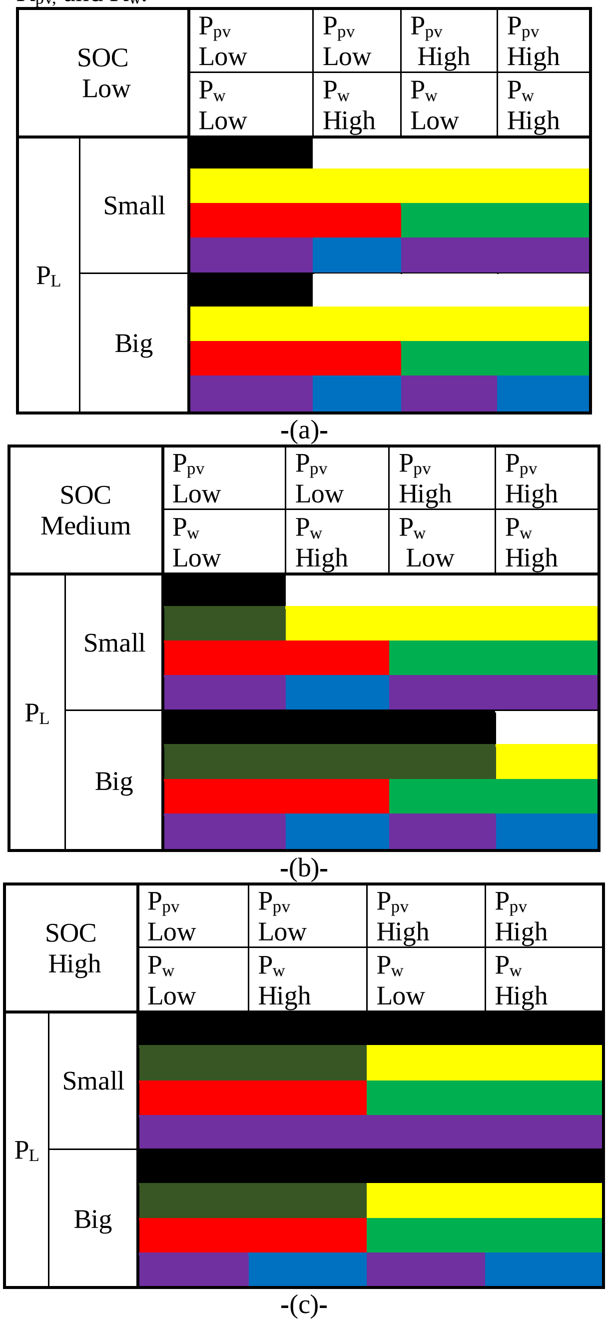
$$K_{b0,b1,PV,W}=\frac{\int_0^1 K_{on}\mu_{b0on}\,dK_{on}}{\int_0^1 \mu_{b0on}\,dK_{on}} \quad (23)$$

4) *Defuzzification*

Relay control is deduced by:

$$\begin{aligned}&\text{If } K_{b0,b1,PV,W}<0{,}5 \text{ then } K_{b0,b1,PV,W} \text{ is Off}\\ &\text{If } K_{b0,b1,PV,W}>0{,}5 \text{ then } K_{b0,b1,PV,W} \text{ is On}\end{aligned} \quad (24)$$

Table.1 defines the fuzzy controller's rule base where the matrix inputs are fuzzy sets of the state of SOC batteries, the photovoltaic and wind power respectively P_{pv} and P_w, the profile of the PL charges. This table's output is the state of four relays, K_{b0}, K_{b1}, K_{pv}, and K_w.



