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Research Article

Concrete-Based Dual-Chamber Microbial Fuel Cell for Continuous Power Generation

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Abstract

The increasing demand for sustainable electricity generation necessitates the exploration of innovative technologies. Biomass technology is emerging as a promising alternative to address the energy crisis for low-power devices and reduce reliance on fossil fuels. One of the methods to generate energy from this biomass is by using microbial fuel cells (MFC). However, the efforts made with this technology are still mainly limited at the laboratory scale, limiting its interest and its utilization for electrical power generation. This paper presents the real-life implementation and feasibility of a dual-chamber microbial fuel cell fabricated with concrete. 15 dual-chamber reactors were manufactured, with a volume of 0.5 liters for each chamber. Inside the anodic chamber, a carbon foam measuring 4.5 x 4.5 cm² was placed and used as the anode electrode. Two different electrode materials were used for the cathode electrodes. Six reactors used 4.5 x 4.5 cm² carbon foam while the other 9 used graphite rods of 5 mm diameter and 15 cm long. The anode chamber was inoculated with a mixture of 25% cow dung and 75% tap water and then sealed airtight. Each cathode chamber was filled with 0.5 liters of saline solution. After 7 days of manipulation, the Open Circuit Voltage (OCV) obtained from this investigation ranged from 0.415 V to 0.732 V. That reflects the successful conversion of chemical energy of this waste in the concrete-based microbial fuel cell reactor into electrical energy. The average maximum power density obtained using graphite rod cathodes was 14.15 mW/m² while an average of 20.21 mW/m² was obtained from the MFCs using carbon foam cathodes. When the MFCs were stacked together in series, a total voltage of 8.5 V was observed.

Keywords

Dual Chamber Microbial Fuel Cell, Cow Dung, Concrete-Based Reactor, Electrical Energy Harvesting

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1. Introduction

In recent times, enormous energy consumption has been reported in conjunction with the fleet growth of the population [1-3]. This goes in line with the increasing of people's comfort. Measures must be taken to sensitize the population as well as to develop additional energy sources. One of these measures is to develop or increase renewable energy sources and attention is paid in this work to microbial fuel cell (MFC) technology. By harnessing the power of microorganisms, MFC offer a promising alternative for renewable energy generation while simultaneously addressing environmental challenges, such as wastewater treatment [4, 5]. The concept of MFCs is based on the principle of bio-electrochemical reactions occurring at the anode and cathode electrodes, facilitated by microorganisms known as electrogenic bacteria [6, 7]. These bacteria oxidize organic substrates to produce electrons and protons. The electrons attach to the anode electrode to form biofilm and protons pass through an exchange membrane to reach the cathode chamber containing an electron acceptor (oxygen is the most used). The movement of electrons to combine with proton and oxygen in the other chamber through an external circuit between the two electrodes generates electricity [8, 9]. The first observation of bioelectricity was done by Luigi Galvani, an Italian physician and physicist in 1790 when he noticed the twitching of a frog leg upon the application of electrical discharge. This led to the coining of the term "bioelectricity" [4]. In 1910, Michael Cresse Potter discovered that organisms could generate voltage and current, specifically studying microorganisms and their ability to degrade organic compounds. Potter's work in 1911 involved the use of platinum electrodes to extract electrical energy from cell cultures of *Escherichia coli* and *Saccharomyces*, leading to the development of a basic MFC [10]. With time, MFC has gained more attention and a good understanding has been gained regarding its operational principle, which most often takes place in two different structures such as a one-chamber structure [11, 12] where the cathode is exposed to air, or two chambers where each electrode is placed inside its compartment [13]. However, the practical implementation of this technology is still in its infancy, and significant research is underway to optimize its efficiency or boost its production to a level where it can be effectively used at the same scale such as photovoltaics, wind energy, and many others, possibly even more.

Initially, it was thought that increasing the reactor's volume would produce more energy. However, the opposite was quickly demonstrated, as increasing the volume causes a slow movement of charge carriers, which increases the internal resistance of the system and consequently reduces the maximum power generated [14, 15]. Therefore, the option that is increasingly attracting researchers is based on assembling several small-volume cells (Firstly optimizing the efficiency of each cell) in different configurations to increase production to a level where it can be used to power electrical devices [15, 16]. As of now, the feasibility of this has already been proven, but what materials (easily manageable, waterproof, and available) can be efficient in constructing the MFC system on a small or large scale?

