MODELLING AND FACTORING CRITICAL SYSTEM COMPONENTS OF PV-MFC SYSTEMS FOR IMPROVED AND EFFICIENT ENERGY GENERATION AND TREATMENT OF MUNICIPAL EFFLUENT AT THE EAST COASTAL REGION(S) OF SOUTH AFRICA: CASE STUDY UMHLATHUZE MUNICIPALITY

MELUSI NHLEKO & FREDDIE L. INAMBAO

Department of Mechanical Engineering, University of KwaZulu-Natal, Durban, South Africa

ABSTRACT

Developing a hybrid system that assists government institutions such as municipalities with provision of clean sustainable energy and clean water discharge to the environment from wastewater treatment plants has been an on-going goal in recent years as stringent legislative precepts have been mandated for both public and private sector institutions. However, the focus has been legislative compliance and the procurement and implementation of improved mono-systems that focus on one specific desired aspect. Recent studies and developers have indicated the cost-effective benefits of hybrid systems. Research for better and more efficient performing systems that ensure affordable and socio-economic viability so as to gain government buy-in is the foundation or platform for any business operation and improved quality of life for citizens. Procurement of affordable technology by municipalities affords citizens, industries and businesses such as small-to-medium enterprises, an opportunity to conduct social and trade activities at affordable rates, thus improving economic quality of the region under study and sustainability of life. This paper highlights areas in the development of photovoltaic microbial fuel cell (PV-MFC) hybrid systems that can be improved for better and efficient systems, especially for municipalities in the South African east coastal regions. The areas highlighted and discussed are, however, subject to the proximity and abundance of required resources in relation to the municipality under study, such as the sea for access to seawater, biomass collection station (such as wastewater treatment plant and macerator stations) and the type of industrial wastes that are discharged to the municipal sewer pipeline. The importance of stating the above is that each municipality has characteristic resources that are readily available and industrial discharges that carry impurities such as sulphides that the municipality, in this case, uMhlathuze municipality must treat so that the hybrid system can efficiently function when generating clean energy. Based on literature, generic equations are provided with the aim of ensuring that critical components of hybrid system(s) are critically designed and/or modified. The dual function of hybrid systems is presented in this paper to enhance municipal confidence in addressing both operational and economic viability of their function when hybrid systems such as (PV-MFCs) are critically evaluated and employed.

KEYWORDS: Energy Generation, Efficiency, PV-MFC Hybrid Technology, Photovoltaic, Microbial Fuel Cells.

Received: Feb 14, 2021; **Accepted:** Mar 04, 2021; **Published:** Mar 27, 2021; **Paper Id.:** IJMPERDJUN20212

1. INTRODUCTION

Hybrid systems are cost effective and initially cost less compared to the installation of photovoltaic (PV) systems alone (Pazmino, 2007, as cited in Fiedler, 2014). A study conducted by Promethium Carbon and the South African National Energy Development Institute (2017) describes hybridisation as the coupling of one renewable energy technology with another technology for the purpose of delivering energy services. The main purpose of employing

hybridised energy systems according to this paper is introducing renewable based hybrid technology to address shortfalls in demand and to ultimately replace the existing conventional fossil fuel (coal) based energy generation. Other auxiliary reasons exist, motivating the use of hybrid systems. This paper emphasises generation and reliability of supply by reflecting on and reviewing critical aspects and components of PV and MFC systems based on studies by authors and researchers that significantly improve the efficiency and performance of hybrid systems when they are properly designed, reviewed and modelled, and implemented. The hybrid system that is critically evaluated in this paper is the photovoltaic microbial fuel cell (PV-MFC) hybrid system. The aim is to enhance government (municipality's) consideration of and buy-in on hybrid systems such as PV-MFC systems for effective delivery of services at improved efficiencies and affordable, multi-functional delivery of duties. uMhlathuze municipality located at the north east coast of the KwaZulu-Natal province of the Republic of South Africa is used to demonstrate the objects of this paper.

2. METHODOLOGY

2.1. Background

Rycroft (2016) states that most municipal wastewater treatment plants in South Africa are aerobic in nature and consume substantial amounts of energy to produce activated sludge. Pabi et al. (2013) concur and state that approximately half of energy consumption at wastewater treatment plant (WWTP) is due to the energy requirements of the aeration process. Bachamann (2015) states that biological treatment of the primary sludge in wastewater plants results in activated sludge. Gikas and Tsoutsos (2013) confirm and state that activated sludge from municipal wastewater treatment plants can be used in MFCs. Franco (2013) states that anaerobic treatment is a lucrative alternative to aerobic activated sludge treatment and that anaerobic digestion process reduce energy related costs and that residue from MFCs compared to residue from aerobic treatment processes are less harmful to the environment when discharged and require no or far less handling. Huggins et al. (2013) state that since the oxidation process of organics in the anode chamber of MFCs is anaerobic, MFCs have the advantage of generating very little biomass. Stoll, Jan, and Xu (2018) concur and state that due to low production of sludge and lower energy costs, MFC systems are amongst the best candidate technologies for generating energy and improving wastewater (grey water) and sludge quality and quantity produced.

Procurement of affordable technology by municipalities often afford citizens, industries and businesses such as small-to-medium enterprises (SMEs) with an opportunity to conduct activities at affordable rates to improve economic and quality of life sustainability. In an attempt to enhance the feasibility of technologies, the first thing that must be acknowledged is that whatever investment a municipality undertakes has a direct impact on how businesses can conduct trades and other economic activities and on the overall quality of life. In other words, municipal buy-in is fundamental to the possible achievement of any goal and dream. Thus, technology requires constant review and improvement so that value for money is achieved and most importantly relevance to time-based changing operational demands and needs is maintained at all times by municipalities.

This paper thus attempts to reflect and review critical areas in the development of PV-MFC hybrid systems that can be improved for better and efficient systems for municipalities operating at the east coastal region of the Republic of South African that are bordered by the Indian ocean. The areas highlighted and discussed are, however, subject to the proximity and availability of the type of resources at the disposal of the particular municipal jurisdiction. Each municipality has its own characteristic readily available resource that clean energy can be generated from, and also characteristic impurities contained in mostly industrial waste discharge that influence the results of and processing of the

renewable resource to achieve the desired goals. The desired goals according to this paper are the generation of clean and sustainable energy and treating of effluent or sewer discharge as prescribed by legislation and the South African National of Standards (SANS) in particular SANS 241 before finally being disposed off to the environment. Generic equations are provided towards ensuring that critical components of the hybrid system are critically designed, modelled and/or modified. The dual functioning of the hybrid system as explained in this paper is intended to enhance municipal confidence in the operational and economic viability of hybrid systems when employed.

The PV and MFC technologies reviewed in this paper reflect an innovative alternative to a municipality's conventional operations in relation to the environmental impact that results from the municipality's operations. These technologies are viewed as means of having a positive impact on the safety of person(s) that are and/or can be affected by municipal operations within the workplace and outside of the workplace as prescribed by sections 8 and 9 of the Occupational Health and Safety Act (Republic of South Africa, 1998). Furthermore, such technologies help fulfil the mandates of the Constitution of the Republic of South Africa and that of the municipal finance management act (MFMA) that municipalities must do all that is within their power to procure sustainable and affordable resources in order to provide effective delivery of services to their communities. These technologies support the urgent call by the government of the Republic of South Africa that institutions both private and public must take meaningful steps to address their security of energy supply, effects of global warming/climate change, impact on the surrounding environment and the effects of unreliable energy supply. The PV-MFC technology is thus presented as a viable solution that municipalities located in the east coast region of the country such as uMhlathuze municipality that can establish the economies-of-scale of using such a technology.

Hybridisation combines different energy sources in one supply (Abd El-Aal, 2005). Primo (2016) concurs stating that hybrid systems provide a high level of energy security through a mix of generation methods that when synced together with a storage system such as a battery can ensure maximum supply reliability and a security of supply that can easily be configured to meet the desired range of power needs. Hybrid power systems are, therefore, the result of a combination of different fuel source types aimed at generating electricity.

