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Fuzzy logic control of a hybrid PV/battery/diesel generator system integrated in an electrical network: case study of City of Douala

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ABSTRACT

The control of hybrid systems is a considerable challenge for the energy supply to consumers. For this purpose, this study implemented an intelligent control for a hybrid system connected to the electrical grid to meet the energy demand of a building in the city of Douala, Cameroon. In this work, an intelligent management system using fuzzy logic is proposed to overcome the challenges of this multi-source integration. The proposed method based on a fuzzy logic controller makes it possible to optimize the performance of the energy sources used with a coordination system. Thus, it makes it possible to adjust in real time the system control process based on climatic conditions and the characteristics of the storage devices in order to provide an adequate adaptive control strategy. Furthermore, this system effectively balances the energy supply from all sources. MATLAB/Simulink software and real building data are used to simulate the proposed intelligent management strategy. The results obtained indicate that energy is efficiently supplied to consumers with efficiency of 98% and reduction of fuel consumption of 45% based on the availability of the sources, thus demonstrating the benefits of the control strategy based on fuzzy logic for balanced system operation.

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1. INTRODUCTION

Electrical energy is crucial for industrialization and economic development of countries [1]. In addition, energy consumption is continuously increasing, which represents a major challenge for electrical energy suppliers [2]. Thus, several hybrid energy generation systems are used, including photovoltaic (PV)/diesel systems, PV/wind systems, PV/diesel/wind systems and PV/battery/diesel systems [3]. In addition, many control strategies have been developed, including conventional controls, proportional integral derivative (PID) controls, optimal controls, meta-heuristic controls and intelligent controls [4], [5]. These different hybrid systems make it possible to provide energy to users in a stable and economical manner. Thus, consumers have the possibility to use several energy sources including conventional sources as coal, fuel oil, and natural gas to renewable alternatives, including solar, wind, and hydropower. In addition, these hybrid systems include inverters, rectifiers, storage devices and a control platform ensuring efficient management of the supply of electrical energy to users [6]. Inverters convert the direct voltage of batteries into alternating voltage that can supply consumers. The rectifier converts the alternating voltage from diesel generators and the public network into direct voltage for recharging the batteries. Batteries allow energy to be stored in chemical form [7].

To achieve the objectives of optimal control and reduction of operational cost in the electrical network, optimization techniques are used based on functional constraints. Therefore, in order to achieve optimal intelligent control in a hybrid system connecting a multitude of conventional and renewable energy sources while considering the uncertainties and global constraints of the system, several optimization strategies have been proposed including: adaptive dynamic programming, mixed integrated linear programming (MILP), model predictive control (MPC), robust control, genetic algorithm (GA), operations research, artificial neural network (ANN), gray wolf optimization (GWO), cuckoo search algorithm (CSA), particle swarm optimization (PSO), jaya algorithm (JA), quadratic maximization algorithm (QMA), harmony search algorithm (HS), sliding model control, ant colony optimization (ACO), bee colony algorithm (ABC) and many others [8]-[11].

2. RELATED WORKS

Numerous studies have explored the implementation of integrated energy production systems. Rekioua *et al.* [12] proposed the use of an intelligent control and management system for the power of energy sources. This system allows for the prediction and adjustment of system operating processes based on climatic conditions and dynamic control methods. MATLAB software is used with an RT-LAB simulator to obtain experimental results demonstrating the reliability and applicability of the proposed strategy. The results obtained demonstrate the advantages of the proposed strategy in the balance and operational security of the network. Zhang *et al.* [13] proposes a real-time strategy for the dynamic management of energy that explicitly accounts for system uncertainties. In this approach, the operation of the hybrid system is framed as an optimal-control problem, where several performance indicators are enforced as constraints. To identify the best control actions, the authors implement a reinforcement-learning algorithm that iteratively converges on the optimal solution. A typical hybrid system is used to apply the proposed method with a large amount of data to train the algorithm and obtain the control parameters. The simulation results demonstrate that the proposed approach provides better control and neck reduction of nearly 14.17% compared to other methods.

Aziz *et al.* [14] studied a PV/diesel/battery hybrid system combining a hybrid dispatch strategy, load tracking and charging cycle. HOMER software is used for optimization analysis through a techno-economic and environmental study including a combined load dispatch strategy and charging cycle. The simulation results show that the combined dispatch strategy gives a net present cost and energy cost of $110.191 and $0.21/kWh respectively. Su *et al.* [15] compared several artificial intelligence (AI) applications in hydrogen-based renewable energy hybrid systems. In addition, a case study was implemented on the climate and load data in Tikanlik City, Xinjiang, China. The experimental results show that 99.32% of the relative error of the test data is less than 3%, thus proving that this model can achieve good prediction results.

Talaat *et al.* [16], investigated the integration of renewable hybrid systems using AI in microgrids. Furthermore, the authors studied the integrated systems, integration schemes, requirements, and communication challenges in microgrids. A case study is conducted on a real microgrid integrating renewable sources using AI. In addition, several optimization algorithms are combined with ANNs. The simulation results show that the PSO reaches a normalized mean square error (NMSE) value of 1.10% in 3367.50s. Esan *et al.* [17] presents a new approach to assessing a hybrid energy system's dependability by utilizing the HOMER simulation platform's optimal sizing features. A case study centered on Lade II, a small town in Kwara State, Nigeria, serves as the foundation for the investigation. The daily energy usage in this context is stated to be 171 kWh for residential demand and 2.5 MWh for business customers. With values of 0.769 MW, 0.594 MW, and 0.419 MW corresponding to setups with zero, one, and two diesel generators, respectively, the simulation results show a gradual decrease in load loss. Furthermore, the load loss probability, load loss expectation and total expected load losses are $5.76*10^{-8}$, $5.0457*10^{-4}$hour/year and 0.025344W respectively.

A techno-economic study for a hybrid renewable energy system in Simboya village, Tanzania's Mbeya district, was presented in [18]. The hybrid renewable energy system connected to loads was operated using HOMER software and the GWO approach. Half of the daily demand, or 30 kW, is represented by the residential load profile. According to HOMER software's optimization results, the system's energy costs are $0.1109/kWh, and its total net present cost is $106,383.50. These results show the economic and environmental benefits of renewable resources for the electricity supply of the selected areas and across the world. Kumaravel and Ashok [19] proposed a solar PV/wind hybrid energy system. In this work, solar and wind are used as primary energy sources and batteries are considered for storage to meet the primary load demand. Furthermore, a multi-layer neural network structure is used to achieve the maximum power by considering the intermittent and non-linear nature of solar and wind sources. MATLAB/Simulink software is used to develop the hybrid energy system model. In addition, real climate data and practical demand profile are used to implement the simulations under different scenarios.

