

# Microbial fuel cells for energy self-sufficient domestic wastewater treatment—a review and discussion from energetic consideration

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**Abstract** As the microbial fuel cell (MFC) technology is getting nearer to practical applications such as wastewater treatment, it is crucial to consider the different aspects that will make this technology viable in the future. In this paper, we provide information about the specifications of an energy self-sufficient MFC system as a basis to extrapolate on the potential benefits and limits of a future MFC-based wastewater treatment plant. We particularly emphasize on the importance of two crucial parameters that characterize an MFC: its electromotive force ( $E_{\text{emf}}$ ) and its internal resistance ( $R_{\text{int}}$ ). A numerical projection using state-of-art values ( $E_{\text{emf}}=0.8$  V and  $R_{\text{int}}=5$   $\Omega$ ) emphasized on the difficulty at this moment to reach self-sufficiency using a reasonable number of MFCs at the laboratory scale. We found that a realistic number of MFCs to provide enough voltage ( $=5$  V) at a sufficient current ( $=0.8$  A) to power a pump requiring 4 W would be of 13 MFCs in series and 10 stacks of MFCs in parallel, resulting in a total number of

130 MFCs. That would result in a treatment capacity of 144 L of domestic wastewater ( $0.5$  g-COD  $\text{L}^{-1}$ ) per day. The total MFC system would be characterized by an internal resistance of  $6.5$   $\Omega$ .

**Keywords** Electromotive force · Internal resistance · Microbial fuel cells · Scalability · Stack configuration

## Introduction

Bioelectrochemical systems—in which the anodic and/or the cathodic reactions are catalyzed by electrochemically active microorganisms—allow a variety of applications such as hydrogen (Rozendal et al. 2006; Cheng and Logan 2007a) or methane (Cheng et al. 2009) production or even desalination (Cao et al. 2009). Detailed reviews on these topics are available elsewhere (Logan et al. 2008); yet, most of the research nowadays still concentrates on direct electricity generation from organic matter—performed in a microbial fuel cell (MFC)—and this is also the focus of the present article. MFC is still considered an emerging technology at the present time and has a whole array of exciting applications in the future, including biosensors (Kim et al. 2003; Chang et al. 2004, 2005; Moon et al. 2004) and gastrobots (Kelly 2003; Wilkinson 2000; Melhuish et al. 2006). Among these, the Benthic Unattended Generator (BUG) can be considered as the first practical implementation of MFC to power oceanographic instruments, such as a meteorological buoy, using the organic matter in aquatic sediments (Tender et al. 2002, 2008; Reimers et al. 2001). Nevertheless, most of the research effort so far has been focused toward wastewater treatment and bioenergy recovery, and it is also in this view that we wish to consider MFCs in this paper.

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The popularity of the MFC technology has risen exponentially during the last few years because there is a hope that MFCs will allow to harvest the energy stored in wastewater directly in the form of electricity. This should place MFCs directly in competition with anaerobic digestion (AD) as a more sustainable and environment-friendly alternative to conventional activated sludge (CAS). In Table 1, we compare MFC with conventional aerobic and anaerobic wastewater treatment technologies. Based on current knowledge, MFC seems to be highly efficient as a biological treatment system at low to moderate loading rates, possibly achieving high COD removal, depending on the substrate (Liu and Logan 2004); however, at higher loads, performance appears to decrease quickly (Rabaey et al. 2003). Of course, the MFC technology is still in its infancy and any speculation of the sort can easily be criticized; however, this makes MFC at this time appear more competitive over CAS than over AD, the latter being typically operated at much higher loading rates (Tchobanoglous et al. 2003). Furthermore, the fact that part of the energy bound to wastewater is diverted into electricity in an MFC results in reduced sludge accumulation as compared with CAS (Rabaey and Verstraete 2005).

As a consequence, it appears that the MFC technology could reasonably be seen at the moment as an alternative to CAS—avoiding the cost of aeration if an air cathode is used and generating less sludge to be disposed—when conventional AD is less adequate. This is typically the case for low strength wastewater treatment, such as domestic wastewater, which results in organic loading rates below the 1–2 kg COD m<sup>-3</sup> day<sup>-1</sup> that have been shown as being limiting for biogas production in upflow anaerobic sludge blanket reactors (Lettinga et al. 1993). Another strong advantage of MFC lies in the fact that, unlike conventional AD, which is a two-step process, MFC allows direct harvesting of electricity (all-in-one process). This is an enormous potential advantage because biogas combustion and conversion into electricity is a process with a low yield whereby 70% of the energy contained in the biogas is typically wasted (Pham et al. 2006). However, at the moment, energy wastage is typically higher in an MFC

due to overpotential and reduced Coulombic efficiency, two aspects that will be treated in detail in this paper.

