

LONG TERM FEASIBILITY STUDY OF IN-FIELD FLOATING MICROBIAL FUEL CELLS FOR MONITORING ANOXIC WASTEWATER AND ENERGY HARVESTING

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1. Abstract

In the present work different prototypes of floating MFCs have been tested in anoxic water environments of wastewater plants in Italy, over a period of 3 years. Several configurations of horizontal (flat) and vertical (tubular) MFCs were assembled, using low-cost and light-weight materials, such as plastic lunch boxes, polystyrene or wood to keep the systems afloat, and ceramics for the MFCs. Untreated carbon cloth or veil were used for both anode and cathode electrodes. Felt (flat MFCs) or clay (tubular MFCs) was used as the cation-exchange separator. Single flat MFCs generated power up to 12 mW/m² while a 32 cylindrical MFC stack generated up to 18 mW/m². The testing lasted for more than two years and there was no inoculation other than exposing the MFCs to the denitrification environment. The cathodes of the flat MFCs were spontaneously colonized by algae and plants, and this did not affect the stability of the systems. Natural light increased the power output of the flat MFCs which were smaller than 50x50cm. Diurnal oscillation of temperature and periodic water flow did not significantly affect the performance of the MFCs. The largest flat MFC produced the highest absolute power, although in a disrupted way. A new, simple low-energy remote monitoring system, based on LoRa technology was used for data transmission over distances of >500m. This is a piece of hardware that could potentially be suitable for remote monitoring as part of a network, as it can be directly powered by the deployed MFCs.

Index Term: Floating Microbial fuel cells, long term field operation, wastewater monitoring, low-energy remote data transmission.

Highlights:

- Prototypes of floating MFCs producing power for energy harvesting in anoxic wastewater
- 0.4 – 3 mW (0.2-0.6 V) was generated by the MFCs connected to a DC/DC converter
- More than two years continuous operation of tubular MFCs set in floaters
- Large flat MFCs more productive than a set of smaller flat MFC of equivalent electrodes surface
- Light cycle strongly influences the productivity of small flat MFCs
- Floating MFCs as energy autonomous sensors of biodegradation for remote monitoring systems

2. Introduction

The biotechnological purification of wastewater is based on complex and strictly interconnected physico-chemical and biological processes. The efficiency of the process is achieved only through careful and correct control of crucial parameters, such as nutrient content, organic loading and aerobic/anaerobic conditions. Therefore, **regular** measurement of physicochemical parameters such as temperature, water flow, dissolved oxygen, organic load is regularly carried out in wastewater treatment plants (WWTPs). **The concentration of biodegradable organic matter is the most important parameter of the process, which would require closer monitoring. The frequency of analysis is governed by the instability of the system operation, which is normally more pronounced in smaller treatment plants where the demand for a greater number of controls is often challenged by the availability of resources (human and technical ones). On-line monitoring devices** are often used in modern WWTPs, depending on their dimensions, practice and available resources (Bourgeois

51 et al. 2001), whereas the strict control of the water treatment in emerging economies is often unsustainable,
52 if at all supported. Nevertheless, sensing is becoming increasingly important as a function performed to
53 protect and preserve natural ecosystems, whether in developed or emerging economies.

