AN ABSTRACT OF THE THESIS OF

Ku-Huan Chien for the degree of Master of Science in Biological and Ecological Engineering presented on March 18, 2016.

Title: Life Cycle Assessments for Wastewater Treatment and the Feasibility Study of Microbial Fuel Cell Technology

Abstract approved:

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Hong Liu

The thesis documents research about combining the National Pollutant Discharge Elimination System (NPDES) Permit Program with the Impact 2002+ methodology to conduct a Life Cycle Assessment (LCA) for wastewater treatment processes. The LCA for the operational phase of a local wastewater treatment plant was performed and the environmental impacts caused by wastewater treatment processes were quantified. The results suggest that the base-neutral compounds released from wastewater treatment processes had the most negative influence on human health and heavy metals mainly affected the aquatic ecosystem. The aquatic eutrophication caused by COD was over 7 times higher than ammonia. With respect to global warming effect, the carbon dioxide released from wastewater treatment processes was 2.22 times higher than the methane gas released from the anaerobic digester. In addition to the LCA of

current wastewater treatment processes, the feasibility of using Cloth Electrode Assembly Microbial Fuel Cell (CEA-MFC) technology to replace Activated Sludge technology was explored through comparing the capital and operational costs of the two systems. The results suggest that the CEA-MFC system is a promising technology which can significantly reduce the energy consumption in the conventional wastewater treatment plants.

Life Cycle Assessments for Wastewater Treatment and the Feasibility Study of Microbial Fuel Cell Technology

by
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A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Presented March 18, 2016
Commencement June 2016

Master of Science thesis of Ku-Huan Chien presented on March 18, 2016

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Ku-Huan Chien, Author

ACKNOWLEDGEMENTS

I would like to thank my major professor Dr. Hong Liu, committee members Dr. Yanzhen Fan and Dr. Chih-hung Chang as well as my Graduate Council Representative Dr. Rebecca A. Hutchinson for letting me do research directly connected to our daily life (wastewater treatment processes), giving me guidance when I didn't know how to continue, and evaluating my work with kindness, fairness and encouragement. I also want to expresses sincere appreciation to people who gave me courage and confidence when I really wanted to give up. The research took much longer time than I expected to finish due to my health issues and the difficulties of collecting and analyzing data. The research actually covered three different scientific areas: Life Cycle Assessment, Wastewater treatment processes, and CEA-MFC technology. This research was not an easy task at all; however, only the people who actually did it would know the situation. It was impossible for me to finish the work if criticisms were the only things that I could receive. Their great patience and encouragement helped me complete the research. Finally, I wish to show gratitude to Steve Schnurbusch (Oregon DEQ), Carla Holzworth, Mary Steckel, Tom Hubbard (City of Corvallis), Stan Miller and James Green (Corvallis Wastewater Reclamation Plant) for providing me with valuable data in a supportive and timely manner.

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Chapter 1 – Introduction

1.1 History of Wastewater Treatment in the US

In the early 19th century, the main goal of wastewater treatment in the US was to collect water and prevent diseases. The wastewater treatments at that time stayed at the phase that we call primary treatment in today's wastewater treatment procedures. In 1899, the US government passed the "Refuse Act (the first federal regulation of sewage, Rivers and Harbors Appropriations) to prohibit discharge of solids to navigational waters. Afterwards, different mechanical filters were built and operated. For example, the first trickling filter was installed in Madison, Wisconsin in 1901 and the first activated sludge plant was built in San Marcos, Texas in 1916.

Between 1920 and 1940, removing the BOD from wastewater was developed into the phase that we call secondary treatment in today's wastewater treatment procedures. Subsequently, the Federal Water Pollution Control Act, Clean Water Restoration Act and Clean Water Act were passed to manage wastewater treatments in 1948, 1966 and 1972 respectively.

The Clean Water Act (CWA) is the criteria that the U.S. Environmental Protection Agency (EPA) uses to write wastewater discharge permits for different types of wastewater treatment plants. One of the most important features of the CWA is the National Pollutant Discharge Elimination System (NPDES) Permit Program. The NPDES is used for the control of toxics, industrial pretreatment and sludge (bio-solids) disposal and it is also the guidance for the tertiary phase of modern wastewater treatment procedures.

1.2 Today's Wastewater Treatment in the US

The contemporary wastewater treatment in the US consists of primary, secondary and tertiary treatment phases. In general, there is a preliminary treatment step before the primary treatment phase and a disinfection step after the tertiary treatment phase.

Preliminary treatment: The purpose of this step is to remove large objects: trash, leaves, plastics, sticks, etc. The influent wastewater always has bulky solids that will clog pipes and destroy pumps down the line, so they must be removed or diminished in the beginning of wastewater treatment procedures. Large screens made of steel or iron bar sets are used to wipe out bigger debris. In some wastewater treatment plant, the sizes of these large solids are further reduced by devices such as grinders to ensure that they won't impede the downstream processes. Next, a grit chamber is used to make the gravel and sand in wastewater drop to the bottom for the subsequent primary treatment phase. The removed solid materials are usually incinerated or buried in a landfill.

Primary treatment: This phase utilizes specifically designed clarifiers (sedimentation tanks) to eliminate floatable substances and suspended solids. Clarifiers are settling tanks which utilize mechanical methods to constantly remove solids being deposited by sedimentation. These mechanical methods are simple physical processes: screening, skimming, and settling. Many kinds of suspended solids which are not heavy enough to fall to the bottom of the previous grit chamber will be handled via these physical processes in this phase. They become the so-called sludge and are discharged from the bottom of clarifiers. In contrast with suspended solids, these floatable substances are generally called scum such as oil and grease. They are skimmed

off the top while the wastewater is held in the mechanical clarifiers. The solids removed during the primary treatment stage have another name called primary solids. The primary solids and the floatable substances need to be further treated, dumped or incinerated.

Secondary treatment: In spite of the primary treatment stage, smaller solid materials can still float on the surface or dissolve in the treated wastewater. The secondary treatment phase is a biological process that uses microorganisms to consume these smaller solid materials. The biological process of the consumption can turn floated or dissolved solids into active microorganisms (suspended solids), which is typically called activated sludge, generating cleaner water and carbon dioxide.

The activated sludge process has three variations: suspended growth activated sludge, fixed-growth activated sludge and membrane bioreactors. The suspended growth activated sludge means that microorganisms are suspended anywhere in a tank. The fixed-growth activated sludge inserts different media into a tank to increase the growth of microorganisms which can react with organic materials in wastewater. The membrane bioreactors draw clean water through a membrane filtering equipment at the end of the tank and leave the solids in the tank.

The activated sludge basins generate two types of activated sludge: return activated sludge and waste activated sludge. The return activated sludge contains active microorganisms and will be circulated back to repeat the biological process. On the other hand, the waste activated sludge will be removed for further treatment.

Tertiary treatment: The purpose of this phase is to remove even smaller suspended solids, nutrients and certain specific toxic substances. The nutrients, in particular phosphorus and nitrogen, can aid in the growth of aquatic life such as algae; the excessive plant growth will

make the oxygen dissolved in water for other aquatic life become insufficient. In a word, they enrich many other water bodies and cause eutrophication which damages the quality of water resources.

Disinfection: The goal of this step is to kill or remove pathogenic bacteria and viruses from the treated wastewater. Traditionally, wastewater treatment Infrastructure uses a chlorine solution to disinfect or kill pathogens and the process is called chlorination. However, the chlorine solution generates chlorine gas which is perilous. Furthermore, the chlorine remained in the treated water after the disinfection can harm the aquatic life, so it must be removed by the process named de-chlorination. Typically, sulfur compounds like sulfur dioxide are used to absorb the chlorine remained in the treated water. It is worth mentioning here, the chlorine solution is gradually replaced by sodium hypochlorite solutions due to its toxicity.

Besides using a chlorine solution to disinfect wastewater, there are two more options used for disinfection: ozone and ultraviolet (UV) light. Using ozone to disinfect or kill pathogens is a well-thought-out method since it is safer in comparison to the chlorine solution. Not only can ozone oxidize organic compounds and kill pathogens, but it also can be created onsite without storing in large volumes which can avoid unexpected accidents. As for the second option, the UV light can quickly disinfect or kill pathogens while the wastewater flows through a series of submerged UV light bulbs, so the ultraviolet (UV) light disinfection is relatively considered the safest means for the wastewater disinfection in the present technologies.

As a whole, the current wastewater treatment processes consume too much energy especially in the secondary treatment procedures. They are biological processes in the activated sludge basins. A lot of electricity is used for the aeration purpose. The energy issue will be discussed in the later sessions and chapters.

1.3 Life Cycle Assessment (LCA) for wastewater treatments

Generally speaking, a LCA study can aid in decision-making, the quantification of the overall environmental impact of a wastewater treatments system, and then improve the environmental aspects of the wastewater treatments infrastructure. Nevertheless, the LCA research for wastewater treatments has not been widely performed hitherto. First, collecting data and building a database management system is a time and energy consuming task. Due to limited budgets, human resources and time-limitations, most researchers and the industry hesitate to carry out this sort of research. Second, the LCA research related to wastewater treatments is rather complicated. It is difficult to set up an appropriate model which can properly demonstrate the real wastewater treatments system because the wastewater treatments infrastructure is a dynamic system and many variables interact with each other within the system. For example, the components of the inputs and outputs vary all the time during the wastewater treatments processes. It is hard to predict what substances will come in at the beginning of these processes and what pollutants will be released at the end of these processes. Third, most studies on LCAs for wastewater treatments processes are in fact at a strategic level; they only offer guidance of how to conduct LCAs for wastewater treatments processes and how to perform water footprint assessments.

1.4 Microbial Fuel Cells (MFCs) for wastewater treatments

Microbial Fuel Cells (MFCs) could be promising technologies for wastewater treatment processes since they can generate electricity and clean up wastewater at the same time. Current wastewater treatment systems consume a lot of energy such as electricity and produce a variety of pollutants. Their energy efficiency ratios are low and these processes are environmentally unfriendly. An introduction of MFCs into wastewater treatments processes is expected to be able to offset the consumption of energy and diminish the amount of the pollutants. As it is mentioned earlier, the electricity needed for the aeration in the activated sludge basins is a serious energy issue that should be overcome. The MFC technology could be a solution to this issue and it will be discussed later on.

1.5 Goals of the research

In order to conquer the above difficulties of performing LCAs for wastewater treatment processes, evaluate the applications of MFCs for the protection of environment and energy conservation, building templates and database system for wastewater treatment processes is indispensable. The templates and database system will make LCA research for wastewater treatment processes move forward. The results of the LCA can also be utilized to estimate the possibility of introducing the MFC technology into the system of wastewater treatment processes.

In short, there are three goals in this research. The first goal of the research is to carry out a LCA for wastewater treatment procedures based on their unit processes. The second goal of this study is to quantify and evaluate the overall environmental impacts of wastewater treatments plants by combining the IMPACT 2002+ LCA methodology with the National Pollutant Discharge Elimination System (NPDES)

Permit Program. The final goal of the research is to explore the feasibility of using a microbial fuel cell (MFC) system to replace the activated sludge basins in the traditional wastewater treatment system. In this study, a cloth-electrode assembly microbial fuel cell (CEA-MFC) system was used to achieve the last goal.

Chapter 2: Literature Review

2.1 Microbial fuel cells (MFCs)

The design of a MFC has no obvious differences from other fuel cells in terms of electrochemistry: oxidation and reduction. A rudimentary MFC primarily consists of an anode, a cathode, a wire loaded with a resistor and a proton exchange membrane or a salt bridge. The significant difference of a MFC is that it uses naturally occurring microorganisms to decompose organic compounds and generate electricity. Bacteria in a MFC act as a catalyst to oxidize organic matters. First, an oxidation reaction occurs in the anode compartment of a MFC; that is, bacteria remove electrons from some organic matters (substrates) during the biological process of the decomposition. They will transfer the electrons to the anode. Second, the electrons on the anode are transferred to the cathode of the MFC via the wire loaded with a resistor. Finally, the reduction reaction occurs in the cathode compartment; namely, the electrons on the cathode react with protons and oxygen to form water. As a result, a current and voltage are produced to engender electricity during the continuous electrons flow from the anode to the cathode.

