Avenues to the financial viability of microbial electrolysis cells [MEC] for domestic wastewater treatment and hydrogen production

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We propose targets, based on real world data, necessary to design a financially viable microbial electrolysis cell (MEC) for the treatment of domestic wastewater. By reducing the cost of the anode and current collecting materials by 90%, a viable organic loading rate would be between 800 and 1,400g-COD/m³/d (2–3A/m²). The anode and current collector materials account for 94% of the total material costs; consequently, cost savings in any other material are moot. If the bioanode can be reused after 20 years, further, significant savings could be achieved. To develop targets we used real world data, for the first time, to evaluate the financial viability of MECs against the current predominant method of wastewater treatment: activated sludge. We modelled net present values for eight potential scenarios and the performances required for MECs to break-even. © 2018 The Authors. Published by Elsevier Ltd on behalf of Hydrogen Energy Publications LLC. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

Introduction

Energy use for wastewater treatment accounts for 1–3% of the total electricity used in developed countries [1,2]. A value, which places energy as the second highest cost to water and wastewater utilities, after personnel [3]. This is particularly incongruous because wastewater contains approximately 18kJ/g-COD (chemical oxygen demand) of energy, around 10 times more energy than is currently used to treat it [4]; although not all of the energy is biologically retrievable [5].

Activated sludge (AS) is the most prevalent wastewater treatment technology globally (by volume treated) [6]. AS relies on heterotrophic bacteria to digest the organic compounds present in wastewater; oxygen (O₂) is used as an electron acceptor and carbon dioxide (CO₂) is produced as a waste gas. Around 60% of the energy used in wastewater treatment is for the aeration of AS tanks [7]. In these aerobic conditions large amounts of sludge is produced. To regain some of this energy, investment in the anaerobic digestion (AD) of sludge from the AS process is becoming more widespread [7,8]. However, even with the use of AD, wastewater treatment plants are net consumers of energy [9].

Bio-electrochemical systems have been touted as a sustainable treatment for wastewater [10], as they have the...
potential to retrieve energy rather than consume it. Microbial fuel cells (MFC) and microbial electrolysis cells (MEG) have been of particular interest in addressing this misalignment of energy [11–13]. In these systems, an electrogenic biofilm is grown on an anode in an electrochemical cell [10]. The electrogenic bacteria act as a catalyst: where organic matter is the electron donor, and the anode is the electron acceptor [14]. MFCs and MECs differ in their operation and mode of energy retrieval.

In an MFC the power supplied by the electrogenic biofilm is extracted [10,15]. Electricity must be used directly or stored in external batteries. MFCs require oxygen as the electron acceptor at the cathode. This requires the use of either: large-scale air-cathodes, which are difficult to engineer; or aeration of the cathode chamber, which is energetically expensive. Furthermore, MFCs have been known to undergo voltage reversal, which damages the biocathode, and would incur a high replacement cost. This is prevented in an MEC where voltage is applied [16].

In an MEC, higher value products such as hydrogen gas, or other value-added chemicals, can be recovered at an anaerobic cathode by supplementing the potential difference between electrodes [10,15]. These systems could be easily retrofitted into existing infrastructure and have been demonstrated at pilot scale [17–21]. The applied potential has also been demonstrated to effect the microbial community [22], which could allow a potential ‘tuning’ of this system for oxidation of specific wastes and compounds. Furthermore, by applying a potential, electrogenic organisms have been observed to outcompete aerobic heterotrophs in substrate removal rates [23], which could reduce reactor size and cost. Applied potential has also been shown to decrease start-up time [24].

Hydrogen production is of particular interest as an application of MEC technology. Hydrogen is a storable source of sustainable energy, a feature missing from other sustainable energy sources such as solar and wind. Compared to other electrolytic products, Hydrogen requires only two electrons from the electrochemical process and protons are sufficiently available in water and wastewater. The theoretical potential difference required to produce hydrogen in an MEC is much lower (0.12 V) than conventional electrolytic technologies (1.23 V) [10]. Though in reality, higher overpotentials in an MEC increase this potential difference (~0.6 V) [5].