54 There are currently numerous sensing technologies that are being used for monitoring different
55 environmental parameters, many of which can operate for prolonged periods. The cost however, could be
56 disproportionately high for those WWTPs also requiring strict maintenance regimes, high energy and plenty
57 of consumables. In this context, Microbial Fuel Cells (MFCs) are a promising technology with the dual
58 purpose of harvesting energy and sensing aquatic environments, especially but not exclusively wastewater.
59 Several sediment MFCs have been previously investigated (Reimers et al. 2001) and a MFC-powered rowing
60 float (called Row-bot) has also been recently reported for wastewater environments (Philamore et al. 2015),
61 which is based on the EcoBot principle of operation (Ieropoulos & Melhuish 2005; Ieropoulos et al. 2010)).
62 Several other laboratory experiments confirmed the possibility of using MFCs as sensors for biodegradation
63 in the water (Tront et al. 2008; Kim et al. 2003). The challenge however remains as one of scale up for self-
64 powering MFC sensors for water quality and establishing real environmental (even remote) monitoring
65 networks, where electricity may not be available. More recently floating systems (Schievano et al. 2017;
66 Martinucci et al. 2015) have also been proposed, with promising results. The low concentration of
67 biodegradable organic matter (10's of mgL⁻¹ COD) dissolved in the water of the anoxic tank strongly limits
68 the power production of this kind of MFC (Martinucci et al. 2015). The scaling up of such simple systems,
69 based on microbial catalysis at anode and cathode, would be needed in order to be performing well enough
70 for the desired objectives (power and sensing), optimizing the cell geometry and connecting in series parallel
71 several MFC units (Ieropoulos et al. 2008).

72 In the present study, the performance of floating MFCs suitably designed for anaerobic water
73 environments was tested both for energy harvesting and sensing purposes, in long-term experiments (more
74 than three years) in denitrification tanks of WWTPs, as part of a longer term study (Martinucci et al, 2015).
75 A particular focus was the selection of low cost and readily available materials, parts, electronic components
76 and open-source software, for the purpose of wastewater monitoring and for a possible development of
77 monitoring networks, acknowledging the sense of emerging "citizen science" of the industrialized
78 world (Wildschut 2017). Different designs and geometries of flat and tubular cells were investigated, with
79 electrodes assembled in horizontal and vertical configurations, using plastic lunch boxes or polystyrene to
80 keep the system afloat in contact with the anoxic wastewater. The MFC configuration was based on carbon
81 electrodes avoiding any chemical catalysts or pretreatment, and a simple inert separator (polypropylene or
82 ceramic) between anode and cathode (Figure 1). Experiments were carried out in two Italian WWTP, at the
83 Milano-Nosedo WWTP (2014-2018) and subsequently at the Carimate WWTP (2017-2019). Milano-Nosedo
84 is the largest WWTP serving a population of 1.25 million in the city of Milan, whereas Carimate is one order
85 of magnitude smaller, but with similar aerobic and anoxic treatment processes. Previous work performed
86 with the same flat MFC configuration at the same Milano-Nosedo WWTP demonstrated the possibility to
87 produce energy from such MFC configurations (Martinucci et al. 2015) and higher power densities were
88 achieved reducing the electrode area from 0.125 m² (40 x30 cm) to 0.03 m² (20 x 15 cm). The present study
89 was conducted with the aim of *in situ* assessing such MFC systems in producing power and sensing, whilst
90 exposed to the elements (diurnal cycle, weather conditions) and water parameters (temperature, flow, organic
91 content, etc.). A new generation of low-energy remote data logging system (LoRa) was also developed and
92 integrated into the electronic circuitry, to utilise the generated power from MFCs and transmit signals over
93 long distances; the near-term vision is that such systems become an integral part of a full MFC sensing
94 package for remote area access and telemetry.

95

96 3. MATERIALS AND METHODS

97 *Experiments*

98 Several flat MFCs units of different dimensions were operated in a denitrification anoxic pool at the Milano-Nosedo
99 WWTP during a trial period of more than three years (2014-2017). Some flat MFCs units were operated as individual
100 units and the output was monitored through a resistance of 100 Ω while other units, usually the better performing, were
101 occasionally disconnected from the resistance and connected in parallel with other units, to harvest the generated
102 energy (data not shown). A schematic representation alongside photos to illustrate the system are shown in Figure 1A
103 and 1B. Another long term testing of 6 flat MFCs with small electrodes and anodes short-circuited all
104 together was operated in the anoxic basin of a different WWTP located at Carimate (Milano, Italy) since June

105 2017, for about one year. The generated electricity from these MFCs was also monitored through a connected
106 100 Ω electrical resistance.