(black)	K_{b0} is off	(red)	K_{pv} is off
(white)	K_{b0} is on	(green)	K_{pv} is on
(yellow)	K_{b1} is off	(purple)	K_w is off
(grey)	K_{b1} is on	(blue)	K_w is on

-(d)-

Table.1: -(a)-, -(b)- et –(c)- Controller rule base, -(d)- Command legend

SOC (%)	Low	Medium	High
	0 – 30	30 – 90	90 – 100
P_{pv} (W)	Low		High
	0 - 300		300 – 1400
P_w (W)	Low		High
	0 – 300		300 - 1400
P_L (W)	Small		Big
	0 – 500		500 - 1600

Table.2: Controller inputs parameters

IV. SIMULATION RESULTS

The energy source management algorithm, implemented in the Matlab/Simulink environment, has been implemented and tested by simulations using climate data. The simulation carried out corresponds to a heating period of one day, consecutive to the sunny, moderately sunny, and cloudy winter in Créteil. The results obtained (Fig.1-3) prove that the algorithm fulfills the objectives: relay switching ensures the system's autonomy. Thermal comfort is satisfied. The heat pump and the batteries are properly disconnected when not in use. The photovoltaic and wind power generated, the state of charge of the batteries, and the heat pump's solicitation constitute the input variables of the algorithm. The fuzzy approach imposes subdivisions of input and outputs variables, as shown in Table.3. The results of the defuzzification of the fuzzy controller are the membership functions. The values of the latter fluctuate between 0 and 1. Their behavior follows the meteorological data and the state of charge of the batteries. Indeed, the energy profile of the load varies during the day (Fig.1-3). The membership functions' analog signals are converted to square digital signals controlling the respective electronic switches of the available power sources supplying the load.

The energy demand is important and constant at the beginning of the heating in between 0:00 to 8:00. It varies and, at times, vanishes between 8:00 and 18:00 and becomes almost constant beyond 18:00. When the sun shines, the energy demand is less important because the solar flux contributes to the building's heating in sunny weather, but this is not valid for a cloudy sky. The bulk of solar panel production is used for charging batteries and a low for powering the cap. At nightfall, photovoltaic production vanishes. The storage bench and wind turbine continue to serve the load alone. The heat pump's daily energy consumption and the different proportions of sources are summarized and illustrated in the tables and figures. Finally, whatever the type of sky (sunny, moderately sunny, or cloudy), the energy need is important at the beginning of heating, corresponding to the moments between 0h to 8h. The solicitation of the heat pump remains constant. Only the wind turbine and the batteries respond to this request. In these moments, the solar flux is zero. At 60% of the charge, the batteries are discharged up to 36.35% of its state, and then they recharge from 9h20 when the sun is sufficient.

The use of different meteorological situations presents the results of the heat pump's daily energy consumption, illustrated by the histogram of Fig.4. These weather conditions, sunny skies, moderately sunny skies, and cloudy skies, the present daily electricity consumption of 17.60KWh, 18KWh, and 18.40KWh, respectively. The proportions of each energy source are variable. The batteries are the most stressed, and they feed the cap at 50% of its consumption and whatever the sky. Then the wind turbine provides 40% of the consumption of the heat pump. Finally, photovoltaics contributes to 9.07% of the heat pump consumption in sunny weather but 0% in cloudy or moderately sunny weather. It follows from this analysis that a sunny sky is beneficial for the heating of the classroom. The solar flux contributes greatly to the calorific need of the room. As a result, the heat pump is not very busy during the day, and its power consumption is lower. Most of the photovoltaic production is used for charging the batteries.

V. CONCLUSIONS

This paper studies energy management, supplying a heat pump for heating a classroom equipped with a hybrid system with storage batteries. A management algorithm based on fuzzy logic is developed and implemented in a controller. The latter manages and simultaneously transmits energy to the heat pump according to its demands. Depending on the input variable states, the control signals are generated according to the controller's basic rules. These signals received by the electronic switches allow the change of position of the relays from 0 to 1 or vice versa. Simulation results show good performance and satisfaction of load requests at any time by different sources. Finally, it can be said that the combination of variable sources managed by a fuzzy controller ensures continuity of production. As a result, this management ensures significant electricity savings from the grid if it served the classroom.