The advantages of MEC over AS and AD as a treatment technology include: low energy input; sustainable energy recovery [17,18]; and proven function at low temperatures with dilute domestic wastewater [18,21]. This is important as heating wastewater is a costly endeavour due to its high thermal capacity [25]. Importantly MECs could be, at least partially, retrofitted into existing infrastructure. Wastewater treatment facilities are typically built for 20–50 year service lives [26], yet the biological contents of these tanks could be changed in a matter of weeks or months [24].

The high capital costs and modest performance of the technology under ‘real-conditions’ are barriers to the commercial adoption of MECs [15]. Early estimates by Rozendal et al. (2008) of MEC costs were 10 times that of AD [10]. Nevertheless, material costs have reduced in recent years especially with the use of cheap membranes and stainless-steel cathodes [27]; thus more recent analyses on economics are needed. Rozendal et al. (2008) propose necessary current densities (10A/m²) to break-even, however current density can be increased by means other than removal of organic matter. This therefore requires supplementary targets better suited for the application of wastewater treatment, such as organic loading rates (OLR).

Zhang and Angelidaki (2016) [27] highlight the lack of data available in the literature on capital costs, and the non-standardized reporting methods of capital costs normalised to the performances posed as barriers to commercial adoption. Operating costs and revenue also need to be considered as MECs must be financially competitive with existing technologies. Additionally, using metrics found in the normalised-costs for conventional wastewater treatments, for example OLR [7], would allow for cross-technological comparisons.

Previously, Sleutels et al. (2012) [28] estimated the cost of COD removal at varying current densities for MECs. This study provides an insight into the potential applicability of MECs, however: costs for electricity are low (£0.06/kWh [c.10.05/ kWh]); cathodic efficiencies are high (90%); material costs are low (£100/m²); and the current densities considered are very high (0–50A/m²). High efficiencies and high current densities are unlikely to occur for MECs fed with domestic wastewater and built with low-cost materials. Therefore, empirical data is needed for a more accurate estimation.

Escapa et al. (2012) [29] estimated the financial feasibility of MECs using empirically derived data and concluded that MECs could be viable at loading rates of 2 kg/m³. However, the study was based on an OLR observed at a very small scale (<100 ml), and at a very warm temperature (30 °C). In reality the acceptable loading rate will be a function of temperature. Most treatments plants, even in the tropics, operate at substantially less than 30 °C. Consequently, there is a need to complement these studies with an economic evaluation of MECs based on “real-world” performances using domestic wastewater in a temperate climate.

The material investment costs; operational energy costs; and revenue of a large-scale MEC are considered herewith. Performances and costs based on a pilot-scale reactor [19], built with low cost materials and fed with ‘real’ domestic wastewaters, at ambient temperatures in a temperate climate (55°N). We compare cost-performance ratios against AS, for the equivalent OLRs, using net present value (NPV). NPV is a tool to assess the profitability of a future project in comparison to its initial investment cost by considering the depreciating real value of money over time, due to inflation and missed investment opportunities. A discounted interest rate [30] (typically 3.5% per annum [35]) is applied, which compounds annually. The NPV of AS and MEC after 20 years were compared for eight potential scenarios to assess MEC’s financial competitiveness for domestic wastewater treatment. We identified the impact of each scenario on the financial viability of the MEC design. The analysis can be used to guide the conceptual design of large-scale commercial MEC systems; and focus research on those features of an MEC that must be improved to make the technology financially viable.
Methodology

Case study

Heidrich's design (2014) [19] incorporated low-cost materials and treated “real” domestic wastewater; it is used as the basis of the material and performance projections. The pilot MEC had a total working volume of 88 L, larger than most laboratory scale studies, and operated for 12 months in air temperatures ranging from 1 °C to 22 °C. The hydrogen gas produced was of high quality (98%–99%). The reactor had a ‘cassette’ style design that could, in principle, be retrofitted into other tanks. Stainless-steel wire wool was used as the cathode, which greatly reduces cost compared to original estimates [10] by up to 97% [32]. The membrane was Rhinhode (€1.50/m²) (Entek, UK), which costs much less than Nafion (€400/m² [c.€350/m²]) [10]. Carbon felt anodes (€285.90/m²) (Olmec, UK) were combined with stainless-steel current collecting frames (€30.80/m²) (Unkammen Supplies, UK). The anode and current collecting frames combined, constituted the highest proportion of the cost, and therefore the most important element to cost correctly. We also incorporated potential costs for hydrogen capture and storage (Supporting Information).