107 Several tubular MFCs inserted in a polystyrene frame shaped as a boat were also tested close to the flat
108 ones in the same denitrification anoxic pool at Milano-Nosedo WWTP (Fig. 1C-E). The tubular ceramic
109 MFC units shown in the picture and diagram of Fig. 1C were connected in two different floating stacks, one
110 with 16 MFC units (Small boat, Figure 1D) and the other with 32 MFC units (Big boat, Figure 1E). All the
111 MFCs units of each boat were electrically connected in parallel using stainless steel wire and terminal blocks
112 and an external resistance of 100 Ω was connected between them. The small boat (16 tubular MFCs) was
113 introduced into the Milano-Nosedo WWTP since 2014, close to the flat MFCs of various geometries and was
114 removed in 2018, after more than three years of continuous operation. The big boat (32 tubular MFCs)
115 started to operate at the beginning of March in 2016 and was removed with all the other MFCs in 2018. The
116 different geometries of flat MFCs were operated in the same period.

117 The trends of power generated in long time experiments by the different flat and tubular MFCs, summarized
118 in Table 1, are discussed in this work. The flat MFC geometries tested at Milano-Nosedo WWTP are named:
119 Flat-large (one, with 50x50 cm electrodes), Flat-medium (four, with 18x18 cm electrodes) and Flat-small
120 (six, with 10x13 cm electrodes). Six more Flat-small MFCs with anodes electrically connected together were
121 the ones tested at the Carimate WWTP.

122

123 Table 1. Characteristics of the MFCs types

Type, materials	Electrodes Geometry	Name	Number
Flat, carbon cloth electrodes and PPE felt (1cm)	50 x 50 cm	Flat-large	1
Flat, carbon cloth electrodes, PPE felt (1cm)	18 x 18 cm	Flat-medium	4
Flat, carbon cloth electrodes, PPE felt (1cm)	10 x 13 cm	Flat-small	6
Flat, carbon cloth electrodes, PPE felt (1cm) anode shorted all together	10 x 13 cm	Flat-small	6
Tubular, terracotta (thickness=0.2cm L=7cm, d=1.5cm), filled with activated carbon (cathode); anode in carbon fiber outside	Anode: 280 cm ² Cathode: 20 cm ²	Small boat	16
Tubular, terracotta (thickness=0.2cm L=7cm, d=1.5cm), filled with activated carbon (cathode); anode in carbon fiber outside	anode of 280 cm ² cathode of : 20 cm ²	Big boat	32

124

125 A detailed description of the Milano-Nosedo WWTP, one of the largest plants in Europe, for 1,250,000
126 Population equivalent (PE) and water parameters, has been reported previously (Martinucci et al, 2015) . In
127 brief, the anoxic water is characterized by an incoming BOD₅ of around 170 mgL⁻¹ reduced through
128 biodegradation for 99% (< 5 mgL⁻¹ outlet); an incoming COD of about 300 \pm 100 mgL⁻¹ and COD less than
129 15 mgL⁻¹ in the outlet. The residual COD concentration in the anoxic tank is around 20 mgL⁻¹ measured on a
130 filtrated (0.45 μ) sample, excluding the activated sludge.

131 The Carimate WWTP is a smaller waterworks facility and serves about 70,221 inhabitants in an area close to
132 Milan, producing about 5.000.000 m³/y of wastewater. Part of the treatment is for industrial wastewater,
133 which is about 1,000,000 m³/y and which corresponds to 4,000-5,000 more population equivalent, (as
134 BOD₅). The dissolved COD in the anoxic wastewater of this plant is a little higher than in Milano-Nosedo
135 plant, usually ranging between 10 – 80 mgL⁻¹.

136

137 *Flat MFCs fabrication*

138 Schematic diagrams for the flat MFC are presented in Fig. 1A. The two electrodes of each MFC had the
139 same area and were placed parallel to each other at a distance of 1 cm, separated by a polypropylene (PPE)
140 felt. The cathode and anode were both made of carbon cloth, which was free of any chemical catalyst (cod.
141 SCCT-8, SAATI, Legnano, Italy). An electrical resistance of 100 Ω was connected in the external circuit of
142 each MFC, between anode(s) and cathode.

