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ARTICLE *in* ENVIRONMENTAL SCIENCE AND TECHNOLOGY · MARCH 2010

Impact Factor: 5.33 · DOI: 10.1021/es100125h · Source: PubMed

Life Cycle Assessment of High-Rate Anaerobic Treatment, Microbial Fuel Cells, and Microbial Electrolysis Cells

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Received January 16, 2010. Revised manuscript received February 28, 2010. Accepted March 22, 2010.

Existing wastewater treatment options are generally perceived as energy intensive and environmentally unfriendly. Much attention has been focused on two new approaches in the past years, (i) microbial fuel cells and (ii) microbial electrolysis cells, which directly generate electrical current or chemical products, respectively, during wastewater treatment. These systems are commonly denominated as bioelectrochemical systems, and a multitude of claims have been made in the past regarding the environmental impact of these treatment options. However, an in-depth study backing these claims has not been performed. Here, we have conducted a life cycle assessment (LCA) to compare the environmental impact of three industrial wastewater treatment options, (i) anaerobic treatment with biogas generation, (ii) a microbial fuel cell treatment, with direct electricity generation, and (iii) a microbial electrolysis cell, with hydrogen peroxide production. Our analysis showed that a microbial fuel cell does not provide a significant environmental benefit relative to the "conventional" anaerobic treatment option. However, a microbial electrolysis cell provides significant environmental benefits through the displacement of chemical production by conventional means. Provided that the target conversion level of 1000 $A \cdot m^{-3}$ can be met, the decrease in greenhouse gas emissions and other environmentally harmful emissions (e.g., aromatic hydrocarbons) of the microbial electrolysis cell will be a key driver for the development of an industrial standard for this technology. Evidently, this assessment is highly dependent on the underlying assumptions, such as the used reactor materials and target performance. This provides a challenge and an opportunity for researchers in the field to select and develop appropriate and environmentally benign materials of construction, as well as demonstrate the required 1000 $A \cdot m^{-3}$ performance at pilot and full scale.

Introduction

Bioelectrochemical systems (BESs) use biocatalysts for oxidation and/or reduction reactions at electrodes (*1*). They consist of an anode and cathode, at which oxidation and reduction occurs, respectively. The anode and the cathode are connected via an electrical circuit that allows for adding or harvesting electrical power. In the case where energy is harvested, the system is called a microbial fuel cell (MFC). Alternatively, in the case where energy is invested, the system is called a microbial electrolysis cell (MEC) (*2*). Microbial fuel cells have been widely studied for their capacity to generate electrical power during wastewater treatment, generally by oxidizing the organics in the wastewater and coupling this with oxygen reduction. Microbial electrolysis cells have emerged more recently. Generally, in MECs, additional power is used to decrease the cathode potential to sufficiently low levels (*3, 4*), thereby allowing remediation processes, such as reductive dechlorination (*5*) and uranium reduction (*6*), or the production of biochemicals, such as hydrogen and methane gas (*3, 4, 7*), succinate (*8*), ethanol (*9*), and propionate (*10*).

Thus, BESs combine the advantages of treating wastewater and producing electrical current or other valuable products. However, to achieve similar energy recovery performance as conventional anaerobic treatment with biogas generation, Rabaey and Verstraete (*11*) postulated that MFCs should achieve a power density of 1000 $W \cdot m^{-3}_{reactor}$ during wastewater treatment, at a loading rate of 10 $kg_{organics} \cdot m^{-3} \cdot d^{-1}$. Up until now, these densities have not been obtained when wastewater was used as the substrate (*12, 13*). However, using synthetic substrates, highly conductive media, and small to very small reactors, several studies report power densities of that order (*14*). It remains to be demonstrated whether these results from milliliter-scale MFCs can be extrapolated to more realistic scales for industrial applications (*2*).

A factor which decreases the performance of MFCs is the formation of hydrogen peroxide (H_2O_2) during the reduction of oxygen at the cathode, especially when carbon electrodes are used. Generally, efforts are made to avoid this peroxide formation, as it decreases the attainable power of the MFC and may cause deterioration of the reactor internals due to its high oxidative power. However, peroxide is a valuable product and can be produced at cathodes via electrochemical means (*15*), at concentrations of up to 6−8 wt % (*16*). This principle of MECs for peroxide production was recently demonstrated by Rozendal et al. (*17*).

Previously, several authors have made claims with respect to the sustainability of both MFCs and MECs (*11, 18, 19*). However, to the authors' knowledge, there have been no studies presented thus far that objectively verify the environmental costs and benefits of MFCs and MECs, with respect to the existing standard for medium to high-strength wastewater treatment (i.e., high-rate anaerobic processes). This can be done using life cycle assessment (LCA), which is an internationally standardized methodology for the systematic and quantitative evaluation of environmental impacts from functionally equivalent products or services, through all stages of their life cycles. The framework for conducting an LCA is presented in ISO 14040: 2006 (*20*).

This study presents three life cycle assessments for (i) a high-rate anaerobic wastewater treatment plant, (ii) a MFC wastewater treatment plant, and (iii) a MEC wastewater treatment plant producing dilute hydrogen peroxide. The LCA framework as prescribed by ISO 14040 was used for this comparison.