In this work, the design, implementation, and investigation of a dual-chamber MFC as a means of sustainable electricity generation was carried out by leveraging the feasibility of the microbial metabolism on a concrete-based reactor to produce electricity.

2. Materials and Methods

2.1. MFC Design and Fabrication

2.1.1. Sizing of the MFC Reactor Body

The choice of the MFC structure is not solely based on its efficiency; it also depends on financial resources, equipment, and space available for the implementation of the system. In this regard, a two-chamber structure was chosen for the work presented in this paper, as it does not necessarily require the use of air cathodes (often used in single-chamber structures), which are not only costly to manufacture but also necessitate certain equipment that was not available at the implementation site. This structure consisted of two chambers with an internal volume of 500 ml each, separated by a wall with an opening of 2.5 cm in diameter reserved for inserting the proton exchange membrane, as shown in Figure 1. An opening is provided on the cover of each reactor compartment to facilitate the introduction and/or recycling of materials; another opening is also provided to evacuate exhausted materials from the chamber for a replacement. The diameter of these entry and exit holes for each chamber was set to 2.5 cm. A 6 mm hole was also made on the cathode chamber cover to serve as the opening for electrode placement and a 3 mm hole in the anodic cover for inserting the current collector wire. To safely release biogas produced during anaerobic digestion, a 6 mm hole was incorporated into the cover of the anodic chamber. This hole prevents excessive pressure build-up within the reactor, ensuring the integrity and safe operation of the MFC.

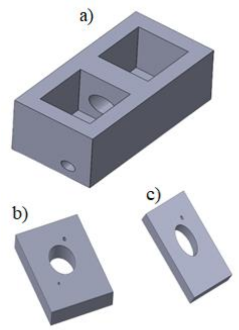

Figure 1. *3D design of (a) a dual-chamber MFC reactor, (b) anode cover, (c) Cathode cover.*

2.1.2. Material Sizing

The anode electrodes constructed from carbon foam, were precisely modeled with exact dimensions and positioned appropriately within their respective chambers. This was made up of a 4.5 x 4.5 cm^2 carbon foam material.

Two different carbon materials were used for the cathode electrode. Six were carbon foam, with dimensions similar to that of the anode and nine were made up of a 5 mm (diameter), 15 cm long graphite rod. The two different materials are shown in Figure 2. The idea of using these two different cathodes is to evaluate and compare their performances. Thus, if graphite is just as effective as carbon foam, it would be preferable to use it for the next experiments, as it is readily available locally.

Figure 2. *a) Carbon foam electrode, b) Graphite rod electrode.*

Well-designed proton exchange membrane (PEM) dimensions improve proton conductivity and mass transport, resulting in higher MFC performance. This was made up of agar with a concentration of 4 g, 100 mL of distilled water, and 0.8 g of Common salt (NaCl). The solution was mixed to form a uniform mixture and heated to a boiling point of 100 degrees in a stainless-steel pot. Then, this was allowed to solidify in 3.1 cm long and 2.5 cm in diameter Poly Vinyl Chloride (PVC) pipes before being placed at the central holes of the reactors which had been designed to support the PEM.

A 0.6 mm stainless steel wire was attached to both the cathode and anode electrodes to serve as charge collectors.

2.1.3. Construction of the MFC

After sizing the MFC, a 3D reactor was designed using SolidWorks, a powerful computer-aided design (CAD) software. Specific dimensions and measurements were considered to accurately represent the reactor's components. The overall housing was meticulously dimensioned to accommodate the anode and cathode electrodes and the ion-selective membrane. Throughout the design process, utmost consideration was given to spatial constraints, fluid dynamics, and structural integrity, with SolidWorks' capabilities utilized to validate the design. Attention was paid to the design thickness of the reactor walls, as adequate thickness ensures mechanical strength, pressure resistance, and durability. It supports electrode placement, facilitates heat dissipation, and aligns with manufacturing processes. Optimal thickness depends on factors such as size, geometry, materials, and operating conditions. Considering these aspects ensures a robust and reliable MFC reactor design, the thickness of the entire model was 2 cm.

2.1.4. Molding of the Dual-chamber MFC Reactors

Figure 3 shows the molding reactor, and 15 MFC reactors were produced. The small cracks observed on the molding reactors were sealed before any operations on the MFCs. The tightness of each chamber was first tested several times with tap water to prevent any leaks during handling. Then, the cells were rinsed with distilled water before adding the waste.