143

144 *Tubular ceramic MFCs building*

145 Tubular MFCs were assembled using terracotta cylinders (L=7 cm, d=1.5 cm, thickness 0.2 cm) that were
146 sealed at one end with a plastic stopper. The anodes were made from carbon fiber veil (280 cm² per MFC)
147 that was folded, wrapped around the cylinder and secured with stainless steel wire (Figure 1C). The cathodes

148 made of activated carbon as previously described (Gajda et al. 2015) were inserted into the cylinders and
149 connected with stainless steel crocodile clip to the wire. A 10 mL plastic syringe was attached to the top of
150 the ceramic cylinder in order to fit the MFCs into the floating 'boat'-like polystyrene material. In this way,
151 the activated carbon is exposed to air through the open top connected to the syringe in the floating part of the
152 boat.

153

154 *Data acquisition and transmission*

155 For each tested flat MFC, the voltage V through the R (100 Ω) resistance was recorded every 10 min, using
156 a multichannel data logger made with Arduino hardware and open source software, as described in
157 Supporting Information (Figure 1S). The generated power P ($V \times I$), where I is the current flowing through
158 the external resistance R , was calculated using Ohm's law ($V=I \times R$). The data acquired were then
159 transmitted using a LoRa low energy transmission system described in Figures 1S and 2S, which was set up
160 and tested for data transmission over distances of >500 m.

161

162

RESULTS AND DISCUSSION

163 Both the flat MFCs and the tubular MFCs types were immersed in the denitrification tank without prior
164 inoculation. The electrode facing the anoxic water quickly developed a biofilm fueled by the residual
165 organics dissolved into the water in contact with the electrode. In the case of the flat MFCs whose electrodes
166 were separated though a porous PPE felt, without any electrolytic membrane, biofilm grew also on the
167 cathode sustaining the catalysis of the cathodic reaction (biocathode). Previous works on laboratory based
168 systems reported that the air breathing biocathode of single chamber and membraneless MFCs using the
169 same anoxic wastewater from Milano-Nosedo plant quickly become anaerobic developing a biofilm rich of
170 bacteria of the sulfur and nitrogen cycles (Guerrini et al. 2014; Rago et al. 2017). . The same microorganisms
171 differently enrich the anode and the cathode, but alone or in synergy with other microorganisms, such as
172 Spirochetes and photosynthetic anaerobic bacteria are able to sustain a good cathodic catalytic activity using
173 atmospheric oxygen just as the end-terminal electron acceptor (Cristiani et al. 2013). This mechanism allow
174 the flat floating MFCs to perform in the anoxic tank. The development of the biofilm at the cathode was
175 inhibited in the case of tubular ceramic MFCs, as the ceramic porosity does not allow the passage of bacteria
176 (Rago et al. 2018), but also due to the fact that the internal cavities of the ceramic cylinders were not directly
177 exposed to the anoxic water. The cathodic operation in this case was facilitated by the activated carbon,
178 whose cathodic catalytic properties, which are higher than the plain carbon cloth, have been well
179 documented (Anon 2017; Dong et al. 2012; Gajda et al. 2014; Wei et al. 2012).