Process Descriptions

The process flow diagrams of the three wastewater treatment options are shown in Figure 1. The basic structure of all

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10.1021/es100125h

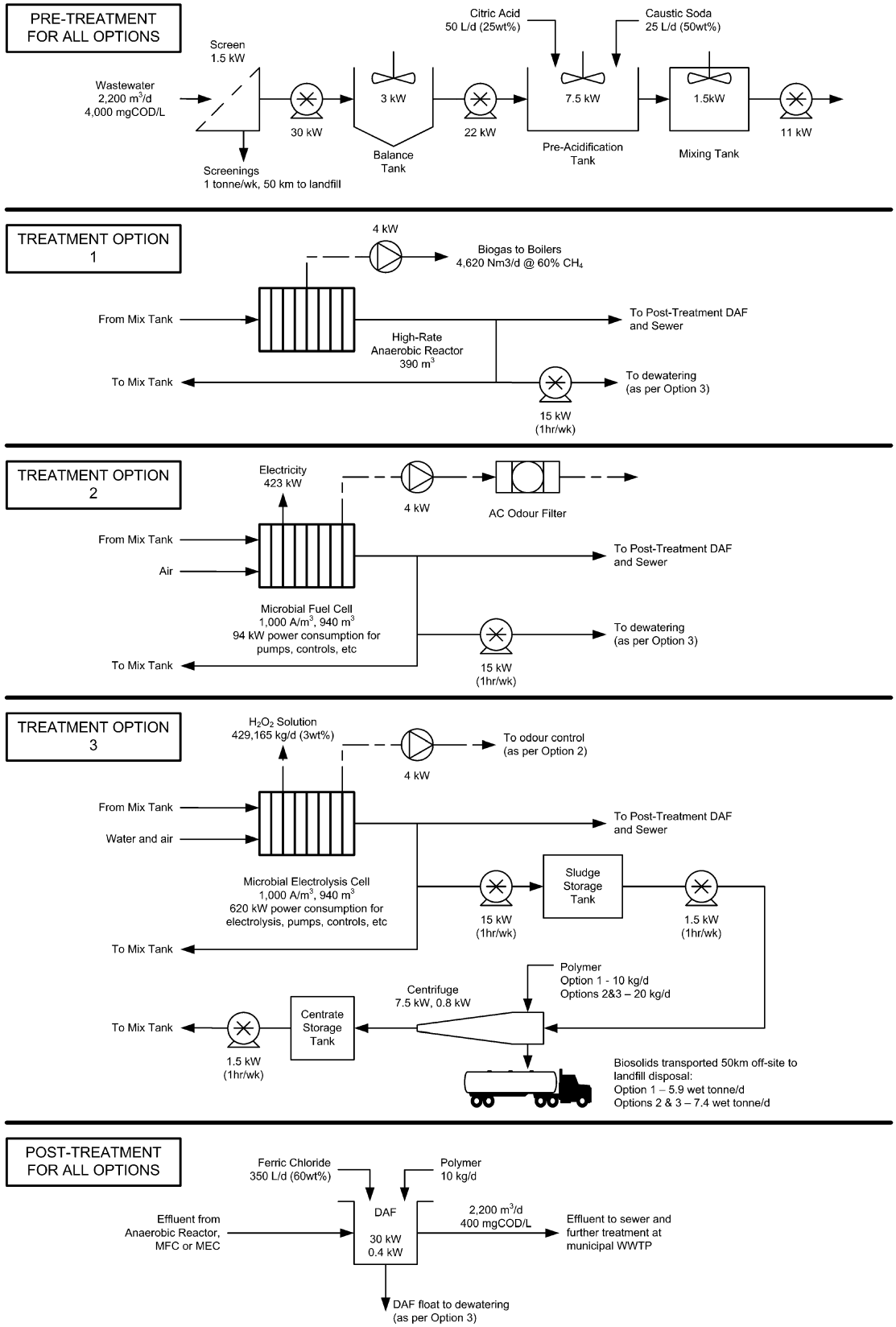

FIGURE 1. Process flow diagrams, equipment sizes, operational power, and chemical consumption for all three options.

three options is similar. First, the raw wastewater was pretreated by being pumped through screens, with flows balanced in a downstream balance tank. From here, the wastewater underwent preacidification for 12 h in a preacidification tank (PAT). Dosing of citric acid and/or caustic soda occurred at this point for pH correction.

In Option 1, the acidified wastewater then underwent anaerobic treatment in a high-rate reactor to produce 4600 N $m^3 \cdot d^{-1}$ of biogas (containing 60 vol % methane) and achieve approximately 90% chemical oxygen demand (COD) removal (*21*). The biogas was then utilized in the operation of an on-site boiler for steam generation and, thus, displaced the

use of nonrenewable natural gas, on a heating value basis. This was included in the LCA by a routine system boundary expansion.

In Option 2, from the PAT, the wastewater underwent treatment in a MFC to produce electricity, at a current density of 1000 $A \cdot m^{-3}_{reactor}$ and a voltage of 0.5 V. The generated electricity was transformed to grid voltage and used to power equipment on-site (423 kW gross, including 90% transformation efficiency from 0.5 V). This displaced the use of standard grid electricity, which was included in the LCA by a routine system boundary expansion. On the basis of the MFC pilot-scale experience at The University of Queensland, the operational energy requirements of the MFC were assumed to be 0.1 $kW \cdot m^{-3}_{reactor}$.

In Option 3, from the PAT, the wastewater underwent treatment in a MEC at a current density of 1000 $A \cdot m^{-3}_{reactor}$ to produce an aqueous hydrogen peroxide solution (3 wt %) in the cathodic compartment at a cathodic efficiency of 90%, with the addition of clean water and air. The aqueous hydrogen peroxide solution was used directly on-site, without any further refinement (e.g., bleaching in a paper mill (*15*), process cleaning/disinfection). This displaced the use of hydrogen peroxide (50 wt % solution) manufactured by the standard Riedl-Pfleiderer AO Process (*22*), which was included in the LCA by a routine system boundary expansion to the factory gate (i.e., transportation emissions associated with the avoided delivery of 50 wt % H_2O_2 solution are not included). Operational energy requirements of the MEC were assumed to be 0.1 $kW \cdot m^{-3}_{reactor}$ plus 0.56 $kW \cdot m^{-3}_{reactor}$ electrolysis energy input (i.e., 0.5 V, 1000 $A \cdot m^{-3}_{reactor}$ at 90% transformation efficiency).

