LIFE CYCLE ASSESSMENT OF MICROBIAL FUEL CELL

by

JUNJIE HOU

(Under the Direction of Ke Li)

ABSTRACT

Bioenergy has been treated as one of the most promising energy alternatives in recent years. In the wastewater industry, one of the bioenergy technologies, microbial fuel cells (MFC), has been developing rapidly. It can use bacterial metabolism to produce electrical current while simultaneously treating wastewater. A comprehensive environmental performance evaluation is needed in order to track its environmental performance with the development of the technology and avoid environmental burden shifting.

In this study, life cycle assessment (LCA) was used to conduct assessment for two lab scale MFC systems-one is vertical design and the other is side-lying design. Their environmental performance was analyzed and compared with an aeration system. From our analysis, it shows that carbon and graphite materials used for electrodes construction and Pt used for cathode construction brought large environmental burden. The inventory methods chose for MFC analysis may have an influence on the result.

INDEX WORDS: Microbial fuel cell, Wastewater treatment, Life cycle assessment, Environmental impact, Electricity production

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INTRODUCTION

1.1 Problem Overview

Since industrial energy use is heavily reliant on fuel and electricity from non-renewable sources, the rapidly growing intensive industrial energy use has triggered a global energy crisis (Pérez-Lombard, Ortiz, & Pout, 2008). Greenhouse gases, such as methane (CH_4) and carbon dioxide (CO_2) are produced when fossil fuels such as oil, coal and gas are burned for energy. It has been demonstrated that human-induced greenhouse gas emission is changing the world's climate (Boulos & Bros, 2010).

The growing concern about climate change issues and future sources of energy has led to the development of alternative energy production solutions. In the wastewater treatment industry, much attention has been focused on bioelectrochemical systems recent years. These systems can produce energy and other valuable products from organic and inorganic materials presented in wastewater (Degrenne, Buret, Allard, & Monier, 2011; Luo, Xu, Roane, Jenkins, & Ren, 2012; Sun et al., 2008).

One of the bioelectrochemical systems is called the microbial fuel cell (MFC); it use bacterial metabolism to produce electrical current from a wide range organic and inorganic substrates in the wastewater, while treating wastewater simultaneously. It can be treated as a promising alternative to traditional wastewater treatment technology. A comprehensive evaluation of this technology is needed to analyze its environmental performance in order to avoid environmental burden shifting and track its environmental impact while developing.

1.2 Energy cost for wastewater treatment plant

Based on the 2010 energy policies and standards worldwide, industrial energy consumption is projected to increase by 42% from 2007 to 2035 (EIA, 2010). The rapidly growing industrial energy use could lead to the exhaustion of energy resources (Pérez-Lombard et al., 2008), since industrial energy use is heavily reliant on electricity and fuel from non-renewable sources (Seryak & Kissock, 2005). In US, 93,000 MW of new generating capacity will be needed by 2020, according to the national energy policy published in 2001(Cheney et al., 2001).

In water industry, wastewater treatment plants (WWTPs) are energy intensive, generally consume large amount of electricity and bring many environmental burdens (Daw, Hallett, DeWolfe, & Venner, 2012; Lekov, Thompson, McKane, Song, & Piette, 2009; Pant et al., 2011). Energy is needed through all stages of the wastewater treatment processes; from raw sewage collection to effluent discharge (Daw et al., 2012). One California case study(USDOE, 2006) shows that energy use for wastewater collection and treatment is much higher than other water cycle segments, including supply and conveyance, treatment, distribution and wastewater discharge. In US, more than 126 billion liters domestic wastewater needs to be treated on a daily basis (Liu, Ramnarayanan, & Logan, 2004), and most of these wastewater was sent to centralized facilities using aeration during the treatment processes. According to some studies, around 60% of the total energy use in a WWTP might be consumed by aeration process

(Bolles, 2006; Rieger, Takács, & Siegrist, 2012), and energy demand for aeration of sewage is about 0.5 KWh/m^3 (Aelterman, Rabaey, Clauwaert, & Verstraete, 2006).

In a EPA research project (EPA, 2009), it points out that optimization of energy use, more efficient equipment and treatment technologies, energy recovery, and even energy production must become part of the services and activities being undertaken by drinking water and wastewater utilities.

1.3 Microbial fuel cell technology

In the wastewater treatment industry, much attention has been focused on bioelectrochemical systems in recent years, because these systems can produce energy and other valuable products from organic and inorganic materials present in wastewaters (Rozendal, Hamelers, Rabaey, Keller, & Buisman, 2008). Many researches have been done on bioelectrochemical systems, or better known as microbial fuel cells (MFC); it use living microbes as a catalyst for electrochemical reactions to convert energy stored in chemical bonds in compounds to electrical energy (Birch, 2010; Du, Li, & Gu, 2007; Feng, Wang, Logan, & Lee, 2008; B. E. Logan et al., 2006). In microbial fuel cell, microorganisms at the anode oxidize the organic and inorganic matter, and release electrons and protons. Then, electrons travel along a circuit to the cathode. The cathode accepts the electrons through a reduction reaction while electrons combined with protons and oxygen to form water (Liu, Cheng, & Logan, 2004; Tyler Hugginsa, 2011; X. Wang, Feng, et al., 2009). Since it can use bacterial metabolism to produce an electrical current from a wide range organic and inorganic substrates in the wastewater, while treating wastewater simultaneously, it can be treated as a promising technology for wastewater treatment.

Different types of MFC used in wastewater treatment analysis

There are two types of MFCs using the same reaction mechanism used in wastewater treatment analysis; one is called the two-chamber MFC, and the other is called the single-chamber MFC.

Two-chamber MFC typically uses a proton exchange membrane (PEM) between the anode and cathode to make two separate compartments (Liu, Cheng, et al., 2004; Rismani-Yazdi, Carver, Christy, & Tuovinen, 2008); therefore bacteria that oxidize organic matter are kept physically separated from the electron acceptor (Du et al., 2007; Liu, Ramnarayanan, et al., 2004). PEM is used here to allow proton transfer from anode to cathode, while avoiding oxygen diffusion into the anode chamber (Liu, Cheng, et al., 2004). There are different practical shapes for the compartment, like cylindrical shape, rectangular shape and so on (Du et al., 2007). The schematic diagram of a typical two-chamber MFC is shown below in Figure 1.

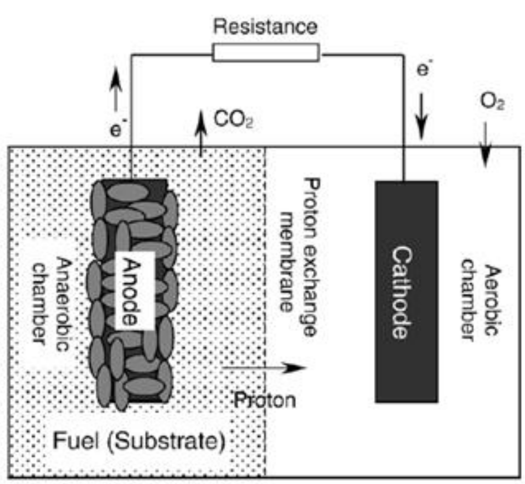

Figure 1: Schematic diagram of a two-chamber MFC (Du et al., 2007)

Single-chamber MFC has been developed in recent years since the development of two-chamber MFC. A single-chamber MFC has one compartment, an anode chamber is put in the cell, and the cathode is merged with membrane which is water proof but exposed to air (Cheng, Liu, & Logan, 2006; B. E. Logan et al., 2006; Pant, Van Bogaert, Diels, & Vanbroekhoven, 2010). The cathode here is also called an air-cathode. There is no PEM used in the fuel cell. The schematic diagram of a single-chamber MFC is shown below in Figure 2.

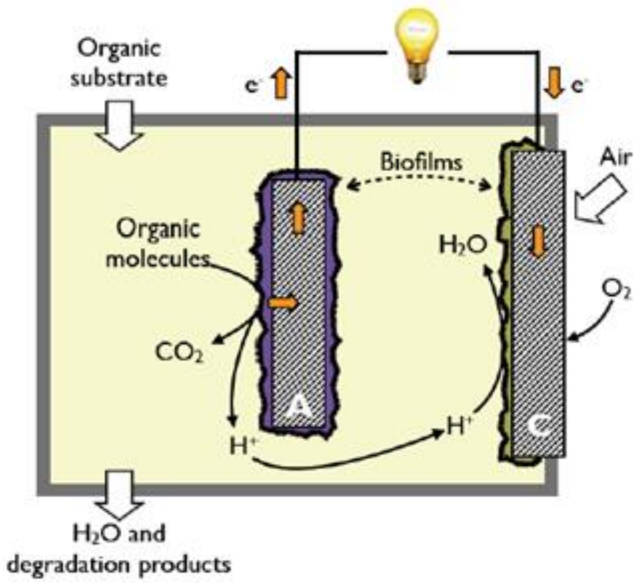

Figure 2: Schematic diagram of a single-chamber MFC((Degrenne et al., 2011))

Some studies have shown the advantages of the single-chamber MFC over the two-chamber MFC. First, much larger power density can be achieved when replacing an aqueous-cathode with an air-cathode (Liu, Cheng, et al., 2004; B. E. Logan et al., 2006; Min, Cheng, & Logan, 2005). Second, because of the removal of PEM and a reduced volume, the cost of materials can be reduced when constructing a single-chamber MFC compared with a two-chamber MFC (Liu, Cheng, et al., 2004). Third, a single-chamber can reduce mass transport loss because of the direct oxygen supply from the air (Pham et al., 2006; Rismani-Yazdi et al., 2008). Last but not least, when thinking about scaling-up, a two-chamber MFC would be difficult to apply for large scale continuously wastewater treatment because of its complex design (Du et al., 2007). There are also two disadvantages of using single-MFC. One is that without PEM, oxygen may be introduced to anode, which may reduce anaerobic condition in the anode (Min et al., 2005). The other is that cathode is prone to flooding, which may lead to mass transfer loss. This water accumulation is because of the oxygen reduction at the cathode and crossover of water from anode (Rismani-Yazdi et al., 2008).