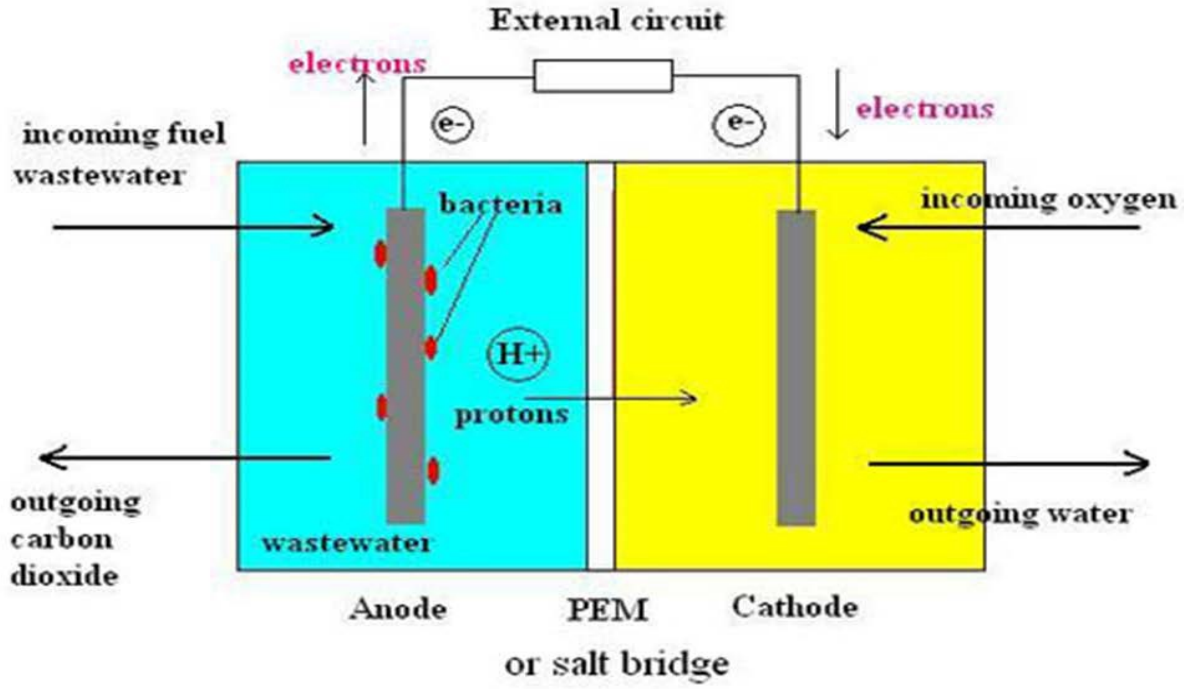


Figure 2.1 Microbial fuel cells Source: www.sciencebuddies.org

2.1.1 History of microbial fuel cells

The history of microbial fuel cells (MFCs) can be traced back to 1780. Luigi Aloisio Galvani, an Italian physician, found that sparks could twitch the muscles of frog's legs even though they were dead [Whittaker, E. T. (1951)]. It is generally considered the beginning of bioelectricity research. Nonetheless, it then took nearly 131 years for scientists to discover the possibilities of converting biological and chemical energy into electricity. In 1911, M. C. Potter, a professor at the University of Durham in England designed an apparatus to explore the electrical effects accompanying the decomposition of organic compounds and the results of the research was published by the Royal Society (Potter, 1911). Nevertheless, M. C. Potter's work didn't draw

enough attention at that time. In 1931, Barnet Cohen, a Russian-born American bacteriologist successfully designed a series of microbial half fuel cells to create electricity by connecting them to each other (Cohen, 1931). From then on, scientists began to put more efforts in this field of bioelectricity.

In 1963, the research team of DelDuca invented a new type of biological fuel cell which was named hydrogen and air fuel cell (DelDuca et al, 1963). Their biochemical fuel cell used the hydrogen from the fermentation of glucose by Clostridium butyricum as the reactant at the anode to make electricity, but these biochemical fuel cells couldn't offer a constant current output as they expected since the bacterial hydrogenase system created by the Clostridium butyricum was extremely unstable. The problem of their work was resolved thirteen years later by the research team of Karube (Karube et al., 1976). Karube et al. stabilized the hydrogenase system in Clostridium buryricum with polyacrylamide gel and successfully remained a constant current of 1.1 to 1.2 mA for their biochemical fuel cell over the observation period of fifteen days.

The revolution of MFCs designs was initiated by MJ Allen and H. Peter Bennetto from King's College London in the UK in 1980s. The two researchers had an ambition of using MFCs to provide developing countries with inexpensive and stable electricity. They re-designed the original MFCs and studied the mechanism about how electricity can be made directly by degrading organic matters in a microbial fuel cell. Their designed MFCs are considered as the start of modern MFCs and are still used even today when researchers make basic MFCs. Afterwards, Kim B.H et al., from the Korean Institute of Science and Technology, found some

electrochemically active bacteria [Fe (III) reducing bacterium, Shewanella putrefacience] (Kim B.H et al., 1999). It was the last meaningful discovery about MFCs in 20th century. It led to the birth of mediator-less and mediator-free MFCs in 21st century and enhanced the possible utilization of MFCs in many scientific fields.

2.1.2 MFC configurations

Generally speaking, air-cathode MFCs have more potentials than MFCs with proton exchange membranes since they generate relatively high power density. Besides, their configurations and cost are simple and low. Nonetheless, a MFC without a proton exchange membrane will face two issues: the risk of short circuit and the influence from oxygen on the activity of the anaerobic bacteria on the anode (H. Liu et al., 2004). Therefore, Fan et al. created the so-called cloth electrode assembly microbial fuel cell (CEA-MFC) to conquer the two challenges (Yan et al., 2007). In their experiment, a J-cloth was sandwiched between the anode and the cathode of a MFC. The purpose of this design was to reduce the internal resistance and the oxygen diffusion rate of the MFC, so that the power density generated by this type of MFC could be expected to be much higher than other types of MFCs. The results of that research showed a promising future of using CEA-MFCs. The coulombic efficiency of the single chamber air-cathode CEA-MFC was increased when a two-layer-J-Cloth was applied on the water facing side of the air cathode (71% versus 35%). This cloth layer significantly reduced the spacing between electrodes and formed a cloth-electrode-assembly configuration. As a result, the designed CEA-MFC in the investigation in 2007 reached very high power densities of 627Wm^{-3} (fed-batch mode) and 1010Wm^{-3} (continuous-flow mode). The two numbers were about 15 times higher than other

types of MFCs using similar electrode materials at that time. The inexpensive J-Cloth improved the Coulombic efficiency and power density of the air-cathode MFCs. A figure of the comparison of the schematic of air-cathode MFCs and air-cathode CEA-MFCs was cited from the original paper for readers review.

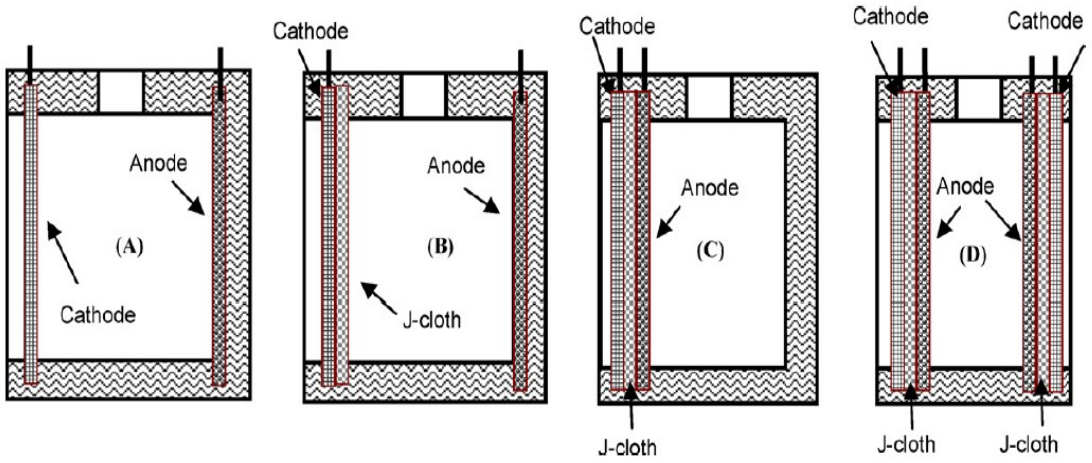
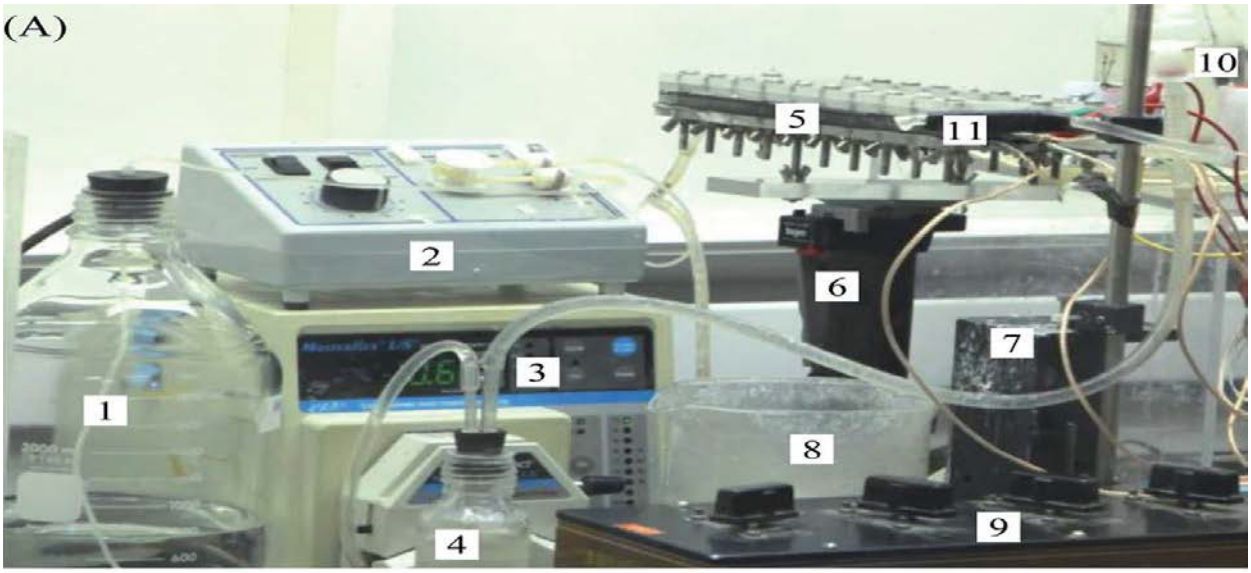


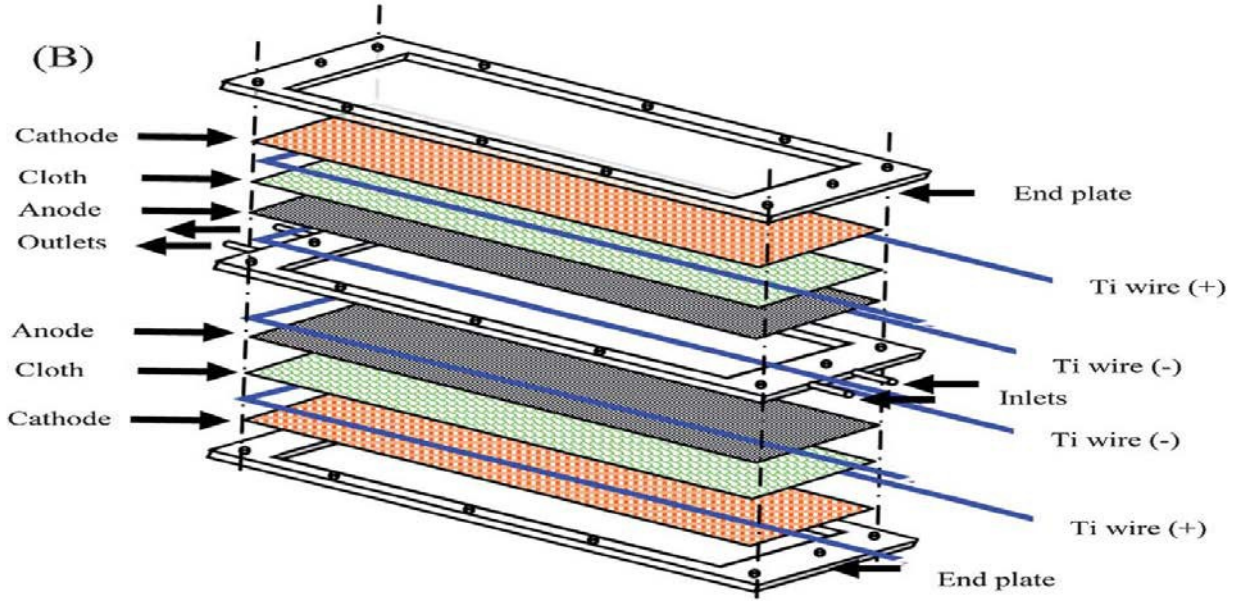
Fig. 1. Schematic of MFCs (A) without J-Cloth, (B) with J-Cloth, (C) with single CEA (cloth electrode assembly), and (D) with double CEAs.