For both the MFC and MEC cases, it was assumed that 90% COD removal was achieved (*23*), as per Option 1 (i.e., effluent COD = 400 $mgCOD \cdot L^{-1}$), and that 15% of the removed COD was consumed for biomass growth. For the anaerobic treatment option, 12% of COD was consumed for biomass growth (i.e., yield 0.08 $kgVSS \cdot kgCOD^{-1}$) (*21*).

For all three options, a final post-treatment stage was undertaken by dissolved air filtration (DAF), before disposal to sewer and downstream treatment in a municipal wastewater treatment plant (WWTP). Polymer and ferric chloride were added to the DAF to assist with solids capture. Waste solids from the process units were dewatered using a centrifuge, with polymer addition for assisted flocculation. Disposal of biosolids was by road transport to landfill.

Life Cycle Assessment

The ISO 14040 LCA standard defines four distinct, but potentially iterative, stages in an LCA: (1) goal and scope definition; (2) inventory analysis; (3) impact assessment; and (4) interpretation. This framework has been successfully applied to other wastewater systems to identify the tensions inherent in systems with competing environmental objectives (*24, 25*). Traditional wastewater systems are a good example of this problem, as they primarily aim to achieve high effluent quality, but (typically) at the cost of high direct energy (i.e., electricity for aeration blowers), indirect embodied energy (e.g., chemicals for enhanced phosphorus removal), and solid waste disposal (e.g., biosolids disposal to landfill or incineration) (*26*).

Goal and Scope Definition

The goal of this life cycle assessment was to compare the environmental impacts of three alternative industrial wastewater treatment systems, as illustrated in Figure 1: Option 1, "conventional" high-rate anaerobic system, producing biogas as a byproduct for cofiring in an on-site gas boiler; Option 2, microbial fuel cell system, producing electricity as a byproduct for on-site use; and Option 3, microbial electrolysis cell system, producing an aqueous hydrogen peroxide solution (3 wt %) as a byproduct for on-site use.

The functional unit of the study was a wastewater flow rate of 2200 $m^3 \cdot d^{-1}$ at a strength of 4000 $mgCOD \cdot L^{-1}$, over 10 years of operation. This functional unit was based on a full-scale operating plant, used as the basis for compiling the life cycle inventory of Option 1. The system boundary is shown in Figure 2 and included first-order environmental impacts, such as direct atmospheric emissions and effluent discharges. It also included second-order impacts, such as the emissions and resources required for upstream electricity generation and chemicals manufacture. Only construction and operating phases were considered. Impacts associated with the end-of-life phase (i.e., demolition) were not included because they are generally negligible, when compared with the operating and construction phases of a WWTP (*27*–*29*). No allowance is made for large-scale system repair or replacement, given the relatively short 10 year time frame, defined for the functional unit.

Life Cycle Inventory

The life cycle models of the three options were constructed using the SimaPro 7.1.8 LCA software package (*30*). The foreground life cycle inventory (LCI) data for Option 1 were compiled directly from detailed design documents and vendor-supplied information. Construction inventory data for Options 2 and 3 were based on the materials inventory of a pilot-scale MFC plant, operated by The University of Queensland. This plant used a cation exchange membrane manufactured from a gel polystyrene, cross-linked with divinyl benzene (DVB). Electrodes were made from carbon fiber. Contactors, brushes, and mesh were made from stainless steel. Piping and reactor encasing were made from polyvinyl chloride (PVC). The detailed construction inventory data for all three options are attached in the Supporting Information. Also attached in the Supporting Information are the summarized calculations for the operational phase inventories of the three options (see also Figure 1). This includes power consumption/generation, chemical consumption/generation, solid waste transportation and disposal requirements, effluent emissions to sewer, and land use requirements.

The background life cycle inventory data (e.g., life cycle inventory of 1 kWh electricity, 1 kg of carbon fiber, 1 tonne of concrete) was provided by the ecoinvent LCI database (*31*), as implemented in SimaPro 7.1.8. These data were entirely European-based and were adopted without alteration for this study. Key background inventory data assumptions were (1) the electricity production profile adopted for this study was based on the United Kingdom (UK) (approximately 32% coal and oil, 40% natural gas, 21% nuclear, 4% imported from France, 3% renewables); (2) production of chemicals was based on European Union averages, where available; (3) effluent from all three options was assumed to undergo further treatment in a typical municipal WWTP (data from Swiss applications); and (4) waste solids were assumed to be disposed to a sanitary landfill (data from Swiss applications).