The model assumes that dimensions of components scale in proportion to anode size, there are no new infrastructure or land purchase costs and staff can be retrained at minimal cost to the water companies.

Material investment costs

The fundamental relationship between COD removal (ΔCOD) and current production (I), presented by Logan (2008) [33] (Eq. (2.1)), forms the basis for understanding of the MECs function:

\[ I = \frac{C_e \cdot F \cdot Q \cdot \Delta \text{COD}}{8} \]  

(Ce) describes the proportion of electrons from the degraded substrate that is passed into the circuit; flowrate (Q) governs the size of the treatment process; the COD removed is divided by the number of electrons in a mole (F) and Farad’s constant (F) is used to convert the rate change in moles of electrons into current (I).

Current density (Iₐ) is equal to electrical current (I) divided by the anodal surface area (SA). This was rearranged to make the anode surface area (SA) the subject (Eq. (2.2)). Current density in this instance is used as a performance indicator for the rate of substrate uptake per area per time by electrogens in the system.

\[ SA = \frac{C_e \cdot F \cdot Q \cdot \Delta \text{COD}}{8 \cdot I_a} \]  

Based upon the surface area of the anode (Eq. (2.2)), the developer software ‘Visual Basic for Applications’ (VBA) within Microsoft Excel was used to estimate the quantity of materials required for a large-scale MEC. Performance parameters are known from empirical data (Table 1) [19]. Population and flow rate, for the hypothetical large-scale reactor, were assumed to be 100,000p.e. and 15,000m³/day (150 L/p.e) [27], and dimensions of cells were assumed to be 4 m x 6 m (typical AS lane dimensions) [25]. Material costs were extrapolated from the unit costs in the case study [19] (Supplementary Information). These are likely to give conservative estimates as economies of scale may reduce unit prices, albeit modestly.

Table 1 – Performance parameters of large-scale MEC.

| Parameter                  | Symbol | Value  |
|----------------------------|--------|--------|
| Coulombic Efficiency       | Cₑ     | 13.3%  |
| Faraday’s Constant         | F      | 96,485 J |
| Influent                   | Q      | 15,000 m³/day |
| COD Removed                | ΔCOD   | 140 g/m³ |
| Current Density            | Iₐ     | 0.3 A/m² |
| Anode surface to volume ratio | Sv  | 0.72 m³/m² |
| Population                 | Pop.   | 100,000 p.e. |

Energy costs and revenue

The price of electricity was assumed to be homogenous across the model (whether buying or selling), at £0.10/kWh, typical of business rates in the UK [34]. Input power to the MEC was based on an input voltage of 1.1V and was multiplied by the current density (0.3A/m²) [19] to give power ratings and therefore electricity costs.

Hydrogen production

Hydrogen production was assumed to have a comparable yield (15L-H²/m³-influent/day) to the pilot-scale reactor [19]. Annual hydrogen production was calculated based on reported yields and a hydrogen density of 0.09 g/L. Cathodic efficiency was approximately 50% (around half of the electrical current was converted into hydrogen). Prices for hydrogen are expected to decrease in the future as more of the gas is produced to meet with the demand for hydrogen powered vehicles [36]. The European target price for hydrogen is €4.00/kg (€3.55/kg) by 2020, and €3.00/kg (€2.66/kg) by 2030 [37]. By 2030 hydrogen is expected to be fully competitive with other fuels. The model assumes a 2020 target price for hydrogen. In addition to calculating annual cash flow, required hydrogen yields to break-even were calculated based on these targets.