MFC technology studies in wastewater treatment

As early as in 1991, MFC technology was considered to be used for wastewater treatment (Habermann & Pommer, 1991). There are many studies analysis MFC used for wastewater treatment over years. They analyze the reactions on electrodes, material use for build electrodes, electricity production, microbes in anode, substrate used to for microbes and so on.

The MFC applications in wastewater treatment need to use electrode materials which have the following properties, large surface area, good electrical conductivity, biological and electrochemical stability and low resistance (Degrenne et al., 2011; B. Logan, Cheng, Watson, & Estadt, 2007; Rismani-Yazdi et al., 2008; X. Wang, Cheng, et al., 2009). Materials used for constructing electrodes in practice are mainly carbon in different forms, with some catalysts. For cathode, graphite (Rabaey & Verstraete, 2005) and carbon paper coater with a Pt catalyst (Jung Rae, Booki, & Logan, 2005; Liu, Cheng, et al., 2004; Min et al., 2005) are used as the materials for construction. For air-cathode, cathode is built based on carbon cloth structure, a carbon base layer with PTFE solution layers on the external air side to avoid water leakage and a Pt/C catalyst layer on the internal solution side to catalytic oxygen reduction (Feng et al., 2008; X. Wang, Feng, et al., 2009). Platinum is costly, so it is not suitable for large scale and long-term application. Nowadays researchers have been investing the use of biocathode (Bullen, Arnot, Lakeman, & Walsh, 2006; Franks & Nevin, 2010). For anode, carbon paper (Jung Rae et al., 2005; Min et al., 2005; X. Wang, Feng, et al., 2009), carbon cloth (Feng et al., 2008), graphite rod (Liu, Cheng, et al., 2004; Liu, Ramnarayanan, et al., 2004), graphite fiber brush (Degrenne et al., 2011; B. Logan et al., 2007), reticulated vitreous carbon(RVC), or graphite granules (Rabaey, Clauwaert, Aelterman, & Verstraete, 2005) were used in previous studies for MFC. Carbon mesh has been used for anode construction in recent years (X. Wang, Cheng, et al., 2009). Study shows that carbon mesh provides good performance when compared with carbon cloth anodes, and it is less expensive than other carbon cloth materials used for anode. There are factors that may influence the performance of the materials that built electrodes. One big factor is substrate (Liu, Cheng, et al., 2004; X. Wang, Cheng, et al., 2009). Substrates play an important role in reaction at anode, because it provides carbon and nitrogen resource for microorganisms. Wastewater was used as substrate, and the most commonly added substrate is acetate (Pant et al., 2010).

There is no power supply added to the reaction in MFC, and this means that the overall reaction should be thermodynamically favorable in order to generate electricity (B. E. Logan et al., 2006; Pham et al., 2006; Rozendal et al., 2008). Gibbs free energy of the overall reaction is used to estimate the reaction occurring in the system, electricity can be generated if Gibbs free energy is negative. In a review study published in 2008 (Rozendal et al., 2008), it gives an example which used acetate as substrate at anode, with solution conditions $[CH_3COO^-]=[HCO_3^-]=10$ mM, pH=7, 298.15 K, $pO_2 = 0.2$ bar.

$$\text{Anode: } CH_3COO^- + 4H_2O \rightarrow 2HCO_3^- + 9H^+ + 8e^-$$

$$\text{Cathode: } 2O_2 + 8H^+ + 8e^- \rightarrow 4H_2O$$

$$\text{Overall: } CH_3COO^- + 2O_2 \rightarrow 2HCO_3 + H^+$$

ΔG =-847.60 KJ/mol, implying that there can be electricity generated from this reaction. There are many ways to evaluate microbial fuel cell's performance. One common measurement is through power output (Pant et al., 2010). The voltage is normally measured by the fixed external resistor (R_{ext}) connected with electrodes (B. E. Logan et al., 2006). The current is calculated as $I=E_{cell}/R_{ext}$. Power is calculated as $P= E_{cell}^2/R_{ext.}$ In order to make comparison with other systems, power is normalized by some characteristic of the reactor (B. E. Logan et al., 2006). Power density is normalized either by the surface area of anode (A_{An}) (Park & Zeikus, 2002; Rabaey, Boon, Siciliano, Verhaege, & Verstraete, 2004) or the reactor's volume(υ) (B. E. Logan et al., 2006). However, sometimes the area of the cathode (A_{cat}) is used for the power density calculation. This is according to some studies showing that the reaction on cathode, which is reduction of molecular oxygen, limits the overall generation of power (Cheng et al., 2006; Franks & Nevin, 2010; B. E. Logan et al., 2006). What's more, anode surface area may be difficult to express sometimes because of the material it use (B. E. Logan et al., 2006). Studies shows that microbial fuel cell researches have resulted in a 10,000-fold increase in the current density obtained from the cell in the past 10 years (Debabov, 2008; Pant et al., 2010). In Cheng and Logan's 2011 study (Cheng & Logan, 2011), it points out a study (Nevin et al., 2008) which used G.sulfurreducens grown on acetate produced 2.15 kW/m^3 anode volume (0.336mL anode volume) is the highest MFC power density reported so far. From this reported value, one can see that the power output is still low. All the analysis of MFCs used for wastewater treatment is mainly lab-scale. One of the main reason imped its application is due to its low power output (Franks & Nevin, 2010). Expensive materials used for construction is also a big concern (Pham et al., 2006; Rodrigo et al., 2007). In order to achieve higher voltage or current output, some researches use MFC in series or in parallel (Jiang et al., 2011; Oh & Logan, 2007), and some studies have been working on reducing cathodic limitations which influence power output (Cheng et al., 2006; Rismani-Yazdi et al., 2008). There are also some studies analyzing less expensive construction materials in order to reduce the cost (Bullen et al., 2006; Franks & Nevin, 2010; X. Wang, Cheng, et al., 2009). Based on the increasing quantity of researches on MFC system and the increasing amount of power output from MFC system, it is very promising that this technology will be applied on large scale in the near future (Pant et al., 2011).

1.4 The need for environmental impact assessment

Since industrial energy use is heavily reliant on fuel and electricity from non-renewable sources, the rapidly growing intensive industrial energy use has triggered a global energy crisis (Pérez-Lombard et al., 2008). Greenhouse gases, such as methane (CH_4) and carbon dioxide (CO_2) are produced when fossil fuels such as oil, coal and gas are burned for energy. It has been demonstrated that human-induced greenhouse gases emission is changing the world’s environment (Boulos & Bros, 2010).

The growing concern about climate change issues and future sources of energy has led to the development of alternative energy production solutions. Bioenergy has been treated as one of the most promising alternatives renewable energy source which can mitigate climate change and reduce the reliance on non-renewable sources (Cherubini & Strømman, 2011). The mitigation climate change idea of biofuels comes from that the

CO_2 released by burning a biofuel was balanced out by the CO_2 that was removed from the atmosphere by photosynthesis of the plants grow. Bioenergy systems have been promoted on a global basis (M. Wang, Huo, & Arora, 2011), and the growing interests in bioenergy in the United States can be proven by the implementation of Energy Policy Act (Congress, 2005) and Energy Independence and Security Act (Congress, 2007).

Despite the promotion of policies, many researches have raised concerns about possible environmental drawbacks bioenergy systems may have when considered the inflow and outflow of the production of biofuel. Take corn ethanol for example, one study shows that when replacing gasoline with corn ethanol, there will be increased eutrophication due to bioethanol's NO_X emission and greater water scarcity caused by intensive irrigation (Yang, Bae, Kim, & Suh, 2012). Some other researchers also points out the environmental pollution brought by fertilizer for growing corn, and indirect land use change required to cropland to make up for the reduced food supply (Cherubini et al., 2009; Searchinger et al., 2008; von Blottnitz & Curran, 2007). However, there are different voices about biofuels' environmental performance; some think they are favorable, while some holds the opposite opinion. The reason for these differences are mainly due to the system boundary they choose, approaches they use in scoping, and the reference system they choose to compare (Cherubini et al., 2009; von Blottnitz & Curran, 2007).

MFC is served as one of the bioenergy system, if consider energy gain during the operation as the only target, some processes during the manufacture maybe overlooked, and could bring negative influence to the overall environmental impact. If the purpose of using MFC is to reduce the burden brought to the environment, it is important that MFC system should be analyzed by a comprehensive environmental evaluation during all the related processes, and designed to bring less pressure to the environment.