Senjaliya and Tejani [20] presented an AI-based autonomous energy management system to optimize the performance of a hybrid heat pump integrated with solar thermal systems in residential buildings. The proposed system integrates real-time data processing and predictive analysis to improve energy efficiency, reduce costs and minimize carbon impact. The simulation results demonstrate the significant improvement in energy efficiency compared to conventional systems with an energy saving of nearly 35%. Singh and Kaushik [21] describes an optimization framework for determining the most economical size of a grid-connected PV/biomass power plant aimed at electrifying a representative Indian village. The approach relies on an ABC metaheuristic to pinpoint the configuration that minimizes both the levelized cost of energy and the system's annualized expenses. Simulation results reveal that the PV–biomass arrangement provides cheaper and more reliable rural electrification than conventional supply options. The study also shows that the ABC search procedure identifies superior solutions compared with those generated by HOMER's hybrid optimization model.

Halabi *et al.* [22] proposed a performance analysis of a PV/diesel/battery hybrid system using HOMER. In this paper, two distributed energy stations in Sabah, Malaysia were used, each comprising solar panels, diesel generators, inverters, and storage batteries. The proposed system showed better economic and environmental performance compared to other systems. Fathy *et al.* [23], a methodology based on the social spider optimizer (SSO) algorithm was employed to achieve optimal sizing of renewable hybrid energy sources integrated within a microgrid system. The application was carried out in a microgrid located in the Aljouf region, Northern Saudi Arabia. The findings indicate that the SSO-based approach yields a more effective configuration of hybrid energy resources compared to alternative optimization techniques, achieving an energy cost of $0.1349/kWh and an energy supply probability of 0.01714. Additionally, the calculated energy costs for two distinct topological scenarios are $0.2180/kWh and $0.2161/kWh, respectively. These results highlight the cost-effectiveness and technical efficiency of the proposed method in microgrid design.

Khaleel *et al.* [24] proposed a hybrid renewable energy storage system including PV, fuel cells and batteries to support the energy demand. In addition, an adaptive neuro-fuzzy inference system (ANFIS) and GA are applied to collect data from the power grid. The results of the application of the hybrid system give a value of 99.6% for single-phase earth fault scenarios and the use of GA in the hybrid renewable energy system gives an injection value of 98.9%. Furthermore, the reduction of voltage unbalance using the proposed system is 76.2%. An AI-based maximum power point tracking (MPPT) technique has been proposed in [25] for an integrated PV-wind turbine-fuel cell hybrid system. The performance of the proposed system based on MPPT techniques is evaluated under different climatic conditions such as solar radiation, wind speed and fuel hydrogen content. The results show that the ANFIS-MPPT platform improves the power of hybrid sources for a single-phase line and reduces simulation time.

The study reported in [26] introduces a frequency regulation strategy based on fuzzy logic control for PV generation within a PV–diesel hybrid system, aiming to mitigate power fluctuations. This approach enables dynamic adjustment of PV power output by considering the operational conditions defined by energy providers to enhance overall power generation. The fuzzy controller generates control signals for the PV output using inputs such as average solar irradiance, its rate of change, and frequency deviations. The proposed control method is benchmarked against both a conventional energy storage–based control system and a MPPT strategy. Simulation outcomes indicate that the fuzzy logic approach not only delivers stable frequency control metrics but also maintains PV output close to the optimal generation level. Furthermore, Mokhtara *et al.* [27] presents an alternative strategy combining demand-side management with PSO for the optimal configuration of a PV–diesel–battery hybrid system, specifically targeting residential electrification in Algeria's Adrar region. The proposed hybrid system is first modeled by MATLAB code on a multi-agent system and then optimized by minimizing the total net present cost related to the integration of renewable energies. The validation was carried out by HOMER software through a technical-economic analysis including the sensitivity study while considering battery technologies. The results show a reduction of 7 to 18% of the total net present cost and an improvement of 15 to 63% of the renewable fraction. In addition, with a wind-diesel configuration, the energy cost is $0.21/kWh which is lower than systems based solely on diesel.

Mokhtara *et al.* [28] outlines a control strategy designed to optimize the operation of a hybrid energy system comprising diesel generators, PV panels, wind turbines, and battery storage, with the goal of electrifying residential buildings in rural Algerian regions. The study investigates how climatic variability and building energy performance impact system optimization. A multi-objective framework is proposed, combining a PSO algorithm with spatial multi-criteria analysis to simultaneously reduce energy costs and enhance both system reliability and the share of renewable energy. Based on the findings, seven geographic zones were identified and further subdivided into seven optimization sites. In locations such as Biskra and Tamanrasset, the optimized system yields an energy cost of $0.21/kWh. When building energy efficiency is factored into the analysis, the hybrid diesel–PV–wind–battery configuration outperforms conventional alternatives in both economic and operational terms.

These control strategies presented in the literature show many limitations, particularly in their inability to adapt to consumer variability, fluctuation in climate change, variations in fuel costs, which can impact consumer income in the long term. Based on these limitations previously mentioned, our work will significantly reduce energy cuts to consumers, reduce energy consumption bills, and ensure permanent availability and good quality of electrical energy. Thus, the main contributions of this work are presented as follows:

- A novel AI approach based on fuzzy logic is proposed to address the need for control and management of a hybrid renewable energy system.
- The proposed hybrid system consists of PV solar panels, a diesel generator, storage batteries, and AC-DC and DC-AC converters to ensure a continuous supply of energy to consumers.
- The proposed control strategy addresses the optimal control problem of the hybrid renewable energy system, achieving several optimization objectives such as reducing operational costs, minimizing environmental pollution, and reducing power losses.
- The use of fuzzy logic rules facilitates the management and hybridization of all these energy sources by considering climate variability such as solar irradiation, temperature, and the power of the PV panels, the diesel generator, and the public grid.
- An optimal experimental setup made of several equipments is used to implement the proposed approach on a building in the city of Douala, Cameroon and obtain the optimal supervision controls.