Another important aspect concerns the energy balance, for which, once again, MFC appears to be intermediate between aerobic and anaerobic treatments. Unlike AD, an MFC at present consumes more energy for its operation than what can be harvested; however, MFC has several advantages over CAS such as the possibility to use gaseous oxygen from the atmosphere using an air cathode (Park and Zeikus 2003), which can potentially greatly reduce operation costs in an MFC-based wastewater treatment plant. It has been hypothesized that MFC, like AD, could become energy positive (Logan 2005), but before even reaching this point, it should already be at least energy neutral to gain more interest from engineers. As a consequence, the objectives of this paper are (1) to provide a practical appreciation of the specifications that must be fulfilled to create an MFC system that both treats wastewater and is self-sufficient from an energy point of view and (2) to discuss the viability of the MFC technology for electricity generation. This will be done first by considering and estimating the essential parameters for MFC characterization and modeling based on the state of the art and second by addressing MFC stacking issues. We will then provide a very practical illustration based on a laboratory-scale model to determine the capacity of an MFC system to pump its own effluent (domestic wastewater). Finally, we will discuss some of the challenges of the MFC technology in relation with our findings.

### Microbiology of MFCs

In an MFC, current is generated when a microbial consortium uses the anode of the system as its electron acceptor. In order to do this, it is necessary to ensure that no acceptor with a higher redox potential—such as oxygen (O<sub>2</sub>) or nitrate (NO<sub>3</sub><sup>-</sup>)—is present in the system; otherwise, they will be used preferentially. If the anode is the electron acceptor with the highest potential available, electron transfer will occur from the microbe cells to the anode. A

**Table 1** Comparison between conventional activated sludge (CAS), anaerobic digestion (AD), and microbial fuel cell (MFC) for wastewater treatment

	Treatment efficiency	Applied load	Sludge production	Energy balance
AS	High	Low	High	--
AD	Moderate (req. polishing)	High	Low	+
MFC	Moderate (req. polishing)	Low to moderate	Low	-

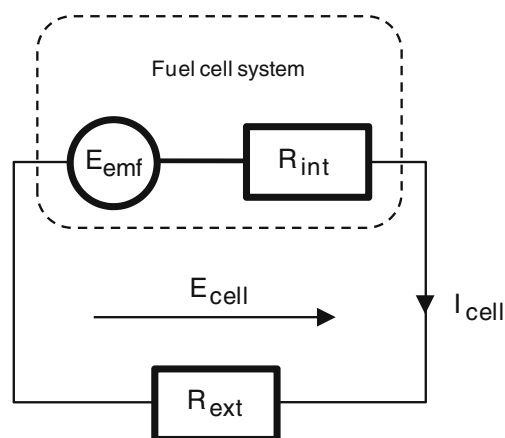
MFC appears to be intermediate between CAS and AD in terms of applied load and energy balance, while being closer to AD in terms of treatment efficiency and sludge production

first mechanism for extracellular electron transfer involves redox mediator shuttles that can either be added externally—such as methylene blue or neutral red (Wilkinson et al. 2006)—or produced by the microbial consortium, e.g., menaquinone (Wang et al. 2007) or phenazine (Rabaey et al. 2005a). Bacteria that are known to be able to use the mediator system include *Pseudomonas* spp. (Rabaey et al. 2004), *Shewanella* spp. (Nevin and Lovley 2002b; Newman and Kolter 2000), *Geothrix* spp. (Bond and Lovley 2005; Nevin and Lovley 2002a), and *Escherichia coli* (Park and Zeikus 2003). However, it has been demonstrated that this phenomenon is marginal in most MFCs because the current level achievable by the shuttle transfer remains 50 to 100 times lower than what has been attained in the recent years. This means that the main way for electron transfer is by direct contact utilizing the electron transport chain present in the bacterial membrane (Lovley 2008). Again, a monolayer of bacteria could not account for high current densities, and conduction phenomena have to be considered in the whole biofilm layer up to tens of micrometers to explain current generation to the levels observed lately (Marcus et al. 2007). Highly conductive pili or nanowires have been observed recently that may favor electron transfer but they have only been observed in few studies and their real importance is yet to be confirmed (Gorby et al. 2006).

Because microorganisms involved in electricity generation transfer their electrons to a solid anode, it is not surprising that the first bacteria identified of having this capability belonged to the iron reducers' group, which have the particularity of using an insoluble electron acceptor. This is so for the case of *Shewanella putrefaciens* (Kim et al. 1999) and *Geobacter* spp. (Nevin and Lovley 2000; Bond and Lovley 2003). However, it was found later that this ability is spread within various groups of bacteria such as the  $\beta$ -Proteobacteria and particularly the Burkholderiales order (Lefebvre et al. 2010). The same study also intended to compare a biofilm collected from an MFC anode with other microbial communities found in various environments, such as anaerobic digesters, corrosion biofilms, and mine drainage waters. The microbial community of the latter was proven to be the closest to that of the MFC biofilms, due to the high proportion of Burkholderiales (e.g., *Leptothrix* sp.) shared by both biofilms. For further details on the microbiology of MFC systems, we refer to reviews dedicated to this topic by Rabaey et al. (2007) and Logan and Regan (2006).

### MFC characterization

As displayed in Fig. 1, a fuel cell can be modeled by an ideal voltage source producing its electromotive force  $E_{emf}$



**Fig. 1** Simplified model showing a fuel cell system characterized by its electromotive force of  $E_{emf}$  and an internal resistance of  $R_{int}$ , and generating a current of  $I_{cell}$  at a voltage of  $E_{cell}$  through an external resistance of  $R_{ext}$

(V) in series with an ideal resistor representing its internal resistance  $R_{int}$  ( $\Omega$ ). These two parameters will in turn affect the cell voltage  $E_{cell}$  (V) and electrical current  $I_{cell}$  (A) flowing through an external circuit whose resistance can be defined as  $R_{ext}$  ( $\Omega$ ).