1.5 Life cycle assessment

Introduction of life cycle assessment

Life cycle assessment is a technique which is used to assess environmental burdens associated with a product or service system through all stages of its life time. In 1990, the Society of Environmental Toxicology and Chemistry (SETAC) established the accepted name for life cycle assessment (James A. Fava, 2011). While SETAC was and is improving and harmonizing LCA's framework, methodology and terminology, the International Organization for Standardization (ISO) has been involved in LCA development since 1994. In 1996, the International Organization for Standardization (ISO) began to publish 14000 series of Environmental Management System (EMS) standards (ISO, 2006a, 2006b). The main task for ISO in LCA development is standardization of procedures and methods. One of the most important 14000 series is ISO 14040. It provides principles and framework for conducting life cycle assessment.

Life cycle assessment (LCA) is a well-established ISO 14040 normalized method used for analyzing the environmental burdens of industrial systems (Vince, Aoustin, Breant, & Marechal, 2008). Its "cradle-to grave" approach begins with the extraction of raw materials from the earth, continues with product development, manufacturing, and finally ends when all materials are returned to earth (ISO, 2006a). Environmental burdens analyzed by the LCA tool not only include current and local environmental impact, like land use, photochemical smog and eutrophication, but also the impact it will bring in the long run and worldwide, like global warming, stratospheric ozone depletion (Tangsubkul, Parameshwaran, Lundie, Fane, & Waite, 2006). Since LCA evaluates the environmental aspects of products or systems through all the life cycle phases, it considers different types of impacts upon the environment without burden shifting. LCA method provides a holistic picture on the overall impact of the system and allows for comparison between different systems on environmental grounds (Friedrich, 2002).

There are four stages that are necessary for conducting a life cycle assessment: goal definition and scoping, life cycle inventory (LCI), life cycle impact assessment (LCIA) and life cycle interpretation.

Data collection and calculation procedures for the life cycle inventory stage are key steps in doing life cycle assessment. One needs to make a process tree for all the processes that need to be evaluated first, and then collect all the relevant inflows (from technosphere and nature) and the outflows (to nature or products) data for each process. There are two basic approaches to obtain life cycle inventory in practice, that is, process-sum method are economic input-output method.

Process-sum method is a commonly used standard life cycle inventory method. It uses bottom-up process model, which is based on facility/site level data (Deng, Babbitt, & Williams, 2011; Zhai & Williams, 2010). Following by the supply chain, material inputs, environmental releases and output are assessed in detail for each process (Suh et al., 2003). This method can give an accurate detailed process-specific analysis. However, in practice it is labor and time intensive, constrained by resource and time limitations. The main drawback of this method is cutoff error, which is brought by lacking of data.

Economic input-output (EIO) method uses top-down economic input-output model, which is based on economic input-output tables. The most detailed tables divide the economy into 400-500 aggregated sectors in the U.S (Hendrickson, Horvath, Joshi, & Lave, 1998). EIO model describes financial transactions, inputs and outputs between sectors in a national economy, and can used to calculate resource demands, economic and environmental effects for the manufacture of a given monetary demand in an industry sector (Hendrickson et al., 1998; Lankey & McMichael, 2000; Zhai & Williams, 2010). It gives comprehensive assessments, which include all direct and indirect environmental effects. However, in EIO method, all the products described a sector represent an average product not a specific one. This method is less adequate for detailed life cycle analyze. The main drawback of this method is aggregation error, which is brought by coarse graining of processes.

With the aim of combining the accuracy of process-sum method and completeness of EIO method, hybrid method has been emerging in order to reduce uncertainty of this assessment (Zhai & Williams, 2010). There are three different categories of hybrid methods, namely, additive hybrid, economic-balance hybrid and mixed-unit hybrid (Suh et al., 2003; Zhai & Williams, 2010).

Life cycle impact assessment procedure is trying to connect life cycle inventory flows to corresponding environmental impacts based on the cause-effect chain between them. According to ISO 14042, two main schools of environmental impact methods have developed. One is classical impact assessment, and the other is damage-oriented methods (Olivier Jolliet et al., 2004). The classical impact assessment approach simplified the quantification of the environmental problems by relating the life cycle inventory flows to midpoint of environmental mechanism, such as climate change and acidification. While the damage-oriented approach modeling the impacts up to the endpoint of environmental mechanism. It indicates the actual damage to the environmental, such as damage to resources, human health and so on. Commonly used EDIP method, CML method and TRACI method are classical impact assessment approach, Eco-indicator and EPS are damage-oriented approach.

Impact 2002+ is a combined midpoint/ endpoint approach which is linking life cycle inventory (LCI) via 14 midpoint categories into 4 main damage categories. Midpoint categories quantify the relevant emissions and resources from the life cycle inventory, in the units of reference substances (O. Jolliet et al., 2003). Each midpoint category is related to one or more damage categories. The 14 intermediate impact categories are human toxicity (carcinogens and non-carcinogens), respiratory inorganics, ionizing radiation, ozone layer depletion, respiratory organics, aquatic ecotoxicity, terrestrial ecotoxicity, terrestrial acid/nutria, land occupation, aquatic acidification, aquatic eutrophication, global warming, non-renewable energy, mineral extraction. Midpoint category results can provide more accurate results, since they are directly related with the materials. However, it is difficult to interpret by decision makers, and require greater knowledge of damage processes by user. The 4 main damage categories included in the Impact 2002+ method includes: human health, ecosystem quality, climate change, and resources, which indicate the environmental impact at the level of societal concern (Olivier Jolliet et al., 2004). Endpoint categories represent quality changes in the environmental. The endpoint results show the environmental impact more clearly, and easy to compare. But there is more modeling uncertainty in the resulting impacts. Providing both mid-point and end-point results using this method can help readers to have a better understanding of the environmental impact, and have a better idea of the possible limitations of the results. Impact 2002+ has developed new methods assessing human toxicity and ecotoxicity, and transferred or adapted methods for other categories from CML 2002 method and Eco- indicator 99 methods (O. Jolliet et al., 2003). In Simapro 7.2 which has been used for this study, 15 midpoint categories are presented, because human toxicity category splits up to carcinogens and non-carcinogens.

Whatever the method, there are two mandatory steps for impacts calculation, namely, classification and characterization. Normalization, grouping and weighting are three optional steps (Ryding, 1999). Mandatory steps convert the inventory flows into impact categories. Optional steps help to get a single indicator subjectively.

Data quality and uncertainty

LCA has been increasingly used as an environmental management tool in reality. However, there is study showing that different studies of a same product can generate widely different results, and it is difficult to check the accuracy of the different results. In a review study (Williams, 2009), it gives examples talking about results got from LCA for same products varies differently. One example is talking about the energy required for manufacturing a desktop computer during its life time. The LCA results vary from 1000 to 8300 mega joules from different studies. It is important to give information on the uncertainty of the model outcomes, in order to provide useful information on the reliability of LCA-based decisions.

Monte Carlo analysis becomes the standard in software to simplify the uncertainty analysis. This method is based on a range of input (parameters of interest) which follows probability distributions function. The analysis involves choosing randomly selected parameter representations from the probability density functions, and performs computation on the inputs and generates the results. The simulation will run many times to fully sample each distribution. The most difficult aspect of using a Monte Carlo analysis is to estimate the probability distributions underlying many variables (Lau, 2005).

Simapro software used in LCA

Simapro software is made according to the ISO standard to facilitate the LCA analysis. It includes database which containing large amount of processes and several impact assessment methods. This allows life cycle analysis of complex systems in an organized way. Process data contained in Simapro are collected by private and academic institutions from all over the world. There are two types of inventory data libraries, one is based on physical value, like Eco-invent and IDEMAT 2001, and the other is based on monetary value, like DK Input Output 99. USA Input Output 98. There are different impact assessment methods included in Simapro. They are BEES, Eco-indicator 99, Eco-indicator 95, Ecopoints 97, Impact 2002+, TRACI and so on. TRACI is developed by US Environmental Protection Agency.

Monte Carlo method is statistical approach to incorporate uncertainty analysis in life cycle analysis. It has been embedded in Simapro software. It generates input randomly from a probability distribution over the domain, and then gets the output.

1.6 The usefulness of life cycle assessment for bioenergy systems

LCA has been treated as one of the best methodologies for the evaluation of the environmental performance of bioenergy systems in the scientific community (Cherubini et al., 2009).

This analysis method could help to provide a holistic picture on the overall impact of the bioenergy system, which enables researches to avoid sub-optimization-that is, a too-narrow focus on only a few processes (Varun, Bhat, & Prakash, 2009). In a review paper published in 2007(von Blottnitz & Curran, 2007), it illustrates a generic life cycle scheme for biofuel system. The main five stage included in this scheme are production of feedstock, agriculture and harvesting, transportation, conversion process and combustion at consumer. In another review paper published in 2012(Wiloso, Heijungs, & de Snoo, 2012), it illustrates a life cycle scheme for bioethanol system. It divided the system into three chains. First is agricultural chain, second is bioethanol production chain, and third is bioethanol use chain. From the life cycle framework defined and data collected, energy and material use, waste and emissions released to the environment though all the stages can be identified. These identified results can give us a better understanding of the whole processes, and help to reveal hot spots associated with the system's process or technology from life cycle perspective. Recommendation of the processes can be given in order to minimize negative environmental impacts.