The rest of our work is structured as follows: section 3 outlines the materials and methodologies employed throughout the paper. The results and discussion are presented in section 4. Finally, we conclude this work in section 5.

3. MATERIAL AND METHOD

3.1. Modeling the proposed hybrid system components

Figure 1 shows the schematic of the hybrid system, which consists of PV solar panels, a diesel generator, storage batteries, DC/AC and AC/DC converters, and a fuzzy logic-based energy control and management platform. The energy supplies by the sources can be either transmit to the loads or is used for battery charging to ensure a permanent availability of electrical energy whatever the period of the day.

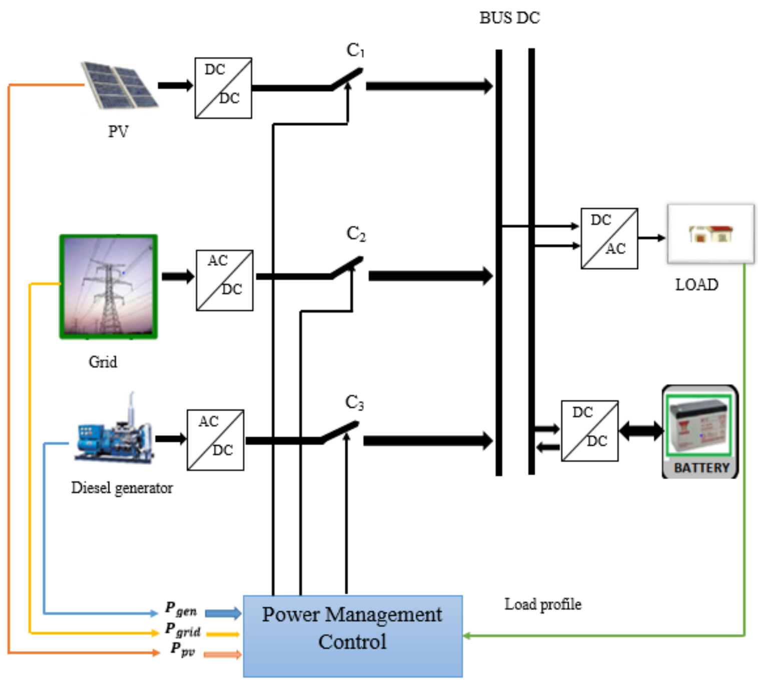

Figure 1. Proposed hybrid system

3.1.1. Modeling the photovoltaic generator

In this work, for the PV generator, we only focus on the power P_{pv} (kW) genereted by the PV system. It is stated as a function of the surface area of the system A_{pv} (m²), its overall efficiency η_{pv}, and the incident solar radiation G_T (W/m²).

$$P_{pv} = \eta_{pv} \times A_{pv} \times G_T \tag{1}$$

With η_{pv} given by the following expression:

$$\eta_{pv} = \eta_r \eta_{pc}\left[1 - \beta\left(T_c - T_{cref}\right)\right] \tag{2}$$

Where η_r is the reference efficiency of the PV module, η_{pc} the load influence efficiency, β the temperature influence coefficient.

3.1.2. Diesel generator modeling

In our system, the diesel generator produces electrical power by burning fuel. The purpose of this device is to compensate for a potential power outage or power outage due to a technical problem that could lead to serious consequences and/or significant financial losses. The consumption curve represented in (3) makes it possible to estimate the amount of fuel consumed to produce electrical energy.

$$F = F_0 Y_{gen} + F_1 P_{gen} \tag{3}$$

With F the amount of fuel consumed, F_0 the intercept coefficient of the curve d, F_1 the slope of the fuel curve, Y_{gen} the rated capacity of the diesel generator, and P_{gen} the electrical power produced by the diesel generator.
The efficiency curve of the diesel generator η_{gen} is given as:

$$\eta_{gen} = \frac{3600 P_{gen}}{\rho_f\left(F_0 + F_1 P_{gen}\right) L_f} \tag{4}$$

Where ρ_f represents the density of fuel and L_f is the fuel's net calorific value.

3.1.3. Battery modeling

In order to power loads in the case of a power outage or failure, batteries are charged using the excess energy generated by PV and diesel sources. For the battery, the charging and discharging processes are presented in (5) and (6), respectively.

$$E_{BSS}(k) = E_{BSS}(k-1) + \left[E_{gen}(k) - \left(\frac{E_{load}(k)}{e_{inv}}\right)\right]\eta_b^{ch} \tag{5}$$

$$E_{BSS}(k) = E_{BSS}(k-1) - \left[E_{gen}(k) - \left(\frac{E_{load}(k)}{e_{inv}}\right)\right]/\eta_b^{dch} \tag{6}$$

With $E_{BSS}(k)$ the battery energy at time k, $E_{load}(k)$ the load energy at time k, $E_{gen}(k)$ the generator energy at time k, e_{inv} the inverter efficiency, η_b^{ch} and η_b^{dch} respectively the battery charge and discharge efficiency.

3.1.4. Converters

A converter is a device that converts electrical energy from AC to DC. These converters connect solar panels, a PV generator, the utility grid, and batteries to the DC bus. Converter efficiency can be expressed as a function of input power P_{input} and output power P_{output} as:

$$\eta_{cnv} = \frac{P_{output}}{P_{input}} \tag{7}$$

3.1.5. Load

Electrical load is a determining factor in a hybrid energy system. The energy consumed can be modeled by (8):

$$E_L = \sum_{i=1}^{n} P_i \times t_i \quad (8)$$

With P_i representing the nominal power of each device and t_i representing the operating time.

3.2. Experimental setup

The experimental setup consists of:

- A Compaq 610 computer with a 6 GHz processor, 16 GB of RAM, Windows 10/64-bit operating system, and a 1 terabyte hard disk.
- MATLAB/Simulink software version 2023 is used to implement the modeling of the hybrid system consisting of solar energy, storage batteries, diesel generator, and static converters. In addition, the advanced control strategy is implemented while respecting the control and operating constraints.