Activated sludge comparison

There are numerous estimates in the literature for the cost of activated sludge, and costs vary between treatment works. Aeration typically costs 40–60% of the total energy of a wastewater treatment plant (WWTP) [7]. This depends upon the strength of wastewater and the size and efficiency of the WWTP [25]. Pant et al. (2011) [27] estimate an energy cost of 0.7–2 kWh/kg-COD removed in Activated Sludge. This equates to an annual saving between £53,000 and £153,000 for an MEC treating 15,000 m³/d and reducing concentrations by 140g-COD/m³. This is an approximate mean saving of £103,000 per year. Averaging this gives an annual average saving of about £103,000. Shi et al. (2011) [7] provide a detailed break-down of energy costs in a real-world WWTP. Electricity use for aeration was assumed to scale linearly with flow rate and was scaled down from 10MGD to 15,000 m³/d. This equates to an annual aeration cost of £105,000, similar to the average given by Pant.
et al. (2011) [27]. A linear assumption is appropriate for aeration but not for the overall treatment works as electricity costs for pumping constitute a higher proportion of electricity usage for smaller sites [25].

Estimated costs of air pipes and diffusers (FLI Water Ltd., UK, personal communication) were based on quotes from a WWTP currently under refurbishment (Seaham, UK). Pipe and diffuser requirements were linearly scaled up from 11,000 m$^3$/d to 15,000 m$^3$/d. Sizes and prices for blowers were also taken from quotes and specifications (APG-Neuros, UK, personal communication). The replacement rate for pipes and diffusers assumed to be 5 years, blowers were assumed to last for at least 20 years, which is consistent with current industrial practice. The cost of sludge treatment was purposefully omitted, as although MECs produce less sludge than AS, and therefore incur less sludge disposal costs, the quantities are not yet clear [4].

**NPV calculation comparison**

NPV was used to compare costs ($C_i$) for MECs and AS over an assumed twenty-year operational period ($n$) with an assumed one-year construction for both (Eq. (2.3)). This is speculative as the construction period for MECs is unknown, as is their operational life span. The rate of return ($r$) was assumed to be equal to that of the UK government discount rate, at 3.5% [31]. As NPV is a measure of economic value, and wastewater treatment does not produce profitable products, all NPVs discussed will be negative. An increase (toward positive values) in NPV for MECs is therefore beneficial for the technology, and a decrease detrimental. The opposite is true for costs, increases in costs are detrimental and decreases in costs are beneficial.

\[
\text{NPV} = \sum_{i=1}^{n} \frac{C_i}{(1 + r)^t}
\]  

(2.3)

**MEC scenarios**

Seven scenarios (Table 2) were considered in addition to the base MEC model (Scenario 0). These include changes in energy input, output and energy prices; return on assets after the investment period, and maintenance such as staff costs and replacement costs. Scenario 1 modelled a doubling of hydrogen yield, a common goal in research. Scenario 2 modelled a reduction in power requirements by decreasing the applied voltage to 0.6V, considered to be close to a lower limit [5]. Scenario 3 considers an energy price increase of 33%, predicted by 2030 [38] and a hydrogen price decrease to 2.66/kg to assess the impact of future markets [37]. Scenario 4 modelled a return on anode and current collectors, at the same value as purchased (assumed re-use) after 20 years of operation; elsewhere it has been noted that if uncorroded, stainless steel in MECs can be an asset at the end of its lifespan [39]. The length of operation of the anode is unknown; performance is dependent on self-replicating microorganisms and can be sustained for at least 12-months [19]. Scenario 5 took into account the annual replacement of the membrane, scenario 6 modelled annual replacement of both the membrane and cathode; it is likely that these components will not last 20 years, an annual replacement was chosen as a conservative estimate. Scenario 7 considers costs if an additional member of staff is required, with an annual salary of £30,000, this could be feasible given that MECs require careful monitoring as compared to AS. In reality many of these scenarios may occur simultaneously, however this exercise serves to demonstrate the impact and importance of each on cost and performance.