Life Cycle Impact Assessment

The life cycle impact assessment (LCIA) methodology adopted for this study was IMPACT 2002+ (v.2.03) (*32*), as implemented in SimaPro 7.1.8 (refer Figure 3). This method combined both midpoint and end-point impact categories and allowed the summing of all end-point impact categories into a single score (without weightings). Midpoint impact categories quantify the relevant emissions and resources from the life cycle inventory, in terms of common reference substances (e.g., kg CO_2-e for global warming, kg SO_2-eq for acidification). Midpoint impact categories are generally based

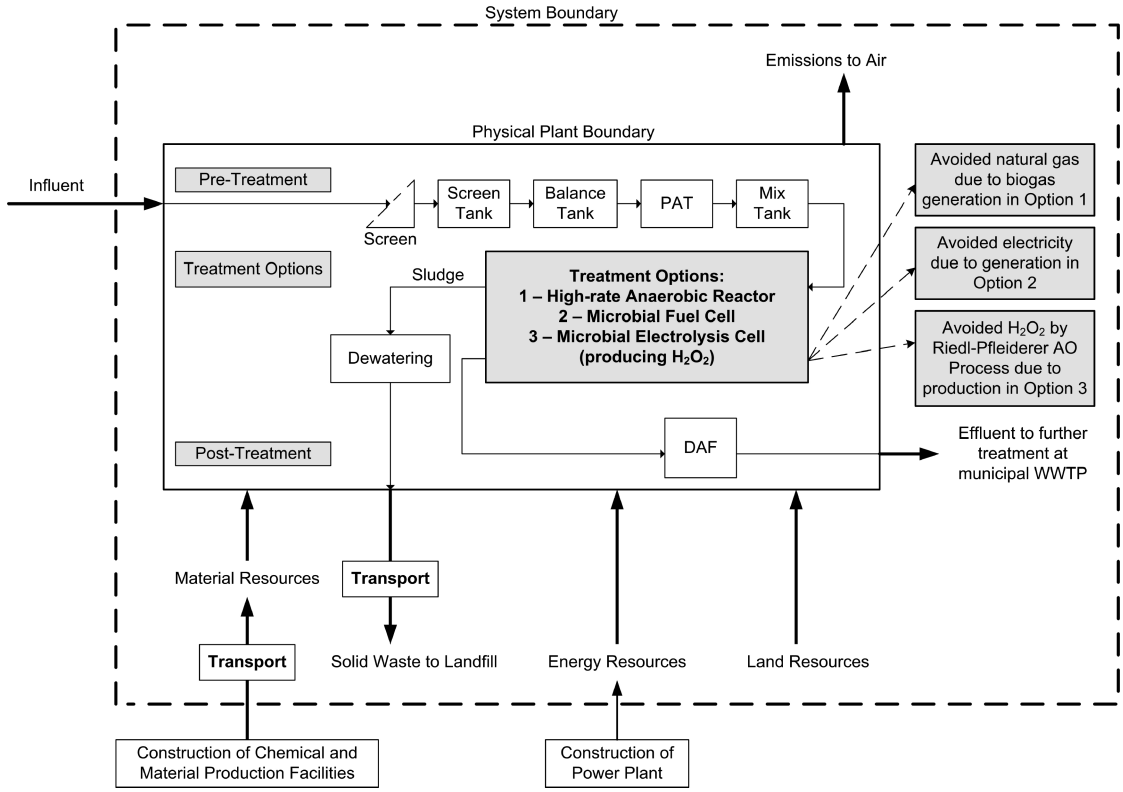

FIGURE 2. System boundary for life cycle assessment.

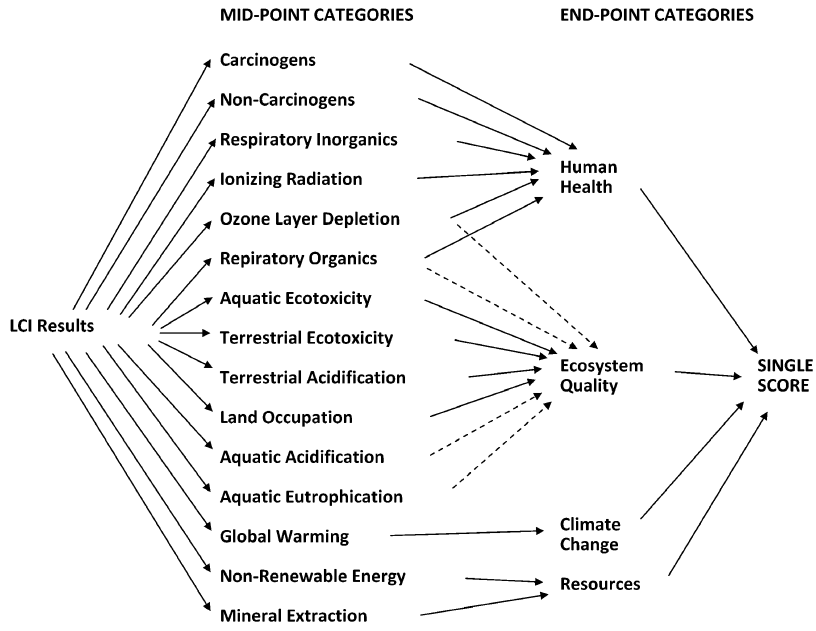

FIGURE 3. IMPACT 2002+ Life Cycle Impact Assessment Framework (*32*). Dotted lines indicate potential environmental impact pathways but have not yet been modeled in IMPACT 2002+.

on sound environmental modeling up to some well-characterized intermediate point along the cause-and-effect chain of environmental processes and mechanisms. End-point impact categories attempt to quantify the potential outcomes at the "end-point" of the cause-and-effect chain, in terms of tangible damage (i.e., disability affected life years, loss of species, loss of resources). However, environmental process and mechanisms are highly complex and interactive; therefore, while the results of end-point assessments are more tangible for stakeholders, the modeling is less certain and more subject to criticism (*33*).

The environmental modeling (fate, exposure, and effect) in IMPACT 2002+ was entirely based on European conditions and was adopted without change for this study. Furthermore, the default normalization data in the IMPACT 2002+ method was based on the European Union population. Therefore, given that both the background inventory data and LCIA method adopted in this study were entirely European-based, the conclusions drawn are strictly limited to this context.