Comparison of the Schematic of Air-Cathode MFCs and Air-Cathode CEA-MFCs
Figure 2.1.2 (a) Source: Fan et al., 2007

Due to the excellent performance and competitive material price of the CEA-MFC, a better double CEA-MFC reactor was again created by Fan et al. in 2012. In that experiment, a new separator material and U-shaped current collectors were introduced into to the bio-reactor. First, a non-woven fabric layer (Armo Style # 6000) replaced the J-cloth used in 2007 to be sandwiched between the carbon cloth anode (CCP, fuelcellearth.com) and the carbon cloth/Pt/PTFE cathode (20% of Pt/C catalyst; E-TEK, USA) to form two CEA-MFCs. Then, U-shaped Ti wires were chosen to be the anode and cathode's current collectors for the two CEA-

MFCs. As a final step, three identical 0.6 cm thick acrylic frames were put beyond, into and under the two CEA-MFCs to form a five-layer sandwich CEA-MFC reactor. The liquid volume of the CEA-MFC reactor was 30 ml and its total effective surface area is 200 cm^2 (Fan et al., 2012). A detailed configuration of the double CEA-MFC reactor was directly cited from the original paper in the next page for readers review.





(A) A photo of the experimental setup testing the large MFC. (1) Feed bottle, (2) feed pump, (3) recirculation pump (optional), (4) recirculation bottle, (5) larger reactor, (6) tilt angle adjusting device for the reactor, (7) outlet level control device, (8) effluent reservoir, (9) precision resistor box, (10) gas sampling port, and (11) effluent outlet. (B) Schematic of the large reactor with double cloth-electrode-assemblies.

Schematic of the double CEA-MFCs and its experimental system
Figure 2.1.2 (b) Source: Fan et al., 2007

The double CEA-MFC was tested by food-processing wastewater to see its potential applications for food manufacturing wastewater treatment. This experiment had an exciting result; a maximum power density of 4.30 Wm^{-2} at a current density of 16.4 Am^{-2} was harvested, and a volumetric power density of 2.87 kWm^{-3} at 10.9 kAm^{-3} was generated. A high average coulombic efficiency (CE) of 83.5% and a high potential COD removal rate of 93.5 kg m^{-3} d^{-1} were obtained in this research due to the high current density. In comparison to the J-cloth used for the previous air-cathode CEA-MFC designed in 2007, the lower cost non-woven cloth separator had a better capacity of reducing the anode–cathode spacing and internal resistance, and significantly increasing the power generation. The results of this research also demonstrated the feasibility of using CEA-MFCs for different kinds of wastewater treatment processes because it obviously appeared that the CEA-MFC structure could effectively maintain its performances during scale-up. One of the biggest challenges of the MFC technology is the difficulty of scaling up. It is because the enlarged anode–cathode spacing during scale-up always comes with decreased performances. In brief, based on the progress and results of Fan et al.'s research in the past eight years, the double CEA-MFC should be able to be further developed and applied for the wastewater treatment industry in the future. In this research, the CEA-MFC reactor designed by Fan et al. in 2012 would be scaled up in theory and then used as a basic unit for municipal wastewater treatment processes. A simulation model would be run to evaluate its potentials for a wastewater treatment plant with 10.4 MGD (million gallons per day) wastewater.

2.1.3 Applications of microbial fuel cells

Microbial fuel cells (MFCs) have a lot of potential applications in many scientific fields: desalination, brewery or food manufacturing, wastewater treatment, sewage treatment, electricity generation, Hydrogen gas production, and so on. Most of the above scientific fields and industries share some common problems; they all consume a lot of energy such as electricity and natural gas to achieve their goals and may create numerous pollutants during their chemical and biological processes. In fact, about 3% of the U.S. electrical energy load was for the wastewater treatments (US EPA 2006). This electricity consumption rate in the US for the wastewater treatment processes is not different from that in other developed countries (Curtis, T. P., 2010). In other words, the high energy consumption rate for wastewater treatment process has become a common challenge that all developed countries in the world are facing. Municipal Wastewater Treatments are good examples to explore and demonstrate the possible applications of MFCs since their treatment processes are energy intensive, and could cause a lot of environmental damages if their operations are not carefully monitored and controlled. It is impossible to ignore the above fact and avoid the problems because our society and civilization cannot continue without having them. Fortunately, MFCs could be solutions to many of these concerns and problems, especially the energy conservations, crises of clean water resources and environmental pollutions from a variety of wastewater treatment processes. MFCs can generate electricity at the same time while they are utilized to treat wastewater. The electricity produced by MFCs can offset the colossal consumptions of energy on the traditional wastewater treatment processes since conventional wastewater treatment plants don't have any facilities in their infrastructure which can generate electricity. In a word, one of the most significant applications of MFC technology is its potential to convert the energy intensive wastewater treatment industry into an energy producer.

2.1.4. Municipal Wastewater Treatment:

Making beer or food consumes a lot of energy and water, so it always creates a great deal of wastewater and it is energy-intensive as well. Treating daily wastewater from individual households and industries in modern cities also face the same or similar issues. Installing MFCs to a brewery or food manufacturing factory could be a wise option to resolve the high energy consumption and wastewater treatment issues simultaneously. First, brewery or food manufacturing wastewater includes many organic matters which can be nutrients for the microorganisms in the wastewater. Second, electricity harvested by MFCs can be used to lower the cost of the high energy consumption. The possibility of using MFCs to generate electricity during wastewater treatment was successfully demonstrated via a single chamber microbial fuel cell (SCMFC) by Hong Liu & Logan (H. Liu. et al., 2004). In that research, the generated electricity of the prototype SCMFC reactor reached a maximum value of 26 mW m-2, and the removal rate of COD of the wastewater was also up to 80%. Later on, more researchers directly used SCMFCs for Brewery Wastewater Treatment and obtained promising results. For example, X. Wang, Y. J. Feng and H. Lee in China used a single chamber membrane-free microbial fuel cell to make electricity from beer brewery wastewater (X. Wang et al., 2008). Their investigations presented that a maximum power density of 483 mW/m2 was achieved at 30 °C and the other maximum power density of 435 mW/m2 was observed at 20 °C for the beer brewery wastewater treatments by using the MFC technology.

2.1.5. Sewage treatment:

According to the previous research conducted by Hong Liu & Logan (H. Liu. et al., 2004), SCMFCs are useful for sewage sludge treatment as well ; they have the capacity of removing nearly constant at 78±2% of organic material in sewage sludge in terms of BOD. On the other hands, the reduction in COD only ranged from 50 to 70%. They concluded that COD removals were typically lower than those for BOD removal since not all organic compounds in the wastewater can be decomposed biologically. Moreover, they discovered that a large percentage of the organic matter in the wastewater was removed by the processes that did not produce electricity. To sum up, in order to obtain better results, non-biodegradable materials in the sludge wastewater are supposed to be removed before SCMFCs are used to clean up the wastewater. Also, it is necessary to increase the fraction of the organic matter that can be converted into electricity. The two things are the extra work required to be done when using SCMFCs to clean up sludge wastewater in comparison to the Brewery or Food Manufacturing Wastewater Treatment. Afterwards, the MFC technology for different sewage sludge types was tested by many research groups. These studies covered a series of sewage sludge types: primary sludge (Zhang et al., 2012: Ge et al., 2013: Yang et al., 2013), digested sludge (Hu, 2008; Xiao et al., 2011; Ge et al., 2013) and raw sludge (Jiang et al., 2009; Xiao et al., 2011; Mohd Yusoff et al., 2013). In 2008, the researcher Zhiqiang Hu used a baffle-chamber membraneless MFC to generate electricity from the anaerobic sludge; a power density of 0.3 mW m−2 was acquired. Next year, in 2009, Jiang et al. used a two-chambered microbial fuel cell (MFC) to degrade excess sewage sludge and to generate electricity. The MFC power output in that research didn’t increase significantly, but the total chemical oxygen demand (TCOD) of sludge

was reduced by 46.4%. In 2011, Xiao et al., used a two-chamber MFC to treat different sewage sludge types: raw sludge, sterilized sludge and base pretreated sludge. All of the voltage outputs and power densities of the targeted sludge types in that research increased: raw sludge (0.30–0.32 V and 19.9–22.6 mW/m2), sterilized sludge (0.34–0.36 V and 25.5–28.6 mW/m2), and base pretreated sludge (0.41–0.43 V and 37.1–40.8 mW/m2). The same year, in 2011, Zhang et al., incorporated bio-cathodes into a three-chamber MFC to treat sewage sludge and a much higher power output of 13.2 ± 1.7 W/m3 was obtained. Subsequently, in 2013, Mohd Yusoff et al., discovered that the activated sludge pretreated by microwave could acquire better electricity productivity in MFCs and a higher COD reduction rate 55%. In the same year, another research group, Yang et al. used single-chamber air-cathode microbial fuel cells (MFCs) to treat the fermented primary sludge and produce electricity. An increased power density 0.32 ± 0.01 W/m2 was observed with the fermented primary sludge. In addition, the soluble COD (sCOD) removal rate was also increased from 84% to 94%. Based on the above studies, the possibility and significance of using the MFC technology for the sewage sludge treatment has become unquestionable.

2.2 Life Cycle Assessment (LCA)

According to the International Organization for Standardization (ISO) 14040:2006(E), a Life Cycle Assessment (LCA) is a compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle. It indicates that the specific analysis evaluates all possible environmental influences of a product or service system throughout its lifetime, that is, the entire cradle-to-grave phases. Concretely speaking, these

phases comprise the extraction of raw materials; the processing, manufacturing, and fabrication of the product; the transportation or distribution of the product to the consumer; the use of the product by the consumer; and the disposal or recovery of the product after its useful life (Tellus Institute in Boston, Massachusetts).

A complete LCA consists of four stages: goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA) and interpretation. The results of a LCA can be utilized in many areas such as product development and improvement, ISO 14040:2006(E). An illustration of an interactive life cycle assessment framework was cited directly from ISO 14040:2006(E) and showed below for better understanding.