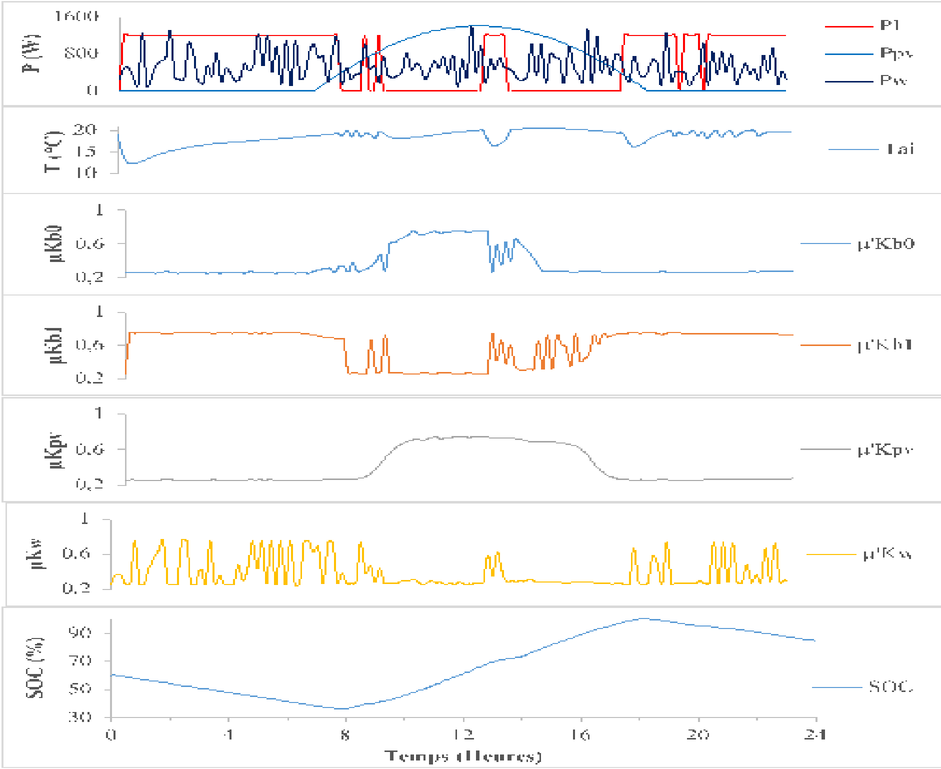


Fig.1: Algorithm response in the case of sunny weather

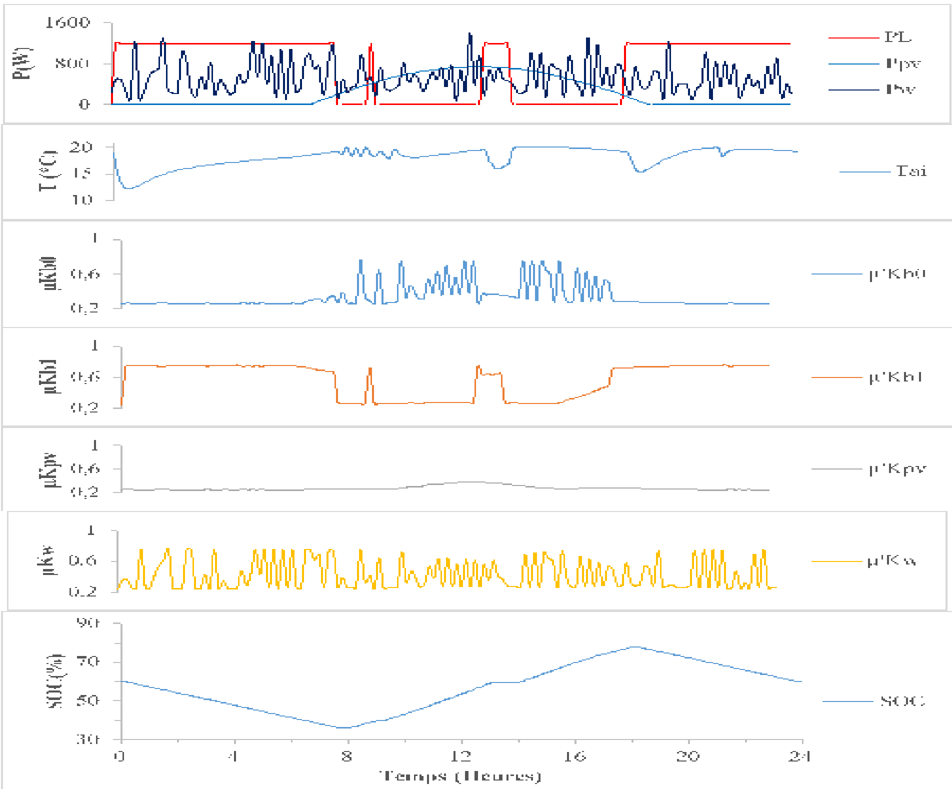


Fig.2: Algorithm response in the case of a moderately sunny sky

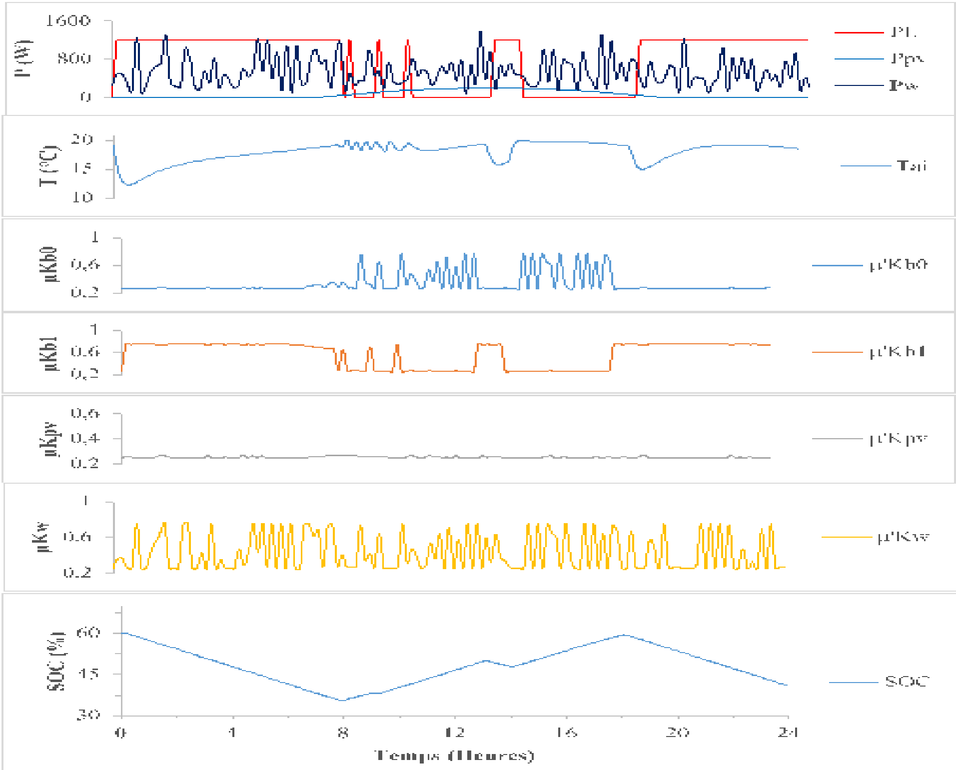


Fig.3: Algorithm response in the case of a cloudy sky

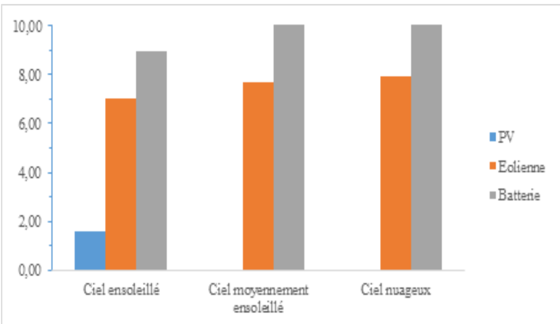


Fig.4: Histogram of the daily energy consumption of a heat pump

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