Theoretical voltage, open circuit voltage, and electromotive force of an MFC

The theoretical voltage ( $E_{theor}$ ) of an MFC is the difference between the anode ( $E_{an}$ ) and the cathode ( $E_{cat}$ ) potentials as determined by the Nernst equation (Logan et al. 2006). In typical MFC conditions ( $T=293$  K,  $pH=7$ ,  $pO_2=0.2$  bar), the potential of an air cathode is  $E_{cat}= +0.805$  V vs standard hydrogen electrode (SHE), whereas the anodic potential can be as low as  $E_{an}= -0.331$  V vs SHE, depending on the microbial culture and organic substrate (Fricke et al. 2008). As a consequence,  $E_{theor}$  can be estimated to be around 1.1 V. A measured open circuit voltage (OCV) of 1.1 V was actually obtained in an MFC by using an enzymatic cathode (laccase) and a redox mediator (Schaetzle et al. 2009). However, those might not prove practical and the observed OCV is usually significantly lower, which shows that there are losses in an MFC even when no external current is applied. These parasitic losses can be at least partially explained by substrate cross-over from the anode to the cathode, resulting in a cathodic potential mixed between that of  $O_2$  and that of the above-mentioned substrate (Harnisch et al. 2009). As a consequence, OCV values of 0.8 V are more frequently seen and can be considered as the state of the art nowadays (see Table 2).

When the circuit is closed, the current starts flowing, and due to polarization, the anode potential increases and the cathode potential decreases, i.e., the potentials of both

**Table 2** State of the art in microbial fuel cell design research in terms of open circuit voltage (OCV), internal resistance ( $R_{\text{int}}$ ), ohmic resistance ( $R_{\Omega}$ ), Coulombic efficiency ( $\epsilon_C$ ), substrate removal efficiency ( $\epsilon_{\text{fuel}}$ ), and hydraulic retention time ( $\tau$ )

Substrate	OCV (V)	$R_{\text{int}}$ ( $\Omega$ )	$R_{\Omega}$ ( $\Omega$ )	$\epsilon_C$ (%)	$\epsilon_{\text{fuel}}$ (%)	$\tau$ (h)	Ref.
Two chambered design, ferricyanide catholyte							
Lactate	0.8	130	–	8	–	24	[1]
Lactate	0.6	22,727	–	2.8	–	–	[2]
Sewage sludge	0.75	40	–	–	46	–	[3]
Two chambered design, aerated cathode							
Acetate	0.6	11	–	65	91	–	[4]
Acetate	0.6	9	1	80	99	6	[5]
Glucose	0.7	122	–	–	–	12	[6]
Single chambered design, open-air cathode							
Domestic ww	–	108	–	12	80	12	[7]
Acetate	0.8	54	8	50	–	50	[8]
Acetate	0.8	71	–	30–60	–	–	[9]
Acetate	–	23	4	20–70	–	–	[10]
Acetate	0.8	93	–	–	–	–	[11]
Acetate	0.85	34	–	–	–	–	[12]
Starch	–	5	–	–	–	–	[13]
Acetate	–	277	–	30–40	–	–	[14]
Acetate	–	169	36	40	–	–	[15]
Acetate	0.4	85	–	30	99	4.7	[16]
Industrial ww	–	213	–	5	96	–	[17]
Acetate	0.6	71	–	51–71	–	–	[18]
Brewery ww	0.65	57	–	20–30	95	–	[19]
Acetate	0.55	42	–	1	30	20	[20]
Domestic ww	0.8	408	–	40	70	20	[21]
Glucose	0.75	26	14	48	78	3.5	[22]

Ref. list [1] (Ringeisen et al. 2006); [2] (Qian et al. 2009); [3] (Jiang et al. 2009); [4] (Freguia et al. 2007); [5] (Freguia et al. 2008); [6] (Deng et al. 2010); [7] (Liu et al. 2004); [8] (Logan et al. 2007); [9] (Cheng and Logan 2007b); [10] (Fan et al. 2007); [11] (Fan et al. 2008); [12] (Rabaey et al. 2008); [13] (Shimoyama et al. 2008); [14] (Li et al. 2009); [15] (Wang et al. 2009); [16] (Lefebvre et al. 2009); [17] (Sun et al. 2009); [18] (Kim et al. 2009); [19] (Zhuang et al. 2009); [20] (Zhang et al. 2009); [21] (Ahn and Logan 2010); [22] (Feng et al. 2010)

electrodes move closer to one another and the cell voltage decreases due to unavoidable losses, which is also known as overpotential (see Fig. 2). These losses can be defined as activation polarization, ohmic losses, and concentration polarization (Logan et al. 2006). Activation polarization is directly associated with slow electrode kinetics and is predominant at low current densities. At high current densities, reactants become rapidly consumed at the electrodes, resulting in concentration gradients and transfer limitations, a phenomenon known as concentration polarization. At intermediate current densities, ohmic losses that reflect the cell internal resistance are dominant. This intermediate zone corresponds to the “working zone” of the MFC and is of prime importance in terms of MFC characterization. In this zone, the cell polarization is a linear function:

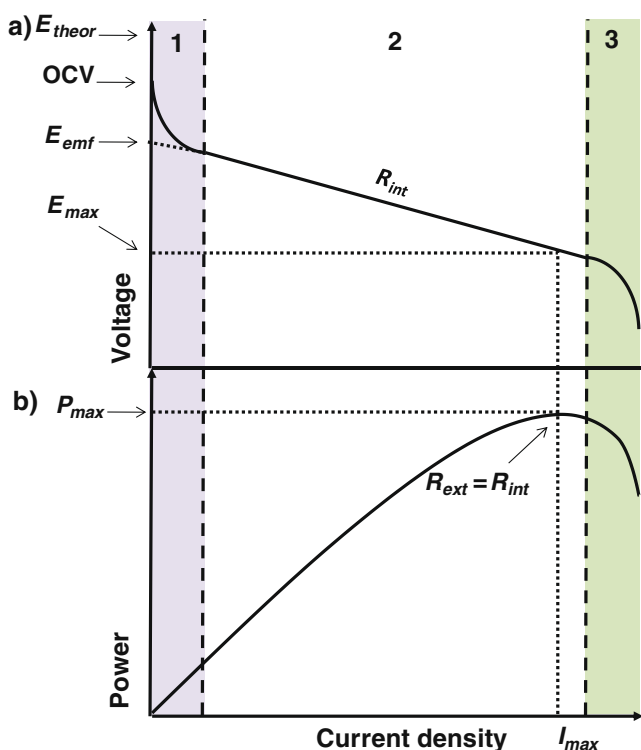
$$E_{\text{cell}} = E_{\text{emf}} - R_{\text{int}} \times I_{\text{cell}} \quad (1)$$

where  $E_{\text{emf}}$  (V) is the electromotive force of the fuel cell.

Consequently, the  $y$ -intercept of this function represents the electromotive force of the battery (see Fig. 2 a). The electromotive force can be defined as the ideal voltage source that drives the fuel cell in its ohmic section and roughly corresponds to the OCV minored by the activation losses. In other words, when activation losses are minimized,  $E_{\text{emf}}$  should approach the value of the measured OCV.

#### Internal resistance and ohmic resistance

The internal resistance of an MFC can be distributed into anodic, cathodic, and electrolyte (including the membrane if present) resistance (Fan et al. 2008), and according to Eq. 1, it can be determined from the slope of the linear section of the polarization curve of an MFC (see Fig. 2 a). Knowing  $R_{\text{int}}$  is important because an MFC generates its maximum power ( $P_{\text{max}}$ , W) when  $R_{\text{int}} = R_{\text{ext}}$  (see Fig. 2 b).



**Fig. 2** (a) Typical polarization curve for an MFC showing the three overpotential zones that affect the cell voltage at increasing current density: 1 activation polarization, 2 ohmic losses, 3 concentration polarization. Also displayed are the variations between the different voltages that can be used to characterize an MFC:  $E_{theor} > OCV > E_{max} = \frac{E_{emf}}{2}$ ; (b) typical power curve for an MFC where  $P_{max} = E_{max} \cdot I_{max}$  and is achieved when  $R_{ext} = R_{int}$

Part of the explanation for the power drop when  $R_{ext}$  becomes lower than  $R_{int}$  lies in the concentration losses that occur at high current densities.  $R_{int}$  can be determined as:

$$R_{int} = \frac{E_{emf} - E_{max}}{I_{max}} \tag{2}$$

where  $E_{max}$  (V) and  $I_{max}$  (A) are the cell voltage and current that give the maximum power.

At the same time, following the Ohm’s law,

$$R_{ext} = \frac{E_{max}}{I_{max}} \tag{3}$$

Hence, when  $R_{int} = R_{ext}$ , Eq. 2 can be substituted into Eq. 3 to yield:

$$E_{max} = \frac{E_{emf}}{2} \tag{4}$$

By combining Eqs. 3 and 4, it is possible to determine the maximum power  $P_{max}$  (W) delivered by the MFC system:

$$P_{max} = E_{max} \times I_{max} = \frac{E_{emf}^2}{4R_{int}} \tag{5}$$

From Eq. 5, it appears clearly that the power output from an MFC can be predicted just by knowing  $E_{emf}$  and  $R_{int}$ . In some studies, MFC systems have been defined not by their internal resistance but by their ohmic resistance ( $R_{\Omega}$ ) instead, using methods such as electrochemical impedance spectroscopy or current interrupt. However, the internal resistance of an MFC covers more than just the ohmic resistance, as it also includes the current dependent anode and cathode overpotentials. As a result,  $R_{\Omega}$  is usually substantially lower than  $R_{int}$ . This is obvious for example in the study of Ieropoulos et al. (2008) who found a value of  $R_{\Omega}$  of 12  $\Omega$  by EIS that was more than 100 times smaller than the value of  $R_{int}$  given by the polarization curve (1,300  $\Omega$ ). More examples of  $R_{int}$  values as compared with  $R_{\Omega}$  are given in Table 2. A direct consequence is that substituting  $R_{\Omega}$  to  $R_{int}$  in Eq. 5 will lead to power overestimation.