Since this "cradle-to grave" method can help to analysis the overall impact of the bioenergy system, the comparison between bioenergy and traditional energy systems, and the comparison between different bioenergy systems are possible by using the same system boundary and functional unit for LCA analysis. The main goal for setting a functional unit is to provide a reference to relate input and output, and is necessary for reasonable comparison. For bioenergy systems, the functional unit, depending on the goal and scope of the study, could be defined in terms of energy output, input land area, absolute emissions, primary energy requirements, or on a per vehicle-km basis when compared with gasoline, diesel as transportation energy provider and so on(Cherubini et al., 2009; Clarens, Resurreccion, White, & Colosi, 2010; Wiloso et al., 2012)

Many researches have used LCA to estimate bioenergy systems compared with fossil fuel energy systems(Bessou, Ferchaud, Gabrielle, & Mary, 2011; Cavalett, Chagas, Seabra, & Bonomi, 2013; Cherubini & Strømman, 2011; Sara González-García et al., 2011; S. González-García, Moreira, & Feijoo, 2012; Kaltschmitt, Reinhardt, & Stelzer, 1997; Tonini, Hamelin, Wenzel, & Astrup, 2012; Yang et al., 2012). When comparing biofuels with conventional fossil fuel as transportation energy source, mitigation of climate change is one of the main driving forces for biofuels development and deployment. From a review paper published in 2009(Cherubini et al., 2009), it concluded that besides a few studies, most of LCA studies show that greenhouse gas emission and fossil energy consumption has been reduced when replacing fossil fuel (gasoline) with biofuel (bioethanol and biodiesel), the GHG emissions per unit output(g CO_2-eq./km) is ranging from 15 to 195 for bioenergy, and 155 to 220 for conventional gasoline, diesel and natural gas used for transportation. However, we cannot only focus on mitigation climate change as the only environmental impact. Several environmental assessments using life cycle point of view revealed that the corn ethanol could have larger environmental impact compared with gasoline considering the increased eutrophication due to bioethanol's NO_X emission, greater water scarcity caused by intensive irrigation (Yang et al., 2012), pollution brought by fertilizer and indirect land use change required to cropland to make up for the reduced food supply(Cherubini et al., 2009; von Blottnitz & Curran, 2007). Talking about land use, in a 2001 published LCA analysis review research(Gagnon, Bélanger, & Uchiyama, 2002), it shows that when using biomass as energy source, direct land requirements for biomass plantation is ranging from 533 km^2/Twh to 2200 km^2/Twh, while for coal, the direct land requirements is only 4 km^2/Twh. One can acknowledge that even though there maybe environmental benefit brought by bioenergy system in some aspects, from the life cycle point of view there maybe environmental cost in some other aspect. LCA could help to detect these environmental costs.

Even though life cycle assessment results show some environmental unfavorable results of bioenergy systems, this method could assist the technology development, and track the development path of the bioenergy systems, so that to make sure it has been developed in an environmental friendly direction. Algae have brought researches interests recent years as a feedstock for biomass energy. They do not compete with food crops(Sheehan, Dunahay, Benemann, & Roessler, 1998), can cultivated on land that are not suitable for food crops, and have the potential to have a higher energy yields compared with other feedstock to make biodiesel(Demirbas & Fatih Demirbas, 2011). When using life cycle assessment to estimate its environmental impact(Clarens et al., 2010), researcher points out the demand for fertilizer and CO_2 emissions in the algae cultivation processes bring large environmental burden. From the analysis, it shows that during algae cultivation, nearly 50% of energy use and CO_2 emissions are associated with fertilizer production. Researchers introduced wastewater effluent used to provide chemical fertilizers and water use for cultivation(Kim et al., 2007). From one life cycle analysis(Clarens et al., 2010), it shows that after this change which used wastewater to replace chemical fertilizer, the environmental burden brought by fertilizers could be reduced by 3% to 134% based on different nutrient densities. Studies also show that with the development of biofuel from first generation to second generation, less environmental burden bioenergy system brings. The first generation biofuels uses sugar, vegetable oils and starch as the raw materials(Sims, Mabee, Saddler, & Taylor, 2010). Some LCA analysis show that limitations of first generation biofuels, when compared with conventional energy source are high energy input required for crop cultivation and conversion(Cherubini et al., 2009), competition for both water and land use for food(Fargione, Hill, Tilman, Polasky, & Hawthorne, 2008). This limitation can be partly overcome by the second generation biofuel uses non-edible lignocellulosic biomass, such as residues from agriculture, industry, plantation or forestry, since they are nonfood materials available from plants. In a recent LCA review study(Wiloso et al., 2012), it shows that 14 out of 16 studies shows a positive energy output when compared with gasoline system, and 26 out of 31 studies shows an GHG saving ranging from 11% to 145% when compared with gasoline system.

Bioenergy systems could help us to reduce the dependence on fossil fuels, diversify the energy supply, and bring GHG savings. However, we cannot ignore the environmental burden such as the direct land use, greater water scarcity and pollutions brought by fertilizer that bioenergy systems bring in. LCA is a necessary tool for bioenergy systems development and application. It could help to identify the hotpot of the system, and keep a track of the change of its environmental performance with the evolution of the technology.

1.7 Life cycle assessment of microbial fuel cell

There are only a few published papers talking about using life cycle assessment to analyze microbial fuel cell.

In one study (Foley, Rozendal, Hertle, Lant, & Rabaey, 2010), environmental performance of "conventional" high-rate anaerobic system, microbial fuel cell (MFC) system and microbial electrolysis cell (MEC) system were compared using life cycle assessment. They use process-sum LCA method for this analysis, and the inventory data for MFC is based on a pilot-scale lab work. From the LCA results they got, they concluded that MFC is not as beneficial as other treatment options. The main drawback of the MFC option is the resource and emissions-intensive materials required for the construction of it. However, the performance parameters for the basic design, like the electricity generation value, was contingent on the optimistic design assumptions, which is 1000 $A \bullet m^{-3}$. Also, the author did not explain the accomplishment for scale-up of MFC system to support its analysis. These could bring large uncertainty of the life cycle inventory data. What's more, their study excluded the recycle and final ends part of the life cycle of the facilities used in the options, which may decrease the environmental impacts of these options. In another study(Pant et al., 2011), life cycle assessment methodology was proposed to analyze environmental impact of an anaerobic treatment with direct biogas generation, a microbial fuel cell (MFC) treatment, and a microbial electrolysis cell (MEC) treatment. They pointed out that the MFC is much better when compared with the other options. However, they did not provide strong evidence to support this conclusion. This study focused on giving explanations and recommendations about how to do the life cycle assessment, but they did not show the detail process conducted by using life cycle assessment to analysis MFC.

1.8 Objective

The overall objective of this study is to use life cycle analysis to evaluate the environmental performance of microbial fuel cell and provide environmental principles for the development of MFC.

Specific objectives are shown below:

- Conduct an LCA for two lab-scale MFC wastewater treatment systems and a lab-scale aerobic treatment system using different inventory methods.
- Find out which components of MFC systems bring largest environmental impact, and identify opportunity for improvement of MFC technology.
- Compare the environmental impact result of MFC system with aeration system.
- Analyze the uncertainty of LCA models and data collection. Identify the way of dealing with and reducing the uncertainty.

CHAPTER 2

METHODOLOGY

2.1 Goal and Scope

The objective of this life cycle assessment is to analyze the environmental impacts of two lab-scale single chamber microbial fuel cells (MFC), and compare their performance with conventional aeration treatment. The functional unit of this study is 1000 gallons of water treated per day (MGD), with a COD removal rate greater than 90%. Two MFC systems analyzed in this study are membraneless and single chamber. One is a vertical design MFC system which placed its cathode on top of the reactor, and the other is a side-lying design MFC system which put cathode on one-side of the reactor.

The system boundary is shown in Figure 3, which includes the reactor's materials, wastewater flow, power input and output, and waste disposal. No system repair or replacement is considered because most of the materials are assumed to have a life span of 5 years. In conventional aeration treatment plant a sedimentation clarifier was added due to equal comparison with MFC system. The life span for the sedimentation clarifier was assumed to be 50 years.

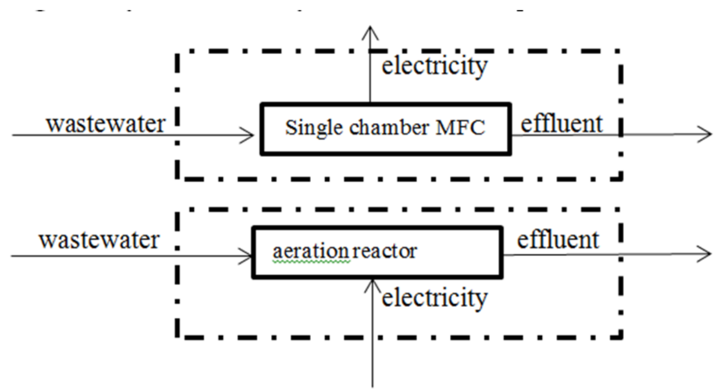

Figure 3: System boundary for the LCA comparison

2.2 Life Cycle Inventory

The life cycle models used in this study were constructed using SimaPro 7.2 LCA software package. EIO method and hybrid method are used to compile life cycle inventory. For the vertical design MFC, commercial products have been used for electrodes construction, so that not much process information is available. For the side-lying design MFC, much process detail is available.