Figures 4 and 5 show the LCIA results for pretreatment, post-treatment, and the three options (i.e., anaerobic treatment, MFC, MEC) at selected midpoint and all four end-

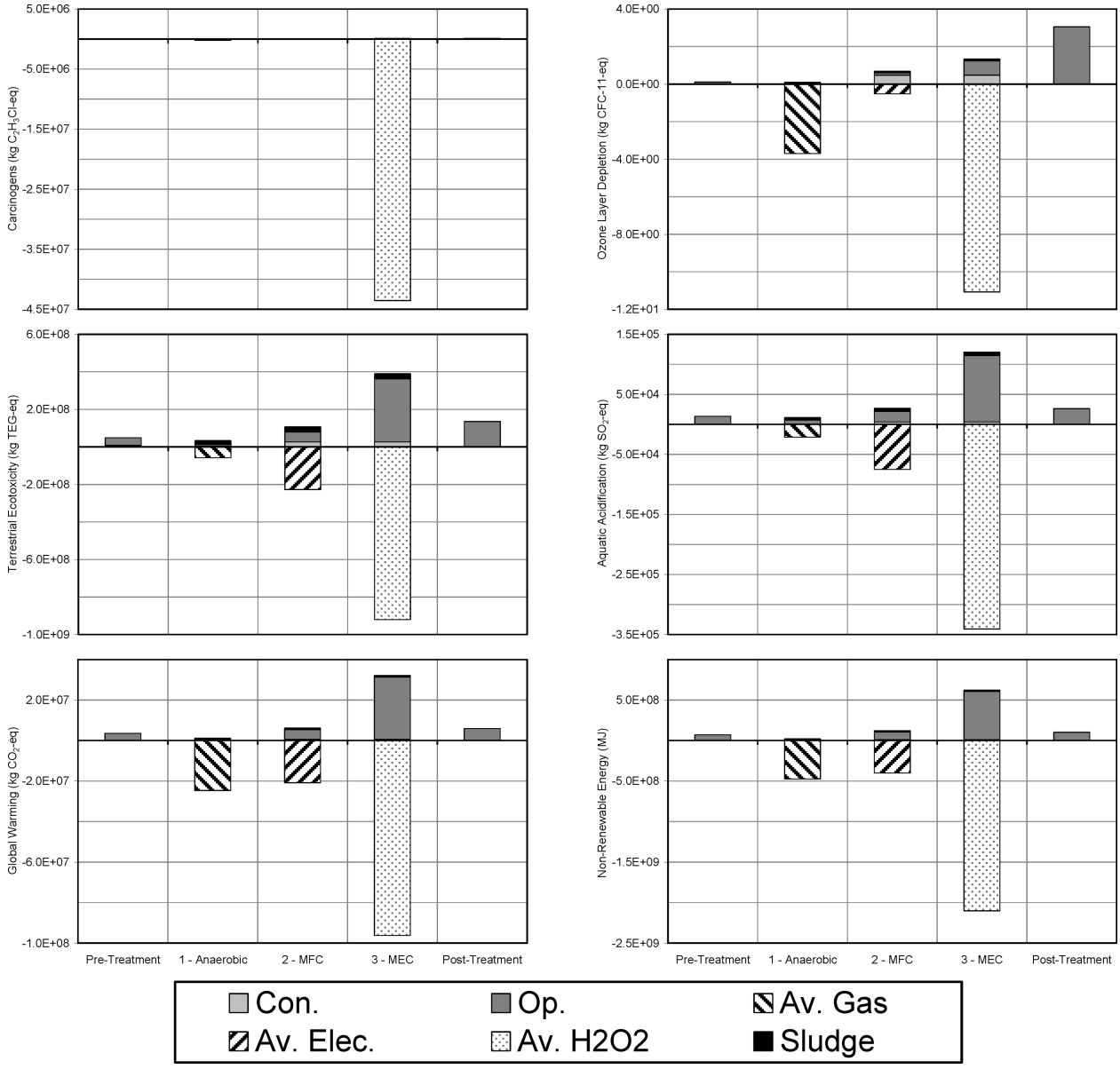

FIGURE 4. Selected midpoint life cycle impact assessment results, disaggregated into the following: "Con.", construction phase; "Op.", operational phase (i.e., power, chemicals, transportation); "Av. Gas", avoided natural gas from operational phase of anaerobic reactor (Option 1 only); "Av. Elec", avoided electricity from operational phase of MFC (Option 2 only); "Av. H_2O_2", avoided AO hydrogen peroxide from operational phase of MEC (Option 3 only); and "Sludge", sludge dewatering and disposal from operational phase. The results are expressed in terms of a reference unit for each environmental impact category (e.g., kg CO_2-eq for global warming, kg C_2H_3Cl-eq for carcinogens). Positive values indicate an adverse environmental impact (i.e., the higher the value, the worse is the impact), and negative values indicate an environmental benefit.

point impact categories. Tabulated results of all the midpoint, end-point, and normalized LCIA results for all options are attached in the Supporting Information. These tables include the 95% confidence interval for each result, based on a 1000-run Monte Carlo analysis, performed in SimaPro on the background inventory data. These confidence intervals do not account for uncertainty in the design parameters of the various units (e.g., current density of the MFC/MEC reactor).

The end-point characterization results for the three options was normalized by comparing them against the environmental profile of an "average European", which is embedded in the IMPACT 2002+ LCIA methodology in SimaPro 7.1.8. These results are shown in Figure 6, in dimensionless units (or "points"), together with a summed (unweighted) total score. This normalization step showed the relative contribution of each option to each end-point impact category, compared against the environmental end-point impacts caused by the average person in the European Union society. For example, the avoided human health impacts caused by the life cycle of the MEC treatment option was equivalent to the human health impacts caused by approximately 21 000 average European Union citizens.