Because there is not much room to further improve OCV values that are limited by thermodynamic rules at around 1.1 V, it might be easier to lower the internal resistance of an MFC to improve its performance. The electrical resistance  $R$  ( $\Omega$ ) of a uniform material of electrical resistivity  $\rho$  ( $\Omega$  m), surface  $S$  ( $m^2$ ), and distance  $L$  (m) is given by Eq. 6:

$$R = \rho \frac{L}{S} \tag{6}$$

Hence, according to Eq. 6, the internal resistance can be reduced by (1) using very conductive materials, (2) maximizing the electrode surface, and (3) minimizing the length of the elements that have to be crossed by charged particles, all of these being reflected on the MFC design.

### MFC materials and architecture

For the reasons explained above, material selection and design are primordial in MFC, and most of the research nowadays is still focused on these aspects that directly influence the internal resistance. Because the anodic compartment of an MFC is a biofilm reactor, the anode material should share common properties with other biofilm reactors, i.e., high specific surface area, high porosity, and limited propensity to fouling or corrosion. On top of it, the anode should be highly conductive, which suggests that silver, copper, gold, and aluminum are favorite choices. However, for economical and biocompatibility reasons, carbon is usually the preferred choice, either in the form of paper, cloth, granules (Rabaey et al. 2005b; He et al. 2005), or fibers (Logan et al. 2007). The latter two have the advantage of a very high specific surface area (up to 20,000  $m^2 m^{-3}$  for carbon fibers). At the cathode, similar material is usually selected, generally coated with a catalyst

to increase the oxygen reduction rate. Typically, the catalyst used in lab-scale studies is platinum; however, for obvious reasons for applications such as wastewater treatment, cheaper alternative catalysts should be sought. Research so far suggests that cobalt (Cheng et al. 2006b; Lefebvre et al. 2009) or iron (Zhao et al. 2005) could be potential replacements of platinum with little reduction in performance, although the lifetime of such materials is not well studied. Finally, ion exchange membranes are often used in MFCs where they allow ion transfer and also reduce oxygen diffusion from the cathode to the anode. Typically, Nafion is used as a proton exchange membrane; however, it can contribute significantly to the electrolyte resistance, and the selection between cation exchange membrane or anion exchange membrane may ultimately depend on ion gradients between the anolyte and the catholyte (Fornero et al. 2009). More details on material selection are available elsewhere (Logan 2010).

Regarding MFC architecture, reviews exist that described several potential designs (Du et al. 2007; Logan et al. 2006). Options include the two-chamber aqueous–air-cathode MFC and the single-chamber MFC with one side of the cathode exposed to the air. The latter design offers the advantage of increased power production and passive (i.e., free) aeration at the cost of a lower Coulombic efficiency because oxygen can permeate into the anode chamber (Liu and Logan 2004).

### MFC energy self-sufficiency at full scale

The concept of sustainability is very complex and embarks not only energy consumption but also the environmental and societal benefits of treating wastewater. However, in this paper, we will restrict the topic to energetic considerations. It is a well-known fact that aeration in wastewater treatment is the principal source of energy demand in a conventional wastewater treatment plant that principally relies on CAS for the liquid treatment. In our view of substituting MFC to the CAS basin, the aeration cost could be nullified if an open-air-cathode system is adopted. Furthermore, electricity could be recovered from wastewater. Domestic wastewater's energy content has been estimated as 14.7 kJ g<sup>-1</sup> of COD (Logan 2008); hence, considering a COD content of 500 mg-COD L<sup>-1</sup>, the volumetric energy stored in domestic wastewater would be  $\varepsilon_{\text{vol}}=7350$  kJ m<sup>-3</sup>. Other important parameters to be considered that depend at the same time on the type of wastewater, on the MFC design and on the operating conditions—mainly the flow rate ( $Q$ ) and hydraulic retention time ( $\tau$ )—are the substrate removal efficiency ( $C_{\text{fuel}}$ ) and the energy efficiency ( $C_E$ ). For domestic wastewater, 80% COD removal for  $C_{\text{fuel}}$  would appear as

a reasonably high target at  $\tau=12$  h, as reported by Liu et al. (2004). Furthermore,  $C_E$  is not known for actual wastewater but can be estimated by the Coulombic efficiency ( $C_C$ ), which represents the fraction of electrons (charge) that contribute to electricity generation. Of course,  $C_C$  depends on the complexity of the food webs that exists in the MFC system, and consequently, MFCs inoculated with mixed cultures and operating with real wastewater are frequently characterized by low  $C_C$  (Liu and Logan 2004; Lefebvre et al. 2008). Hence, for further numerical application, we will consider  $C_C$  equal to 40%, which corresponds to the state of the art as observed by Ahn and Logan (2010) while treating domestic wastewater at  $\tau=20$  h. All reference values selected for numerical projection are compiled in Table 3. The energy that can potentially be recovered from wastewater ( $\varepsilon_{\text{fuel}}$ ) by an MFC is calculated as follows:

$$\mathcal{E}_{\text{fuel}} = \mathcal{E}_{\text{vol}} \cdot C_{\text{fuel}} \cdot C_C \quad (7)$$