**Target finder**

OLR (mass flux of g-COD removed per metre cubed per day) and current densities are used as performance indicators to address the amount of substrate that was taken up by electrogenic species per area per time. OLR and current density correspond with one another (Eq. (2.4)); based, in this case, upon a coulombic efficiency of 13% [19]. The model (Target Finder) was run at incrementing OLRs for each of the scenarios until the NPV after 20-years of operation was less than that of AS. The ‘target’ OLR and current density, meaning the OLR and equivalent current density that would be required to achieve financial viability against AS, for a given scenario, was calculated. This was “outputted” to a worksheet along with; the increase in performance required from the pilot; the NPV for the scenario at current performances; the NPV of the scenario at ‘target’ performances, and any profit margin (Table 3).

In tandem, a sensitivity analysis was conducted to determine the “target” OLRs required for reductions in capital costs (at incrementing steps of 10%) for each of the scenarios (Fig. 3). The model assumes all other parameters remain constant, such as hydrogen yield. Therefore, increasing OLR, also increases hydrogen production. Sensitivity analyses for maintenance scenarios (5, 6) assume that material cost savings are made to components other than the membrane and cathode. This is a legitimate assumption as membrane and cathode costs have already been reduced drastically and are a small percentage of the overall material costs (Fig. 2).

\[
\text{OLR} = \frac{8 \cdot I_a \cdot SA}{Ce \cdot F \cdot V}
\]  

(2.4)

**Results and discussion**

**Current state of financial feasibility**

The capital investment costs for MECs is currently substantially higher than that of AS. For an influent flowrate of...
15,000 m$^3$/day, material costs for MECs were predicted to be £42,700,000. This is comparable to the material cost of Ge and He's (2016) [40] small-scale MEC: scaling up linearly with flowrate, material costs are approximately £45,000,000. The material costs for AS for the same flowrate were estimated to be £172,000, two orders of magnitude less.

This disparity in the initial investment could be a deterrent to commercial adoption. However, MECs have the potential to be energy neutral, if not positive, whereas AS consumes about 0.2 kWh/m$^3$ for aeration alone, throughout the entirety of its life [7]. Annual energy costs were £106,000 for AS and £11,000 for MECs. Annuals costs in MECs are a factor of 10 less than AS. However, current NPV at 20 years was -£42,900,000 for MECs whereas NPV was -£2,000,000 for AS. At present loading rates of 140 g-COD/m$^3$/day (0.3A/m$^2$) the NPV comparison is clearly unfavourable. To make MECs a competitive technology under this baseline scenario (0) the OLR would need to increase to 4,450 g-COD/m$^3$/d equivalent to a current density 10.1 A/m$^2$; a 34-fold increase from the pilot’s performance (Fig. 1, Table 3).

These costs are based on the differences between MEC and AS, and so naturally neglect the costs they have in common. Any minor discrepancies in these costs will be negligible in comparison to the order of magnitude differences we have found.

### Table 3 – 20-year net present value, target current densities, and target organic loading rates for MECs for eight scenarios.

| Scenario$^a$ | NPV at present (4 sf) | Target current density (A/m$^2$) | Target OLR (g/m$^3$/d) | Performance increase required |
|--------------|-----------------------|----------------------------------|-------------------------|-----------------------------|
| Pilot MEC    | £ (42,850,000)        | 0.3$^{19}$                       | 140$^{19}$              | 34                          |
| Scenario 0   | £ (42,480,000)        | 7.8                              | 3437                    | 26                          |
| Scenario 1   | £ (42,610,000)        | 8.5                              | 3746                    | 28                          |
| Scenario 2   | £ (43,120,000)        | 8.6                              | 3790                    | 29                          |
| Scenario 3   | £ (26,790,000)        | 6.3                              | 2776                    | 21                          |
| Scenario 4   | £ (45,430,000)        | 10.7                             | 4715                    | 36                          |
| Scenario 5   | £ (65,750,000)        | 15.6                             | 6875                    | 52                          |
| Scenario 6   | £ (43,280,000)        | 15.2                             | 6699                    | 51                          |
| Scenario 7   | £ (21,510,000)        | 4.1                              | 1806                    | 14                          |
| AS           | £ (2,009,000)         | 500–2,000$^{25}$                 |                          |                             |