Figure 3. *Dual-chamber MFC molding reactor.*

2.2. MFC Inoculation and Implementation

Due to its availability, abundance, and high organic matter content, cow dung was selected as the substrate for this experiment. This was collected fresh from the faculty of agriculture of the University of Buea in Cameroon and a mixture was done with 25% cow dung and 75% tape water to facilitate the flow of the liquid and the movement of charge carriers. The mixture was then poured into the anode chamber containing the anode electrode.

On the cathode side, 500ml of salt solution at a concentration of 20g/L was poured into each chamber to control and maintain its pH and facilitate the movement of the protons. The chamber's inlet was left open to allow the presence of oxygen in the chamber, which serves as an oxidant for the reaction that occurred in the MFC.

The 15 MFC reactors were assembled and by using the 2.5 cm PVC pipes, they were aligned in a 5x3 array format as represented in Figure 4; that is 5 rows, 3 columns. For each anodic chamber, a 5 mm outer diameter pipe was placed over the opening reserved at the cover. At the other end of this pipe, a balloon was attached to collect the gas produced during anaerobic digestion. Table 1 summarizes the materials used along with their characteristics.

Before sealing the reactors, the pH and conductivity were measured using a pH machine (PH-2603, from LOHAND Biological). The mixture had a pH of 7.2 which falls in the neutral medium and a conductivity of 2200 µs/cm. This value of pH was proven to be between the optimal pH value range for electrogenic bacteria growth [17, 18]. As for the conductivity, it was proven to increase with the increase of the power output [19-21].

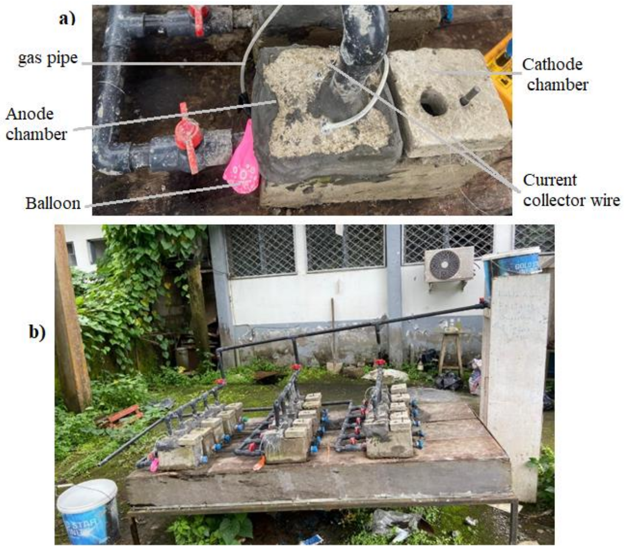

Figure 4. Concrete base dual-chamber MFC: (a) One MFC reactor and (b) The entered system.

Table 1. MFC design characteristics.

Design	Characteristics
Reactor type	concrete material
Structure type	two-chamber MFC
Internal volume	0.5 liters for each chamber
Reactor thickness	2.5 cm
Inlet and outlet hole	2.5 cm in diameter
Anode electrode	4.5 x 4.5 cm² carbon foam material.
Cathode electrode	4.5 x 4.5 cm² carbon foam and 5 mm diameter, 15 cm long graphite rod.
PEM	Agar in 3.1 cm long and 2.5 cm diameter PVC pipe
Inoculum/Substrate	25% cow dung mixed with 75% tap water
Current collector	stainless steel 0.6 mm in diameter
Gas pipe	a 5 mm outer diameter pipe

3. Results

3.1. Generated Voltage

Once the system was set up, the open circuit voltage (OCV) of each cell was measured twice daily for seven days using a high-impedance multimeter (DT-9205A digital multimeter), with a time gap of around 6 hours between measurements.

At the beginning of the experimentation, when the reactors were just sealed hermetically, a residual voltage could already be observed as detailed in Table 2 for each cell. In less than 24 hours, the voltage across all cells had evolved significantly.

Table 2. OCV results for the 15 MFCs at the beginning and at the End when they are stabilized.