Solving Eq. 7,  $\varepsilon_{\text{fuel}}$  for domestic wastewater can be estimated to be around 0.65 kW h m<sup>-3</sup>. As compared with the typical energy demand for aeration in CAS that ranges from 0.2 to 0.4 kW h m<sup>-3</sup> of domestic wastewater treated (Tchobanoglous et al. 2003), this is a major improvement and it clearly shows that MFCs have the potential to make

**Table 3** Specifications of domestic wastewater, lab-scale DC pump, and microbial fuel cell (MFC) considered for numerical projections in this paper

MFC specifications			
Electromotive force	$E_{\text{emf}}$		0.8 V
Internal resistance	$R_{\text{int}}$		5 $\Omega$
Max. power	$P_{\text{max}}$		32 mW
Hydraulic retention time	$\tau$		12 h
Flowrate	$Q$		0.1 L min <sup>-1</sup>
Anodic volume	$V_{\text{an}}$		0.6 L
Removal efficiency	$C_{\text{fuel}}$		80%
Coulombic efficiency	$C_C$		40%
Energy recovery from fuel	$\varepsilon_{\text{fuel}}$		0.65 kW h m <sup>-3</sup>
No. of cells in series	$n$		13
No. of cells in parallel	$m$		10
Int. resistance of stack	$R_{\text{int, total}}$		6.5 $\Omega$
Anodic volume of stack	$V_{\text{an, total}}$		70 L
Wastewater specifications			
COD concentration			500 mg L <sup>-1</sup>
Volumetric energy	$\varepsilon_{\text{vol}}$		7,350 KJ m <sup>-3</sup>
Pump specifications			
Operating power	$P$		4 W
Operating voltage	$V$		5 V (DC)
Operating current	$I$		0.8 A
Max. flowrate	$Q_{\text{max}}$		0.11 L min <sup>-1</sup>

the whole wastewater treatment system energy positive. However, due to the limited voltage achievable in a single MFC, the problem is more complex, and in the remainder of this paper, we provide a simple example based on laboratory-scale MFC systems to illustrate the concept of MFC energy self-sufficiency in a different way.

**MFC energy self-sufficiency at the laboratory scale: a pedagogical example**

**Specifications**

At the laboratory scale, we can simplify the concept of energy self-sufficiency or energy neutrality in an MFC system as comprising three facets:

1. The MFC ability to power its pump, i.e., it should generate enough current at a sufficient cell voltage.
2. The pump ability to provide a flow rate high enough to distribute the wastewater into the MFC system. If the MFC was to directly power its own pump in the laboratory, it would be convenient that the pump can work on continuous current (DC). In this study, we selected a small water pump model N3 5VDC (Alita, USA), whose specifications are listed in Table 3.
3. The fuel ability to bring the energy to the MFC, i.e., its energy content must be high enough, and it must be supplied at a sufficiently high flow rate.

**MFC stackability**

If a single cell was to power the pump, it would need, according to Eq. 4 and considering  $E_{emf}=0.8$  V, to operate at  $E_{max}=0.4$  V and consequently,  $I_{max}=10$  A. It is more realistic to consider MFC stack designs where a number of

cells are connected in series and/or in parallel in order to achieve the desired voltage and current and, ultimately, power.

Considering an MFC characterized by its cell voltage  $E_{cell}$  and internal resistance  $R_{int}$ , a series connection of  $n$  stacks of MFCs with each stack comprises of  $m$  MFCs connected in parallel (see Fig. 3); the  $n \times m$  resulting MFCs can be considered as a single MFC having a voltage of:

$$E_{total} = n \cdot E_{cell} \tag{8}$$

and an internal resistance of:

$$R_{int,total} = \frac{n}{m} R_{int} \tag{9}$$

Consequently, in order to operate an electrical device at a voltage  $V$  (V), the number of MFC stacks ( $n$ ) required to be connected in series shall be:

$$n = \left\lceil \frac{V}{E_{max}} \right\rceil = \left\lceil \frac{2V}{E_{emf}} \right\rceil \tag{10}$$

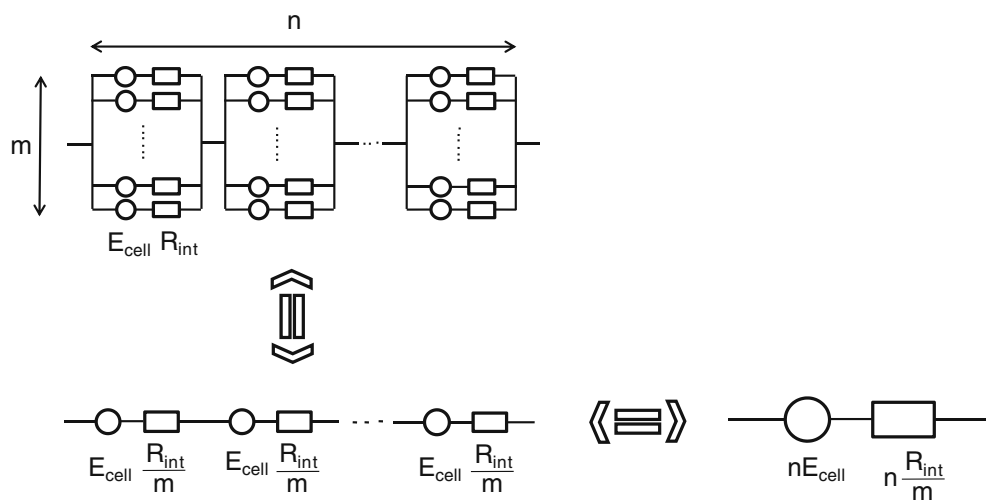
Similarly, in order to operate an electrical device at a current  $I$  (A), the number of MFCs ( $m$ ) required to be connected in parallel in each stack is:

$$m = \left\lceil \frac{I}{I_{max}} \right\rceil = \left\lceil \frac{2I}{E_{emf}} R_{int} \right\rceil \tag{11}$$