When designing for the coupling of the different components of a hybrid system, the main elements that need to be observed are: the system's expandability, the general adaptability of the system, the compatibility of the system for the desired application, the cost reduction factor, the system control needs and advancement, and the incorporation of desired aspects of maintenance of the system (Abd El-Aal, 2005). Kleinkauf et al. (2019) adds by stating that the proper designing of and installation of an output power (current) conditioning unit such as an inverter has the potential to significantly improve efficiency and reduce energy wastage and associated costs when using and operating the technology under correctly defined operation conditions.

In agreement with the views expressed by Abd El-Aal (2005), Sahin and Okumus (2017) list among other needs that require addressing when designing for a hybrid system using renewable sources as follows:

- The purpose for wanting to generate electricity from a renewable source such as reducing energy bills, powering the treatment facility from a renewable energy source that makes supply sustainable and reliable, address energy shortages, produce energy through processes that are eco-sensitive and products that are eco-friendly, etcetera must be established.

- Determine the amount of power required and the abundantly available renewable energy source that will support the goal of powering any defined desired facility such as wastewater treatment plant.
- Determine the location and logistics of where the system will be installed with careful consideration of all resources that will make the renewable energy project profitable.
- Selection of affordable and effective technology to be used and how must it function taking into account environmental effects of the place where the project is implemented.
- Determine the feasibility of undertaking the project with full understanding of monetary and non-monetary benefits such as money-saving(s), economies-of-scale in terms of cost-benefit analysis (including financial payback models), etcetera.

In agreement with the above view reflected by Sahin and Okumus (2017), Aznar et al. (2019) states that the above is necessary and important with regards to the design of energy-efficiency and high performance systems that satisfy desired goals with ease. The authors cite Busquet (2003) regarding items that must be identified, fully understood and addressed when designing an energy hybrid system that is intended to solve unreliable supply and energy shortages. Some of the items are listed as follows:

- Define the target application because inadequate targeting may lead to misdirected energy subsidies.
- Decide on the most energy-efficiency investments that reduce long-term energy burden yet maintains adequate supply that meets the demand and phase out conventional energy generation in the long term.
- Attain adequate access, engagement and commitment of partners that support initiative at all stages so that risk is shared and capital investment opportunity is heightened.
- Secure sustainable funding source and program that are well-understood and in place, meeting as little resistance as possible.
- Ensure that the system is simple, tailor-made, flexible, can be easily integrated in phases by means of decentralisation and of multidimensional strategy that accounts for diverse participation with no or minimum resistance.
- Review the implementation strategy and application of the designed system with regards to relevancy, adaptability and productivity.

Primo (2016) recommends that MFCs must be used or sequenced to backup or supplement electricity or be a secondary supply to the PV in the PV-MFC hybrid system. That is, the hybrid system must follow the sequence of firstly using energy generated from a PV/battery system and then when the energy is exhausted. The MFC system commences supply to carry the site load. The author highlights that solar and biomass hybrid systems such as PV-MFCs are becoming popular for providing electricity, reducing costs of generating electricity, and cleaning municipal wastewater. Deval and Dikshit (2013, as cited in Barua et al., 2018) state that MFC can play a major role in green production of bioenergy and for treating waste water.

Abd El-Aal (2005) states that designing or modifying a hybrid system through simulation allows for the effective examination of various factors or system parameters that influence system performance and satisfy the system/user

requirements. The mathematical and empirical expressions required to model each system component considered critical and represent the entire system operation are determined. Further, Abd El-Aal (2005) states that in simulating system functions and operations with regard to performance, technical characteristics (specification) of the system must be determined and clearly defined, climatological (weather) data obtained as well as user load demand. The author adds that in determining the size of the system components (the storage and the energy transforming units), the major influence is user load demand. Thus, to find the optimum size and operation conditions, simulations must be conducted to ensure that required conditions are maintained for the system to perform optimally. Due to the absence of comprehensive feasibility report(s) due to the required financial investments that must be committed to conduct detailed feasibility studies regarding uMhlathuze municipality which reflect actual and accurate data of resources on site, an attempt to simulate uncaptured variables would reduce the credibility of this paper. Thus, a generic approach is used.

2.2. Technical Aspects

2.2.1 Modelling and Simulating a Photovoltaic Fuel Cell Hybrid System

Boaro et al. (2013) states that hybrid systems function by interchanging supply if the other part of the system is unable to produce electricity. Abd El-Aal (2005) concurs and states that the PV-Battery-Fuel Cell hybrid system uses the fuel cell system as a back-up when the batteries reach a minimum allowable charging level and/or when the load (peak loads) exceeds the power produced by the PV system. Primo (2016) states that MFCs have gained success as a source of power for wastewater treatment plants around the world and can be used as either primary or backup power supply system. Boaro et al (2013) states that a storage system (battery) must be designed to store surplus energy generated from the system when the power required has been determined and also under conditions when there is not sufficient energy. Abd El-Aal (2005) observes that diesel generators provide the rated power to the load in a few seconds after start up, but a fuel cell system needs more time to provide the same rated power and the output should only be increased slowly after start up. The principal observation by the author calls for pursuit of an alternative approach that must be modelled for and incorporated in simulation of the whole operation of the hybrid system for high performances and optimisation to be achieved. The author highlights that the significant advantage of the fuel cell as a back-up is that fuel cells have high conversion efficiency and very low maintenance cost.

The suggested alternative of operating the hybrid system as one system backing-up the other, a blended approach can be ensued whereby a baseline energy requirement comprising of night load and the amount of energy required to charge the energy storage unit (battery) is determined and is supplied by the energy generated by the MFC and the rest of the total demand load being catered for by the PV system. For a municipality such as uMhlathuze that discharges an average of 25 000 m³ per day of continuous municipal sewer discharge from both commercial and households, a 25% - 30% of the total energy demand can be satisfied through MFC generation, with the remainder of the total energy demand including peak demands being catered for by the PV system. Subject to the findings of a comprehensive feasibility study, the most feasible blend approach of either generating against night load and battery capacity or 25% - 30% of the total energy demand using MFC technology system must be determined and implemented. This approach counteracts the observation by Abd El-Aal. Thus, the viability and low costs of operating PV-MFC hybrid system for generating electricity despite the high initial investment cost must be determined in the feasibility study for accurate and credible recommendations.

2.2.2. Determining Maximum Solar Position using an MPPT

According to Sahin and Okumus (2017), based on the views of Er (2016) and Boaro et al. (2013), solar panels must be designed and installed with a tracking system that ensures that the solar (PV) panels are always at the right angle to the sun's irradiance for maximum harnessing of solar energy to occur at all times. Er (2013) adds and states that understanding the relationship of the earth to the sun at various geographical locations is paramount for MPPT functioning as the fundamental unit of solar time is day and is comprised of sunrise (time when the upper part of the sun is visible) and sunset (when the last part of the sun is about to disappear).

Abd El-Aal (2005) states that site climate, the load profile, the characteristic of the components, and the storage volume required influences the design of the hybrid system. Considering the PV modules of the hybrid system, the maximum power point tracker (MPPT) is responsible for maximising the exposure of the module to the solar radiation. The MPPT is used to adjust the actual operating voltage and current of the PV system so that the power generated approaches maximum value at any given time with the amount of available sunlight at that particular moment in time (Abd El-Aal, 2005). Further, the author states that the operation of a PV system at its maximum power point (MPP) involves matching the impedance of the load to a PV module (electricity generator). MPPTs can be classified as direct or indirect based on the method used (Abd El-Aal, 2005):

- The direct method is algorithm based whereby the system continuously searches for an output that determine and maintain the maximum of the power curve without any interruption of the normal operation of the system. For each increment, if the power output is greater than that obtained from the previous increment, the search direction is maintained at the position where the power output has a higher value.
- The indirect method uses the outside condition to generate a signal that estimate MPP, which includes but is not limited to the measurement of solar radiation, measurement of module temperature, the short circuit current, or open circuit voltage of the reference PV cell.