The error bars in Figure 6 indicate the 95% confidence interval for each results. They are reflective of the uncertainty inherent in the background inventory data and are generated using a Monte Carlo analysis (1000 iterations) in SimaPro.

The largest uncertainty arises for human health impacts of the MEC option. This is principally because of the uncertainty in background inventory data for the avoided

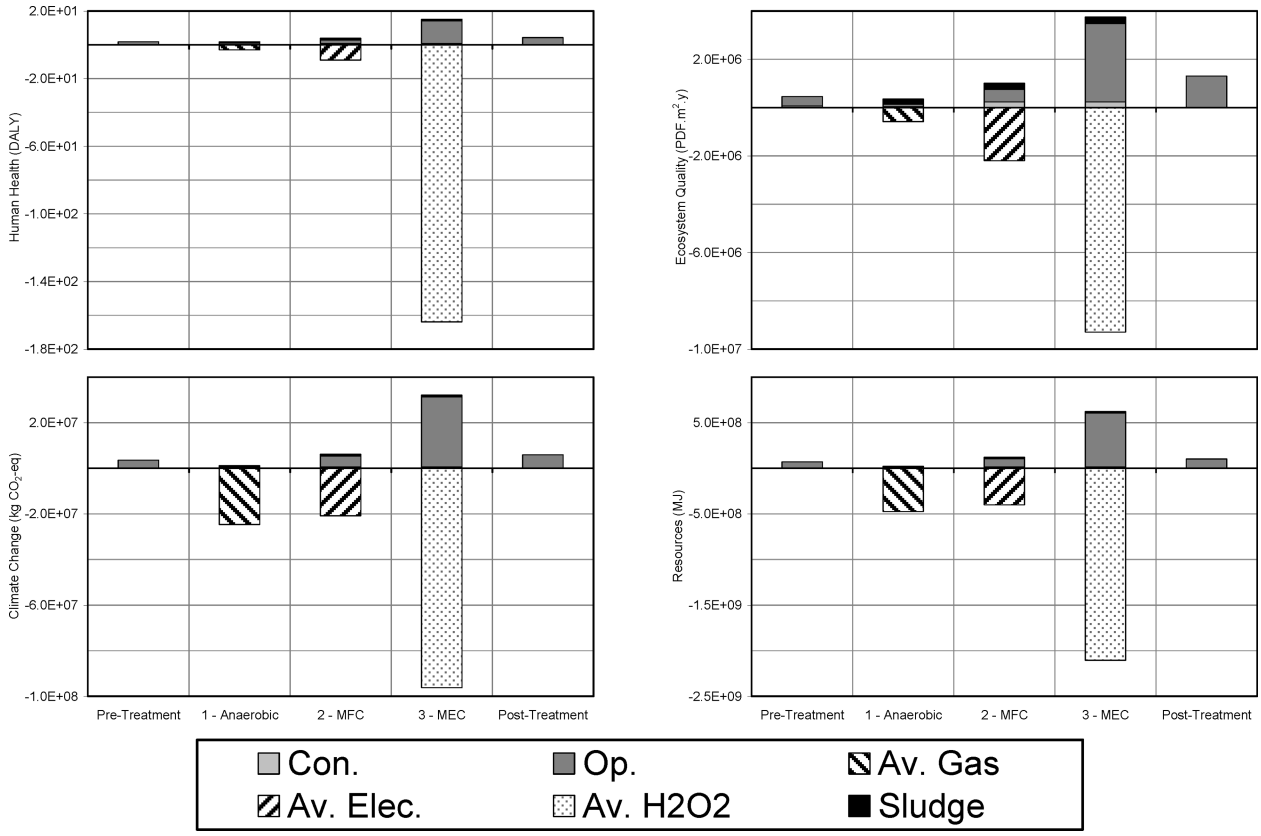

FIGURE 5. End-point life cycle impact assessment results, disaggregated as per Figure 4. The results are expressed in terms of "DALYs" (disability-affected life years) for human health, "PDF·m²·years" (potentially disappeared fraction of species, integrated over an area and time) for ecosystem quality, kg CO_2-eq emissions for climate change, and primary energy usage (MJ) for resources consumption.