$^a$ Scenario 0: baseline MEC model; Scenario 1 – Double hydrogen yield; Scenario 2 – Applied voltage reduced to 0.6V; Scenario 3 – Energy price changes; Scenario 4 – Anode and current collector value returned after 20 years. Scenario 5 - Membrane replaced annually; Scenario 6 - Membrane and cathode replaced annually; Scenario 7 - Additional staff member required.

### Fig. 1 – Target cost-performance ratios for financially competitive MECs treating domestic wastewater.
Material costs

The material costs accounted for 99% of NPV. Of this, the anode constitutes the greatest proportion of material costs (75%) and the current collector the second greatest (19%). Together these features account for 94% of total costs (Fig. 2). This contrasts Rozendal et al. (2008)\textsuperscript{10}, where the cathode constituted the greatest proportion of the capital investment (Fig. 2). This change is due to the use of cheaper cathode and membrane materials (Supporting Information). Significantly, the membrane was less than 1% of total costs, contradicting the impact on economics that membrane-less systems are hypothesized to make \cite{35}.

Hydrogen production

Under scenario 1 (a doubling of current yields to 30 L/m\textsuperscript{3}) the positive cash flows generated at 2020 prices (£15,000/year) (Table 3, Fig. 3) had a negligible impact on NPV because of the cost of materials (assuming current performances). It is
therefore unlikely hydrogen production alone will account for MEC capital costs.

To break-even under the baseline scenario (0), either hydrogen would need to be priced at £5.09/kg (more than the EU’s target of £3.55 by 2020, and £2.66 by 2030) or yields will need to increase from 15 L/m³ to 21.5 L/m³ by 2020 and 28.7 L/m³ by 2030 (an increase of 43% and 91%, respectively). Cathodic efficiencies are relatively high and therefore to increase yields, coulombic efficiencies and OLR will need to increase. Nevertheless, even if hydrogen is sold at a loss in order to be competitive with other sources of hydrogen, electricity costs in MECs are minimal compared to AS.

**Applied voltage**

Reducing the applied voltage to 0.6V, whilst maintaining yields (scenario 2), likewise provided positive cash flows by reducing energy input. Current density targets were reduced to 8.5A/m² (3,750g-COD/m³/d) (Table 3, Fig. 3), however as applied voltage directly impacts hydrogen production this may not be technically achievable.

**Future energy prices**

Energy and hydrogen prices are expected to change in the future (scenario 3). Predicted changes had modest impacts on NPVs for both AS and MECs. 20-year net loss for AS increased by 8% (NPV: £2,160,000), whilst MEC net loss increase was negligible, at less than 1%. This shows MECs are currently less sensitive to price rises due to their material costs. However, a modest change in target performances was observed 3,790g-COD/m³/d (8.6A/m²). This means the price of electricity increase in the future, as predicted, MECs will become more competitive.

**Asset recovery**

Recovering the current collector and anode materials value after 20 years (scenario 4) had the largest effect on NPV, which improved to £27,000,000. Target current densities were reduced to 6.3A/m² (2,780g-COD/m³/d) (Table 3, Fig. 3). It may also be possible to recover value from other components to further increase MECs value such as the cathode, however this only accounts for 4% of the material costs. Reusing assets and reducing capital costs would make MECs more competitive, however corrosion and fouling will need to be prevented.

**Maintenance: replacement costs**

Replacing the membrane annually (scenario 5) was detrimental to NPV by about £3,000,000. Current densities would need to be 10.7A/m² (4,720g-COD/m³/d) (Table 3, Fig. 3) to pay for the replacement: a small increase from baseline targets (10.1A/m²). Thus, fears about the use of membranes at full scale [27] are probably misplaced as the membrane is 1% of the cost.