Er (2016) states that in order to gain a full understanding of the sun's position relative to the solar collector, the concept of solar time must be fully understood. Solar time must be classified as apparent true solar time (sundial time) and mean solar time (clock time). When considering the installation of a solar system or the solar PV component of a hybrid system, the location of where the system must be installed is very important as the direction, angle and location of the solar collector must be determined.

Understanding the importance and correlation (effect) of the sun's position with the earth's rotation around its own axis and around the sun's orbit form the basis for the angle at which solar radiation from the sun hits the surface of the earth. This enables prediction of the sun's position and development of an algorithmic code for the solar collector movement described by angles, solar altitude, and solar azimuth (horizontal direction of the sun at sunrise and sunset) (Er, 2016). Er (2016) state that the trigonometric correlation of the different angles to determine the sun's position are: solar altitude angle (α), solar declination angle (δ), sunrise hour angle (ω_s), solar azimuth angle (γ_s) and sunset and sunrise (ω_o), and described as by using the following expressions:

- $\sin(\alpha) = \sin(\varphi) \sin(\delta) + \cos(\varphi) \cos(\delta) \cos(\omega)$
- $\delta = 23.45^\circ \sin\left(\frac{360(284+n)}{365}\right)$

- $\omega_s = \cos^{-1} (-\tan(\phi) \tan(\delta))$
- $\tan(\gamma_s) = \frac{\sin \omega}{\sin(\phi)\cos(\omega) - \cos(\phi)\tan(\delta)}$
- $\omega_o = \cos^{-1} (-\tan(\phi) \tan(\delta))$, where n is the number of days of the year starting from the first of January each year, and ϕ is the latitude of the related location (in degrees).

Er (2016) states that in order to develop an effective code for a solar collector (PV system); the two core classes that the code must consist of are the daily fixed term calculations and the daily variable algorithm calculations. The daily fixed term calculations are parameters such as calendar days and dates, altitude, latitude, declination angle, sun set degree (angle), sun clock sun rise hour, sun clock sun set hour, standard clock sun rise hour, standard clock sun set hour, day length and time difference, etcetera. The daily variable algorithm calculations consist of parameter values of time difference, declination angle based on location of where the system is set to be installed, altitude of where the system is to be installed, clock angle, sun elevation angle and azimuth angle, etcetera (Er, 2016).

According to Er (2016), the main purpose of developing and classifying software tools to be used for hybrid systems such as MFC-PV systems is to provide for either simulation or economic evaluation or selection of appropriate design and data analysis for decision-making and planning or various combinations of the mentioned factors. A clearly defined application of a system together with a full understanding of the objectives of the renewable energy project makes it possible for the software developer to program against known inputs and variables with few or no uncertainties.

Solar power derived from the PV component of a hybrid system depends on the intensity of the sun's irradiance, the trigonometrical terms between the sun and the surface of the system at known geographical location, and the meteorological data. Thus, knowledge of solar radiation data and continuous review and improvement of MPPT are important in designing systems operating on solar energy for a specified region. Solar calculations are the basis and background for forecasting and system performance. This provides system operators with more certainty about what weather and peak solar output and overall solar production that can be achieved at any particular day (Er, 2016).

2.2.3. Determining and Modelling the Flow Rate of Municipal Sewer Discharge as a Source of Biomass for Continuous Operation

Abd El-Aal (2005) states that MFCs are power generators that can operate continuously as long as the fuel and oxidant are made available and supplied to the fuel cell. Assuming that the fuel (municipal sewer discharge or influent) has undergone all the treatment processes to required quality, the feed of the same to the anodic chamber of the MFC is detrimental to the effective performance of the MFC in the hybrid system. This is to say that the fuel must be fed at required and known quantities (concentration and flow rate) so that the ratio of the microbes acting on the organic matter of the municipal sewer is kept optimal. Khaloufi (2019) states that the nature (mix and concentration) of the substrate (wastewater influent) is most important for efficiency and performance of a microbial cell as substrates are a source of nutrients for microorganisms. Modelling, monitoring and reviewing the rate of feed is crucial in avoiding the consequences of high flow rate or low flow rate of the fuel to the anodic chamber and ensure efficient functioning of the MFC in producing the desired energy. To achieve the needed quality, the influent must frequently be tested and monitored to ensure correct concentration of organic matter and the detection and treating of traces of any unsolicited elements found.

Polymer electrolyte membrane fuel cells (PEMFC) is an attractive energy generating system because of its affordability, ability to function at low temperatures, of low maintenance costs, only depend on established municipal sewer discharge volumes and that no additional cost of acquiring electrolyte is incurred when compared to other types of fuel cells such as Phosphoric acid fuel cells (PAFC). The advantages of PEMFCs with effective membrane is that they directly convert bio-chemical to electrical energy, they display excellent characteristics even during partial loading, are fuel flexible, have zero or very low noise during operation, and there is high availability of lower temperature units for use. Disadvantages of PEMFCs are, according to Abd El-Aal (2005), the relatively high initial investment cost, special treatment of fuel is required before being fed to the fuel cell, platinum is expensive and yet it is the most effective catalyst. Taylor (2003, as cited in Abd El-Aal, 2005) states that although the main barrier towards the implementation of MFCs is investment cost, related, research over the years has made MFC technology affordable. Further, Abd El-Aal (2005) states that although operational costs of MFCs are influenced by cost of acquiring the fuel (that is, costs of pumping sewage drained from residential and commercial places to the inlet of the macerator station-where the biomass waste is treated to fuel), the operation mode of both PV and MFC technologies and the cost for stack replacement for both technologies, Abd El-Aal (2005) suggests the following must be pursued as means for reducing investment costs; Improve the fuel cell stack design to increase power density in the most efficient manner, use low cost materials to construct system and minimize temperature constraints that affect electricity generation through use of lower costing material. Membrane and catalyst material must be reviewed and changed based on ongoing research to equivalently efficient low cost material and modelled for up-scaled application. Costs of acquiring biomass fuel are already incurred by the municipality and accounted for in its primary operation.

Although the initial capital investment or outlay of PV-MFC hybrid-based technologies present a barrier for the implementation of up-scaled PV-MFC hybrid systems, the benefits of having long-lasting reliable and sustainable energy supply with low or no carbon emissions and cheap electricity generation costs outweighs cost implications and thus calls for immediate pursuit. The report by Promethium Carbon and South African National Energy Development Institute (2017) reflects that the bioenergy part of the PV-MFC hybrid system is site specific and that its feasibility and appropriateness is dependent on the availability and sustainable biomass feed at low cost and the abundance of sunlight.

2.2.4. Modelling of System Components of Each of the Systems and the Hybrid System

Abd El-Aal (2005) lists three models that can be used to describe the equivalent electrical circuit of PV cell module or array: the one-diode model that represents the electrical behaviour of p-n junction, the two-diode model that describes in detail the recombination process of charge carriers on the surface and the bulk material, and the empirical model that provides the best-fit line for the measured current-voltage (I-V) curve of a PV cell module and array. The parameters reflected by the empirical model as according to Abd El-Aal (2005) are $P_{\max}$, I_{sc} , V_{oc} , $\frac{\delta V_{oc}}{\delta T_j}$, $\frac{\delta V_{oc}}{\delta E_s}$, $\frac{\delta I_{sc}}{\delta T_j}$, where T_j is the cell temperature and E_s is the solar radiation. The empirical model not only accounts for the produce of PV cells and arrays but also the changes that result from change in voltage due to change in the cell and solar radiation collected by the cell respectively and the change in maximum current produced at no load due to change in cell temperature. The advantage of using the empirical model though not as accurate as the two other models is that the empirical model accounts for how actual conditions (changes in cell temperature [heat generated in the cell] and change in solar radiation) influence the production of the current density, and subsequently the power density from the cell.