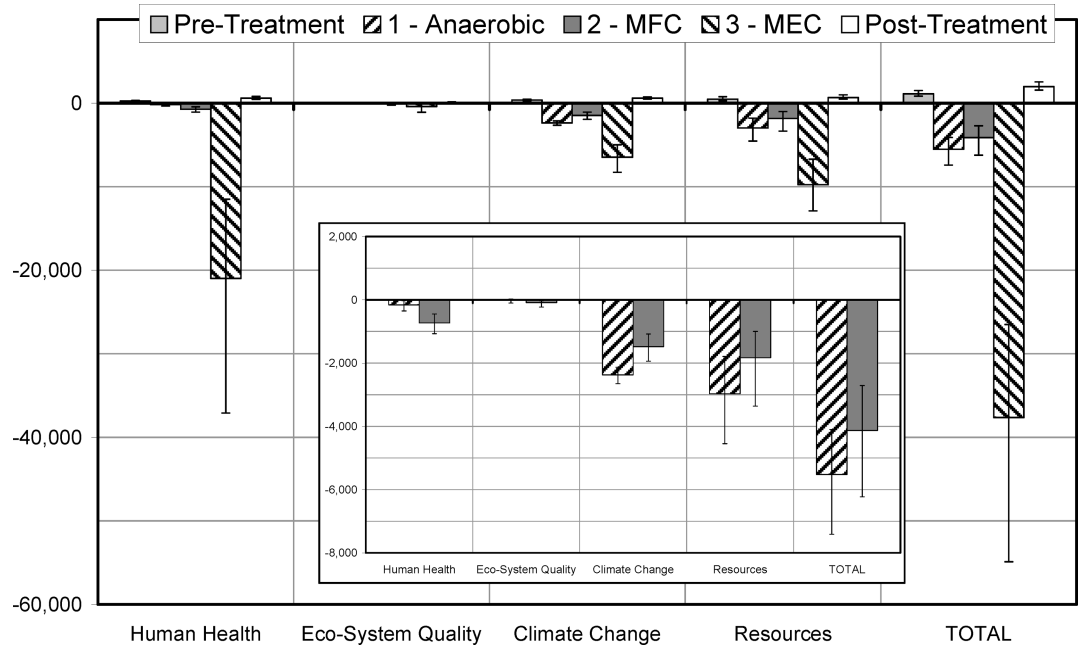

FIGURE 6. Comparison of IMPACT 2002+ normalized end-point scores, including Monte Carlo analysis uncertainty ranges. Inset shows a magnification of the comparison between Option 1 (anaerobic) and Option 2 (MFC). Error bars (95% confidence interval) indicate the uncertainty inherent in the background inventory data for the three options. This uncertainty range is generated using a Monte Carlo analysis (1000 runs) on each option in SimaPro.

impacts from the Riedl-Pfleiderer AO process and the associated toxicological characterization factors in IMPACT 2002+. Despite the large uncertainties associated with Option 3, Figure 6 shows that the difference between the other options is still statistically significant (i.e., no overlapping of 95% confidence intervals).

Life Cycle Assessment Interpretation

Pretreatment. The end-point impacts associated with the pretreatment stage were small in comparison to the main treatment stage options. Approximately 90% of the total life cycle impacts from this process stage arose from electricity consumption in the operational phase, with the balance mainly due to chemical consumption (i.e., citric acid and caustic soda for pH correction in the PAT) and some construction materials. Apart from improvements in energy efficiency and process optimization, there is limited opportunity in the pretreatment stage to reduce the environmental impacts.

Option 1: Anaerobic Treatment. In Option 1, the negative environmental impacts were more than balanced by the positive impacts that arose from the displacement of natural gas as a fuel for the on-site steam boiler, giving this option an overall net environmental benefit (on an unweighted, normalized single score basis). These benefits were mainly in the "global warming", "non-renewable energy", and "respiratory inorganics" midpoint impact categories, when considered on a normalized basis (refer to Supporting Information). The majority of negative environmental impacts in Option 1 were caused by electricity consumption and transportation/disposal of biosolids. This is a common finding for wastewater treatment processes, with energy consumption (e.g., for pumping and aeration) often dominating the environmental profile (*34*). The negative environmental impacts of the anaerobic reactor construction phase were relatively minor in all midpoint categories, except "mineral extraction", in comparison to the environmental benefits from the displacement of natural gas.

This LCA highlighted the considerable environmental benefits that can be achieved by the displacement of fossil-based natural gas, with biogenic biogas from anaerobic wastewater treatment processes. For example in this LCA, the life cycle global warming emissions from biogas were calculated to be 0.03 kg CO_2-e per MJ heating energy. This was in comparison to the manufacture and combustion of natural gas at 0.07 kg CO_2-e per MJ heating energy.

Option 2: Microbial Fuel Cell. Similar to Option 1, the negative environmental impacts associated with Option 2 were mainly associated with electricity consumption in the various process units and transportation/disposal of biosolids. The positive environmental impacts in Option 2 arose solely from the displacement of grid electricity. Under the IMPACT 2002+ LCIA framework, these positive benefits were large enough to outweigh the other negative impacts, giving this option an overall net environmental benefit (on an unweighted, normalized single score basis), although it must noted that the attendant uncertainty in the background data for this calculation was high and the overall result was contingent on the optimistic design assumptions for electricity generation. Achieving the 1000 $A \cdot m^{-3}$ target at 0.5 V net voltage will be a major challenge. Similar to Option 1, these normalized benefits were mainly accounted in the "respiratory inorganics", "global warming", and "non-renewable energy" categories.

The construction phase of Option 2 was more prominent than Option 1. These impacts were largely due to the manufacture of carbon fiber electrodes, polystyrene membranes, stainless steel components (contactors, mesh, and brushes) and, to a lesser degree, PVC for the reactor enclosure.

This LCA highlighted the considerable environmental benefits that can be achieved by the displacement of largely fossil-fuel based electricity generation (i.e., 72% of the UK electricity mix is from coal, oil, or natural gas), with electricity generated directly by MFC technology in a wastewater treatment process. For example, in this LCA, the life cycle global warming emissions from MFC-generated electricity were calculated to be 0.40 kg CO_2-e per kWh. This was in comparison to 0.56 kg CO_2-e per kWh for UK grid electricity.

The main drawback in this option was the resource and emissions-intensive materials required for MFC construction (i.e., stainless steel, membrane materials, carbon fibers, PVC). This represents a substantial opportunity for future improvements by appropriate materials selection and development.

Option 3: Microbial Electrolysis Cell with Hydrogen Peroxide Production. Similar to Option 2, the negative environmental impacts associated with Option 3 were mainly due to electricity consumption in the various process units, transportation of biosolids, and construction of the electrolytic cell. The MEC profile in this regard was significantly higher than the MFC, due to the additional electrolysis energy input required (0.56 $kW \cdot m^{-3}_{reactor}$).