3.3. Methodology

3.3.1. Fuzzy logic

A. Introduction to fuzzy logic

Fuzzy logic is a new processing method that appeared before the 1940s for adjustment and decision-making problems using the notion of membership. Zadeh introduced the concept of fuzzy subsets in 1965. While classical sets are based on the notion of all-or-nothing type, the fuzzy notion is of a different type based on a relaxation of the notion of membership consisting of expressing the results as probability rather than as certainty. The interest of fuzzy logic lies in its capacity to process imprecise and uncertain information, or to classify information whose boundaries are poorly defined, it thus approaches human reasoning which can decide and act in a relevant way despite the vagueness of the available information. The fuzzy approach shows applications in the regulation or control of industrial processes, for which the available information is often imprecise, in sometimes incomplete control loops [29].

Fuzzy logic terminology consists of the following elements:

- Linguistic variable: these are variables that have natural language expressions in the form of words or phrases rather than numbers. Some, frequently hot, cold, quick, slow, huge, and tiny are examples of fuzzy terms that are typically used when describing a certain circumstance, phenomenon, or process. Expressions of this type form the linguistic values that a linguistic variable in fuzzy logic can take. To enable numerical processing, it is essential to subject them to a definition using membership functions.
- Fuzzy sets: fuzzy set theory generalizes classical set concepts by allowing elements to belong to a set to varying degrees rather than in an entirely binary fashion. Consider a Universe of Discourse U whose individual members are denoted by u. A fuzzy set A⊆U is specified through a membership function, μA(u): U → [0,1]). For every element u ∈ U, the value μA(u) indicates the extent to which uuu is regarded as a member of A, with 0 representing no membership and 1 signifying full membership.

The fuzzy set A can therefore be represented by:

$$A = \{(t, \mu A(u))/t \in U\} \quad (9)$$

When U is continuous, the fuzzy set A is represented by:

$$A = \int t\, \mu A(t)/t \quad (10)$$

When U is discrete, A is represented by:

$$A = \int \mu A(ti)/ti \quad (11)$$

An element in a classical set will have a membership function $\mu A = 0$ or 1, but a fuzzy set may be thought of as an extension of a classical set. Thus, fuzzy sets allow an element of the set to have a membership degree of any real value between 0 and 1 which is called the membership degree. This value determines to what extent an element belongs to a set [30].

- Membership functions: each linguistic value is characterized by a membership function. There are two ways to define the membership function of fuzzy sets: numerical and functional. The numerical definition expresses the degree of membership function of a fuzzy set as a vector of numbers whose dimension depends on the number of discrete elements in the universe of discourse. The functional definition characterizes the membership function of a fuzzy set in an analytical expression where the degree of membership for each element is calculated. Some standard forms of membership functions are commonly used to represent fuzzy sets based on the universe of discourse. The most commonly used membership functions are: S-function, π-function, triangular form, trapezoidal function, exponential function and the Gaussian function.

B. Basic structure of a fuzzy controller

A fuzzy controller is a nonlinear system that makes decisions by connecting an input data vector to an output vector. Its four primary modules the rule basis, fuzzification, inference engine, and defuzzification are founded on specialized knowledge. A fuzzy logic controller's construction is depicted in Figure 2 [31].

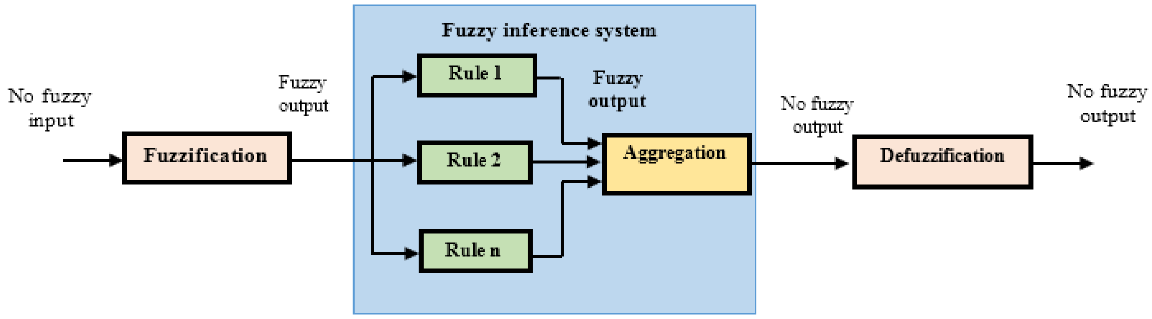

Figure 2. Structure of a fuzzy logic controller

3.3.2. Fuzzy logic-based hybrid system management method

In this work, we use a fuzzy logic controller to manage a hybrid energy system while responding to load demands efficiently and optimally at all times. As shown in Figure 1, this hybrid system combines multiple renewable and/or conventional energy sources to provide an energy supply solution for urban and rural areas. This solution remains a major challenge to manage given the diversity of sources. Since power from renewable sources is intermittent and dependent on several uncontrollable conditions, an effective management system is required to make decisions for better energy use. For the energy management in our hybrid system we used the MATLAB/Simulink tool for writing the different fuzzy algorithms (fuzzification, rules, and defuzzification) and for the energy management in the system. In MATLAB, a set of grouped instructions and custom functions in the form of algorithm and rules were designed from the block codes and functions for the implementation of the control and management strategy of the hybrid renewable and non-renewable energy system. As shown in Figure 3, in this block function, we specified the necessary inputs for the function (the arguments), as well as the outputs produced by the function. The input values consisting of the PV, diesel generator, and utility grid and load powers are used to provide data to be processed in the MATLAB function, while the outputs consisting of the control signals of the three switches are used to return the results of the function. The fuzzy logic instructions inside the function block describe the operations that the function must perform.

Figure 3. MATLAB block function for hybrid system management

The purpose of the energy management strategy depicted in Figure 4 is to ensure that the hybrid system reliably satisfies load demands under varying meteorological conditions while efficiently regulating power distribution and maintaining a stable DC bus voltage. This approach utilizes both the energy produced by the available sources and the energy stored in battery units to match the load requirements. To enhance the coordination between generation and storage components, a supervisory control system based on fuzzy logic has been developed. This intelligent control framework, implemented in the MATLAB/Simulink environment, is designed as a multi-input, multi-output fuzzy controller with four inputs and three outputs, which deliver control signals to the system's switching elements. The controller's rule base is formulated to account for all feasible operating scenarios of the hybrid configuration while respecting predefined system constraints. For this purpose, PV energy is the priority source for the load power supply and when the PV energy is decreasing, the energy of Cameroon (ENEO) power source will be requested to supply the loads. In the event of a power outage, the diesel generator is used as a backup source for the supply of electricity. In this work, the energy stored by the storage system only intervenes during the transition from one source to another to avoid intermittent outages. The overall power balance, taking into account these operating states, can be written:

$$P_l = P_{pv} + P_{grid} + P_{gen} \mp P_{batt} \tag{12}$$

With: P_l the power of the load, P_{pv} the power of the PV source, P_{grid} power of the public source, P_{gen} power of the diesel generator and P_{batt} power of the batteries.