**Numerical projection**

For easy reference, the results of the numerical projection can be found in Table 3. The total number of MFCs required to power the pump is 130 (i.e.,  $n \times m$ ). The total MFC system would be characterized by an internal resistance of  $6.5 \Omega$  (by solving Eq. 9) and would be able to power the pump at its maximum flowrate. These calculations were computed assuming that  $R_{ext}=R_{int}$ ; hence,

**Fig. 3** Schematization of  $n$  series stacks of  $m$  parallel MFCs. Each MFC being characterized by their cell voltage ( $E_{cell}$ ) and their internal resistance ( $R_{int}$ ), the whole system has a voltage of  $n \cdot E_{cell}$  and an internal resistance of  $n \cdot \frac{R_{int}}{m}$



**Table 4** Experiments on stacked microbial fuel cells indicating the number of cells connected in parallel (p) or in series (s), the open circuit voltage (OCV), maximum power ( $P_{\max}$ ) and corresponding cell potential ( $E_{\max}$ ) and current ( $I_{\max}$ ), and the internal resistance ( $R_{\text{int}}$ ) of a single cell and of the stack

No. of MFCs	OCV (V)	$P_{\max}$ (W m <sup>-3</sup> )	$E_{\max}$ (V)	Stack eff. on $E$ (%)	$I_{\max}$ (mA)	Stack eff. on $I$ (%)	$R_{\text{int}}$ ( $\Omega$ )	Ref.
1	0.69	167	0.331	–	30.3	–	3.9	[1]
6p	0.67	263	0.354	–	269	148	$\approx$ 1.3	
6s	4.16	308	2.279	114	49	–	$\approx$ 49.1	
1	ND	15.4	ND	–	ND	–	5.3	[2]
12p	0.56	129	ND	–	ND	–	0.64	
1	0.792	6.54	0.475	–	5.8	–	14.6	[3]
4p	0.785	22.8	0.338	–	27.0	116	5.3	
4s	2.020	14.69	0.730	38	8.0	–	108	
1	0.44	0.44	0.139	–	0.02	–	$\approx$ 1,750	[4]
10p	0.44	0.81	0.196	–	0.26	130	$\approx$ 95	
10s	1.4	0.45	0.567	41	0.05	–	$\approx$ 1,730	

The stack efficiency on the voltage ( $E$ ) and on the current ( $I$ ) was calculated based on the experimental values provided by the authors as compared with the theory

Ref. list [1] (Aelterman et al. 2006); [2] (Shimoyama et al. 2008); [3] (Wang and Han 2009); [4] (Ieropoulos et al. 2008)

another issue is that the pump's resistance—which will be a part of  $R_{\text{ext}}$ —may well be higher than this value of 6.5  $\Omega$ . This shows that it may not be possible in real applications to make MFCs work in the conditions where they produce the maximum power.

The power available from the fuel ( $W$ ) can further be derived from Eq. 12:

$$P_{\text{fuel}} = Q \cdot \varepsilon_{\text{fuel}} \quad (12)$$

and the corresponding working volume of the anodic compartment  $V_{\text{an}}$  (L) can be found by solving Eq. 13:

$$V_{\text{an}} = \frac{Q\tau}{nm} \quad (13)$$

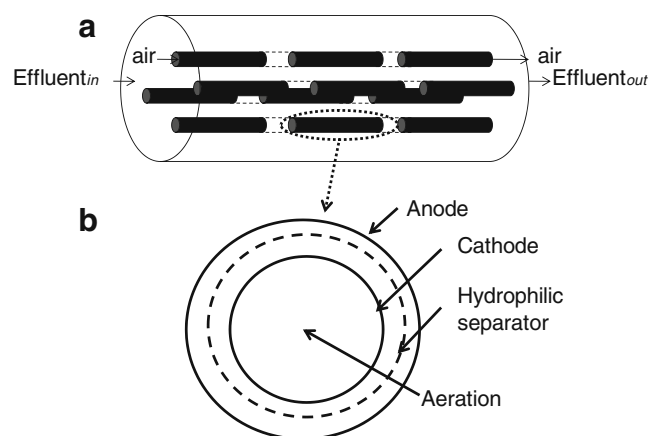
Hence, the minimum flowrate and anodic volume that would ensure to provide  $P_{\text{fuel}}=4$  W would be  $Q=0.1$  L min<sup>-1</sup> and  $V_{\text{an}}=0.6$  L. According to these specifications, the full MFC system (130 MFCs) would have a minimum total anodic volume of 70 L. Practically, the actual system is likely to be larger due to the cathode compartment and additional non-working components; however, using the anodic volume as a basis for calculation, the volumetric resistance of the MFC system would be 455 m $\Omega$  m<sup>3</sup>, which is in accordance with the general trend that this parameter increases with reactor size (Clauwaert et al. 2008).