The construction and operational data for vertical design MFC and aeration systems are based on a sample experiment conducted by the University of Colorado. The wastewater used for experiment is collected from effluent of the Coors Wastewater Treatment Plant's primary clarifier in Golden, CO, with a COD concentration of 1300mg/L and average final COD concentration of 0.001g/L after treatment for both systems. The hydraulic retention time (HRT) is 13 days for aeration and 15 days for MFC reactor. The aeration treatment consumed electricity at 624Wh/HRT, while the MFC reactor had a net energy gain of 0.353Wh/HRT. The vertical design MFC had a cathode made from platinum on carbon cloth (19cm X 19cm) treated with Nafion and an anode made by graphite fiber brush. Electrical wire was made from copper, and the reactor encasing (5 gal.) was made from polyvinyl chloride (PVC). One can see the schematic diagram of vertical design MFC in Figure 4. The aeration tank consisted of an air pump (2W; 1200cc/min), tubing, and reactor encasing (5 gal.). Both tubing and reactor encasing are made from PVC. A sedimentation clarifier was added for aeration system, because the TSS concentration after aeration process is 139 mg/L which is above the EPA standard of 45mg/L 7–Day Average. The life span of the sedimentation clarifier is assumed to be 50 years in this analysis.

The construction and operational data for side-lying design MFC is based on lab-scale experiment conducted by Nankai University. Its schematic diagram is shown in Figure 5. The wastewater was diluted beer brewery wastewater, with a COD concentration 780 mg/L and 70mg/L after treatment. The hydraulic retention time (HRT) of this MFC reactor is 2 days with a net energy gain of 0.007 to 0.009 Wh per HRT. The anode is made of carbon mesh, and the cathode is built based on carbon cloth base layer with PTFE solution layers on the external air side and a Pt/C catalyst layer on the internal solution side. The reactor was made from synthetic glass. Electrical wires were made from titanium.

The detailed information about life cycle inventory of this study is shown in appendices.

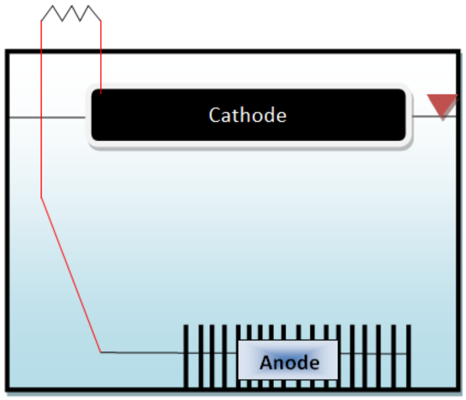

Figure 4: Schematic diagram of vertical design MFC

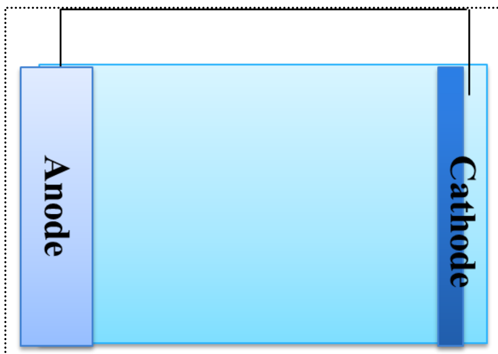

Figure 5: Schematic diagram of side-lying design MFC

2.3 Environmental impact assessment

The impact assessment method used for this study is Impact 2002+, which is a combined midpoint/ endpoint approach which is linking life cycle inventory (LCI) via 14 midpoint categories into 4 main damage categories. Midpoint categories quantify the relevant emissions and resources from the life cycle inventory in the units of reference substances (O. Jolliet et al., 2003). Each midpoint category is related to one or more damage categories. The 14 intermediate impact categories are human toxicity (carcinogens and non-carcinogens), respiratory inorganics, ionizing radiation, ozone layer depletion, respiratory organics, aquatic ecotoxicity, terrestrial ecotoxicity, terrestrial acid/nutria, land occupation, aquatic acidification, aquatic eutrophication, global warming, non-renewable energy, mineral extraction. Midpoint category results can provide more accurate results, since they are directly related with the materials. However, it is difficult to interpret by decision makers, and require greater knowledge of damage processes by user. The 4 main damage categories included in the Impact 2002+ method includes: human health, ecosystem quality, climate change, and resources, which indicate the environmental impact at the level of societal concern (Olivier Jolliet et al., 2004). Endpoint categories represent quality changes in the environmental. The endpoint results show the environmental impact more clearly, and easy to compare, but there is more modeling uncertainty in the resulting impacts. Providing both mid-point and end-point results using this method can help readers to have a better understanding of the environmental impact, and have a better idea of the possible limitations of the results. Impact 2002+ has developed new methods assessing human toxicity and ecotoxicity, and transferred or adapted methods for other categories from CML 2002 method and Eco-indicator 99 method (O. Jolliet et al., 2003). In SimaPro 7.2 which has been used for this study, 15 midpoint categories are presented, because human toxicity category splits up to carcinogens and non-carcinogens.

2.4 Uncertainty analysis

The management of uncertainty is one of the key to establish LCA as a reliable tool to help with decision-making. For the purpose of analyzing the uncertainty of the result, Monte-Carlo simulation model incorporated in SimaPro software has been used in our study. We will only focus on uncertainties brought by data variability in process-sum model and price uncertainty in EIO model, and we will discuss other qualitative aspects that may bring uncertainty.

For side-lying design MFC analyzed in this study, original data uncertainty is brought by electrical energy output per batch which ranging from 25 to 33J, the PTFE solution amount used for making a cathode ranging from 1000 uL to 1200 uL, and individual components amount of Nafion solution which have different ranges of weight proportion as shown in Table 1. Price of the materials uncertainty is brought by price use for acetone used for cathode construction, sodium acetate used as substrate, Ti wire used for connect anode with cathode. Different chemical companies offered different prices for the three materials mentioned.

Table1. Typical composition of Nafion solution

Property	Nafion(D-520)
polymer content (wt %)	5.0-5.4
Water content (wt %)	42-48
1-propanol content (wt %)	45-51
Ethanol content (wt %)	<4
Mixed Ethers and other VOCs content (wt %)	<1

CHAPTER 3

RESULTS AND DISCUSSION

3.1 Vertical design MFC analysis

By using the inventory data, and impact assessment method mentioned in the previous section, the overall environmental impact of treating 1 kGD wastewater by using vertical design MFC treatment option is presented in Figure 6. As shown in this figure, one can see that the single score of EIO LCA is 0.704 (unit: point), while hybrid LCA is 0.333 (unit: point). This vertical design MFC system brings larger impact on human health than other damage category, and environmental impact result got from EIO method is approximate 2 times greater than hybrid method for each damage category. The difference between EIO result and hybrid result may due to the chose input category in SimaPro and the inventory method itself. For example, when using EIO model, SimaPro input category: carbon and graphite products were used to represent both cathode and anode, which are constructed by different carbon and graphite materials. The impact brought by an average carbon and graphite product may not be the same as a specific product, since different carbon and graphite fibers and products are all included in carbon and graphite products sector. Compared with EIO method, hybrid method use material data for cathode. It is possible that hybrid method may bring more accurate results than EIO method.

Figure 7 presents environmental impact brought by each component of vertical design MFC system. As shown in this figure, the largest environmental burden is brought by cathode from EIO method result, while the largest burden is brought by anode from hybrid method result. Even though the component which brings largest environmental impact is not the same from these two methods' result, one can see that burden brings by electrodes are larger than electrical wire and holding tank. It is clear that development of more environmental friendly materials for electrodes construction could be a way to reduce the environmental burden of vertical design MFC. For environmental burden brought by electrical wire, since the result is based on a lab scale data, the electrical wire is much shorter than a full scale, so the unit cost can be higher than a full scale. When scaling up, the impact burden ratio of electrical wire to electrodes could be smaller. For holding tank, the material use for construction is plastic materials. When scaling up, concrete materials maybe used, the impact burden ratio of holding tank to electrodes could be larger. It is also worthy to notice that the environmental benefit brings by electricity generation during MFC operation is very small.