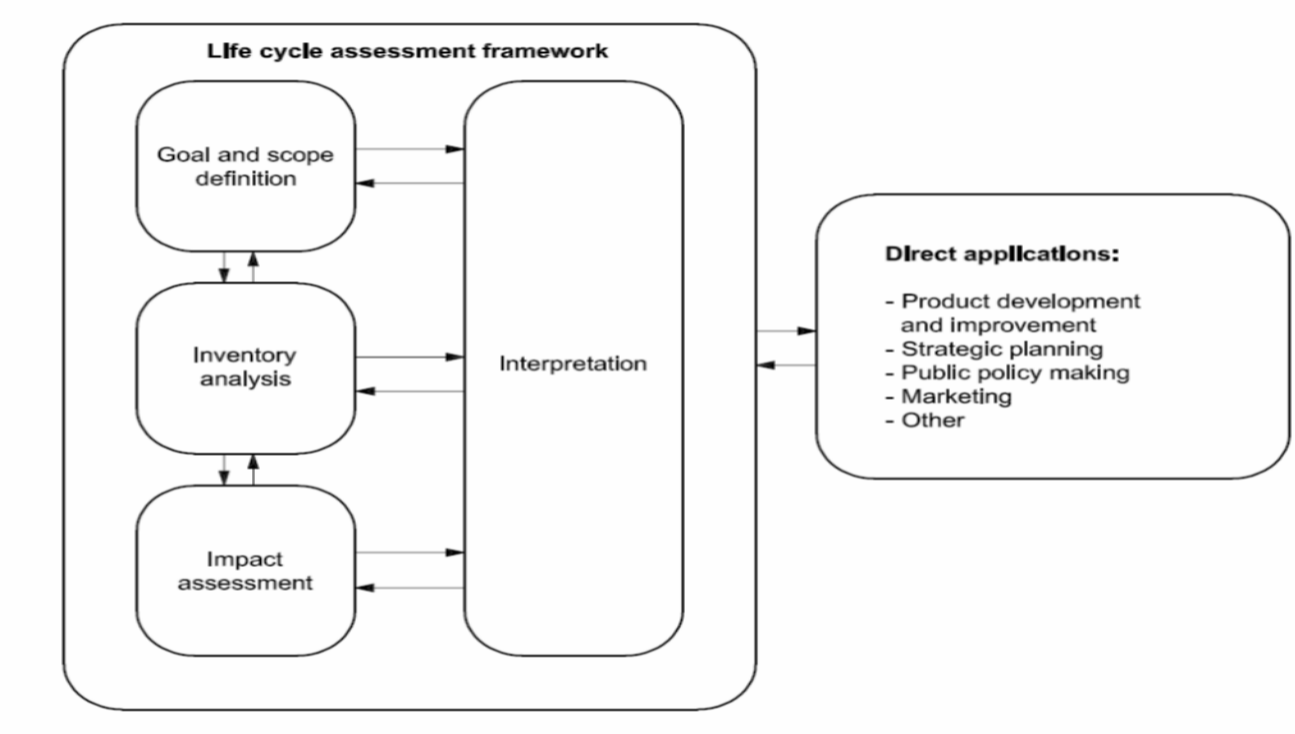


Figure 2.2 LCA framework source: ISO 14040:2006(E)

Goal and Scope Definition:

The first stage of conducting a LCA is to clearly define its goal and scope. It is impossible to obtain decent results which can accurately reflect the real environmental impact from all related elements in a production system without defining the goal and scope of the research. The goal of a LCA usually is the intended applications of the targeted subjects or the reasons for conducting the research, so it is not difficult to be defined. However, the definitions of the scope of a LCA are relatively complicated since the items needed to be considered for the scope are more than those for the goal. The scope often contains the function unit, system boundary, allocations, assumptions, limitations and so on. Among these items, the function unit and system boundary are more necessary for carrying out the research. The intention of defining a function unit is to ensure that all related items in different system can be compared on a common basis. The purpose of setting up a system boundary is to define the unit processes to be included in the system. Additionally, all inputs and outputs at this boundary should be elementary flows. The following items are common considerations when establishing a system boundary: acquisition of raw materials, input and output in the main manufacturing or processing sequence, disposal of process wastes and products, etc. [ISO 14040:2006(E)]

Life cycle Inventory analysis (LCI):

The second stage of performing a LCA is to collect and calculate data because an inventory analysis requires this information to quantify the relevant inputs and outputs of the studied production system. Most of the data are information about energy flows, products & wastes,

emission to air, discharge to water or soils, and so on. [ISO 14040:2006(E)] This is an iterative and time-consuming process, but it is inevitable when conducting a LCA.

Life cycle Impact assessment (LCIA):

This is the third stage of a LCA. The stage begins to use the results of the inventory analysis (the second stage) to assess the potential environmental impact of the studied system. First, choose impact categories, category indicator, and characterization models from the mandatory elements of the system. Second, assign the LCI results (classification). Third, calculate the category indictor results (characterization). After the three steps are completed, the results for the LCIA can be obtained. If a more detailed LCIA profile is required, calculate the magnitude of category indictor results (normalization).

Interpretation:

Interpretation is the last stage of a LCA. It puts the results of Life cycle Inventory analysis and Life cycle Impact assessment together to provide its intended audience and researchers with comprehensive conclusions and recommendations which are consistent with the previously defined goal and scope. Scholars and decision-makers can use the interpretation of the LCA to make new scientific proposals or public policies.

2.3 IMPACT 2002+ for Life Cycle Assessment

The Swiss Federal Institute of Technology Lausanne (EPFL) in Switzerland is the original developer of the IMPACT 2002+ for Life Cycle Assessment. Olivier Jolliet, an assistant professor at EPFL, worked with his colleagues and other researchers from different research institutes to develop the novel Life Cycle Impact Assessment Methodology. The result of their research (IMPACT 2002+) was published on the International Journal of Life Cycle Assessment 10 (6) in 2003. The IMPACT 2002+ has drawn many attentions since its publication. It has become one of the most popular Life Cycle Assessment methodologies and been utilized by many LCA experts nowadays.

The IMPACT 2002+ methodology for Life Cycle Assessment is a combination and improvement of Classical impact assessment methods and Damage oriented methods. The former indicates CML (Guinéeet al. 2002) and EDIP (Hauschild and Wenzel 1998) while the latter refers to Eco-indicator 99 (Goedkoop and Spriensma 2000) or EPS (Steen 1999).

One of the features of the IMPACT 2002+ is that the comparative assessment of human toxicity and eco-toxicity has been created in this methodology. Besides, the mean responses replace the conservative assumptions to calculate the toxicity and eco-toxicity effect factors in the IMPACT 2002+ [Jolliet et al. (2003a)].

There are fourteen midpoint categories (human toxicity, respiratory effects, ionizing radiation, ozone layer depletion, photochemical oxidation, aquatic ecotoxicity, terrestrial ecotoxicity,

terrestrial acidification/nutrification, aquatic acidification, aquatic eutrophication, land occupation, global warming, non-renewable energy, mineral extraction) in the IMPACT 2002+ methodology, and they are eventually connected to four endpoint (damage) categories (human health, ecosystem quality, climate change, resources) to show an overall environmental impact of a production system.

A midpoint category indicates an elementary flow. Different midpoint categories are possible to be connected to the same or different endpoint categories since they are on an intermediate position between the LCI results and the final environmental damage impact. In contrast, an endpoint category is a sum of influences from diverse midpoint categories and a quantified representation of the damage impact.

The units used in the IMPACT 2002+ are unique and specifically defined. They can be discussed at three levels: midpoint level, damage level and normalized damage level. At midpoint level, "kg substance $s\text{-}_{eq}$" ("kg equivalent of a reference substance s") is used as its unit. It means that the targeted contaminants are expressed by the amount of the reference substance s that has same environmental impact. At damage level, first, the "DALY" ("Disability-Adjusted Life Years") is the unit used to calculate mortality and morbidity. Second, the unit of "$PDF \cdot m^2 \cdot yr$" ("Potentially Disappeared Fraction of species per m^2 per year") is used to measure the impacts towards ecosystems. Third, the unit of MJ ("Mega Joules") is used to measure the amount of energy needed for extracting the resource. At normalized damage level, points are the unit used for this level. The average impact in a specific category from a person in a year is considered one point.

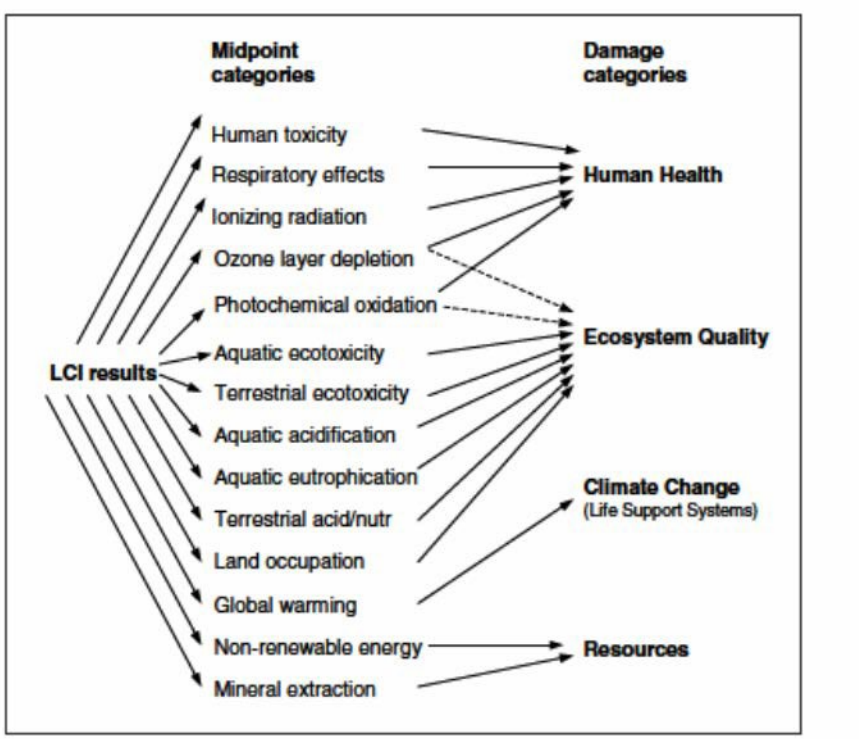


Figure 2.3: Overall scheme of the IMPACT 2002+ framework, linking LCI results via the midpoint categories to damage categories, based on Jolliet et al. (2003a)

The IMPACT 2002+ methodology allows normalizations to be performed at both midpoint and endpoint. At this time, about 1500 different LCI-results are covered in the IMPACT 2002+. The 1500 LCI-results are the data of their midpoint characterization factors, damage factors, normalized midpoint characterization factors and normalized damage factors. They can be used directly when conducting different types of LCAs.

2.3.1 Midpoint Categories of IMPACT 2002+

1. Human toxicity: carcinogenic and non-carcinogenic effects

The calculation of Human toxicity includes all possible effects on human health, but it doesn't consider influences from ionizing radiation effects, photochemical oxidation effects, respiratory effects caused by inorganics and ozone layer depletion effects since different approaches are used to evaluate their impacts. The cumulative toxicological risk and potential impacts of considered pollutants are shown in a quantified form of a reference substance that can cause equal damage to human beings. The Human toxicity CFs use chloroethylene as a reference substance and their calculations are made based on the amount of (kg Chloroethylene-$_{eq}$) chloroethylene emitted into air.

2. Respiratory effects (caused by inorganics)

This midpoint category adopts the results and Data from Eco-indicator 99 (Goedkoop and Spriensma 2000) to calculate or set up the Characterization factors (CF) values of considered pollutants. The unit of the CFs for Respiratory effects is expressed in DALY/ kg $PM_{2.5\text{-}eq}$ into air. The $PM_{2.5}$ refers to all particles which are smaller than 2.5 μm. The calculations of the CFs of pollutants are made based on the amount of the $PM_{2.5}$ pollutants emitted into air.

3. Ionizing radiation

The midpoint Characterization factors (CFs) for Ionizing radiation use Carbon-14 as a reference substance and their values are shown in the form of the amount of Carbon-14 emitted into air. They are expressed in DALY/Bq Carbon-14-eq into air.

4. Ozone layer depletion

Trichlorofluoromethane (CFC-11) is used as a reference substance for this midpoint. The midpoints CFs for Ozone layer depletion are expressed in DALY/kg CFC-11-eq into air. These data come from the US Environmental Protection Agency Ozone Depletion Potential List (EPA).

5. Photochemical oxidation

Ethylene is used as a reference substance for the photochemical oxidation midpoint category. The calculations of the CFs for photochemical oxidation consider the emissions into air only since these types of pollutants are not likely to be emitted into soil or water. The midpoints CFs for Photochemical oxidation are expressed in DALY/kg Ethylene-eq into air. Photochemical oxidation could have negative influences on both human health and ecosystem quality.