Finally, to be able to move enough wastewater required to power the MFC system, the pump should be able to provide a flowrate higher than 0.1 L min<sup>-1</sup>, which is within the pump capacity in our specific example. Operating this pump at 4 W would correspond to a total electrical energy use of 2,400 kJ m<sup>-3</sup> of wastewater. This might seem high but considering the very small size of the setup, the MFC system could still consider to be competitive over the

conventional activated sludge system (Tchobanoglous et al. 2003).

### Challenges of the MFC technology in relation with energy self-sufficiency

The purpose of this section is to address the issues raised in this paper in terms of energy self-sufficiency, MFC stacking, and design. Aspects such as the characteristics of the wastewater (e.g., alkalinity, conductivity, and energy content) are out of scope because these parameters might be difficult to alter in practice. Earlier, we had addressed the issue of energy self-sufficient wastewater treatment using MFC from a broad point of view as compared with CAS,



**Fig 4** (a) Concept of a modular MFC wastewater treatment plant consisting of a stack of MEA-MFCs; (b) detail of an MEA-MFC consisting of an anode wrapped around a hollow-tube cathode, inside which air is blown, and electrically isolated from the cathode by a hydrophilic separator



and based on energy balance, we had demonstrated the potential benefits of this technology. We further gave a very practical example of the characteristics that an MFC system should fulfill if one wanted to directly power its own pump, based on the state of the art at the laboratory scale. As evidenced in this paper, a crucial parameter for MFCs to be developed will be their internal resistance in order to minimize the number of MFCs needed. A total number of 130 MFCs to power a small DC pump does not look reasonable to us, especially if the cathode has to be coated with platinum to reach its optimal performance. We are conscious that small DC pumps are not as efficient in terms of energy management as larger AC pumps; however, and even though this pump was selected for the mere sake of illustration,  $R_{int}$  would still need to be further reduced by at least an order of magnitude such that the total number of MFCs required is reasonable even with a more efficient pump.

Another issue of concern is the stacking of MFCs. The number of studies in this aspect is few, but parallel connection of MFCs seems to be efficient. In one pioneer study on stacked MFC, Aelterman et al. (2006) connected six MFCs in parallel, which resulted in a current equal to the sum of individual MFCs, while the voltage was similar to the average of the individual MFCs (see Table 4). Upon series connection, the voltage of individual MFCs was added, and the current was similar to the average individual MFC. However, during series connection, some of the individual MFC voltages diverged and the MFCs experienced cell polarity reversal. Others have confirmed the feasibility of parallel connection of MFCs with a stack efficiency of up to 116–130% (probably due to bacterial acclimation), but series connection of MFCs remains particularly challenging due to energy losses, and the series stack efficiency was seen to be as low as 38–41% (see Table 4).

This takes us to our latest point, i.e., transposing the MFC technology from laboratory to full scale while addressing the stacking issues. For wastewater treatment, we have to consider the feasibility of allowing the wastewater flows freely throughout the anode and/or cathode compartments without clogging them and without increasing unnecessarily the footprint of the plant. Because the cathode is limiting in most of modern MFCs, an ideal design should arguably have a cathode surface area much larger than the anode surface area (Fan et al. 2008)—which can be achieved by using cathode materials with a high specific surface area—and the electrodes should be kept as close as possible to one another to facilitate cation transfer (Min and Logan 2004; Cheng et al. 2006a). In Fig. 4 a, we suggest a design for a modular MFC treatment plant. Each MFC (i.e., one module) of the treatment plant should be made as simple as possible and could for instance consist of

an anode wrapped around a hollow-tube cathode and electrically isolated by a hydrophilic separator to form a membrane electrode assembly (MEA), as showcased in Fig. 4 b. MFCs with an MEA have already shown their capacity to generate increased power density at higher Coulombic efficiencies as compared with MFCs with cathode separated from the anode (Pham et al. 2005). In order to maximize the working/non-working volume ratio of each MFC, the cathode should be utilized for wastewater treatment by circulating the anolyte inside the cathode, providing aerobic polishing, while simultaneously increasing proton availability at the cathode (Freguia et al. 2008; Clauwaert et al. 2009).

In terms of material considerations, we already mentioned the necessity to include economic factors. Even if silver or gold electrodes might be the best choices to reduce resistivity, those materials are too expensive to be used for wastewater treatment at full scale and can only be limited to very specific applications of MFCs. Similarly, costly precious metal catalysts, such as platinum, should be prohibited for applications such as wastewater treatment, and cheaper alternative catalysts should be found before MFCs can be scaled-up to full plant application. Furthermore, although carbon cloth is commonly found suitable for biomass attachment, its resistivity is relatively high ( $\rho=3.5 \times 10^{-5} \Omega \text{ m}$ ) and larger MFC systems will need to consider the use of current collectors such as stainless steel (Bergel et al. 2005). It has been estimated elsewhere that the cost of current collectors could represent up to 40% of the total cost of a full-scale MFC system (Rozendal et al. 2008).

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