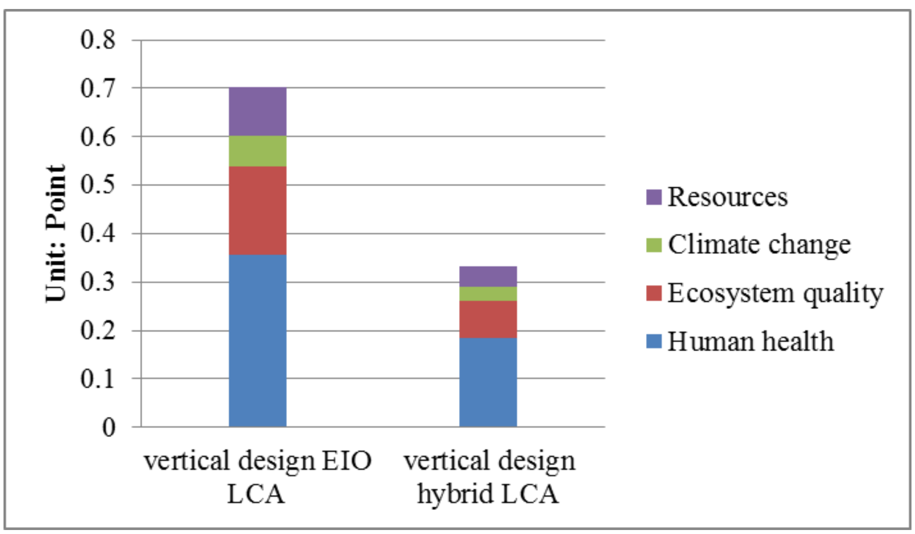

Figure 6: Vertical design MFC overall environmental impact per damage category (EIO method and hybrid method single score result)

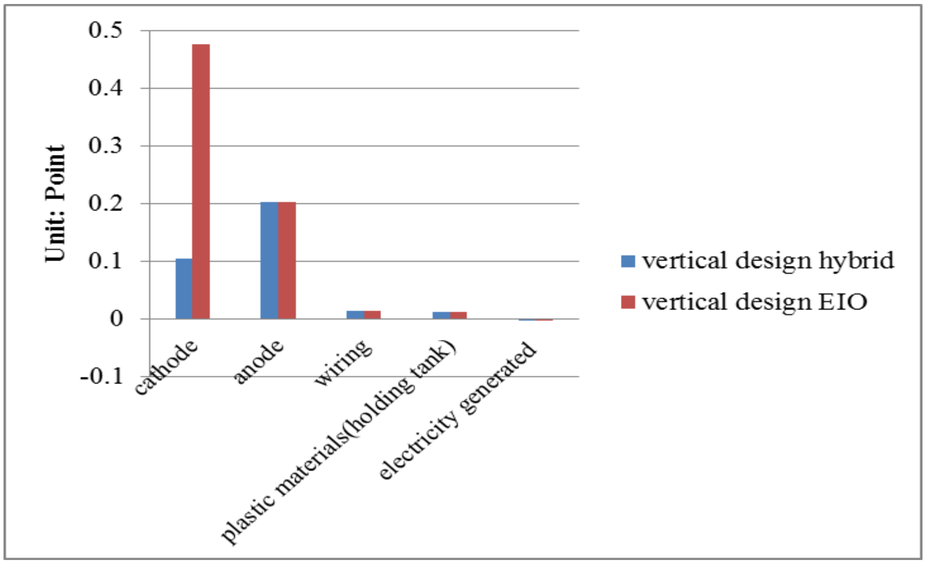

Figure 7: Vertical design MFC overall environmental impact per component (EIO method and hybrid method result)

When analyze the negative environmental impacts that the vertical design MFC brings in depth using hybrid method, Table 2 shows the impact expressed in different mid-point categories. The normalized basis result of different mid-point categories comparison is shown in Figure 8 (unit is point). As can been seen in Figure 8, the top five impact categories brought large environmental impact are non-carcinogens, respiratory inorganics, terrestrial ecotoxicity, non-renewable energy, global warming, sequentially. These five categories bring 74% of total environmental burden. When relate each category with materials and energy used for this system, one can see that anode graphite material brought large environmental impact to each of these five dominate categories. The input category chose for anode graphite material in SimaPro is carbon and graphite products in USA Input Output Database 98. From SimaPro specified analysis of production process for making carbon and graphite products, nonferrous metal ores (except copper) mining process contributes most to non-carcinogens category;

process for products of petroleum and coal contributes most to respiratory inorganics category; copper ore mining process contributes most to terrestrials ecotoxicity, process for crude petroleum natural gas contributes most to non-renewable energy category and carbon and graphite products contributes most to global warming process. Pt has the largest negative impact on respiratory inorganics, which contributes 48% of the total impact of that category. Carbon black, used in making cathode, has little environmental impact when compared with other inventories.

Table 2. Vertical design MFC overall environmental impact per midpoint environmental category (hybrid method result)

Impact category	Unit	Total
Carcinogens	kg C_2H_3Cl eq	26.5
Non-carcinogens	kg C_2H_3Cl eq	249.6
Respiratory inorganics	kg $PM_{2.5}$ eq	0.77
Ionizing radiation	Bq C-14 eq	951
Ozone layer depletion	kg CFC-11 eq	0.00
Respiratory organics	kg C2H4 eq	0.39
Aquatic ecotoxicity	kg TEG water	336749
Terrestrial ecotoxicity	kg TEG soil	127124
Terrestrial acid/nutri	kg SO_2 eq	10.44
Land occupation	m2org.arable	8.01
Aquatic acidification	kg SO_2 eq	6.35
Aquatic eutrophication	kg PO_4 P-lim	0.01
Global warming	kg CO_2 eq	282
Non-renewable energy	MJ primary	6619
Mineral extraction	MJ surplus	0.42

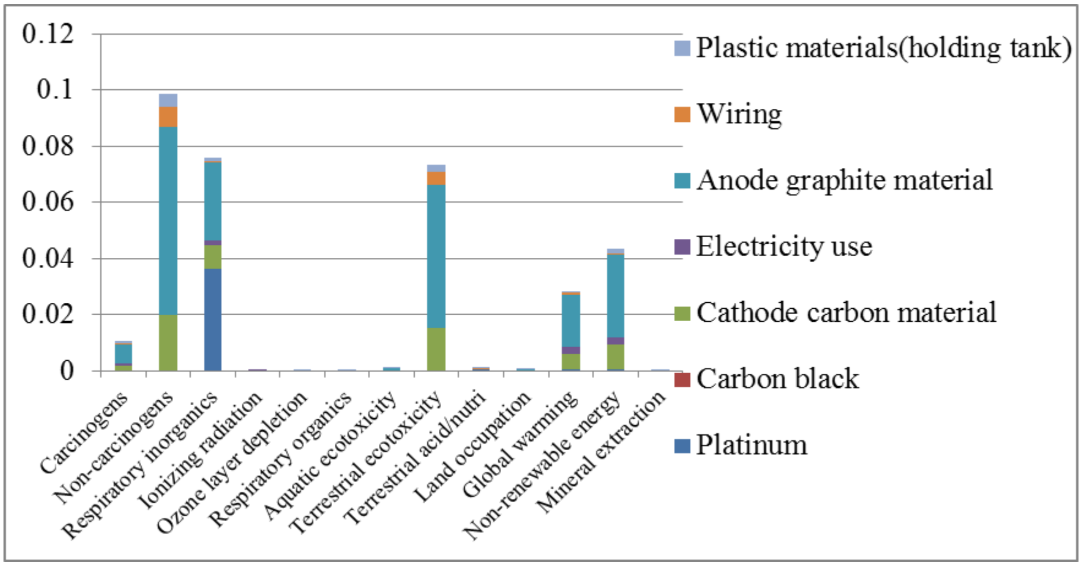

Figure 8: Normalized vertical design MFC environmental impact per midpoint category (hybrid method result)

3.2 Side-lying design MFC analysis

In Figure 9, it shows the overall environmental impact of treating 1 kGD wastewater by using side-lying design MFC treatment option. As shown in this figure, one can see that the results got from EIO method and hybrid method differ a lot. The environmental impact score calculated by EIO method is 18 times larger than hybrid method results. It is possible that price value used for EIO method could be a factor that brings this difference. When we convert process material value to dollar value for calculation, some of the material prices we found are purchase price offered by different companies, we convert purchase price to producer price, and consider inflation for price value added into SimaPro which use USA Input Output Database 98. It is likely that purchase price we use may not represent the actual price value of that material, because of the limited available data.