180

181 *MFC power performance*

182 The power output from the flat and tubular MFC systems (boats) floating in anoxic wastewater, over a long
183 period of time, is shown in Figures 2-7. The lack of data in Figure 2 (May 2016) is due to technical issues
184 with the data acquisition system and is not an indication of the MFCs ceasing to work. The data shown
185 represent significant parts from the whole 3-year operational period. After approximately 2 weeks from the
186 initial immersion, all the MFCs reached a maximum voltage, varying between 0.2 - 0.5 V depending on type.
187 In the case of the small boat, a peak voltage of 0.7 V (about 2 mW of power) was produced within the first
188 month of operation (Figure S1 of supplementary information). Output levels suddenly dropped, before
189 stabilizing, possibly due to humidity, which would have caused short-circuiting and the uptake of
190 atmospheric oxygen. The small boat had been generating power in the range of 0.04 - 0.31 mW, showing
191 power density up to 9.6 mW/m² especially during the first period of the operation, although not continuously.
192 Performance however dropped continuously in the second year, when the Big boat was put side by side
193 (Figure 2), which outperformed the smaller boat. The big boat MFCs, swiftly reached a power output of 1.15
194 mW in November 2015 and reached about 0.9 mW (Figure 2), corresponding to a power density of 14
195 mW/m² and continued to generate power with a similar trend during the whole experimental period. The
196 better performance of the big boat, compared to the smaller one, is not simply due to the higher number of
197 MFCs connected in series/parallel (32 instead of 16) alone, but also due to the fact that the MFCs in the
198 small boat had probably undergone cathode clogging due to moisture penetration and sludge accumulation
199 resulting from water splashes, as it was operating for a longer period of time. Hence, the decrease in the
200 oxygen supply to the cathode had probably caused the decrease of MFC performance.

201 **The flat MFCs required slightly longer periods to start power generation, but all reached a peak in less**
202 **than one month from the immersion.** The Flat-large MFC produced higher absolute power, with peaks of 3
203 mW (Figure 3) corresponding to a density of 12 mW/m², which **were** more evident over weekly rather than

204 daily periods. Nevertheless, a minimum of approximately 0.4 mW was consistently generated. Oscillation
205 trends were already shown in previous experiments (Martinucci et al. 2015), and it was particularly
206 highlighted in smaller flat MFCs (Figures 4-7).

207 Figure 4 shows the trend of power produced by 4 identical flat-medium MFCs during about 4 months of
208 continuous operation. The maximum peak power (1.5 mW) was almost half compared to Flat-large MFC
209 with a similar power density (12 mWm²), since the total electrode area (1296 cm²) was approximately half.
210 On average, the performance was generally inferior. **The inferior performance, more marked in the case of**
211 **the Flat-small MFCs**, can be attributed to a high variability of the power produced by the single MFCs
212 (Figure 2S of supplementary information). Indeed, the performance between the four MFCs was inconsistent
213 with some producing less power than others, in this way negatively affecting the power density. The power
214 trend produced from 6 of this MFC type is shown in Figure 5. The power produced peaked at 0.5 mW,
215 corresponding to a power density of 6.4 mWm², which was inferior to the larger ones.

216 Figure 6 shows three (out of six) of the better performing Flat-small MFCs, which produced 13.6, 9.4
217 and 4.6 mWm² respectively. These results point to a severe concern regarding the achievement of a stable
218 power from the smaller MFCs for energy harvesting. In fact, the problem of spatial distribution and stability
219 affected these flat MFC more than the others, especially in cases of storms and pronounced changes of water
220 flow. The increased rate between perimeter and area characterizing the electrodes of the smallest flat MFCs
221 resulted in the anaerobic conditions becoming rate limiting for the anode, which operated next to the water
222 surface. Consequently, the possibility of polarity reversal of the cells has to be taken into account for these
223 MFCs, causing the decay of produced power. A phenomenon such as this is reported in Figure 6, documented
224 in the power trends of the six Flat small MFCs operating in the Summer of 2017.