6. Aquatic eco-toxicity

Only the effects on streams and lakes (fresh water) are quantified to show their environmental influences. Triethylene glycol is used as a reference substance for aquatic eco-toxicity. The midpoints CFs for aquatic eco-toxicity are expressed in PDF·m^2·yr/kg Triethylene glycol-eq into air, water and soil. At this time, no data (CFs) for emissions into groundwater, ocean and stratosphere are offered. The CFs of heavy metals for aquatic eco-toxicity, only the metals emitted in their dissolved forms (ions) are included for this midpoint category.

7. Terrestrial eco-toxicity

Triethylene glycol is still the reference substance for this midpoint. The midpoints CFs for terrestrial eco-toxicity are expressed in PDF·m2·yr/kg Triethylene glycol-eq into air, water and soil. Also, the midpoints CFs of heavy metals for terrestrial eco-toxicity, only the metals emitted

in their dissolved forms (ions) are considered. General speaking, both of CF values for terrestrial eco-toxicity and aquatic eco-toxicity are calculated by similar methods.

8. Aquatic acidification

The midpoints CFs for aquatic acidification use SO_2 as a reference substance and are expressed in kg SO_2-eq into air, water and soil. The midpoint category adopts the database of the CML (Guinée et al. 2002). However, this midpoint category cannot connect to its endpoint at present because no sufficient data to link them with each other now. The Swiss Federal Institute of Technology Lausanne (EPFL) is still conducting research to put it all together.

9. Aquatic eutrophication

The midpoints CFs for aquatic acidification use PO_4^{3-} as a reference substance and are expressed in kg SO2-eq into air, water and soil. The midpoint category also adopts the database of the CML (Guinée et al. 2002). It is just like the aquatic acidification midpoint category; this midpoint category cannot connect to its endpoint at present because of the same reasons. The Swiss Federal Institute of Technology Lausanne (EPFL) is still developing the linkage.

10. Terrestrial acidification & nitrification

The midpoints CFs for terrestrial acidification & nitrification also use SO_2 as a reference substance, but they are expressed in kg $SO_{2\text{-eq}}$ into air only. The database from Eco-indicator 99 (Goedkoop and Spriensma 2000) is used for its endpoint characterization factors. The midpoints

CFs are calculated by dividing the damage factor of the substance considered by the damage factor of the reference substance (SO_2 into air).

11. Land occupation

The midpoints CFs for Land occupation use m^2_{eq} organic arable land*year as a reference substance. The database from Eco-indicator 99 (Goedkoop and Spriensma 2000) is also used for its endpoint characterization factors. The midpoint characterization factors are calculated by dividing the damage factor of the considered type of land by the damage factor of the reference substance (organic arable land·yr).

12. Global warming

The midpoints CFs for global warming use CO_2 as a reference substance, and they are expressed in kg $CO_{2\text{-}eq}$ into air only. The time horizon for global warming is 500 years. The IPCC list (IPCC 2001, and IPCC 2007 for CH4, N2O and CO) is the database source of its midpoints characterization factors for global warming.

13. Non-renewable energy

The midpoints CFs for Non-renewable energy are expressed in MJ. Their reference substance is MJ total primary non-renewable or kg_{eq} crude oil (860kg/m^3). The database from ecoinvent (Frischknecht et al. 2003) is used for its endpoint characterization factors. The midpoint characterization factors are calculated by dividing the damage factor of the considered substance by the damage factor of the reference substance (crude oil (860 kg/m3)).

14. Mineral extraction

The midpoints CFs for mineral extraction are expressed in MJ. Their reference substance is MJ additional energy or kg_{eq} iron in ore. The database from Eco-indicator 99 (Goedkoop and Spriensma 2000) is used for its endpoint characterization factors. The midpoint characterization factors are calculated by dividing the damage factor of the considered substance by the damage factor of the reference substance (iron (in ore)).

2.3.2 Damage (endpoint) categories and Normalization of IMPACT 2002+

1. Human health

The "human health" damage category is the total impacts from the following five midpoint categories: human toxicity, respiratory effects, ionizing radiation, ozone layer depletion and photochemical oxidation. The unit for the human health damage category is expressed in "DALYs" (Disability-Adjusted Life Years).

2. Ecosystem quality

The "Ecosystem quality" damage category is the total impacts from the following six midpoint categories: "aquatic ecotoxicity", "terrestrial ecotoxicity", "terrestrial acid/nutr", "land occupation, aquatic acidification" and "aquatic eutrophication". The unit for the Ecosystem quality damage category is expressed in ""$PDF.m^2.y$" (Potentially Disappeared Fraction of species).

3. Climate change

The damage category “Climate change” has no difference from the midpoint category “global warming” since it is not like other damage categories which have more than one impact from different midpoint categories. For the same reason, its unit is expressed in “kg CO_2-eq” as well.

4. Resources

The “Resources” damage category is the total impacts from the following two midpoint categories: “non-renewable energy consumption” and “mineral extraction”. The unit for the Resources damage category is expressed in MJ.

5. Normalization

With a view to scrutinizing the contributions from each single impact on the overall damage of the considered category, normalization is supposed to be performed when conducting LCAs. With the normalization, different categories can be compared on the same ground. In a word, the normalization can help with the interpretation phase of LCAs. The calculation of normalization is to divide the impact (at damage categories) by the respective normalization factors.

6. Summary of IMPACT 2002+

The table in the next page is a brief summary of the IMPACT 2002+ methodology. The data and information about the IMPACT 2002+ methodology shared here and before are mainly cited and summarized from the IMPACT 2002+: A New Life Cycle Impact Assessment Methodology (Jolliet et al., 2003) and IMPACT 2002+: User Guide version 2.1(Sébastien Humbert et al., 2011). They will be utilized to conduct LCAs for wastewater treatment in the next chapter.

No. of LCI results covered [source]	Midpoint category	Midpoint reference substance	Damage category	Damage unit
769 [a]	Human toxicity (carcinogens + non-carcinogens)	kg_{eq} chloroethylene into air	Human health	DALY
12 [b]	Respiratory (inorganics)	kg_{eq} PM2.5 into air	Human health	
25 [b]	Ionizing radiations	Bq_{eq} carbon-14 into air	Human health	
22 [b]	Ozone layer depletion	kg_{eq} CFC-11 into air	Human health	
130 [b]	Photochemical oxidation [= Respiratory (organics) for human health]	Kg_{eq} ethylene into air	Human health	
			Ecosystem quality	–
393 [a]	Aquatic ecotoxicity	kg_{eq} triethylene glycol into water	Ecosystem quality	PDF * m^2 * yr
393 [a]	Terrestrial ecotoxicity	kg_{eq} triethylene glycol into water	Ecosystem quality	
5 [b]	Terrestrial acidification/nutrification	kg_{eq} SO_2 into air	Ecosystem quality	
10 [c]	Aquatic acidification	kg_{eq} SO_2 into air	Ecosystem quality	*Under development*
10 [c]	Aquatic eutrophication	kg_{eq} PO_4^{3-} into water	Ecosystem quality	*Under development*
15 [b]	Land occupation	m^2_{eq} organic arable land·year	Ecosystem quality	PDF * m^2 * yr
38 [b]	Global warming	kg_{eq} CO_2 into air	Climate change (life support system)	(kg_{eq} CO_2 into air)
9 [d]	Non-renewable energy	MJ Total primary non-renewable or kg_{eq} crude oil (860 kg/m^3)	Resources	MJ
20 [b]	Mineral extraction	MJ additional energy or kg_{eq} iron (in ore)	Resources	

Table 2.3.2 IMPACT 2002+ source (Jolliet et al., 2003): Number of LCI results covered, main sources for characterization factors, reference substances, and damage units used in IMPACT 2002+. Sources are: [a] IMPACT 2002 (Pennington et al. 2003a, 2003b), [b] Eco-indicator 99 (Goedkoop and Spriensma 2000), [c] CML 2002 (Guinée et al. 2002), and [d] ecoinvent (Frischknecht et al. 2003)

Chapter 3: Life Cycle Analysis of wastewater treatments

3.1 Background, objective and scope:

Although LCA is a powerful and useful tool to evaluate the environmental impacts caused by a production or service system, it has not been introduced to many applicable areas. Wastewater treatment plants in Oregon are no exception. Currently, the performances and environmental influences of wastewater treatment plants in Oregon are monitored by the Oregon Department of Environmental Quality (DEQ). The Oregon DEQ uses the National Pollutant Discharge Elimination System (NPDES) Permit Program to control water pollutants and maintain water quality. They evaluate the environmental impacts of a wastewater treatment plant by monitoring the concentrations of different pollutants in the final discharged water. Although the NPDES Permit Program details the maximum tolerance amount of each single pollutant or parameter. It doesn't have the feature in quantifying the environmental impact of each single pollutant or parameter; let alone have the capability to show the whole environmental impacts caused by wastewater treatment plants. Incorporating a LCA methodology with the current system (NPDES) can better evaluate the overall environmental impacts of a wastewater treatment plant.

However, conducting a LCA for wastewater treatments is a daunting task because too many unpredictable and uncontrollable variables need to be taken into consideration such as temperature, rainfall and PH. In addition, the collection, organization and calculation of data are tedious and complex. Due to the above reasons, LCA studies for wastewater treatments are difficult to be found. This research is conducted to raise awareness for the importance of LCAs

for wastewater treatments, demonstrate how to perform a life cycle assessment (LCA) for wastewater treatments by using the IMPACT 2002+ methodology. The ultimate objective of this LCA research is to explore the feasibility of using the cloth-electrode assembly microbial fuel cell (CEA-MFC) to replace the activated sludge basin in a wastewater treatment system.

3.2 Materials and Methods

According to the DEQ, there are 212 different sizes of wastewater treatment plants in Oregon. The Corvallis wastewater treatment plant at 9.7 MGD is considered a large wastewater treatment plant whose ranking is in the top five percent in Oregon. In this study, the Corvallis wastewater plant is chosen to build the basic model to perform a LCA because it is large enough to represent almost all operational units in a conventional wastewater treatment plant. In addition, this model can be easily adjusted to smaller or larger wastewater treatment plants in Oregon because of their similarities. The detailed materials and methods used for this LCA research will be descripted step by step in the following sections.