The expression that reflects the relationship between the voltage of the PV cell and the current produced is reflected by Abd El-Aal (2005) as; Cell voltage, $V_s = V_{oc} \left[1 + \frac{1}{20.7} \ln \frac{I_{sc} - I_s}{I_{sc}} \right] - R_s I_s$. V_{oc} is the open circuit voltage, I_{sc} is the short circuit current, I_s is the cell current and R_s is the cell resistance. Theoretical P_{max} is the product of V_{oc} multiplied by I_{sc} , whereas actual P_{max} is the product of V_s multiplied by I_s . In light of the work conducted by various researchers and authors, an attempt to improve the conversion process of solar energy to electrical energy together with increasing the efficiency of PV modules increases costs for very small performance increase. Thus, cheaper alternative material is continuously sought for equivalent efficiencies that make PV systems more affordable. In view of the electrochemical component of the hybrid system due to MFC functioning, the author states that a reacting system that is at non-equilibrium condition will continue to react until equilibrium is achieved. The general equilibrium equation of a chemical reaction as quoted by Abd El-Aal (2005) together with the equilibrium constant expression is: $\chi A + \gamma B \rightleftharpoons \zeta C + \varepsilon D$, and equilibrium constant (EC) = $\frac{a_D^\varepsilon \times a_C^\zeta}{a_B^\gamma \times a_A^\chi}$ respectively. Where a_i is the activity of species calculated from concentration.

Abd El-Aal (2005) states that the theoretical cell voltage when converting chemical energy under spontaneous oxidation-reduction reaction conditions to electrical energy through a known electromotive force (emf) can be computed by using the expression, $V_{th} = V_o - \frac{RT}{nF} \ln[EC]$. Where V_o is the equilibrium cell voltage at standard conditions, R is the universal gas constant of 8.314 J/K/mol, T is the cell temperature measured in K, F is the Faraday's constant of 96485.309 C/mol, and n is the charge number. Abd El-Aal (2005) provides an analytical model for determining the performance of a PEMFC system by taking into account the physical and theoretical aspects that affect the functioning of the MFC system. Through this model, the ideal performance of the PEMFC is determined and the corresponding losses calculated and deducted from the overall performance, determining the actual operation performance of the PEMFC system. The actual amount of electrical energy in terms of voltage (actual cell voltage) for the current drawn from the fuel cell can be computed by using the expression, $V_{actual} = V_{th} - V_{anode} - V_{cathode} - V_{ohm}$, the difference that results when all losses occurring at the anode, cathode, and external circuit are deducted from the ideal (theoretical) voltage. The model presented by Abd El-Aal (2005) excludes the influence of water management on the PEMFC performance and based on the views by Barbir (1997), as cited by Abd El-Aal (2005), ideal performance of fuel cells such as PEMFC are mainly influenced by the effectiveness (complete reaction and reaction rate) of the electrochemical reactions in the fuel cell under standard conditions.

Municipal sewer discharges varying concentrations of hydrogen sulphide gas and the concentration of this gas depends on the make-up of the municipal sewer system that influences the flow rate and retention of sewer in the system as sewer ferments. This fact must be taken into account and modelled for when PEMFC performance is considered. Abd El-Aal (2005) states that the theoretical (ideal) PEMFC voltage can be analysed through the use of the following expression, which accounts for the effect that changes in partial pressures of hydrogen and oxygen have on performance when the fuel cell temperature is constant at all the points in the fuel cell stack. The fuel to the anodic chamber of the MFC is the municipal sewer that produces hydrogen based gases when the organic matter is acted upon microbes (an anaerobic process). The cathodic chamber is an aerobic process that uses oxygen. The theoretical voltage, $V_{th} = V_o - (T - 298.15) \times \frac{\Delta S}{nF} \times \frac{RT}{nF} \ln \left[\frac{p_{H_2} \times p_{O_2}^{0.5}}{p_{O_2}^{0.5}} \right]$, where ΔS is the entropy of the reaction in J/K/mol. Abd El-Aal (2005) highlights that the theoretical effectiveness of the electrochemical reaction is based on the assumption that the gases in the fuel cell behave ideally and

that fuel cell variations are isothermal, whereby the change in molar enthalpy and change in molar entropy at varying temperatures are equal to their value at standard temperature. The author states that when the value of the actual cell voltage approaches the theoretical voltage value of the cell, the fuel cell is high performing. Furthermore, the author states that to have a high performance fuel cell or fuel cell with minimum over potential, modifications in the design of the fuel cell is required. Abd El-Aal (2005) lists the aspects of the fuel cell design that must be modified and modelled as including: improvement in the structure and material composition of the electrodes in terms of conductivity-durability-affordability and maintainability, improve electro-catalysis of the fuel cell, improve conductive electrolyte, reduce resistance of the nanowire (external circuit) by shortening the length and manipulating the cross-sectional area of the nanowire, etcetera. Regarding improvement of the operating conditions of the fuel cell, the author states that the concentration of fuel must be optimized in relation to the concentration of bacteria at the anodic chamber, the temperature conditions must be kept conducive and fairly constant for optimum bacterial activity and the impurities in the fuel must be minimized and even eradicated to prevent poisoning of bacteria and limiting of the reduction-oxidation (redox) reaction and reduced conductivity of ions. Abd El-Aal (2005) accounts for the efficiency of PEMFC as the ratio between the electrical power output and the fuel input (in Watts). The ideal efficiency of a microbial fuel cell is $\eta_{fc} = \frac{\Delta G}{\Delta H} = \frac{P_{fc}}{F_{in}}$. Where P_{fc} is the electrical power output of the fuel cell, F_{in} is the input fuel to the cell, ΔG is the change in Gibbs energy which represents the electrical energy output of the fuel cell and ΔH the reaction enthalpy change which represents the thermal input energy. The standard conditions for a fuel cell also known as the standard free energy of the cell reaction are indicated as temperature, $T = 25^\circ\text{C}$, pressure, $P = 100\text{kPa}$, thermal input energy, ΔH_o (hydrogen/oxygen reaction) = -268kJ/mole , and free energy available for useful work = 237.3kJ/mole . The maximum theoretical efficiency in a PEMFC is generally 0.83 (Abd El-Aal, 2005). Abd El-Aal (2005) states that the efficiency of the actual fuel stack, $\eta_{fc,stack} = 0.83 \times \frac{V_{actual}}{V_{th}}$. Thus, the author provides that an increase of the actual cell voltage subsequently increases the fuel cell efficiency.

Why the efficiency of the fuel cell is of utmost importance is because a decrease in the current density requires the active cell area to be increased in order to maintain the required power. Abd El-Aal (2005) states that when designing a fuel cell with high efficiency, the capital costs tend to increase, but the operating costs must be kept minimum or decreased. Bocklisch (2003, as cited in Abd El-Aal, 2005) states that in order to compute the total efficiency of the fuel cell system, losses of the peripheral power components such as air blower, control system, etcetera must be incorporated. The expression for computing the total efficiency of the system is: $\eta_{fc,system} = \frac{P_{fc}}{F_{in} + P_{periph}} = \frac{\eta_{fc,stack}}{1 + \left[\frac{P_{periph}}{1.482 \times N_s \times I} \right]}$, where N_s is the number of cells in the stack, I is the output current of the fuel cell, and 1.482 is the theoretical thermal voltage of the cell at standard conditions in volts.

To conclude modelling and analysing of fuel cells, the rate at which electrons are produced at the anodic chamber must also be considered. Using Faraday's law that the rate of hydrogen generated or supplied to a fuel cell is directly proportional to the rate of transfer of electrons at the electrodes, the principle of analysing the rate at which electrons are produced depends on the concentration of required organic matter (ingredient in fuel) to produce hydrogen ions when acted upon by microbes. Busquet (2003, as cited in Abd El-Aal, 2005) indicates that the concentration or flow rate of organic matter for several cells connected in series (the mass flow rate of biodegradable organic matter by these microbes) is $\dot{m} = \frac{N_s \times I}{n \times F} \times \frac{1}{\eta_F}$, where $\dot{m}$ is the flow rate of organic matter in the fuel or substrate that produces hydrogen when acted by the bacteria in the fuel cell, $n = 2$, the number of electrons per mole, η_F is faraday's efficiency.