As control parameters we have: a PV system control switch (C_1), an ENEO control switch (C_2) and a diesel generator control switch (C_3). As shown in Figure 4, the fuzzy logic-based hybrid system management algorithm proceeds as follows:

a) If the solar panel power P_{pv} is greater than or equal to the load power, then the load power is equal to the panel power to supply energy to consumers.

b) If the panel power is less than the load power and is greater than zero (average), and the Eneo power is greater than the load power, then the load power is equal to the Eneo power plus the panel power.

c) If the Eneo power P_{grid} is greater than the load power and the panel power is zero (zero), then the load power is equal to the Eneo power.

If the Eneo power is less than zero (zero), particularly in the event of a power outage or breakdown, then the load power is equal to the diesel generator power.

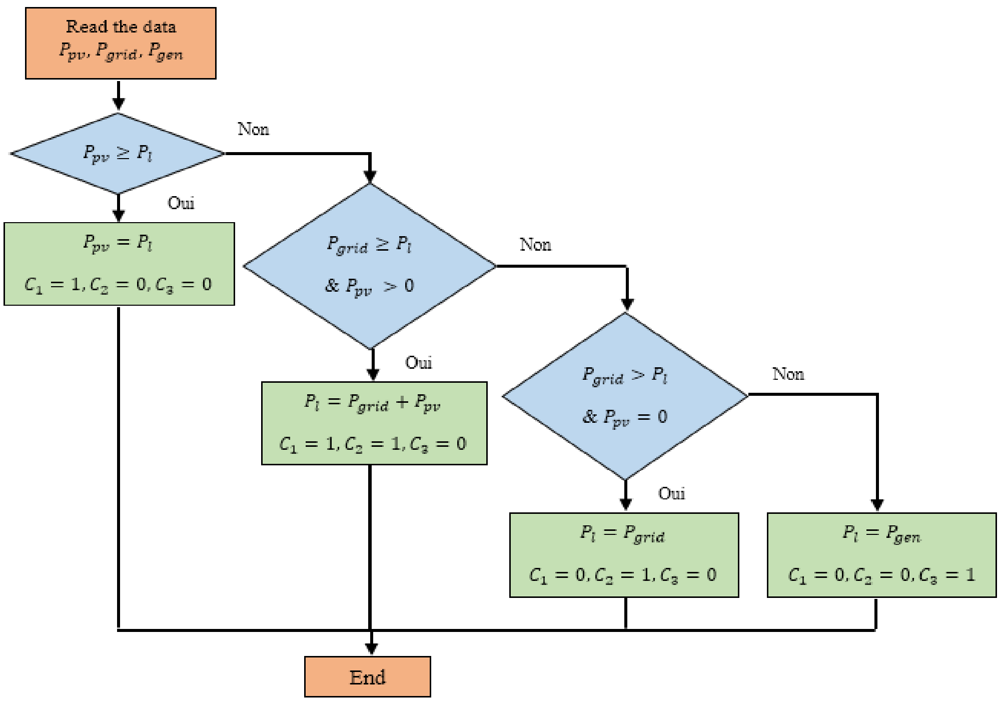

Figure 4. Fuzzy logic-based hybrid system management algorithm

Figure 5 shows the PV system + BOOST chopper simulation diagram in MATLAB/Simulink. We can see that the solar panels depend on solar irradiance and ambient temperature. The solar panels therefore provide a DC voltage on the DC bus via a Boost chopper, which adjusts the average value of the voltage supplied by the PV panels.

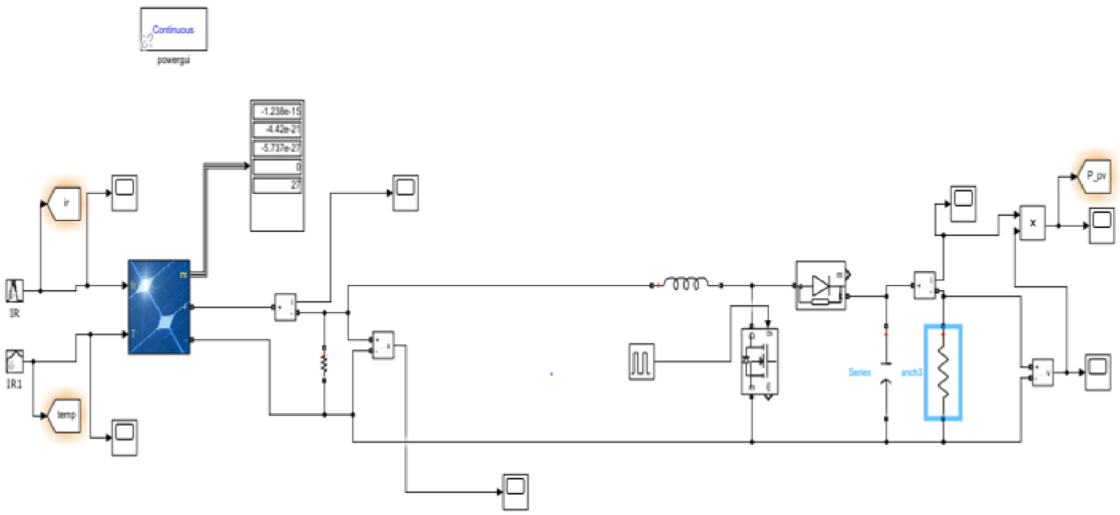

Figure 5. Schematic diagram of the PV system + BOOST chopper in MATLAB/Simulink

4. RESULTS AND DISCUSSION

The hybrid system control is designed to ensure continuous energy availability to consumers by manipulating the switches controlling all energy sources, including the solar source, the diesel generator, the Eneo source, and the storage batteries. This system must ensure that the voltage of the solar panels and the diesel generator is equal to the DC bus voltage. This stabilizes the system and extracts the greatest amount of power, taking into account solar irradiation, the amount of fuel in the diesel generator, and the state of charge of the batteries. The control algorithm coordinates energy exchanges between the different sources to ensure a stable and reliable supply of electricity.