3.2.1 Defining the functional unit

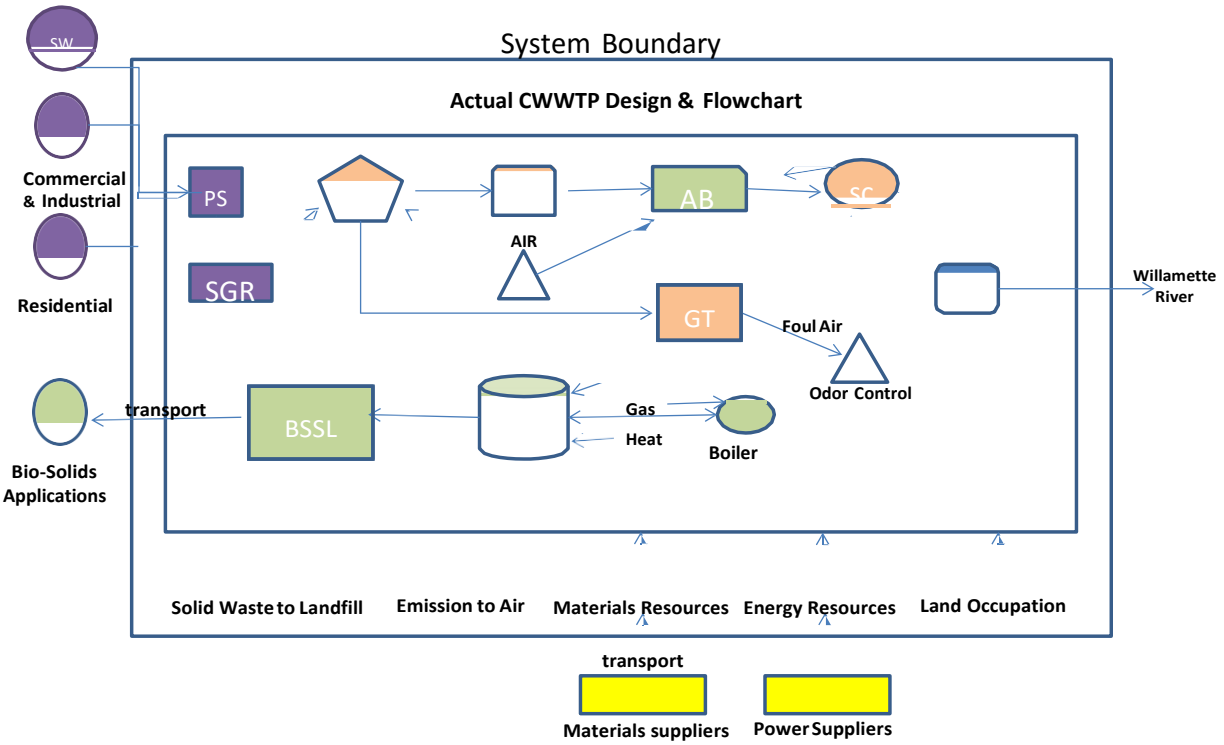
The first step of performing a LCA is to define the functional unit. It is the most important part of a LCA research. The functional unit is utilized to measure the performance of a production or service system. It provides a reference for both inputs and outputs to guarantee comparability of results (Vlasopoulos N et al., 2006). In this LCA research for wastewater treatments plants, there are three possible functional unit options: quantity of removed pollutants, quantity of resulting sludge and volume of treated wastewater. The quantity of removed pollutants is the

most relevant function, but it comes with many issues. For instance, choosing a single pollutant BOD5 will cause much of uncertainty; choosing multiple standards (BOD_5, NTK, TSS, etc.) will lead to allocation issues. On the other hand, the quantity of resulting sludge could become an unwise choice since the treatment technology may cause variations. Using the volume of treated wastewater as the functional unit for this LCA study could beseems the best option because it is easy and clear to establish inventory. Thus, in this study, the functional unit was defined as 3.95E+07 liters of treated wastewater per day in the Corvallis Wastewater Reclamation Plant in 2014.

3.2.2 System Boundary

In theory, numbers of elements or units processes describing the entire “cradle-to-grave” life cycle in a system could be extremely numerous or nearly infinite; it is necessary to set up a system boundary to decide on which elements should be included in the system. In this LCA research, the “Relative Mass Energy and Economic Value Method (RMEE)” was adopted to select the systems boundary (Marlo Raynolds et al., 2000]. The RMEE method uses a so-called cut-off ratio to decide whether or not an upstream process of an input should be included in the system. The calculations are based on the relative ratio of the input to the functional unit regarding their mass, energy and economic value. When any of the three RMEE ratios are greater than the pre-defined cut-off ratio, that upstream process input is supposed to be included in the system boundary. This procedure is repeated until all of the upstream inputs are below the cut off threshold. Since the cut-off ratio 0.05 was chosen in this study, it indicated that all upstream inputs which had more than 5 percent contributions on mass, energy or

economic value towards the functional unit (3.95E+07 liters) were included in the system boundary.



Abbreviations: CWWTP- Corvallis Waste Water Treatment Plant, PS-Pump Station, PC- Primary Clarifier, TF-Trickling Filters, AB- activated sludge basins, SC- Secondary Clarifier, DC- Disinfection Chamber, GT- Gravity Thickeners, AD- Anaerobic Digester and BSSL- Bio-Solids Stabilization Lagoons, SW- storm water, SGR: Screening & Grit Removal, Purple: Preliminary treatment, Orange: Primary treatment, Green: Secondary treatment, Pink: Tertiary treatment, Blue: Disinfection, Yellow: Materials suppliers and Power Suppliers

Figure 3.2.2 System Boundary

3.2.3 Parameter (pollutants) choices and data sources

The data used for this LCA were provided by the Department of Environmental Quality (DEQ) of Oregon and the Corvallis Wastewater Reclamation Plant in Oregon. Most of these data were collected daily, weekly, monthly and or quarterly by the Corvallis Wastewater Reclamation Plant in 2014. An average values for these data were used to calculate their environmental impact by using the Impact 2002+ LCA methodology. Additionally, not all data obtained from the Oregon DEQ and Corvallis Wastewater Reclamation Plant could be used to carry out the LCA. It was because the IMPACT 2002+ Version 2.1 and the NPDES Permit Program sometimes didn't have the relevant data or information on all midpoint and endpoint items to calculate the environmental impacts.

The parameters for this LCA research were divided into ten categories: Metals, Volatile Organic Compounds, Acid-Extractable Compounds, Base-Neutral Compounds, Pesticide Compounds, COD (Final Effluent), Ammonia, Carbon dioxide, Digester Gas and Natural Gas. The detailed items and their data used for this LCA study for the first five categories are shown in the following 5 tables.

Table 3.2.3 (a): Outputs for wastewater treatment plant: Generalized Monthly Metals in 2014 (Source: Oregon DEQ)

Outputs	Unit (µg/L)	Case number	Quantity (kg/day)
Antimony	0.25	7440360	9.45E-03
Arsenic	0.85	7440382	3.21E-02
Beryllium	0.02	7440417	7.56E-04
Cadmium	0.03	7440439	1.13E-03
Chromium	1.19	7440473	4.50E-02

Copper	6.74	7440508	2.55E-01
Lead	0.54	7439921	2.04E-02
Mercury	0.003	7439976	1.13E-04
Nickel	2.12	7440020	8.01E-02
Selenium	0.65	7782492	2.46E-02
Zinc	38.36	7440666	1.45E+00

Table 3.2.3 (b): Outputs for wastewater treatment plant: Generalized Quarterly Volatile Organic Compounds in 2014 (Source: Oregon DEQ)

Outputs	Unit (µg/L)	Case number	Quantity (kg/day)
Acrolein	<0.5	107028	1.89E-02
Acrylonitrile	<0.5	107131	1.89E-02
Benzene	<0.2	71432	7.56E-03
Bromoform	<0.2	75252	7.56E-03
Chlorobenzene	<0.2	108907	7.56E-03
Chloroethane	<0.2	75003	7.56E-03
Chloroform	<0.62	67663	2.34E-02
1,1-Dichloroethane	<0.2	107062	7.56E-03
1,1-Dichloroethylene	<0.2	75354	7.56E-03
1,2-Dichloroethane	<0.2	107062	7.56E-03
1,2-Dichloropropane	<0.2	78875	7.56E-03
Ethylbenzene	<0.2	100414	7.56E-03
1,1,2,2-Tetrachloro-ethane	<0.2	79345	7.56E-03
Toluene	<0.2	108883	7.56E-03
1,2-Trans-Dichloroethylene	<0.2	156605	7.56E-03
1,1,2-Trichloroethane	<0.2	79005	7.56E-03

Table 3.2.3 (c): Outputs for wastewater treatment plant: Generalized Quarterly Acid-Extractable Compounds in 2014 (Source: Oregon DEQ)

Outputs	Unit (µg/L)	Case number	Quantity (kg/day)
2-Chlorophenol	<0.25	95578	9.45E-03
2,4-Dichlorophenol	<0.25	120832	9.45E-03
2,4-Dimethylphenol	<0.25	105679	9.45E-03

2,4-Dinitrophenol	<0.25	51285	9.45E-03
Pentachlorophenol	<0.25	87865	9.45E-03
Phenol	<0.46	108952	1.74E-02
2,4,6-Trichlorophenol	<0.25	88062	9.45E-03

Table 3.2.3 (d): Outputs for wastewater treatment plant: Generalized Quarterly Base-Neutral Compounds in 2014 (Source: Oregon DEQ)

Outputs	Unit (µg/L)	Case number	Quantity (kg/day)
Acenapthene	<0.25	83329	9.45E-03
Acenapthylene	<0.25	208968	9.45E-03
Anthracene	<0.25	120127	9.45E-03
Benzidine	<0.88	92875	3.33E-02
Benzo(a)Anthracene	<0.25	56553	9.45E-03
Benzo(a)Pyrene	<0.25	50328	9.45E-03
3,4-Benzoflouranthene	<0.25	205992	9.45E-03
Benzo(ghi)Perylene	<0.25	191242	9.45E-03
Benzo(k)flouranthene	<0.25	207089	9.45E-03
Bis(2-Chloroethyl)-Ether	<0.25	111444	9.45E-03
Bis(2-Chloroiso-Propyl) Ether	<0.25	108601	9.45E-03
Bis(2-Ethylhexyl) Phthalate	0.43	117817	1.63E-02
Butyl Benzyl Phthalate	0.1	85687	3.78E-03
2-Chloronaphthalene	<0.25	91587	9.45E-03
Chrysene	<0.25	218019	9.45E-03
1,2-Dichlorobenzene	<0.20	95501	7.56E-03
Di-n-Butyl Phthalate	0.265	84742	1.00E-02
2,4-Dinitrotoluene	<0.25	121142	9.45E-03
2,6-Dinitrotoluene	<0.25	606202	9.45E-03
Di-n-Octyl Phthalate	<0.25	117840	9.45E-03
Fluoranthene	<0.25	206440	9.45E-03
Fluorene	<0.25	86737	9.45E-03
Hexachlorobenzene	<0.25	118741	9.45E-03
Hexachlorobutadiene	<0.25	87683	9.45E-03

Hexachlorocyclo-pentadiene	<0.25	77474	9.45E-03
Hexachloroethane	<0.25	67721	9.45E-03
Indeno(1,2,3-cd) Pyrene	<0.25	193395	9.45E-03
Isophorone	<0.25	78591	9.45E-03
Naphthalene	<0.25	91203	9.45E-03
Nitrobenzene	<0.25	98953	9.45E-03
Phenanthrene	<0.25	85018	9.45E-03
Pyrene	<0.25	129000	9.45E-03
1,2,4-Trichlorobenzene	<0.20	120821	7.56E-03

Table 3.2.3 (e): Outputs for wastewater treatment plant: Generalized Quarterly Pesticide Compounds in 2014 (Source: Oregon DEQ)

Outputs	Unit (µg/L)	Case number	Quantity (kg/day)
Aldrin	<0.00054	309002	2.04E-05
BHC alpha	<0.000785	319846	2.97E-05
BHC beta-	<0.000558	319857	2.11E-05
BHC gamma – (Lindane)	<0.002545	58899	9.62E-05
Chlordane	<0.008	57749	3.02E-04
DDD 4,4'-	<0.003057	72548	1.16E-04
DDE 4,4'-	<0.000718	72559	2.71E-05
DDT 4,4'-	<0.000685	50293	2.59E-05
Dieldrin	<0.000818	60571	3.09E-05
Endrin	<0.00095	72208	3.59E-05
Heptachlor	<0.00084	76448	3.18E-05
Haptachlor Epoxide	<0.000698	1024573	2.64E-05
PCB, Arochlor 1016 1	<0.02485	12674112	9.39E-04
PCB, Arochlor 1254 1	<0.0197	11097691	7.45E-04
PCB, Arochlor 1260 1	<0.02445	11096825	9.24E-04
Toxaphene	<0.09225	8001352	3.49E-03
PCB, Arochlor 1254 1	<0.0197	11097691	7.45E-04

The data used for the other five categories in the LCA were organized and listed in the below table for reference.

Table 3.2.3 (f): the other five categories (Source: Oregon DEQ)

Parameters	Unit (mg/L)	Case number	Quantity (unit)
COD (Final Effluent)	3.98E+00 kg	N/A	2.11E+02 (kg/day)
Ammonia	1.08E+01 kg	7664-41-7	5.72E+02 (kg/day)
Carbon dioxide	1.56E+03 m^3	124-38-9	1.56E+03 (m^3/day)
Digester Gas	1.83E+03 m^3	74-82-8	1.83E+03 (m^3/day)
Natural Gas	1.20E+02 m^3	N/A	1.20E+02 (m^3/day)

3.2.4 Life Cycle Inventory

The data in the following two tables were utilized to quantify the relevant inputs and outputs of the studied wastewater treatment system for its life cycle inventory analysis.