Cell N°	Cathode electrode	Initial residue OCV(V)	Final stable OCV(V)
1	Graphite rod	0.073	0.731
2	Graphite rod	0.067	0.506
3	Graphite rod	0.156	0.708
4	Graphite rod	0.142	0.641
5	Carbone foam	0.070	0.430
6	Carbone foam	0.071	0.415
7	Graphite rod	0.049	0.510
8	Carbone foam	0.085	0.500
9	Carbone foam	0.037	0.535
10	Graphite rod	0.082	0.618
11	Carbone foam	0.150	0.650
12	Graphite rod	0.080	0.718
13	Carbone foam	0.073	0.487
14	Graphite rod	0.053	0.600
15	Graphite rod	0.056	0.481

The MFCs were continuously monitored and data were collected. Around the fifth day, all the MFCs had almost reached stability. This stability was monitored and confirmed over the next two days. The data collected were used to plot the graph in Figure 5. Figure 5a represents the Average OCV curve of the cells using graphite rod cathodes while Figure 5b shows the average OCV curve using carbon foam cathodes. The average stable OCV values were 0.613 ±0.96 V for the graphite rod and 0.503 ±0.85 V for the carbon foam.

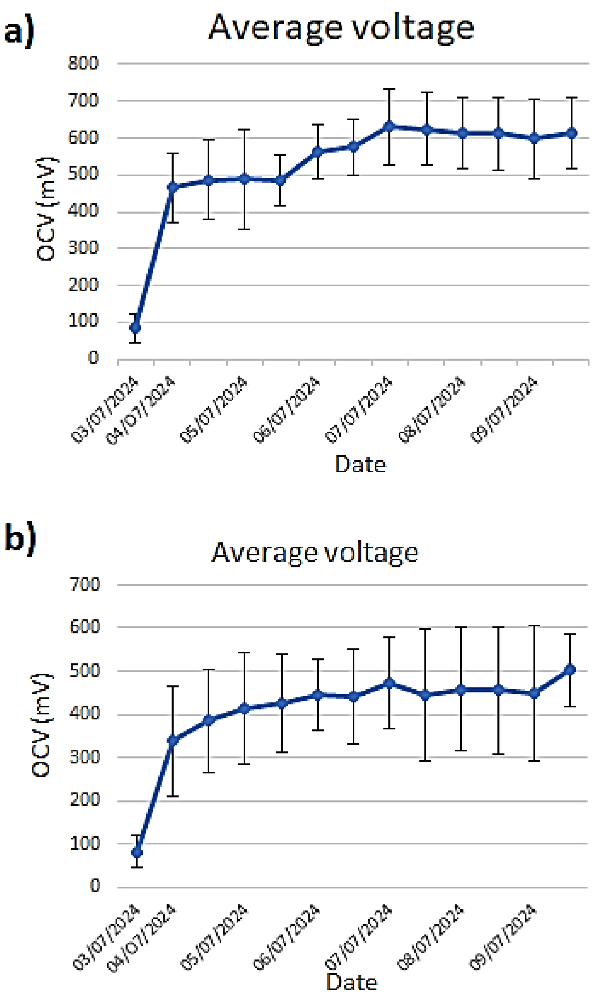

Figure 5. *Average OCV curves (a) using graphite rod cathode electrodes, (b) using carbon foam cathode electrodes.*

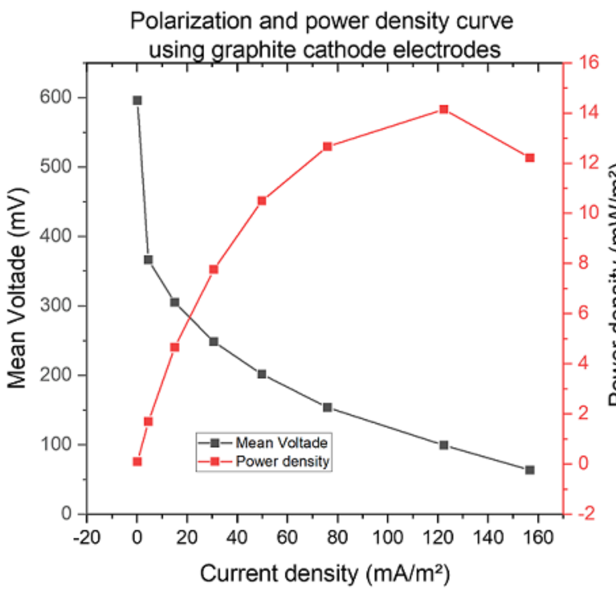

Figure 6. *Polarization and power density curve for the MFC using graphite rod as cathode electrode.*