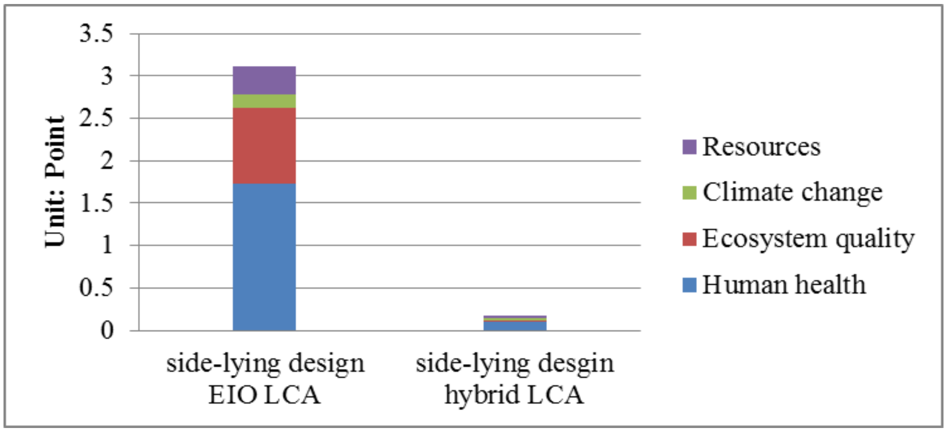

Figure 9: Side-lying design MFC overall environmental impact per damage category (EIO and hybrid method single score result)

The environmental impact brought by each component of side-lying design MFC system is presented in Figure 10. It is clear that from EIO method result several components besides electrodes shows large environmental impacts, namely, wiring, synthetic glass and substrate. Also, EIO method results shows that largest burden is brought by wiring device, while hybrid method results shows the largest environmental burden is brought by cathode. When comparing different components' environmental impact by score ratio, the result from two inventory methods differs. The environmental intensive material Ti used for wiring and the high price of Ti could be the reason why electrical wire shows large environmental impact from EIO method results. The inventory category chose for substrate is industrial inorganic and organic chemicals in EIO method analysis, while the substrate we use is sodium acetate for this experiment. The model may overestimate the environmental burden brought by sodium acetate, since we use the industrial inorganic and organic chemicals sector to represent one organic chemical. Even though the difference results from two inventory methods, it is worth to notice that synthetic glass used for container brings large environmental impact in both methods when compared with other components. From hybrid result, impact brought by anode is only 9% of cathode, which is different from vertical design that anode brings approximately 2 times larger environmental burden than cathode. The reason for this result could be that side-lying design uses carbon mesh which provides good performance but less expensive material was used to build anode, while for vertical design more expensive graphite fiber brush was used for anode.

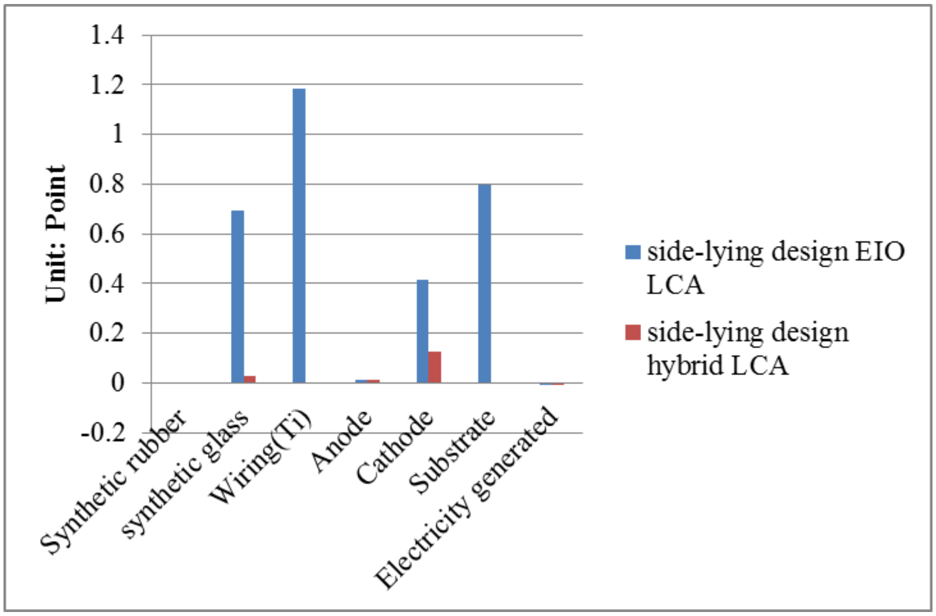

Figure 10: Side-lying design MFC overall environmental impact per component (EIO LCA and hybrid method result)

Table 3 shows the negative environmental impacts brings by side-lying design MFC expressed in different mid-point categories by hybrid method. The normalized basis result of different mid-point categories comparison is shown in Figure 11(unit is point). As can been seen in Figure 11, the top five impact categories brought large environmental impact are respiratory inorganics, non-renewable energy, non-carcinogens, global warming, terrestrial ecotoxicity, sequentially. These five categories bring 97% of total environmental burden; respiratory inorganics category alone brings 39% of the total environmental burden. It is the same categories as from vertical design which brings large environmental impact, but not the same order. When relate each category with materials and energy used for this system, one can see that Pt has the largest negative impact on respiratory inorganics, which contributes 64% of the total impact of that category. Synthetic glass contributes 36% to non-renewable energy category and 38% to global warming category. Also, cathode carbon material contributes 75% of total impact of terrestrial ecotoxicity category.

Table 3. Side-lying design MFC overall environmental impact per midpoint environmental category (hybrid method result)

Impact category	Unit	Total
Carcinogens	kg C_2H_3Cl eq	9.72
Non-carcinogens	kg C_2H_3Cl eq	65.67
Respiratory inorganics	kg $PM_{2.5}$ eq	0.68
Ionizing radiation	Bq C-14 eq	2146.96
Ozone layer depletion	kg CFC-11 eq	0.0019
Respiratory organics	kg C_2H_4 eq	0.13
Aquatic ecotoxicity	kg TEG water	91738.30
Terrestrial ecotoxicity	kg TEG soil	33863.80
Terrestrial acid/nutri	kg SO_2 eq	10.44
Land occupation	m2org.arable	2.989
Aquatic acidification	kg SO_2 eq	7.09
Aquatic eutrophication	kg PO_4 P-lim	0.027
Global warming	kg CO_2 eq	247.44
Non-renewable energy	MJ primary	4484.04
Mineral extraction	MJ surplus	0.57

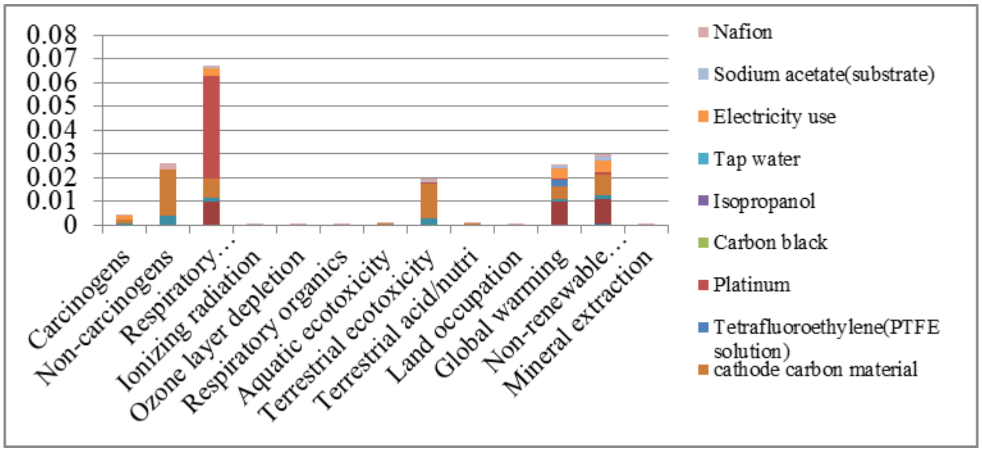

Figure 11: Normalized side-lying design MFC environmental impact per midpoint category (hybrid method result)

3.3 MFC treatment compared with aeration treatment

As it has been illustrated before, energy use during operation brings large environmental burden in traditional wastewater treatment processes (Corominas et al., 2013; Sharma, Guildal, Thomsen, & Jacobsen, 2011). In our study, energy input for aeration treatment is 156 kwh per 1000 GPD.

Figure 12 provides comparison information of MFC system with aeration system. As shown in this figure, even though environmental impact scores bring by different configuration of MFC with different methods varies largely, aeration treatment brings less environmental impact than MFC treatment. There are several reasons which may lead MFC brings larger environmental impact than aeration. First, materials used for MFC constructions bring larger environmental impact than aeration. If this is the reason, improvement of MFC system may be needed in order to reduce its environmental impact. Second, aeration is a well-developed technology, the price for all the materials used for the system may be cheaper and stabilized, while MFC is a newly developing technology, price for materials used in MFC system could be more expensive. Third, there is limited categories chose in SimaPro software for MFC system, so based on the categories chose for MFC in SimaPro software, the result may not be accurate.

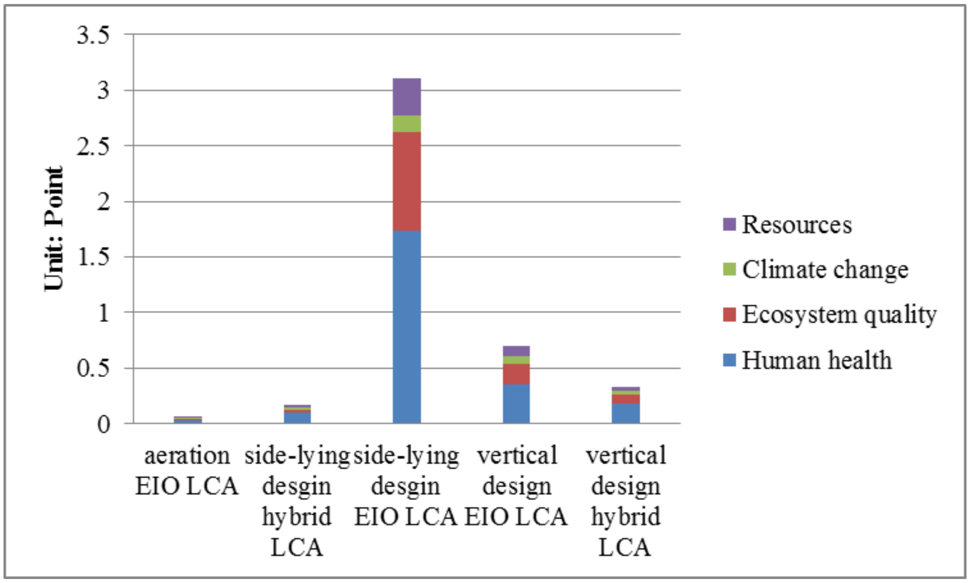

Figure 12: Environmental impact comparison of MFC systems with aeration system

3.4 Uncertainty analysis

Monte-Carlo analyses results for vertical design MFC is shown in Table 4. The statistic result is based on 1000 runs, and values that contain uncertainty are only 0.00822%. From the numbers showing before, it is clear that the uncertainty brought by data variability in process-sum model is very small.