The positive environmental impacts in Option 3 arose solely from the displacement of hydrogen peroxide production by the traditional Riedl-Pfleiderer AO Process, which is currently the predominant manufacturing method. Under the IMPACT 2002+ LCIA framework, these positive benefits were substantially larger than the other negative impacts, giving this option an overall net environmental benefit (on an unweighted, normalized single score basis). In particular, major environmental benefits were realized in the categories of "carcinogens", "respiratory inorganics", "global warming", and "non-renewable energy". The latter three impact categories have already been shown to be associated with electricity consumption in Options 1 and 2. Therefore, this analysis suggests that MEC technology has an environmental advantage over the Riedl-Pfleiderer AO process with regard to energy efficiency. The strong "carcinogen" signature for the AO process arose because of the emission of aromatic hydrocarbons to the air in the ecoinvent inventory (*31*). The ecoinvent AO process inventory data was based on average emissions from eight European producers.

This LCA suggests that the MEC technology has a highly positive overall net environmental benefit and highlighted the substantial environmental benefits that can be achieved by the displacement of traditional hydrogen peroxide manufacturing, with hydrogen peroxide generated directly by MEC technology in a wastewater treatment process. For example, in this LCA, the life cycle global warming emissions from MEC-manufactured H_2O_2 are calculated to be 0.87 kg CO_2-e per kg H_2O_2 (100 wt %). This is in comparison to 2.05 kg CO_2-e per kg H_2O_2 from the Riedl-Pfleiderer AO process. Substantial opportunities exist for future improvements to MECs, via appropriate material selection and, more importantly, reductions in the electrolysis energy input.

Post-Treatment. Similar to the pretreatment stage, the impacts associated with the post-treatment stage were small in comparison to the main treatment stage options. However, unlike the other treatment stages in this study, these negative impacts were due in equal parts to electricity consumption, ferric chloride consumption, and downstream treatment of the discharged effluent in the municipal WWTP. Apart from improvements in energy efficiency, reduction in ferric chloride dosing, and process optimization, there is limited opportunity in the post-treatment stage to reduce the environmental impacts.

Comparison of Options. As illustrated in Figure 6 and suggested by the discussion of individual options, Option 3 had more significant net positive impacts than both Options 1 and 2 (t-dist., $\alpha = 0.05$) in all normalized end-point impact categories, based on the Monte Carlo uncertainty analysis. Traditional anaerobic treatment technology (Option 1) had more significant benefits than MFC technology (Option 2) in the end-point impact categories of "climate change" and "resources" but not "human health" or "eco-system quality" (t-dist., $\alpha = 0.05$), based on the Monte Carlo uncertainty analysis. This was because, despite anaerobic treatment

having achieved greater net energy recovery than the MFC, the human health and eco-system quality benefits of avoided UK grid electricity generation are greater than those associated with avoided natural gas production and combustion. In the "resources" category, there was considerable overlap between the 95% uncertainty intervals of Options 1 and 2, based on the background inventory data. This level of uncertainty in the background data will also be compounded by the assumptions made for the foreground data. If the assumed current density of 1000 $A \cdot m^{-3}_{reactor}$ cannot be achieved, then the microbial fuel cell would suffer an even less favorable comparison to traditional anaerobic treatment.

It is also important to note that the conclusions of this study must be viewed only within the tightly framed context of this study. Different construction materials, operating performance parameters, background inventories (e.g., Australian energy mix), and different LCIA methodologies may alter the outcomes, particularly in comparing Options 1 and 2. However, these results presently suggest that the performance of an MFC definitely needs to exceed 500 $W \cdot m^{-3}_{reactor}$ to be environmentally competitive with existing anaerobic treatment technology.

The environmental benefits garnered in Option 3 would appear to be so substantial, however, that a change in LCIA methodology would not greatly affect the relative outcome. However, it must be noted that hydrogen peroxide production by MEC technology has only been recently demonstrated in the laboratory (*35*), and much work remains to realize this process at pilot and full scale. Therefore, it is possible that unknown elements of the MEC life cycle inventory (e.g., additional exotic construction materials) may have been omitted that would alter the outcome.

Using the internationally standardized LCA framework, this study has compared the anaerobic treatment technology conventionally adopted for medium-strength industrial wastewater, against the likely full-scale implementation of a microbial fuel cell and a microbial electrolysis cell. Using inventory data from full-scale (Option 1), pilot-scale (Option 2), and lab-scale (Option 3) applications, this life cycle assessment has demonstrated the substantial environmental benefits that can be realized through the displacement of fossil fuel-dependent resources (i.e., natural gas, grid electricity, or chemicals manufacture). In all options, the environmental benefits garnered through the displacement of these products was sufficient to outweigh the environmental costs of constructing and operating the treatment plant. In the case of the MEC alone, the net environmental benefit is quite evident and the result would appear to be independent of any uncertainty in the background inventory data. However, for the MFC and MEC to be viable options, the performance parameters (i.e., 1,000 $A \cdot m^{-3}_{reactor}$) adopted as the basis for design in this study need to be validated in the field. Moreover, as the energy input has a large impact on the result of the comparison, it also needs to be validated for MECs whether the required energy input is sufficient under field conditions or whether a higher applied voltage than 0.5 V is required. Notwithstanding this considerable scale-up challenge, this study suggests that there is sufficient cause from an environmental perspective to pursue the development and commercialization of BES technology, particularly microbial electrolysis cells.

Acknowledgments

We acknowledge the assistance of Maryam Charehsaz (GHD) and Aquatec-Maxcon with the collation of inventory data. K.R. is supported via the ARC Discovery program (ARC DP0879245). R.A.R. is supported by the University of Queensland (Early Career Researcher scheme). This project has been partly funded by the ARC Discovery Project DP0666927.

Supporting Information Available

Construction phase inventory data; operation phase inventory data; midpoint, end-point, and normalized life cycle impact assessment results, with 95% confidence intervals. This material is available free of charge via the Internet at http://pubs.acs.org.

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