Given the simulation constraints in MATLAB, we ran the simulation over a time of 0.24 seconds, which corresponds to 24 hours, so 1 hour corresponds to 0.01 seconds. In addition, we chose a variable load profile over 24 hours, and the converters are of the perfect type. The ambient temperature and solar irradiance are shown in Figures 6 and 7 respectively. The load profile is shown in Figure 8. Figures 9 to 11 detail the power outputs of the solar panels, the public grid, and the diesel generator, respectively. We see that the PV power ranges from 0 to 2500 W, while the diesel generator power ranges from 0 to 3000 W.

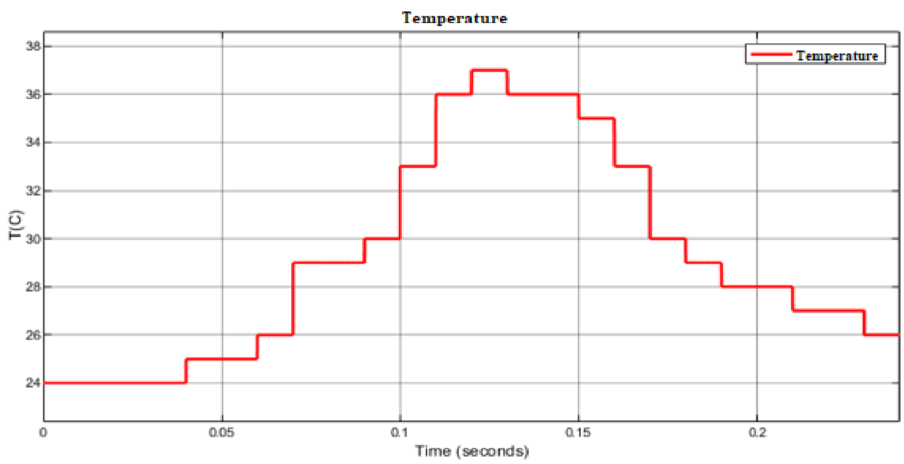

Figure 6. Ambient temperature measurements

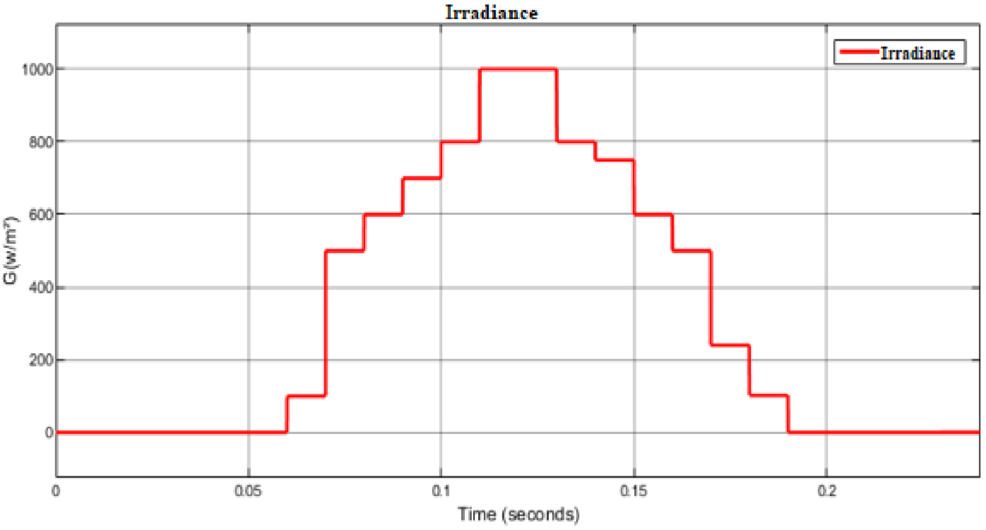

Figure 7. Solar irradiance measurements

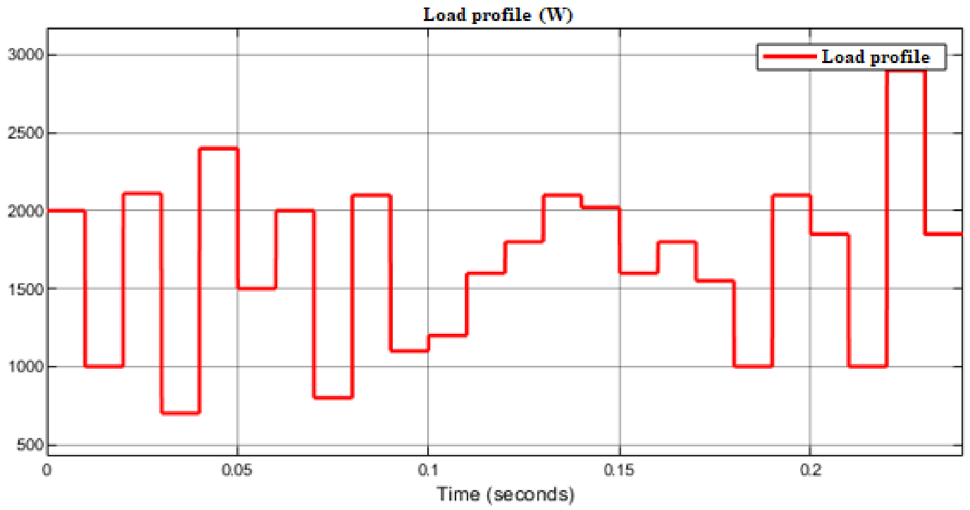

Figure 8. Load profile

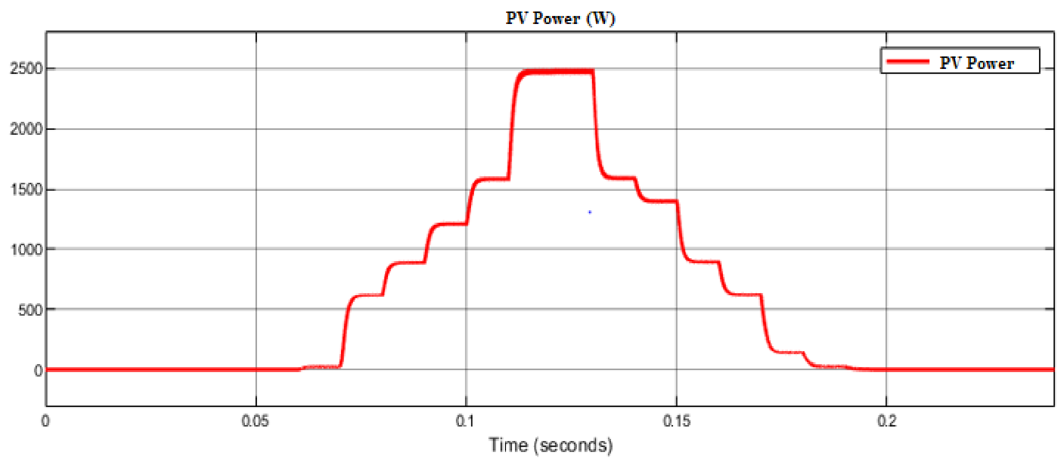

Figure 9. PV power profile

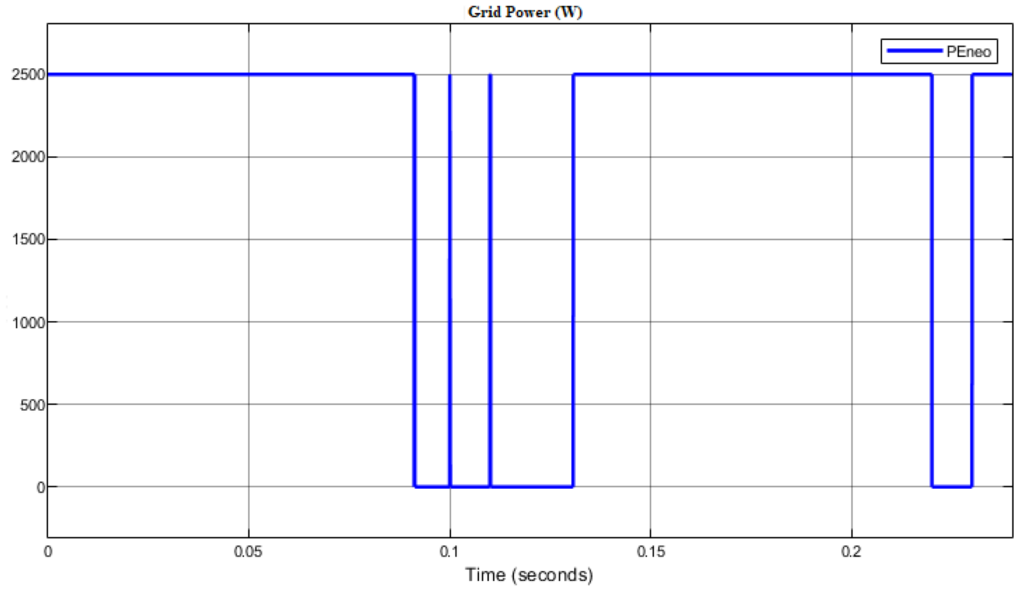