Since in actual PEMFCs, the organic matter in the substrate responsible for the production of hydrogen ions is slightly higher than the theoretical maximum value (stoichiometry). Abd El-Aal (2005) states that the more the organic matter there is than the concentration of microbes acting on the matter (incomplete redox reaction), the current efficiency reduces or the Faraday's efficiency of the cell reduces. In relation to hydrogen production, Faraday's efficiency is described as the ratio between the theoretical maximum value of organic substance (hydrogen based elements in organic matter) consumed in the fuel cell and the actual value. Abd El-Aal (2005) expresses Faraday's efficiency in relation to hydrogen production as: $\eta_F = \frac{\dot{m}_{th, hydrogen\ produce\ from\ substrate}}{\dot{m}_{actual\ hydrogen\ from\ substrate}}$. Thus, the concentration of organic matter in the municipal sewer must be modelled and monitored for corresponding adjustments in the flow rate. Although the Faraday's efficiency is highly dependent on the temperature conditions for bacterial activity, the concentration of organic matter must be modelled in terms of flow rate and temperature.

Temperature conditions must, according to Abd El-Aal (2005), be kept at levels that lower resistance, reduce current losses, and improves Faraday's efficiency. The empirical expression of Faraday's efficiency that accurately depicts the release of hydrogen ions after bacterial activity on substrate or fuel to produce hydrogen molecules is: $\eta_F = \zeta_i \times e^{\left[\frac{\zeta_2 + T\zeta_3}{\left(\frac{1}{A_c}\right)} + \frac{\zeta_4 + T\zeta_5}{\left(\frac{1}{A_c}\right)^2} \right]}$. Where ζ_i are Faraday's parameters, T is the temperature of the fuel cell [°C], I is the fuel cell current, and A_c is the contact or surface area of the electrode.

Hydrogen is the simplest element that aside from the photovoltaic effect in PV systems is a base element in MFC systems that makes both systems to complement each other with respect to ensuring consistent concentration of hydrogen ions (Primo, 2016). Another benefit of hydrogen is that it maintains the temperature of biomass reservoirs at temperatures that enable the production of controlled power generation as at low temperatures biomass plants collapse (Primo, 2016).

2.2.5. Modelling the Power Conditioning Unit

Since the power conditioning device formats the output of generated electricity to required form for application, the analysis provided through the modelling of the power conditioning unit (PCU) provides a characteristic efficiency curve of the entire hybrid system. According to Abd El-Aal (2005), two models exist for a power system: a model of a system without any energy storage, whereby the power output (generated) from the system equals to the load demand and a model of a system with energy storage, whereby the input effort during normal operation determines the power supplied through the PCU. The latter is applicable to this study under the expressions $\eta = f(P_{in})$ and $P_{out} = f(P_{in})$. Three models exist that can be used to describe energy conversion by PCUs. These are listed and described by Abd El-Aal (2005) as:

- The linear PCU model that functions to describe power output (P_{out}) based on examining the relation of the three parameters; input power P_{in} , the standby power consumption $P_{standby}$ that corresponds to operation at no load (open circuit), and the efficiency η_{rated} at rated power. The expression is: $P_{out} = \eta_{rated} \times (P_{in} - P_{standby})$.

Where $P_{standby} = 0.01 \times P_{rated}$ when $P_{in} < P_{standby}$, the efficiency is assumed zero. And when P_{in} approaches the rated power P_{rated} , the standby power consumption is negligible. When $P_{in} \geq P_{standby}$, $\eta_{out} = \frac{\eta_{rated} \times P_{rated}}{P_{rated} - P_{standby}}$.

However, Dumbs (1999, as cited in Abd El-Aal, 2005) highlights that this expression gives an underestimate of the inverter's efficiency of about 5 % to 10% for high values of P_{in} .

- The quadratic PCU model. Although the quadratic PCU model has limited accuracy at low input power levels, the quadratic PCU model is best-suited for high input power. Abd El-Aal (2005) states that the three parameters extracted from the experimental data are simulated in such a manner that the power curve (power output) is computed from efficiency and input power. The expressions used in this model are:

$$P_{out} = \begin{cases} P_{in} - P_{loss} \\ 0 \end{cases}, \text{ where } P_{loss} = K_0 + K_1 P_{out} + K_2 P_{out}^2, \text{ and } P_{standby} \leq P_{in} \leq P_{in,max}. \text{ where } P_{out} = P_{in} - P_{loss}.$$

According to Abd El-Aal (2005), K_0 is described as the load independent losses (self-power consumption losses) that is equal to $P_{standby}$, K_1 is the linear load proportional losses (voltage drops in semiconductors), and finally K_2 is the load Ohmic losses that includes magnetic and all other losses. Magnetic and other losses are losses that are incurred due to capacitors, inverters, etcetera. What can be depicted with this model is that when the output power is closer to the rated value, the Ohmic losses have more influence on the efficiency due to voltage drop. And that the reduction of these losses (self-power consumption parameters) mainly increases (improves) the rated power efficiency. This model best describes solar PV performances. According to Macagnan (1992, as cited in Abd El-Aal, 2005), the efficiency of PCU is expressed by the expression:

$$\eta = \frac{P}{P + n_o + mP^2}, \text{ where } P = \frac{P_{out}}{P_{rated}}, n_o = \frac{1}{99} \left(\frac{10}{\eta_{10}} - \frac{1}{\eta_{100}} - 9 \right) \text{ and}$$

$m = \left(\frac{1}{\eta_{100}} \right) - n_o - 1$. Where η_{10} is the efficiency of the PCU at 10% of the rated power, and η_{100} is the efficiency of the PCU at 100% of the rated power. Also, the power output relates to the average power consumption. The expression is:

$$P_{out} = \begin{cases} C_o + C_1 P_{in} + C_2 P_{in}^2 \\ 0 \end{cases} \text{ where } P_{standby} \leq P_{in} \leq P_{in,max}. C_o \text{ is negative and indicates the average power consumption at no load (} P_{out} = 0 \text{). The value of power consumption is 1\% of the PCU rated power (Abd El-Aal, 2005).}$$

- The piece wise linear PCU model is a value resulting from the interpolation between measured efficiency values for corresponding PCU input power values (Abd El-Aal, 2005). The advantage of using this model is that the efficiency of the PCU can be predicted over the entire range of the input power by dividing the input power into values at equal intervals that measure the PCU efficiency. Since the model computes the efficiency by linear interpolation between measured efficiency (η_{low} and η_{up}) at the lower and upper ends of the selected input power ($P_{in,low}$ and $P_{in,up}$), then efficiency η at any intermediate level of P_{in} is expressed as: $\eta = \eta_{low} + \frac{(P_{in} - P_{in,low}) \times (\eta_{up} - \eta_{low})}{(P_{in,up} - P_{in,low})}$.

2.2.6. Modelling for Storage Unit

A capacitor is an electrical component that is used to store energy. Supercapacitors are the future of storing energy (Abd El-Aal, 2005). As an integral part of PV-MFC hybrid system, it is important to describe and model their characteristic functioning and incorporate their effect on performance (Abd El-Aal, 2005). To establish the best performing energy storage unit, modelling the performance of a series of capacitors or supercapacitor must form part of any hybrid system that is intended to generate and supply energy (Abd El-Aal, 2005), hence they form a part of this study. This is because, the more efficient the storage unit, the more effective and improved the performance of the hybrid system.

The supercapacitor is, according to Abd El-Aal (2005), made-up of the equivalent series resistance (ESR) and capacitor. The supercapacitor model is expressed based on two characteristic elements: its self-discharge current (I_{dis}) and the internal equivalent series resistance (ESR). The ESR accounts for all the losses that occur in supercapacitors (Abd El-Aal, 2005).