However, annual replacement of the cathode and membrane (scenario 6) decreased NPV by £23,000,000 and target current densities increased to 15.6A/m² (6,880g-COD/m³/d, 54% increase from baseline) (Table 3, Fig. 3). It will therefore be necessary to protect the cathode from fouling if performances are to be sustained and annual costs kept to a minimum. Fouling of the cathode is more likely to happen when operating with ‘real’ wastewater due to the complex microbial and chemical environments [41].

**Maintenance: personnel**

Increasing the number of staff by one member, on a £30,000 salary, had a negligible impact on NPV (-£43,000,000), however performance targets were increased significantly at these capital costs (15.2 A/m², 6,700g-COD/m³/d) (Table 3). It would therefore be beneficial for MECs to be easy to operate, and staff easily and readily retrained. There is a discrepancy between higher OLRs at high capital costs and lower target OLRs at lower capital costs. This is because salaries do not change with respect to OLR. Therefore, a greater OLR (which increases hydrogen production and revenue) is required to induce a positive cash flow and mitigate the effects of a high capital cost; whereas at lower capital costs less mitigation is required - although OLRs are still higher than baseline (Fig. 3).

**Space**

At presently achieved OLRs, MECs would be too large to simply retrofit most existing AS aeration basins. Therefore more space and civil works (which were not costed in this paper) would be required. However, due to the order of magnitude differences found in material costs, it will be necessary to reduce OLRs for material costs to be comparable. In scenarios where target OLRs for MECs are higher than AS (Table 3), the new technology could be refitted within existing facilities and therefore the cost of supplying extra space for MECs with a low OLR is moot. Moreover, increased performances have been observed in MECs that were pre-treated using fermentative reactors, which require the retention of sediment to operate correctly [42]. Combining these two novel technologies may reduce the need for large sedimentation tanks, “freeing-up” more space. Secondary sedimentation facilities could be retained as humus tanks to further improve effluent quality, though if they could be decommissioned, further cost savings could be made.

**Making financially viable MECs**

A reduction in the cost of the anode and current collector by 90% (a reduction in total material costs of 84%) had a large impact on NPV. OLRs required to break-even for most scenarios (0–3, 5, 7) are reduced to 800–1,400g-COD/m³/d (Fig. 3): an order of magnitude higher than presently achievable (440gCOD/m³/d) [19], but much less than baseline targets (4,450g-COD/m³/d), and within the ‘middle range’ of AS removal rates (500–2000 g/m³/d) [27]. This therefore seems feasible given that electrogenic organisms have been observed to outcompete aerobes, in terms of removal rates, given the correct conditions [23]. Subsequently, target current densities at these costs (2–3A/m²), are much less than baseline targets (10.1A/m²) and early predictions (10A/m²) by Rozendal et al. (2008) [10]. Reusing (or reselling) the anode and current collecting materials after 20-years could lead to large improvements in cost-performance ratios (Fig. 3). Under this scenario (4) MECs
could be financially competitive at current performances (140-gCOD/m^3/d [0.3A/m^2]); if anode and current collecting material costs were reduced by around 80% (and assuming sufficient space was available).

**Conclusion**

At the present cost of MEC design, target OLRs are more than an order of magnitude higher than pilot-scale performances achieved under “real” conditions (140-gCOD/m^3/d). Although we demonstrate a range of cost-performance targets, we propose that viable targets presuppose a 90% reduction in anode and current collector cost, and an increase in OLR to between 800 and 1,400-gCOD/m^3/d (equivalent to 2 – 3A/m^2). Neither annual membrane replacement, nor additional staff members would preclude a commercially viable MEC; as both costs are modest compared to the expense of other materials. Regular replacement of the cathodes would be highly detrimental to MEC competitiveness. Contrary, recovering the value of the anodes significantly reduces target OLRs, and could be another avenue to achieving financial viability. The strategic targets for MEC costs and performances identified in this paper are presented as a guide for researchers in this field to deliver a commercially competitive technology.

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**Appendix A. Supplementary data**

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijhydene.2018.12.029.

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