225

226 *MFC output vs temperature and water flow*

227 The generated power by the tubular MFCs on the boat and the relationship with temperature and
228 water flow (Q) measured at the plant inlet during the same period of time is reported in Figure 2. The
229 variation of power appears to be affected by the large variation of flow rate that was consistent
230 with the adverse weather events (mainly rainfall and storms) which diluted the incoming wastewater whilst
231 increasing the flow causing temporary decreases. No direct correlation of power with the water temperature
232 is noticeable, neither for the diurnal cycle, nor for the whole experimental period. Nevertheless, the MFC
233 performance decreased to very low levels during winter time, when the environment temperature generally
234 dropped below 15°C impacting on the temperature of the first layer of water. This result is consistent with
235 mesophilic bacterial metabolism, which has an optimum between 20 – 35°C, in the context of the Arrhenius
236 law of temperature. The daily oscillation of power from both Small and Big boats were negligible, like in the
237 case of the flat MFC with much larger cathodes (Figure 3). In fact, cylindrical cathodes of the boats were not
238 exposed to light since they are positioned inside the terracotta cylinder and immersed in water. The observed
239 increases in power can be consequently, correlated with the diurnal cycle and also with the concentration of
240 organic substance through the anodes. Also the power oscillations of Flat-large MFC are only marginally
241 dependent on the temperature and water flow as for MFC boats (Figure 3). In fact, the decay in performance
242 was mainly coinciding with periods of intense rain and other events that significantly diluted the dissolved
243 organic substance, changing organic load in the stream.

244 The daily power oscillations of Flat-medium MFCs are evidenced in Figure 4, which is also
245 highlighted in the zoomed graph of the power trends of the single MFCs during ten days of June 2015. This
246 graph shows for all the four MFCs a daily variation of power much more pronounced than the weekly or
247 multi-day variation, which results synchronized with the sun hours and the variation of flow rate rather with
248 the temperature variation. The same oscillating behavior was noticed for Flat-small MFCs (Figures 5-7).
249 Daily power trends of Flat-small MFCs (three of six) and of both boats during a single day are shown in
250 Figure 6 with Temperature, Q and COD concentration of the wastewater sampled at the plant inlet (20-21
251 June 2017). The graphs show that the MFC performance improves concurrently with daytime, the increase of
252 the COD dissolved and the increase of water flow. A noticeable power peak for the Flat-small MFCs is, in
253 fact, in advance of hours with respect to the water temperature variation.

254 It could be inferred that the cathode electrode was limiting in the case of small size MFCs, not able
255 to sustain the anodic oxidation, especially when anodes are exposed to very low levels of substrate (10-20
256 mg/L COD). The presence of microalgae could favor the local increase in the concentration of oxygen on the
257 cathode resulting in higher power output (Gajda et al., 2015) when exposed to light, and higher power over
258 the long term. Also a contribution of photosynthetic microorganisms in producing the power could be
259 responsible for MFCs performing well during the hours of solar radiation. Several microorganisms as well

260 cyanobacteria could be involved, as reported in the literature (Rosenbaum et al. 2010; Huarachi-Olivera et al.
261 2018). For instance, purple non sulfur bacteria were frequently detected in biocathodes of single chamber
262 microbial fuel cells (Cristiani et al. 2013) during previous tests performed at laboratory level using the same
263 wastewater from the nitrification tank of the Milano-Nosedo WWTP (Cristiani et al. 2013; Rago et al. 2017).
264 This aspect deserves further investigation in any future analyses.

265 It may be finally noted that the black color of the material used for the cathode electrode could
266 increase the temperature oscillation in it, affecting the intensity of the MFC response due to sun exposure.
267 Nevertheless, a test performed with a thermoresistance (PT 100) placed on the electrode surface of a flat
268 MFC exposed to the sun demonstrated that the temperature variation during insulation did not vary more
269 than 2-3°C with respect to the temperature of the water bulk, thereby excluding the immediate effect of
270 temperature.