The voltage-current relationship of a supercapacitor is expressed as: $V_{Scap} = (ESR \times I_{Scap}) + \frac{1}{C} \int_0^t (I_{Scap} - I_{dis}) dt + V_{Scap}(0)$, where $V_{Scap}(0)$ is the initial voltage across the capacitor of capacitance C , V_{Scap} is the terminal voltage, and I_{Scap} is the current that flows into the supercapacitor. In order to achieve a higher voltage and current rating, a supercapacitor module must be developed which consists of supercapacitors that are connected both in series and parallel with the voltage across the supercapacitor module fluctuating above and below the base DC bus voltage (Abd El-Aal, 2005). These fluctuations are related to the excessive incoming and outgoing currents during operation. The self-discharge current depends on the temperature T_{Scap} and the voltage V_{Scap} of the capacitor of the supercapacitor, whereas the ESR depends only on temperature. Abd El-Aal (2005) lists the above as:

- The characteristic of the self-discharge current, $I_{dis} = f(V_{Scap}, T_{Scap})$, measured in ampere.
- The characteristic of the internal resistance, $ESR = f(T_{Scap})$, measured in ohms.

2.2.7. Factoring Improvement on MFCs for Efficient Performance of PV-MFC Hybrid System

Sinha (2008) and Khaloufi (2019) state that microbes oxidise fuel molecules of the substrate (wastewater) at the anodic chamber to produce electrons and hydrogen ions and enhance oxygen reduction at the cathode. Khaloufi (2019) indicates that the strength of produce depends on the type of electrolyte used together with the choice of electrodes, which form a basis for improved performance (electricity generation). Koroglu et al. (2019) state that MFCs generate electrical energy by the relationship between microbial metabolism and solid electron acceptors. Flimban et al. (2018) state that in order to achieve improved performance, solution (electrolyte) concentrations at the anode and cathode must be produced together with the 'right' mix of substrate that supports an improved proton concentration gradient and potential difference. Although the challenge of lower yields of energy due to loss of microbial activity from immobilisation of microbes at the electrode surface persists, research is ongoing to improve performance. Khaloufi (2019) states that PEMFC are effective under optimum conditions, but the very costly exercise of conducting feasibility studies to obtain customized data conditions for each proposed MFC plant pose as a limit. Thus, views expressed by authors and researchers form the basis for the literature review of improved performance of PV-MFC hybrid systems.

The high performance of PEMFC depends on the effectiveness of polymer electrolyte membrane (PEM) in only allowing the flow of protons (hydrogen ions) and not the flow of electrons and leak of oxygen through. The selection of an effective membrane is based on computing the impermeability of oxygen through the membrane, the mass transfer coefficient of oxygen (K_o), and oxygen diffusion coefficient. The general expressions used to determine the mass transfer coefficient of oxygen is $K_o = \frac{-V}{A.t.ln[\frac{C_o - C}{C_o}]}$, where V is the volume of the substrate at the anodic chamber, A is the cross-sectional area of the PEM, C_o is the oxygen concentration at the cathodic chamber, and C is the oxygen concentration at the anodic chamber, the oxygen diffusion coefficient is, $D_o = K_o \times L_t$, where L_t is the material's thickness of the membrane.

Miyahara, Kouzuma, and Watanabe (2015) conducted a study of how the introduction of NaCl concentration (seawater) affects the anode microbe and power generation of MFCs. The authors found that within specific seawater (NaCl concentration) thresholds, diluted seawater supported the growth and growth rate of *Geobacteraceae* (a specific type of geographically located community of microbes or bacteria) at the anode and that the abundance ratio of *Geobacteraceae* relative to the total bacteria at the anode significantly increased. The study indicated that NaCl is a major determinant of ionic strength in the electrolyte and that since *Geobacteraceae* bacteria are responsible for MFC power generation, *Geobacteraceae* are optimum when seawater is diluted. Further, Miyahara et al. (2015) indicated that increased concentrations of NaCl (seawater) drastically reduce the open circuit potential and corresponding maximum power output. According to Naga Samrat et al. (2017), seawater contains various microbes that have the ability to reduce and oxidise substances like iron, sulphur and nitrates. This consortium of seawater bacteria can now be used in MFCs. Liu, Ramnarayanan and Logan (2004) state that microbes must be developed anaerobically. Pandit and Das (2018) concur stating that microbially operated MFCs transform organic matter anaerobically at the anode into free electrons to create a potential variance among both anode and cathode chambers that result in current generation in the MFC. According to Rahimnejad et al. (2015), MFCs are able to change over energy through accessible bio-convertible substrate through straightforward means to electricity. Primo (2016) adds that the performance of MFCs to change chemical energy to electrical energy is based on strength of the two separate electrochemical reactions that occur within the MFC: the oxidation half-reaction that occurs at the anodic chamber whereby electrons are released from the fuel substrate and the reduction half-reaction at the cathode whereby electrons are absorbed.

Ohmic losses result from internal resistance of the electrode material and that of the wire (external circuit). Khaloufi (2019) states that the potential loss due to Ohmic losses is determined using an expression by Heijne et al. (2006): Ohmic over potential, $\Delta V = \frac{\delta W \cdot I}{\sigma}$, where δW is the distance between the anode and the cathode, I is current normalised to the anodic surface area, and σ is the solution conductivity. Khaloufi (2019) suggests that to improve MFC performance the solution conductivity must be increased and the distance between electrodes must be reduced to reduce the Ohmic losses in MFCs. Adding to the above, Nhleko and Inambao (2020) expressed the view that designing and selecting appropriate pre-treatment processes improve MFC performance. Barua et al. (2018) adds that multi-chambered MFCs connected in series provide optimal results by yielding higher electricity than double-chambered MFC.

2.2.8. Modelling for a Hybrid System

Energy efficiency increases access to energy especially when utilities are struggling to keep up with demand, hence the importance of designing an effective energy efficiency program that is based on the performance of energy efficiency devices (that is, the effectiveness of such devices) when installed and observing (monitoring and managing) the energy efficiency based on infrastructure conditions and overall energy demand and consumption trends. Investment in such a program can provide consumers with long-term energy bill reduction (Aznar et al. 2019). To model for energy efficiency, Figure 1 derived from Hamby, Juan and Kabamba (1996) can be used as a guide for modelling each system and reducing the complexities of modelling for efficiency of a hybrid system.

Where i^+ is the raw input (variables), f^- is the feedback signal or improvement variables, e_i is the efficiency equipment variables resulting from assumptions made when the equipment(s) and technology used to measure and monitor were developed, i is the resulting input into the internal system (components and the various sub-systems), d_i is the internal disturbance(s) in and of the system such as vibrations, system technology, efficiency drop of the various

components due to wear and/or application, sub-system and system, etcetera., and d_o is the external disturbances such as maintenance effectiveness, operating conditions, environmental exposures, budget constraints, etc.

$d_i d_o$

Figure 1: Modelling for the Efficiency of a Hybrid System. Source Derived from: Hamby, Juan & Kabamba (1996)

Since technologies are not all the same, modelling for considered technology is necessary to establish the correlation and effect of the technology on a defined system. Figure 1 can thus be used as a basis to factor in technological factors to system variables and harmonizing the two to get a modelling expression that defines a particular system-technology for specified applications. Although each institution has its own system requirements and specifications which depend on a lot of factors such as the environment (geographical location, climate behaviours and trends, collected impurities, etcetera), operational requirements, scale-up or expansion expectations, load forecast, legislation, socio-political and economic factors, financial muscle of the institution and goals and targets determined by the institution in consideration factoring the mentioned assists local government institution or utility to decide the approach that must be undertaken to either increase supply by modifying or building new infrastructure or by decreasing energy demand by improving energy efficiency (Xia and Zhang, 2015). The IEA (2013) report reflects that technological advancement based on precise modelling of a system's make-up and application positively influences the inclination towards energy efficacy and energy savings. This principle is also applicable in the treatment of wastewater before disposing off it to the environment.