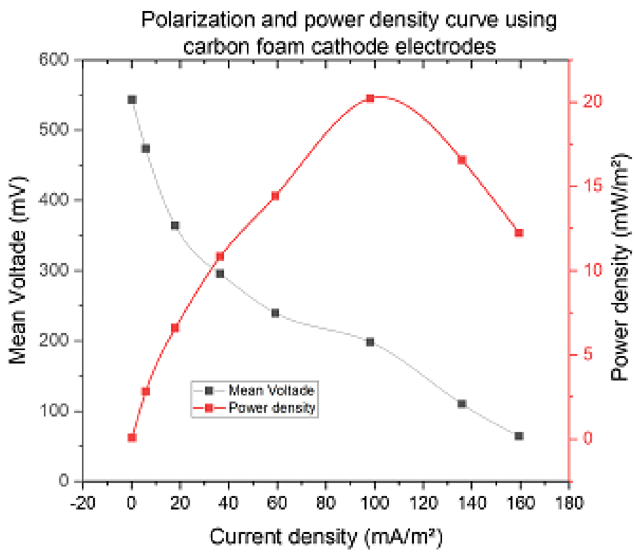

Figure 7. *Polarization and power density curve for the MFC using carbon foam as cathode electrode.*

3.2. Maximum Power

After the MFCs stabilized, characterizations were performed using a decade resistance box (Voltcraft R-BOX 01), varying several resistance values from largest to smallest. The obtained voltages were used to determine the current values using Ohm's law, and the power values were deduced using the relationship P=VI. These values were then normalized in terms of power density (power per anode surface area) and current density (current per anode surface area). For the characterizations of cells using graphite rod cathode electrode, 8 cells were characterized out of 9. MFC n°7 was not characterized because its solution in the cathode chamber was accidentally drained off. The average of these 8 cells was used to plot the polarization and power curves shown in Figure 6. For the MFCs using the carbon foam cathode, characterizations were conducted on 6 cells, and their average was used to plot the curves of Figure 7.

The maximum power density obtained from the two graphs is 14.15 mW/m ^{2} and 20.21 mW/m ^{2} for the graphite rod and carbon foam cathodes, respectively.

After these different characterizations, the cells were connected together in series to study the total capacity of the system. The assembly's OCV was 8.5 V.

4. Discussion

In the overall system, no leaks were observed throughout the handling process, apart from the cap that was accidentally opened for cell n°7 just before the characterizations. The latter was therefore not characterized.

The acclimatization of the MFCs followed a normal course. The results of this acclimatization show that even in an open circuit, the MFC output varies from one cell to another no matter the type of electrode material. From the OCV results obtained, the disparity could be observed between the cells using graphite rod cathodes as well as those using carbon foam. Their average OCV voltage were respectively 0.613±0.96 V and 0.503±0.85 V although all the reactors were inoculated similarly. The environmental conditions have proven to greatly influence microbial activities and consequently the output production of the MFC [22-25]. Even though these cells are placed outdoors in the same location, it seems as if the temperature or sunlight direction might have affected them from one position to another. Given that the system is designed to operate continuously, these parameters will be controlled and confirmed the next time the reactor is refilled. It would also be advantageous to rotate the system to confirm the influence of the cell arrangement on the MFC system. Another way would be to manipulate the cells in the same position over a long period or throughout seasons to note any differences in behaviour.

Different characterizations allow us to obtain the cells' electrical performance and compare the results with the two different cathode electrodes used. It was noticed from this that the average power density obtained with carbon foam cathodes is 1.43 times greater than those obtained with cathode rods. This contradicts the results obtained with open-circuit voltages. It can be concluded that the open circuit voltage results are not sufficient to make a conclusion on the electrical performance of MFCs. Furthermore, it is also noted that the type of electrode used at the cathode can influence the results of MFCs, even from one type of carbon material to another. The reasons for these differences may be due to the shape and arrangement of this material in the chamber, the porosity of the material, and its exposed surface to charge carriers and to the oxygen.

Comparing the results of this work with those in the literature as presented in Table 3, we note that the methodology adopted for this work produces better results. When looking at those using single-chamber structures in this table, it is noticed that not only are the reactor materials (resin, PLA, acrylic plate) and their design very costly, but the installation of the air cathodes is also very complex. For the MFC experiments in two-chamber structures, although the reactors were made from simple, inexpensive materials, the results of those made from concrete (cheap) material in this work remain the best. One reason why these results are better than others may be due to the watertightness of the concrete reactors. This provides a good environment for the development and multiplication of microorganisms. The material sizing as well as the electrodes used can also explain these differences in the results.