271

272 *MFC output vs environmental factors*

273 Figure 6 shows the trend of the six floating cells immersed in the anoxic basin of the Carimate WWTP, with
274 electrodes measuring 10 x 13 cm and anodes short-circuited. In this way, the different output of the single
275 cell is due to the cathode performance and not to the (common) anode. The figure show daily oscillating
276 power trends as already registered for the smallest flat MFCs operated at Milano Nosedo WWTP. Therefore,
277 power limit, in this case as in the case of the other small flat MFCs, is underlined with the underperforming
278 cathodes. The graph shows a strong daily variability especially during the first months. At the end of
279 November, the cathodes were variously covered by a layer of mud that strongly limited the exchange with
280 the oxygen of the air as well as impeding, to some extent, the arrival of light on the cell. In that period, the
281 power, and also the daily variation, were much more contained, although a direct relationship of power
282 production with sun irradiation and meteorological events was still maintained. The presence of
283 photosynthetic anaerobic bacteria producing hydrogen in such condition could played a relevant role,
284 enhancing the cathodic reaction in synergy with the rich anaerobic pool (Cristiani et al. 2013; Rago et al.
285 2015). This phenomenon deserve further investigation to be confirmed. Figure 6 shows also a zoom of the
286 voltage trend of the six flat cells immersed in the anoxic tank of the Carimate WWTP with the solar
287 irradiation measured with a commercial solarimeter (Futura electronics, code 8220-DVM1307). Rain
288 precipitation, expressed as mm of water, is also reported in the graph. The rain causes the dilution of the
289 wastewater, and consequently a reduction of the organic content. This phenomenon can be easily correlated
290 with the power drop.

291

292 *MFC output vs COD concentration*

293 The trend of COD concentration measured by colorimetric method (Hatch Lange kits and instrumentation)
294 every hour at the inlet of the (Milano–Nosedo) WWTP during one day (20-21 June 2017) with power trends
295 of the Flat-small MFCs and of both the boat MFCs immersed in the same anoxic tank is reported in the
296 Figure 7. The graph shows a significant difference in the trend of the different MFC types.

297 The correlation between the increase in the signal and the period of light is evident for the Flat-small MFCs,
298 even if, in this period, it is not the sole phenomenon that determines the intensity of the power.

299 In fact, the COD fluctuation in the denitrification tank also affected the MFC power production of each type
300 and size. The larger boat output could be better correlated to the COD level than the others exposed to the
301 light and also the small boat, as it was not performing well during that period. The dynamic behavior of
302 nutrient concentration could then be monitored via on-line signal, and the treatment could be more efficiently
303 controlled, and therefore cost effective in the long term (Tanwar et al. 2008).

304

305 *Energy harvesting and data transmission*

306 The simple low-energy remote system (LoRa) that was set for the MFC data transmission is described in
307 Supplementary information (Fig. S3, S4). It was successfully tested over a distance of 500 m, between the
308 transmitter and the receiver installed at the WWTTPs. This system requires a minimum tension of 3.3 V and 0.3
309 mA (about 1mW) to operate in sleeping mode and consumes about 130 mA (during the data transmission,
310 that lasts only about 70 μ s.

311 Based on the results achieved, it could be concluded that a single Flat-large MFC which produced
312 continuously an average between 0.4 – 3 mW (0.2-0.6 V) connected to a DC/DC converter in an harvesting
313 circuit, like those described in previous works (Schievano et al. 2017), is able to supply enough power for

314 the transmitter. For a two time a day message, the additional power of 858 mW for 140 μ s is needed, which
315 is, in term of energy (0.12 mWs), negligible with respect to the sleeping mode consume.

316 In case of Big boat, the minimum requested power of 0.4 mW is not produced in continuous mode.
317 Therefore, the number of MFCs for the future construction of the boat should be increased.

318 In both cases, due to the variability of the produced power in time, the connection of two or more MFC
319 systems should be recommended to reliably power the LoRa transmitter.
320

321 *Post operation observation of flat MFCs*

322 Image of immersed flat and cylindrical reactors in a MFC boats during operation are reported in Figure S5
323 and S6 in Supplementary information. Post operation observation of flat MFCs are reported in Figure S7.