Figure 10. Power profile of the public source

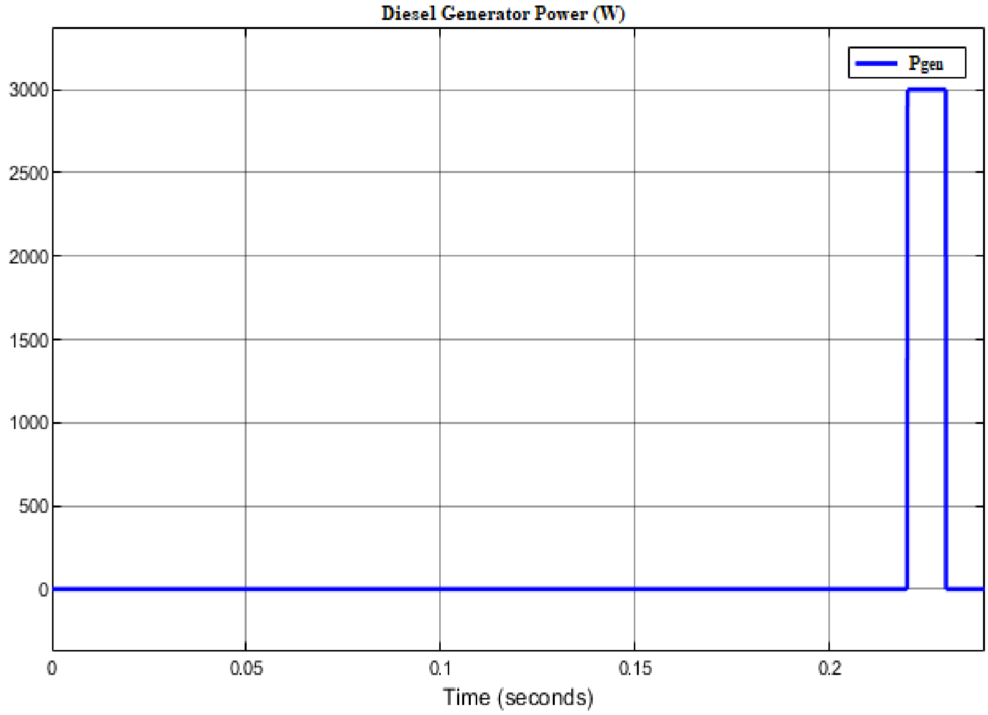

Figure 11. Diesel generator power

Figure 12 shows the stability of the DC bus voltage. This stability is due to the fact that we used a storage system with a reversible current converter. Figure 13 shows the operation of the PV + Eneo hybrid system. As shown in Figure 13, between midnight and 6 a.m., solar irradiance is very low (zero), and the load is powered only by Eneo. Between 6 a.m. and 9 a.m. and 1 p.m. and 6 p.m., the PV system produces low power; the Eneo source fills this gap to optimally power the load. Between 9 p.m. and 10 p.m., the system is not powered because the PV and Eneo sources are below zero. In this case, another energy source will be needed to fill this gap. Figure 14 shows the load voltage profile for hybrid operation (PV + ENEO + diesel generator). We can see that the voltage across the load terminals is stable due to the use of a DC bus.