Table 3.2.4 (a): Inputs for the LCA (cited or calculated based on the data from Oregon DEQ and Corvallis Wastewater Reclamation Plant)

Inputs	Quantity	Units	Cost
Plant flow	3.95E+01	ML/Day	N/A
Sodium bisulfite used	2.26E+02	L/Day	$657.8/Day
Chlorine used	1.06E+02	Kg/Day	$83.57/Day
Electricity used	1.87E+04	KWH/Day	$1066.79/Day
Natural Gas Used	1.20E+02	M^3	$22.41/Day
COD (Raw Influent)	1.75E+05	Kg/Day	N/A

Table 3.2.4 (b) Outputs for the LCA (cited or calculated based on the data from Oregon DEQ and Corvallis Wastewater Reclamation Plant)

Outputs	Quantity	Units
Reclaimed Water produced	3.78E+01	ML/Day
Carbon dioxide produced CO2	1.56E+03	M^3/Day
Digester Gas produced	1.83E+03	M^3/Day
COD (Final Effluent)	2.11E+02	Kg/Day
Ammonia	5.72E+02	Kg/Day

3.2.5 Results of the Life cycle Impact

The results of the LCA for the operational phase of wastewater treatment processes are shown below in a series of figures. Not all of the fourteen categories were included in the final results. It was because the required data are missing not available or that specific category didn't apply to wastewater treatment processes at all. A detailed discussion would be done in the result and conclusion sessions right after the illustration.

Table 3.2.5 (a): Carcinogenic risk on human health at midpoint level (calculated based on the IMPACT 2002+ Version 2.1 and data from Oregon DEQ)

Normalised mid-point characterization factor	Unit [pers*yr/kg]
Metals and other tests	2.56E+02
Volatile Organic Compounds	3.35E+00
Acid-Extractable Compounds	1.83E-01
Base-Neutral Compounds	4.72E+02
Pesticide Compounds	1.28E+02
COD (Final Effluent)	0.00E+00
Ammonia	0.00E+00
Carbon dioxide	0.00E+00
Digester Gas	0.00E+00
Natural Gas	0.00E+00

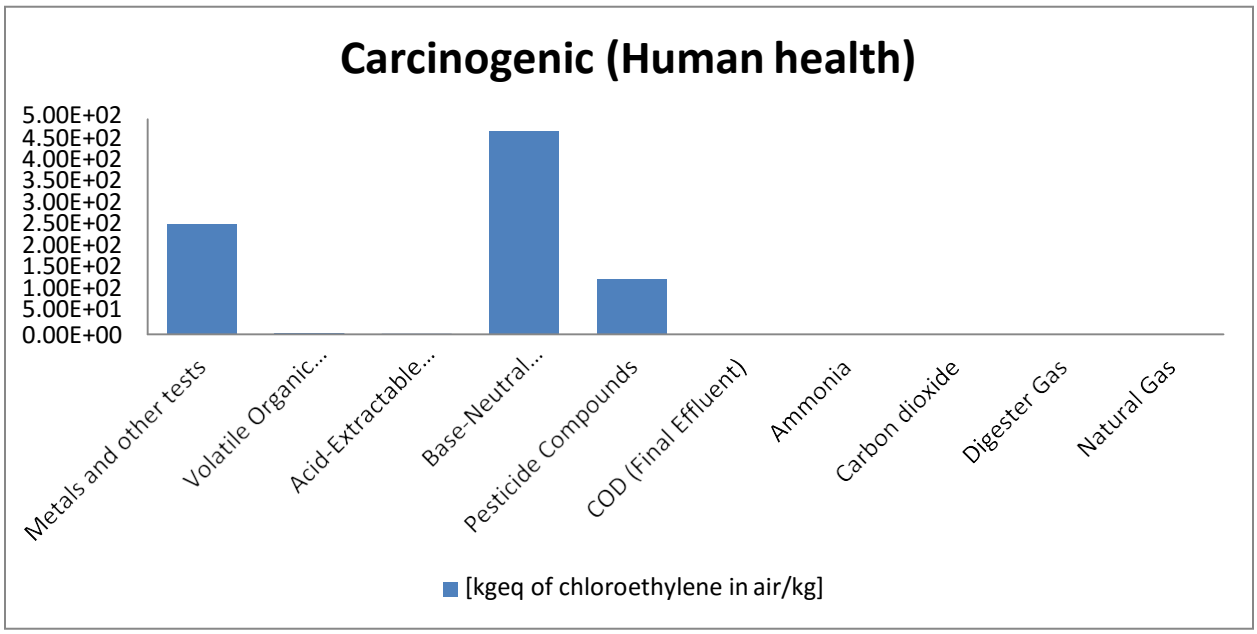


Figure 3.2.5 (a): Carcinogenic risk on human health at midpoint level

In the carcinogenic mid-point category, the first five parameters have influences on environment. However, the volatile organic compounds and the acid-extractable compounds are relatively have less impact on environment in comparison to the other three parameters, so their influences can only be seen from the table 3.2.5 (a).

Table 3.2.5 (b): Non-Carcinogenic risk on human health at midpoint level (calculated based on the IMPACT 2002+ Version 2.1 and data from Oregon DEQ)

Normalised mid-point characterization factor	[pers*yr/kg]
Metals and other tests	1.18E+03
Volatile Organic Compounds	4.23E-01
Acid-Extractable Compounds	6.85E-02
Base-Neutral Compounds	1.33E+03
Pesticide Compounds	1.00E+03
COD (Final Effluent)	0.00E+00
Ammonia	1.45E-01
Carbon dioxide	0.00E+00

Digester Gas	0.00E+00
Natural Gas	0.00E+00

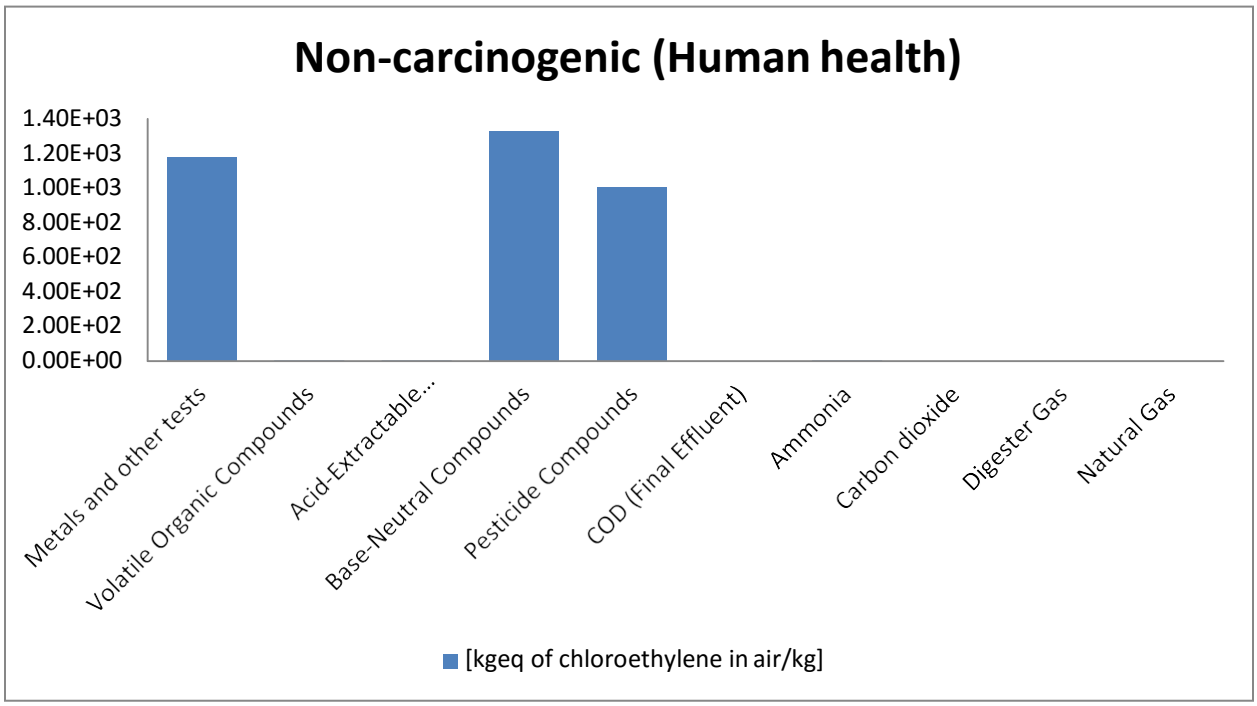


Figure 3.2.5 (b): Non-Carcinogenic risk on human health at midpoint level

In the non-carcinogenic mid-point category, besides the first five parameters, ammonia also has influences on environment. Their contributions to the environmental impact can be seen on both of the table and figure 3.2.5 (b).

Table 3.2.5 (c): Environmental impact on aquatic system at midpoint level (calculated based on the IMPACT 2002+ Version 2.1 and data from Oregon DEQ)

Normalised mid-point characterization factor	[pers*yr/kg]
Metals and other tests	2.02E+03
Volatile Organic Compounds	4.91E+00
Acid-Extractable Compounds	3.12E-03
Base-Neutral Compounds	9.40E+02
Pesticide Compounds	8.80E+01

COD (Final Effluent)	0.00E+00
Ammonia	8.10E+01
Carbon dioxide	0.00E+00
Digester Gas	0.00E+00
Natural Gas	0.00E+00

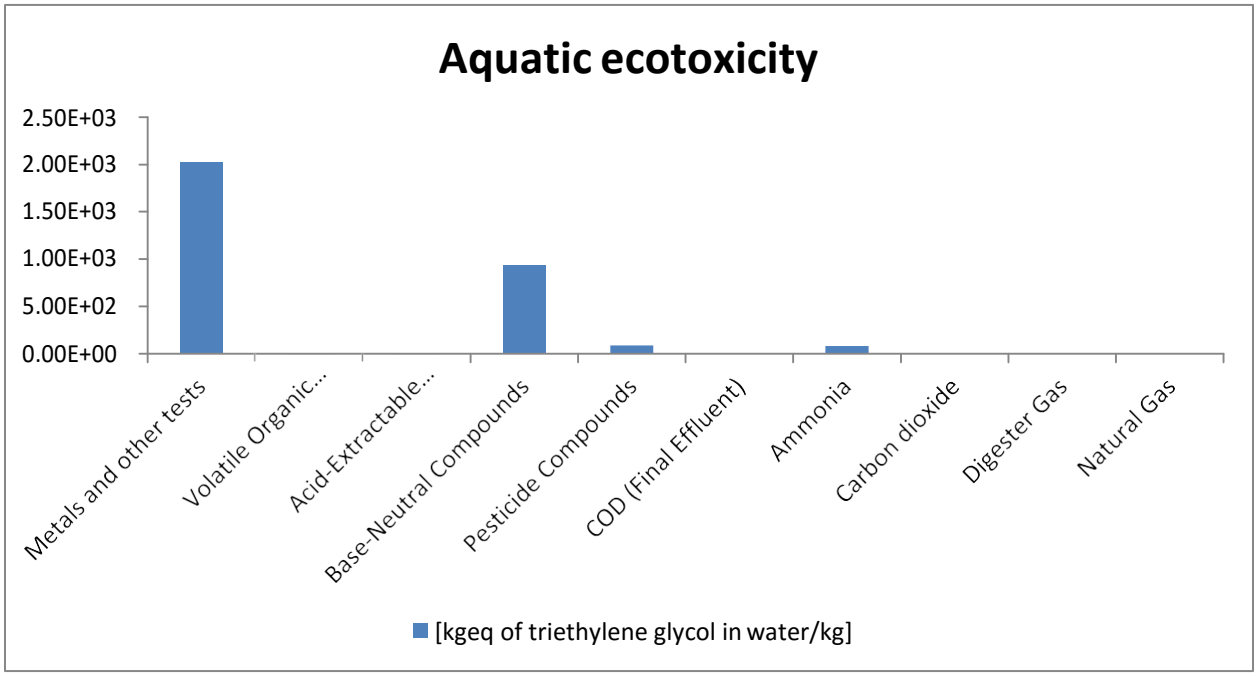


Figure 3.2.5 (c): Environmental impact on aquatic system at midpoint level

In the aquatic system mid-point category, the first five parameters and ammonia have influences on environment. Their contributions to the environmental impact can be seen on both of the table and figure 3.2.5 (c), but the extents are different from those of the non-carcinogenic mid-point category.