324 The flat MFCs were quickly covered by photosynthetic organisms (Figures S7, supplementary information).
325 As time progressed, spontaneous vegetation of grass, herbs and shrubs grew on the cathode of these MFCs
326 (top surface, exposed to air), somewhat demonstrating a wetland phenomenon, whose root system gently
327 covered the electrode without damaging it, allowing the oxygen to reach cathode and preventing its
328 permeating through (Figure 6S in Supplementary information). This phenomenon probably allowed Flat-
329 large MFC to outperform other set-ups in long time. For the tubular configuration in the boats there were no
330 vegetation growth on the cathodes. Differently, activate sludge can excessively accumulate on the cathodes,
331 inhibiting the power production. The tubular cathodes, i.e. internal cathodes, suffered for sludge incoming
332 which obstructed aeration, especially the ones in the small boat as they operated for a longer period of time
333 (since 2014). This last phenomenon in particular resulted critical and have to be prevented for using small
334 size of both kinds of MFC.
335

336 **4. Conclusions**

337
338 Both the tested floating MFCs types (flat and tubular) were demonstrated to be able to provide electric
339 power for years, although with oscillations, despite the low concentration of organic matter in the wastewater
340 of the denitrification tanks. They clearly demonstrated the viability of the MFC system as an energy
341 harvester in a real environment.

342 The dissolved COD in the wastewater as well as the meteorological conditions (sun irradiation and
343 rainfall), mainly caused the oscillation in MFC's output. The daily temperature and water flow variations had
344 a negligible effect.

345 Floating MFCs reached a power peak in about two weeks from the installation and do not need
346 maintenance during the whole experimental period. Photosynthetic species (bacteria, microalgae and plants)
347 growing on the floating MFCs have a positive effect, both as visual impact and in avoiding mud encrustation
348 on the cathodes. These aspects allowed a long time operation of the MFCs. On the contrary, sludge
349 accumulation on the cathodes of both tubular and flat MFCs resulted in a much reduced output and most
350 critically required prevention in future designs of MFC's as sensors and energy harvesters. A new, simple
351 low-energy remote transmission system (LORA) successfully tested, shows great promise for a cost effective
352 way of data transmission that could be implemented in monitoring and controlling water quality based on
353 floating MFCs.

354 A single unit of Flat-large MFCs and boats are able to guarantee energy enough for a daily remote
355 transmission of signals from the tested system, although not continuously.

356 The simplicity in setting up such a monitoring system lends itself well towards the development of citizen
357 science and for remote environmental control.
358

359 **Figure captions**

360
361 Figure 1. Scheme of a flat MFC (A) and set-up of six MFC elements in a frame ready for the immersion in
362 wastewater (B). Single tubular MFC element and its scheme (C). Tubular MFC elements
363 integrated into a styrene boat: Small boat with 16 elements (D); Large boat with 32 elements (E).
364

- 365 Figure 2. Power trends of the Small boat and Large boat MFCs during more than one year (April 2016-July
366 2017) in an anoxic tank (Milano-Nosedo WWTP); trends of temperature and wastewater flow
367 incoming in the plant is also reported.
368
- 369 Figure 3. Power trend of the Flat-large MFC (50 x 50 cm) operated from January to July 2017 (Milano-
370 Nosedo WWTP); trends of temperature and wastewater flow incoming in the plant is also
371 reported.
372
- 373 Figure 4. Power trends of the Flat-medium MFCs (18 x 18 cm) operated from April to July 2017 (Milano-
374 Nosedo WWTP); trends of temperature and wastewater flow incoming in the plant is also
375 reported. The graphs on the bottom are ten days zoomed.
376
- 377 Figure 5. Total power and single voltage trends produced by 6 Flat-small MFCs (10 x 13 cm) during one
378 month operation (June-July 2017) at Milano-Nosedo WWTP. Wastewater temperature and flow
379 are also reported.
380
- 381 Figure 6. Power trend of 6 Flat-small MFCs (10 x 13 cm) with shortened anodes (Carimate WWTP). A
382 detail of power trend (November-December 2017) with meteorological measurements (sun
383 irradiation and rain) is also reported.
384
- 385 Figure 7. One day (20-21 June 2017) power trends of three Flat-small MFCs and of the two boats.
386 Temperature, flow and COD concentration in the wastewater sampled at the inlet of the Milano-
387 Nosedo WWTP is also reported.
388

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