Table 3. *MFC experimentation using cow dung: comparison of the results with those in the literature.*

MFC Reactor Design	Electrodes	Power (mW/m^2)	Ref.
acrylic resin single Chamber	Plain graphite anode, air cathode With Nafion PEM	0.34	[26]
acrylic plate single Chamber	Carbone fiber brush anode, Roll-pressing air cathode with conductive graphite	1.734	[27]
PLA single chamber	Carbon foam anode, air cathode with Nafion PEM	14.1	[28]
PVC bottles double chamber	Copper rods with agarose PEM	9.47E^{-04}	[29]
Plastic containers double chamber	Graphite rod, Lamp wicks PEM	6E^{-04}	[30]
Concrete-based dual-chamber	Carbon foam anode and cathode with agar PEM	20.21	This work
	Carbon foam anode and graphite rod cathode with agarose	14.15	

The ultimate goal of this project is to stack the MFCs to increase power for use in powering low or medium-power devices. Although the feasibility of the construction of a concrete-based dual-chamber MFC structure was demonstrated, the most significant work still lies ahead. It is crucial to monitor and evaluate the system's performance to ensure it aligns with the project's goals. There will be a need to characterize the MFC in series configuration and investigate various other configurations such as parallel, series-parallel, and parallel-series and also to study the methods of limiting voltage imbalance to minimize losses and improve the system's efficiency. The voltage imbalance occurs when multiple MFCs are connected with different voltage values, and the less charged cells tend to draw energy from the more charged ones. This results in lower-than-expected outcomes and can even lead to polarity reversal [31-33].

The total budget for implementing the system has been estimated at around $255. A deeper analysis will assess the benefits of the installation with the environmental rehabilitation, the importance of installing such a system in remote areas where access to conventional electricity is difficult, and its benefits in combating the energy crisis and greenhouse gas emissions.

5. Conclusions

To make MFC technology accessible, concrete material was proposed and used to construct the reactors for the experiments of this work. Cow dung was selected to inoculate these reactors and subsequently evaluate their capacity to produce electrical energy. Two types of electrodes (carbon foam and graphite rod) were used as the cathode electrodes to assess their respective performances in order to make a better choice for future experiments. After various characterizations, the study demonstrated the successful conversion of organic matter into electricity. The maximum power density obtained was 14.15 mW/m^2 and 20.21 mW/m^2 respectively for the graphite rod and carbon foam cathodes. Although the generated power remains low, this work's results are better than most of the results in the literature using cow dung (see Table 3). The concrete-based dual-chamber MFC configuration enabled enhanced control and improved performance, highlighting its potential for addressing energy and environmental challenges using MFC technology. However, further study, analysis, and optimization are needed to further improve the performance and the system's scalability.

Abbreviations

MFC	Microbial Fuel Cell
PEM	Proton Exchange Membrane
PVC	Poly Vinyl Chloride
CAD	Computer-Aided Design
OCV	Open Circuit Voltage

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Nicole Adela ïde Kengnou Telem: Formal Analysis, Investigation, Project administration, Supervision, Writing – review & editing

Ayuk Ngang Valdo Ayuk: Conceptualization, Resources, Software, Project administration, Writing – original draft

Pierre Tsafack: Formal Analysis, Investigation, Project administration, Supervision, Writing – review & editing

Olivier Ondel: Formal Analysis, Investigation, Methodology, Project administration, Supervision, Writing – review & editing

Fabien Mieyeville: Methodology, Project administration, Supervision, Writing – review & editing

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Data Availability Statement

The data supporting the outcome of this research work has been reported in this manuscript.

Conflicts of Interest

The authors declare no conflicts of interest.

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Biography

Marie Norbertine Kamdjou Douma is a PhD student under the joint program between the University of Buea (Faculty of Engineering) in Cameroon and the University of Claude Bernard Lyon1 (Department of Electronic, Electrotechnics, and Automatic) in France. She completed her Master of Engineering in power systems in the Department of Electrical and Electronic Engineering in the Faculty of Engineering and Technology of the University of Buea, Cameroon in 2021, and her Master in Physics, from the Faculty of Science of this same University in 2018. Her research interests are Renewable Energy Systems, power systems, and electronics. She had 6 months of learning in renewable energy at the School of Engineering (Department of Renewable Energy) of the University of Zambia, Lusaka, Zambia. She participated several times in the online training offered by RES4Africa Foundation concerning renewable energy and microgrids.