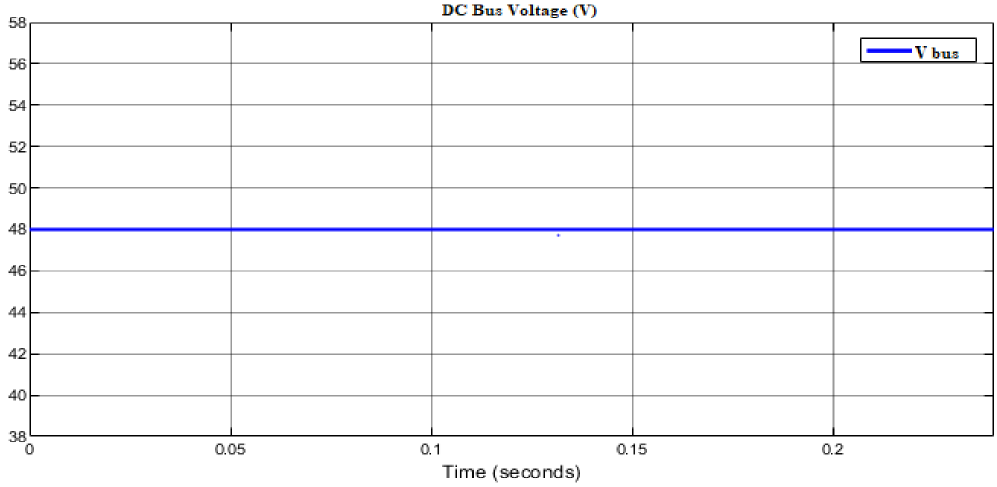

Figure 12. DC bus voltage

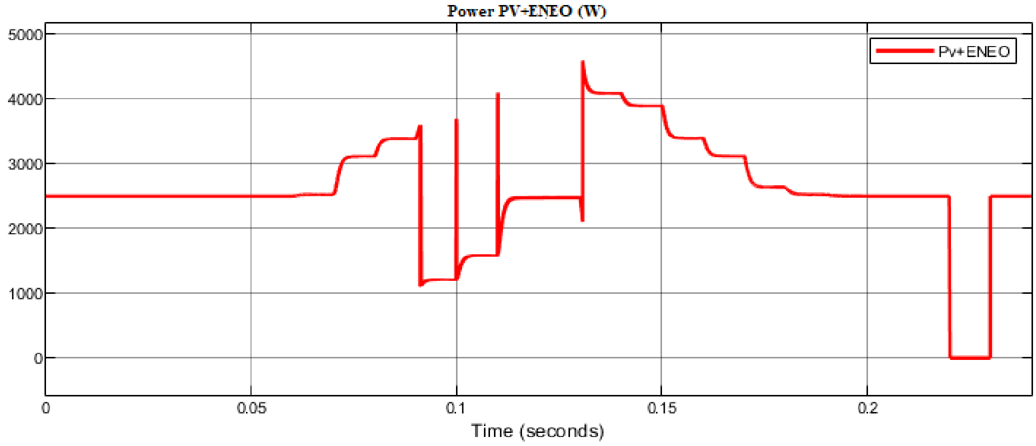

Figure 13. Power of the PV + Eneo hybrid system

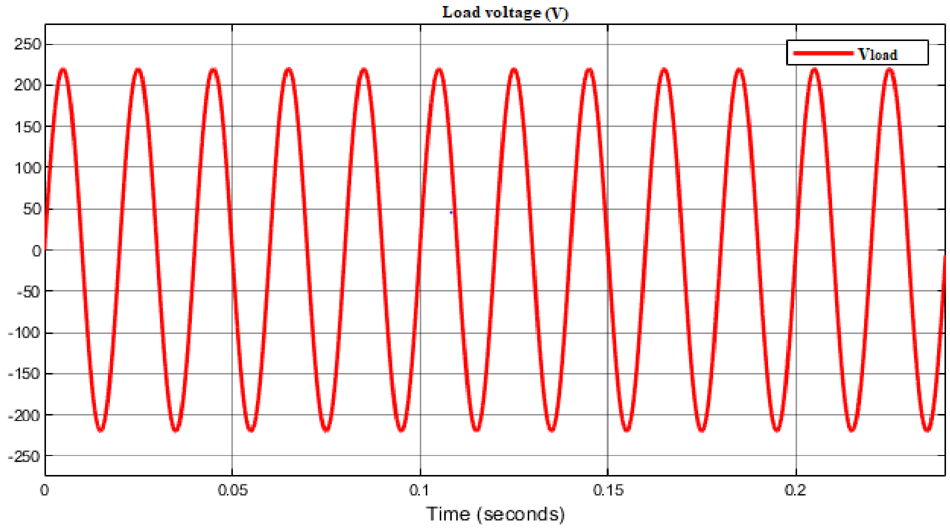

Figure 14. Load voltage for hybrid operation (PV + ENEO + diesel generator)

These visual illustrations demonstrate the effectiveness of the proposed energy management and control strategy in terms of voltage profile, power profile, operating modes, consumption profile, and battery state of charge to meet consumer requirements. This relevant results therefore provide a valuable contribution to improving the performance of hybrid energy systems by taking into account various climate changes, thus confirming the feasibility of the implemented approach.

5. CONCLUSION

In this work, we proposed a fuzzy logic-based method for managing a hybrid energy system composed of a solar source, a diesel generator, a public source, and storage batteries. The novelty of the proposed approach, based on a fuzzy logic controller, lies in its consideration of dynamic and adaptive variables for the efficient control and balancing of multiple energy sources. Unlike traditional techniques in the literature, the method developed in this article allows for variations in climatic conditions such as temperature and irradiance to be considered, thus contributing to the resilience and efficiency of the hybrid management system for renewable and non-renewable energy sources. Furthermore, the proposed strategy allows for immediate and optimal satisfaction of consumers' energy needs while ensuring long-term energy stability, demonstrating its superiority over existing methods. Furthermore, this fuzzy logic-based energy management method was tested on a residential building in the city of Douala, Cameroon. MATLAB/Simulink software was used to implement the developed management strategy. This hybrid system also ensures the availability of electrical energy and maintains the batteries at an optimal state of charge. The results obtained show that the proposed strategy is effective in ensuring continuity of energy supply in urban and rural areas, thus contributing to the region's techno-economic development. This work can be further improve by consideration of other energy management approaches for the integration of electric vehicles comprising storage batteries into the system. In this case, the effectiveness of the renewable resources would be improve with the vehicle-to-grid integration devices.

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AUTHOR CONTRIBUTIONS STATEMENT

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are available on request from the corresponding author, [ABE].

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