2.2.10. Factoring in and Modelling for Anode and Cathode Surface Areas

When scaling-up MFCs, Dewan (2008, cited in Kim et al. 2012) states that the surface area of an anode is critical and must be factored in when designing large MFCs. Attempting to increase the size of the anode surface area often results in a non-linear power density decrease that affects the MFC into having low efficiency due to increased internal resistance of the cell. According to a surface area calculator by Wattyl (2004 cited in Kim et al., 2012), corrugated sheets add approximately 10.5 % to the effective flat surface area and trough section sheets of the same material add approximately 50 %. Peen, Keong and Hassanshahi (2019) found that although computations of the total surface area of a perforated carbon cylinder is tedious, perforated carbon cylinders lessen the initial surface area for microbial activity and that perforations on cylinders significantly affect the structural response and capacity of the cylinder. If solid cylinders have multiple systematic dents at the surface, the increase in surface area is negligible to increase bacterial activities. Ghasemi, Emborg and Cwirzen (2016) examined the various shapes of granules and surface areas of the same and found that when the size of the granules decreases, the surface area grows faster than the corresponding volume. The investigation by Ghesami et al. (2016) indicates that tetrahedron shaped granules are more effective when considering specific surface area (SSA) to volume or growth of surface area/volume ratio (SA/V) and in view of the various mathematical equations and calculations,

Ghasemi et al. (2016) reflects that the less spherical shaped a particle is the greater and more effective is the SSA which makes tetrahedron shaped granules best suited for use for bacterial activities in MFCs. However, due to the possibility of granules getting saturated and getting lost in the system, the use of carbon granules is considered expensive and unreliable as granule concentration must be kept constant and available for microbial activities. But, once microbes react at the surface of granules, less surface area is available for microbial activities, while replenishment of granules in the anode chamber requires intense monitoring and management. With respect to examining the efficiency and maintainability of cylinders and trough section sheets, trough section sheets are efficient as they have lower internal resistance and they are easy to clean and maintain.

The other critical part that must be improved is the cathode surface area. According to Khaloufi (2019) Logan (2005, as cited in Khaloufi, 2019), when the cathode surface area is doubled power generation is increased by 62 %. Taking into consideration the relative costs of materials used for electrodes (cathodes) such as platinum and/or aluminium when scaling-up an MFC, Khaloufi (2019) indicates that since each of these materials are relatively expensive and have specific microorganisms that work like biocatalysts with each of the metal cathodes, an alternative such as bio-cathodes must be considered as alternatives to reduce the relative costs.

3. RECOMMENDATIONS

Although, the above is indicative of the criticality of observing and factoring in the latest reviews or factors that improve the performance of PV-MFC hybrid systems, the process of undertaking detailed examination and modelling of various factors is not only complex but also costly. In order to reduce the costs while yielding improved outcomes, each municipality in coastal regions must allocate appropriate budgets for detailed feasibility studies that examine and factor in all possible variables from readily available resources.

In 2015/2016 financial year, the uMhlathuze municipality through a private-public partnership (PPP) financing agreement conducted a detailed feasibility study of close to R30 million to conduct a study of “the feasibility of re-use wastewater to produce potable water”. Data from the feasibility report on using wastewater to produce potable water and the following factors are favourable in anticipating a positive outcome when conducting the feasibility study of using PV-MFC hybrid system to generate electrical energy. The factors are: consideration of wastewater volumes from the feasibility report of the re-use project will produce required and sufficient daily activated sludge towards the implementation of the PV-MFC hybrid system; use of the less than three kilometres away from a 10MI desalination plant to obtain treated (diluted) seawater; the Indian ocean that borders the municipality; the presence of Foskor Acid Division (FAD) that produces pure sulphuric acid and phosphoric acid that can be used to amongst other functions dope (treat) electrodes in MFCs and photoelectric material in PVs. Outcomes from undertaking such a feasibility study and model development provides the conditions to improve and optimise PV-MFC hybrid system performance.

At this juncture, taking into consideration the modification and modelling of system components and parameters that must be factored in for improved performance and based on the study by Miyahara, Kouzuma, and Watanabe (2015) on improving the quality of the substrate, capital costs on a PV-MFC hybrid system can be significantly reduced and yield be improved when Figure 1 and the various expressions are used to factor-in and model each of the components considered critical in this paper for a PV-MFC hybrid system.

Er (2016) states that in order to evaluate the effectiveness and performance of software tools or systems, the “simulation”, “economic evaluation-payback model” and “data analysis and planning” process must be undertaken with the appropriate funds and commitment. Promethium Carbon and South African National Energy Development Institute (2017) suggest that a PV-bioenergy hybrid system can have a payback period of between 4 to 6 years after commencement depending on financial models and fees used by financial institutions to fund such a project.

4. CONCLUSIONS

System efficiency must not be a reactive process of gathering data from energy bills, energy demand and consumption but must be planned before-hand so that all variables can be factored in and modelled to improve system performance. The process of gathering data must be used as a tool to checking performance and not for planning performance, because the culture of gathering data and attempting to improve performance results in misdiagnosis, procurement of misaligned technology, lack of commitment by government and government institutions and deterred attitudes from government personnel in procuring and operating technologies and systems that could be beneficial and loss of opportunity to correct or modify system behaviours that would result in improved systems. Hybrid systems such as PV-MFCs described in this paper offer the advantage of reduced capital or investment costs and multi-purpose function when employing reviews that re-model and factor in parameters that improve the viability and performances of PV-MFC hybrid systems.

REFERENCES

1. Abd El-Aal, A.M. (2005). *Modelling and simulation of a photovoltaic fuel cell hybrid system. Doctoral thesis. University of Kassel, Kassel, Germany.*
2. Aznar, A., Logan, J., Gagne, D., & Chen, E. (2019). *Advancing energy efficiency in developing countries: Lessons learned from low-income residential experiences in industrialized countries. National Renewable Energy Laboratory, USAID-NREL partnership. USA.*
3. Barua, E., Hossain, S., Shaha, M., Islam, E., Zohora, F.T., Protity, A.T., Mukharjee, S.K., Sarker, P.K., Salimullah, M., & Hashem, A. (2018). *Generation of electricity using Microbial Fuel Cell (MFC) from sludge. Bangladesh Journal of Microbiology, 35(1), 23-26.*
4. Boaro, M., Fuselli, D., De Angelis, F., Liu, D., Wei, Q., & Piazza, F. (2013). *Adaptive dynamic programming algorithm for renewable energy scheduling and battery management. Cognitive Computatation, 5, 264-277.*
5. Busquet, S. (2003). *Study of a standalone power system based on a photovoltaic field, an electrolyser and a fuel cell: Test bench and modelisation. Doctoral thesis, Centre d'Energetique, Ecole des Mines de Paris, France.*
6. Er, Z. (2016). *A study of evaluation of solar energy simulation and modeling systems. International Conference on Computational and Experimental Science and Engineering. Acta Physica Polonica A. 130(72),72-77.*
7. Fiedler, F. (2014). *PV hybrid systems. Solar Energy Research Center: Lecture Notes. Hogskolan Dalarna.*
8. Flimban, S.G.A., Kim, T., Ismail, I.M.I., & Oh, S. (2018). *Overview of microbial fuel cell (MFC) recent advancement from fundamentals to applications: MFC designs, major elements, and scalability. Preprints 2018, 2018100763.doi: 10.20944/preprints201810.0763.v1*
9. Franco, Y.R. (2013). *Scale-up opportunities of microbial electrolysis cells for hydrogen production from wastewater. Doctoral thesis. McMaster University, Ontario Canada.*