Musong Louis Katche completed his Ph.D. degrees in Power Systems Engineering and Energy Studies from the University of Buea in Cameroon and Moi University in Kenya respectively in 2023, and his Master of Engineering in Power Systems from the University of Buea in 2017. He is an Instructor in the Department of Electrical and Electronic Engineering, Faculty of Engineering and Technology, University of Buea. Additionally, Musong is a member of the National Order of Electrical Engineers (ONIGE) in Cameroon. He holds a certificate of Excellence from the Florence School of Regulation in Italy for Regulation of SDG 7. He is a certified Energy Transformation Expert by the Renewables Academy (RENAC) based in Germany. His research interests are Renewable Energy Systems, Power Electronics and Control, Power Systems, Microgrids, and Energy systems modeling and policies. He has had a research collaboration visit to the Ampere Laboratory at INSA Lyon in France.

Nicole Adelaïde Kengnou Telem completed her PhD degree in electronics in the faculty of Sciences of the University of Dschang, Cameroon. She completed her Master's degree in Electronics in 2012 in the same faculty. She graduated from the Advanced Teacher’s Training College for Technical Education (ENSET) – University of Douala, with DIPET 1 (Bachelor in Electrical and Electronics Engineering) and DIPET 2 respectively in 2003 and 2005. She is currently employed as an Instructor at the University of Buea, Cameroon, within the Electrical and Electronic Department of the College of Technology. Her primary research focus lies in the domain of Biomedical Signal and Image Processing for telemedicine purposes, where she harnesses the potential of chaos systems and Artificial Intelligence (AI) techniques. Machine Learning (ML) and Deep Learning (DL), as integral components of AI, offer valuable tools for enhancing healthcare by assisting medical professionals in patient care and clinical data management.

Ayuk Ngang Valdo Ayuk is a recent graduate of the University of Buea, where he earned a Bachelor of Engineering degree in Electrical and Electronic Engineering, with a specialty in Power Systems Engineering. His academic journey has equipped him with a solid foundation in power system design. Ayuk is particularly interested in renewable energy solutions, electronics, electrical machines, and their integration into modern power systems. He has actively participated in projects that focus on enhancing energy efficiency and exploring innovative technologies in the field. Committed to advancing the field of electrical engineering, Ayuk seeks opportunities for collaboration and research in the diverse field of power systems.

Pierre Tsafack is an Associate Professor in Electronic Engineering. He completed his Ph.D. in Applied Electronics under a joint program between the National Advanced School of Engineering (Polytechnic), Cameroon, and “Laboratoire Ampere -Institut National des sciences appliquées de Lyon-France’’ in 2011. He obtained his Master's degree in Electronics from the University of Yaoundé I in Cameroon. He assumed duty as Assistant Lecturer of Electronics Engineering in the Department of Electrical and Electronic Engineering, Faculty of Engineering and Technology, University of Buea in August 2012. Prior to this, he worked as an Instructor in the Department of Electrical and Telecommunications Engineering at the National Advanced School of Engineering (Polytechnic) of the University of Yaoundé-1 for six years. He is now an Associate Professor and Head of the Department of Electrical and Electronic-Engineering at the Faculty of Engineering and Technology, University of Buea in Cameroon.

Research Field

Marie Norbertine Kamdjou Douma : Renewable energy, power systems, microbial fuel cell, microgrids, 3D technologies.

Musong Louis Katche: Renewable energy, power systems, power electronics and control, microgrids, Energy policies.

Nicole Adelaïde Kengnou Telem: Applied physics/electronic, Biomedical image and signal processing, machine learning, cryptography and security, Internet of medical things, PV solar system, computer aided diagnosis.

Ayuk Ngang Valdo Ayuk: Power systems, electronics, renewable energy, artificial intelligence, microgrids.

Pierre Tsafack: Energy harvesting materials and technologies, Renewable energy technologies, Sensor design and application to agriculture, RF communication and security, Energy storage system technologies.

Olivier Ondel: Electronic converter, microbial fuel cell, electrical engineering, energy harvesting, health monitoring and diagnosis.

Fabien Mieyeville: Internet of Things, autonomous embedded systems, Energy harvesting for IoT, Frugal Artificial Intelligence, Ressources Constrained Environment Embedded Systems.