Table 4. Uncertainty analysis result for hybrid method side-lying design MFC

Damage category	Unit	Mean	Median	SD	CV (Coefficient of Variation)	2.5%	97.5%	Std.err.of mean
Single score	Pt	0.173	0.173	0.000329	0.19%	0.172	0.173	0.0000602

Price uncertainty is analyzed by changing some unit price of materials used for MFC system construction. Different companies offered different purchase price as seen in Table 5. Column A provides prices (without tax and shipping) of acetone, sodium acetate and Ti wire from Sigma Aldrich Company. These prices are used for previous analysis in side-lying design MFC using EIO method. Column B offers prices information from other companies, which are cheaper compared with Sigma Aldrich Company. Prices (without tax and shipping) for acetone and sodium acetate are found from Alfa Aesar Company. Bulk price for Ti is found on air express website. Running analysis again with the changing price value, the different environmental impact score is shown in Figure 13. As can been seen in the figure, option A's results is approximately 2 times larger than option B. This difference shows that price values used for materials in side-lying design MFC is very important for determining the final results.

Table 5.Price difference for A and B option of chose materials

	A	B	unit
acetone	36.75	20.52	$/L
sodium acetate	78	45.2	$/Kg
Ti wire	81.14	0.03	$/g

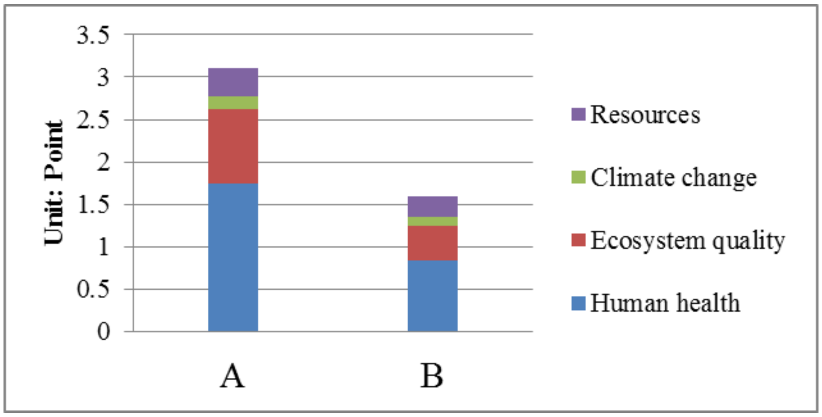

Figure 13: Comparison of A and B options' environmental impact results

Other qualitative aspects which bring uncertainty could be impact method and the database used in this study.

The impact method IMPACT 2002+ is based on European data, while this study was performed in the United States. Though the method allowed the user to select the United States data for some materials and there is EIO database which allows adding US dollar as input, not all of the materials were available from US database.

The database available in SimaPro for the material input for MFC system is also limited. There is no direct category for Nafion solution, and carbon materials or electrodes that are used in MFC system. In our analysis, since we know the components of Nafion solution, we divide Nafion solution by its components, calculates the dollar value for ethanol and 1-propanol first, then subtract this value from the total price of Nafion solution, the remaining dollar value is the value for polymer, which is associated with plastics materials and resins sector in an EIO model. Mixed Ethers and other VOCs content which is less than 1 % (wt.) and water content are ignored in the analysis. There is another study talked about Nafion in their LCA study(Staffell & Ingram, 2010), they mentioned that when dealing with Nafion solution, they either exclude this solution for comparison with one and another system or use standard plastics such as polypropylene to substitute Nafion solution for analysis. For the carbon and graphite materials used in MFC, we choose carbon and graphite products sector in EIO model to represent graphite fiber brush for vertical design MFC's anode, carbon mesh for side-lying design MFC's anode and carbon cloth for both vertical design and side-lying design MFC's cathode carbon material. There can be reduced accuracy when using this one sector to represent different materials.

CHAPTER 4

CONCLUSION

This study analyzes MFC systems' environmental impact using life cycle assessment method, two configuration of MFC were estimated, one is vertical design MFC and the other is side-lying design MFC. From the hybrid method results, it can be concluded that for MFCs, large environmental burden is brought by the carbon and graphite materials used for electrodes construction and environmental intensive metal Pt used for cathode construction. When considering the container encasing building material, if synthetic glass is chosen, it brings large environmental burden. The environmental benefit brings by electricity generation during MFC operation is very small. In sum, technology improvement is needed for the MFC. Less environmental intensive materials should be found to build the electrodes used in MFC system. Also, technology for large amount of electricity production in MFC should be investigated, so that to bring a larger net benefit of the electricity production during the operation of MFC.

When compared different inventory methods results, EIO method provides at least two times large environmental impact results than hybrid method result. It can be concluded that different methods chose for MFC analysis using LCA may bring out different results, and change components' environmental impact ratio among different components. If LCA is used for further MFC analysis studies, more representative materials' price data used for MFC construction is needed in order to give a more accurate result, and more carbon and graphite material categories are needed to be constructed in SimaPro Database.

There is possibility that when the system is scaled up, its environmental performance will change since the materials used for cell container and wiring may change. Future analysis should be performed on MFC along the development of the system with more detailed process data and more representative price data.

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APPENDICES

Appendix A. Vertical design MFC system inventory table

EIO LCA

Products	Simapro input	Unit	Unit/ 1kGD
cathode	Carbon and graphite products	USD	309.27
Anode	Carbon and graphite products	USD	131.44
Electrical Wire	Wiring devices	USD	6.13
Holding Tank	Plastic materials and resin	USD	5.25
Electricity Production	Electricity mix/US S	Wh	88.25

Hybrid LCA

Products	Simapro input	Unit	Unit/ 1kGD
Cathode	Platinum, primary, at refinery/RU S	mg	370.89
	Carbon black I	mg	556.34
	Carbon and graphite products	USD	38.66
	Electricity mix/US S	kWh	32.74
Anode	Carbon and graphite products	USD	131.44
Electrical Wire	Wiring devices	USD	6.13
Holding Tank	Plastic materials and resin	USD	5.25
Electricity Production	Electricity mix/US S	Wh	88.25

Appendix B. Side-lying design MFC system inventory table

EIO LCA

	Simapro input	Unit	Unit/1KGD	
Rubber	Synthetic rubber	USD	$1.14	
Synthetic glass	Plastics materials and resins	USD	$316.54	
Titanium Wire	Wiring devices	USD	$514.33	
anode	Carbon and graphite products	USD	$8.64	
cathode	Carbon and graphite products	USD	$267.09	$273.85
Substrate	industrial inorganic and organic chemicals	USD	$185.91	
Electricity Production	Electricity mix/US S	kwh	0.94	1.24

Hybrid LCA

Product		Simapro Input	unit	Unit/ 1kGD	
	Rubber	Synthetic rubber, at plant/RER S	g	589.82	
Reactor	Synthetic glass	PMMA I	kg	16.30	
Wire	Titantium Wire	Titanium I	g	10.49	
	Acetone	Acetone E	g	41.02	
anode	Carbon mesh	carbon and graphite products	$	7.25	
	Carbon cloth	carbon and graphite products	$	38.00	
	PTFE solution	Tetrafluoroethylene, at plant/RER S	g	153.61	192.01
	Pt	Platinum, primary, at refinery/RU S	g	0.44	
	Carbon Black	Carbon black I	g	7.70	
	Pure iso-propanol	Isopropanol, at plant/RER S	g	11.65	
	Energy consumption	Electricity mix/US S	kwh	61.73	
	DI water	Tap water, at user/RER S	g	3.69	
		1-propanol, at plant/RER S	g	12.95	
		Methanol, at plant/GLO S	g	0.77	
cathode	Nafion	Plastics materials and resins	$	2.85	
substrate	acetate	sodium acetate, trihydrate, at plant	kg	3.79	
Electricity	Energy generated	Electricity mix/US S	kwh	0.94	1.24

Appendix C. Aeration system inventory table

EIO LCA

Product	Simapro input	Unit	Unit/ 1kGD
Air Pump	Pumps and compressors	USD	7.49
Tubing	Plastic materials and resin	USD	4.55
Holding Tank	Plastic materials and resin	USD	4.55
Electricity Consumption	Electricity mix/US S	kWh	156.00
sedimentation clarifier	concrete products, except block and brick	USD	0.02
sludge		kg	1.475