10. Ghasemi, Y., Emborg, M., & Cwirzen, A. (2016). *Quantification of the shape of particles for calculating specific surface area of powders. International RILEM Conference on Materials, Systems and Structures in Civil Engineering Conference. Technical University of Denmark. Lyngby: Denmark.*
11. BAIG, MAUGHAL AHMED ALI, and ASHUTOSH SAXENA. "MAXIMIZATION OF PHOTOVOLTAIC ENERGY GENERATION BY TIME AND." *International Journal of Mechanical and Production Engineering Research and Development (IJMPERD)* 8, 4, Aug 2018, 437-444
12. Dewan, A., Beyenal, H., & Lewandowski, Z. (2008). *Scaling up microbial fuel cells. Environmental Science & Technology*, 42, 7643-7648.
13. Hamby, E. S., Juan, Y., & Kabamba, P. T. *Optimal hold functions for digital control systems. Control and Dynamic Systems. Vol. 79. Academic Press, Inc.*
14. ASHWIN, JS, and N. MANOHARAN. "RENEWABLE ENERGY BASED MICRO-GRID SYSTEM FOR POWER QUALITY IMPROVEMENT." *International Journal of Mechanical and Production Engineering Research and Development (IJMPERD)* 8, 1, Feb 2018, 883- 888
15. Huggins, T., Fallgren, P., Jin, S., & Ren, Z. (2013). *Energy and performance comparison of microbial fuel cell and conventional aeration treating of wastewater. Journal of Microbial and Biochemical Technology* 2013, 6.
16. Inglesi-Lotz, R. & Pouris, A. (2012). *On the causality and determinants of energy and electricity demand in South Africa. Energy Sources, Part B: Economics, Planning, and Policy*, 11(7), 84-89. <https://doi.org/10.1080/15567249.2013.801536>
17. Alrwashdeh, SAAD S. "An Energy Production Evaluation from PV Arrays with Different Inter-Row Distances." *International Journal of Mechanical and Production Engineering Research and Development* (2019): 9-5.
18. International Energy Agency. (2013). *International Energy Outlook 2013 with Projections to 2040. U.S. Energy Information Administration. https://www.eia.gov/outlooks/ieo/pdf/0484(2013).pdf*
19. Kim, D., An, J., Kim B., & Jang, J. K. (2012). *Scaling-up microbial fuel cells: Configuration and potential drop phenomenon at series connection of unit cells in shared anolyte. ChemSusChem*, 2012. <https://doi.org/10.1002/cssc.201100678>
20. Sari-Ali, I., B. Chikh-Bled, and B. Benyoucef. "Effect of shading on the performance on solar photovoltaic." *Int J Appl Eng Res Dev (IJAERD)* 4.2 (2014): 41-8p.
21. Khaloufi, Y. (2019). *Microbial fuel cells for electricity generation. Al Akhawayn University. http://www.aui.ma/sse-capstone-repository/pdf/spring-2019/MICROBIAL%20FUEL%20CELLS%20FOR%20ELECTRICITY%20GENERATION%20.pdf*
22. Kleinkauf, W., Ibrahim, M., Haas, O., & Gruf, B. (2003). *Basics of hybrid technology for grid compatible stand-alone plants, 2nd European PV-Hybrid and Mini-Grid Conference, Kassel, Germany, 2003, pp. 61-67.*
23. Akbar, HUSSAIN S. "Design of Sun Tracker System for Solar Energy Applications." *Journal of Physics and Research (IJPR)* Vol 1 (2015): 29-34.
24. Koroglu, E. O., Yoruklu, H. C., Demir, A., & Ozkaya, B. (2019). *Microbial fuel cell: Power generation. In: S. Venkata Mohan, A. Pandey, & S. Varjani (Eds.). Scale-up and commercialization issues of the MFCs: Challenges and implications (pp. 565-583). Elsevier B.V. https://doi.org/10.1016/C2017-0-00856-X*
25. Lam, P.2001. *The energy industry in China: Development and prospects. China Perspectives, https://journals.openedition.org/chinaperspectives/2783*
26. EMEARA, MOHAMED S., AHMED FAROUK ABDELGAWAD, and AHMED H. EL ABAGY. "A CASE STUDY OF CAIRO INTERNATIONAL AIRPORT "CIA": PROPOSED INSTALLATION OF PHOTOVOLTAIC "PV" FOR HIGH ENERGY-

- PRODUCTION." *International Journal of Mechanical and Production Engineering Research and Development (IJMPERD)* 10, 5, Oct 2020, 399–410
27. Lazar, J. & Colburn, K. (2013). Recognizing the full value of energy efficiency. Regulatory Assistance Project. Knowledge Center, September 9, 2013. <http://www.raponline.org/wpcontent/uploads/2016/05/rap-lazarcolburn-layercakepaper-2013-sept-9.pdf>.
 28. Lin, Y. & Liu, S. (2010). Grey systems: Theory and application. Springer-Verlag. <http://www.scielo.org.za/pdf/jesa/v27n1/02.pdf>
 29. Liu, H., Ramnarayanan, R., & Logan, B.E. (2004). Production of electricity during wastewater treatment using a single chamber microbial fuel cell. *Environmental Science and Technology*, (38), 2281-2285.
 30. Miyahara, M., Kouzuma, A., and Watanabe, K. (2015). Effects of NaCl concentration on anode microbes in microbial fuel cells. *AMB Express*, 5(34), 1-9
 31. Naga Samrat, M.V.V., Rao, K.K., Ruggei, B., & Tommasi, T. (2018). Denitrification of water in microbial fuel cell (MFC) using seawater bacteria. *Journal of Cleaner Production*, 178, 1-29. doi: 10.1016/j.jclepro.2017.12.221
 32. Nhleko, M., and Inambao, F. (2020). Energy efficiency at municipal wastewater treatment plants using microbial fuel cell technology. *International Journal of Mechanical Engineering and Technology*, 11(1), 133-145. <http://www.iaeme.com/ijmet/issues.asp?JType=IJMET&VType=11&IType=1>
 33. Pabi, S., Amarnath, A., Goldstein, R. and Reekie, L. (2013). Electricity use and management in the municipal water supply and wastewater industries. Denver, CO: Water Research Foundation. https://www.sciencetheearth.com/uploads/2/4/6/5/24658156/electricity_use_and_management_in_the_municipal_water_supply_and_wastewater_industries.pdf
 34. Pandit, S., & Das, D. (2018). *Microbial fuel cell: Principles of microbial fuel cell for power generation*. Springer.
 35. Peen, W. Y., Keong, C. K., & Hassanshahi, O. (2019). Behaviour of hollow circular section with multiple perforations under compression, flexure and torsion. *Latin American Journal of Solids and Structures*.16(2). <https://doi.org/10.1590/1679-78255387>
 36. Primo, J. (2016). *Solar and fuel cells technology fundamentals & design*. PDH Center. [Available online: www.PDHonline.org]
 37. Promethium Carbon and South African National Energy Development Institute. (2017). *Technical Report: Appraisal of implementation of fossil fuel and renewable energy hybrid technologies in South Africa*. Retrieved from <https://www.sanedi.org.za/img/wp-content/uploads/2018-01-15%20Hybrid%20Technologies%20in%20South%20Africa%20full%20report.pdf>.
 38. Rahimnejad, M., Adhami, A., Darvari, S., Zarepour, A., & Oh, S.E. (2015). Microbial fuel cell as new technology for bioelectricity generation: A review. *Alexandria Engineering Journal*, 54, 745-756.
 39. Raissicharmakani, S. (2018). A programmatic assessment of the U.S. Department of Energy Low-income Weatherization Assistance Program. Master thesis, University of Michigan. https://deepblue.lib.umich.edu/bitstream/handle/2027.42/143155/RaissiCharmakani_Shiva_Thesis.pdf?sequence=1&isAllowed=y.
 40. Republic of South Africa. (1998). *Occupational Health and Safety Act, No. of 1998*. Pretoria: Government Printer.

41. Rycroft, M. (2013). Hybridising renewable energy systems. *Energize*, November, 44-46. https://www.ee.co.za/wp-content/uploads/legacy/Energize_2013/08_ST_02_Hybridising.pdf
42. Sahin, M.E., & Okumus, H.I. (2017). The design steps of a hybrid system. *International Conference on Computational and Experimental Science and Engineering*, 132(3),1160-1164.
43. Stoll, Z.A., Jan, D.& Xu, P. (2018). Minimum performance requirements for microbial fuel cells to achieve energy-neutral wastewater treatment. *MDPI Journal of Water*, 10(243), 1-13.
44. Tsoutsos, T. & Gikas, P. (2013). Near zero energy wastewater treatment plants for the Greek Islands. *Technical University of Crete, Chania*.
45. Xia, X. & Zhang, J. (2015). Operation efficiency optimisation modelling and application of model predictive control. *IEEE/CAA Journal of Automatica Sinica*,2(2), 166-172.