Table 3.2.5 (d): Comparison of environmental impact from COD and ammonia in on aquatic eutrophication at midpoint level (calculated based on the IMPACT 2002+ Version 2.1 and data from Oregon DEQ)

Normalised mid-point characterization factor	[pers*yr/kg]
Metals and other tests	0.00E+00
Volatile Organic Compounds	0.00E+00
Acid-Extractable Compounds	0.00E+00
Base-Neutral Compounds	0.00E+00
Pesticide Compounds	0.00E+00
COD (Final Effluent)	1.21E+01
Ammonia	1.72E+00
Carbon dioxide	0.00E+00
Digester Gas	0.00E+00
Natural Gas	0.00E+00

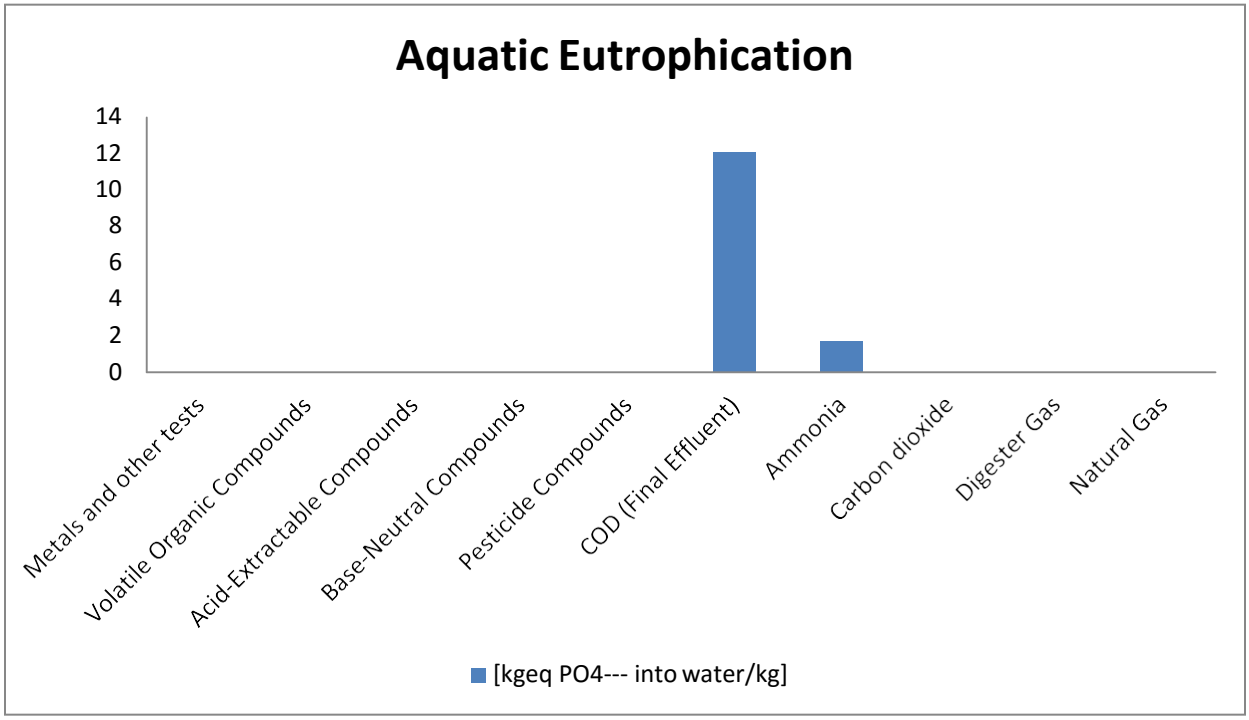


Figure 3.2.5 (d): Comparison of environmental impact from 10 parameters on aquatic eutrophication at midpoint level

Only two parameters have the environmental impact in the aquatic eutrophication midpoint category: the final COD effluent and ammonia.

Table 3.2.5 (e): Comparison of environmental impact from 10 parameters on global warming at midpoint level (calculated based on the IMPACT 2002+ Version 2.1 and data from Oregon DEQ)

Normalised mid-point characterization factor	[pers*yr/kg]
Metals and other tests	0.00E+00
Volatile Organic Compounds	0.00E+00
Acid-Extractable Compounds	0.00E+00
Base-Neutral Compounds	0.00E+00
Pesticide Compounds	0.00E+00
COD (Final Effluent)	0.00E+00
Ammonia	0.00E+00
Carbon dioxide	1.13E+02
Digester Gas	2.51E+02
Natural Gas	0.00E+00

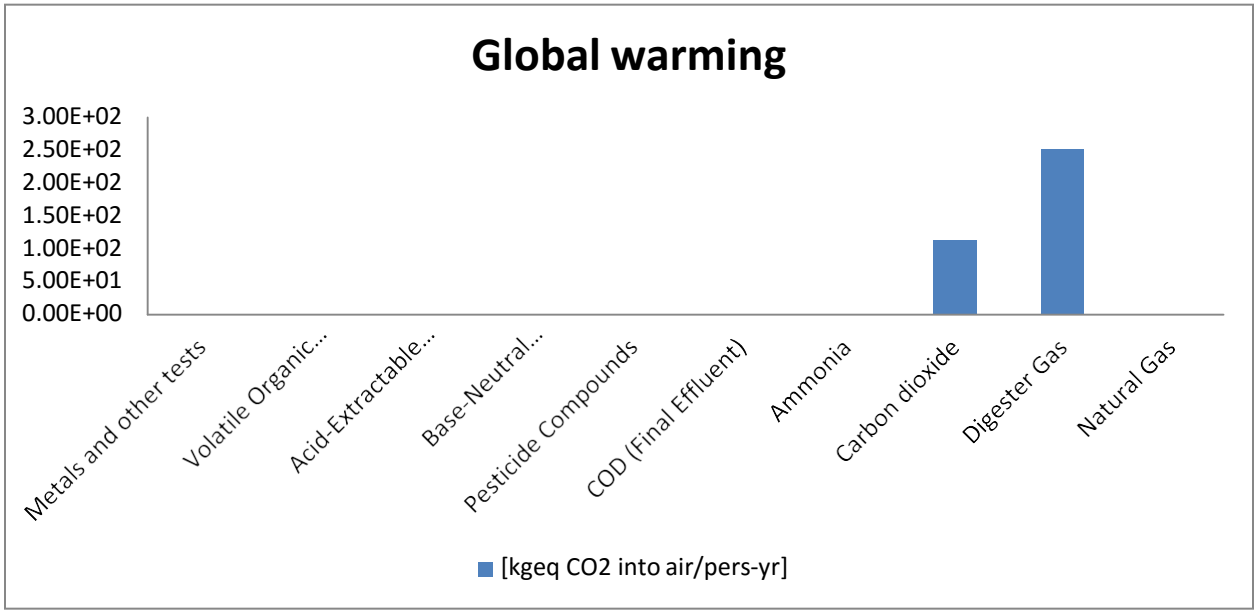


Figure 3.2.5 (e): Comparison of environmental impact from 10 parameters on global warming at midpoint level

The global warming effect is mainly caused by the release of carbon dioxide and the produce of digester gas during the wastewater treatment procedures.

Table 3.2.5 (f): Comparison of environmental impact from 10 parameters on non-renewable energy at midpoint level (calculated based on the IMPACT 2002+ Version 2.1 and data from Oregon DEQ)

Normalised mid-point characterization factor	[pers*yr/kg]
Metals and other tests	0.00E+00
Volatile Organic Compounds	0.00E+00
Acid-Extractable Compounds	0.00E+00
Base-Neutral Compounds	0.00E+00
Pesticide Compounds	0.00E+00
COD (Final Effluent)	0.00E+00
Ammonia	0.00E+00
Carbon dioxide	0.00E+00
Digester Gas	0.00E+00
Natural Gas	9.24E+00

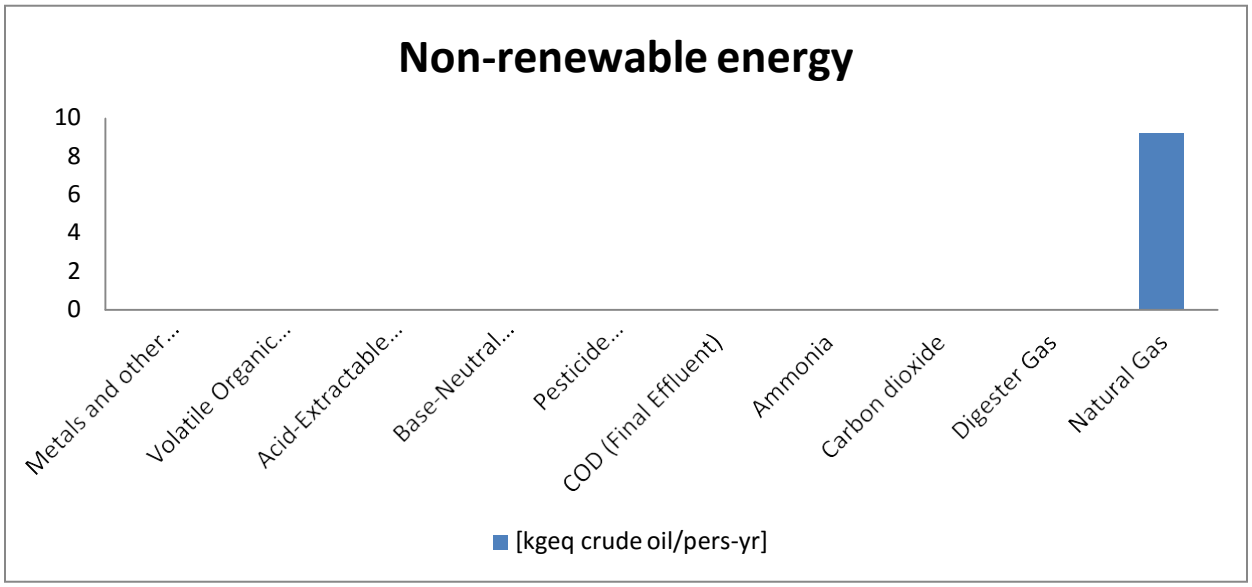


Figure 3.2.5 (f): Comparison of environmental impact from 10 parameters on non-renewable energy at midpoint level

The use of natural gas for wastewater treatment processes actually reduces our natural resources which are not renewable.

Table 3.2.5 (g): Total environmental impact from 10 parameters at midpoint level (calculated based on the IMPACT 2002+ Version 2.1 and data from Oregon DEQ)										
Natural Gas	Digester Gas	Carbon dioxide	Ammonia	COD (Final Effluent)	Pesticide Compounds	Base-Neutral Compounds	Acid-Extractable Compounds	Volatile Organic Compounds	Metals	
0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.28E+02	4.72E+02	1.83E-01	3.35E+00	2.56E+02	Carcinogenic
0.00E+00	0.00E+00	0.00E+00	1.45E-01	0.00E+00	1.00E+03	1.33E+03	6.85E-02	4.23E-01	1.18E+03	Non-Carcinogenic
0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	Resp-Inorg
0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	Radiation
0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	Ozone
0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	Resp-Org
0.00E+00	0.00E+00	0.00E+00	8.10E+01	0.00E+00	8.80E+01	9.40E+02	3.12E-03	4.91E+00	2.02E+03	Aqu-Terr
0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	Terr-Acid-Nutri
0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	Aqua-Acid
0.00E+00	0.00E+00	0.00E+00	1.72E+00	1.21E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	Aqua-Eutro
0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	Land-Occupation
0.00E+00	2.51E+02	1.13E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	Global-Warming
9.24E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	Non-renewable-energy
0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	Mineral extraction

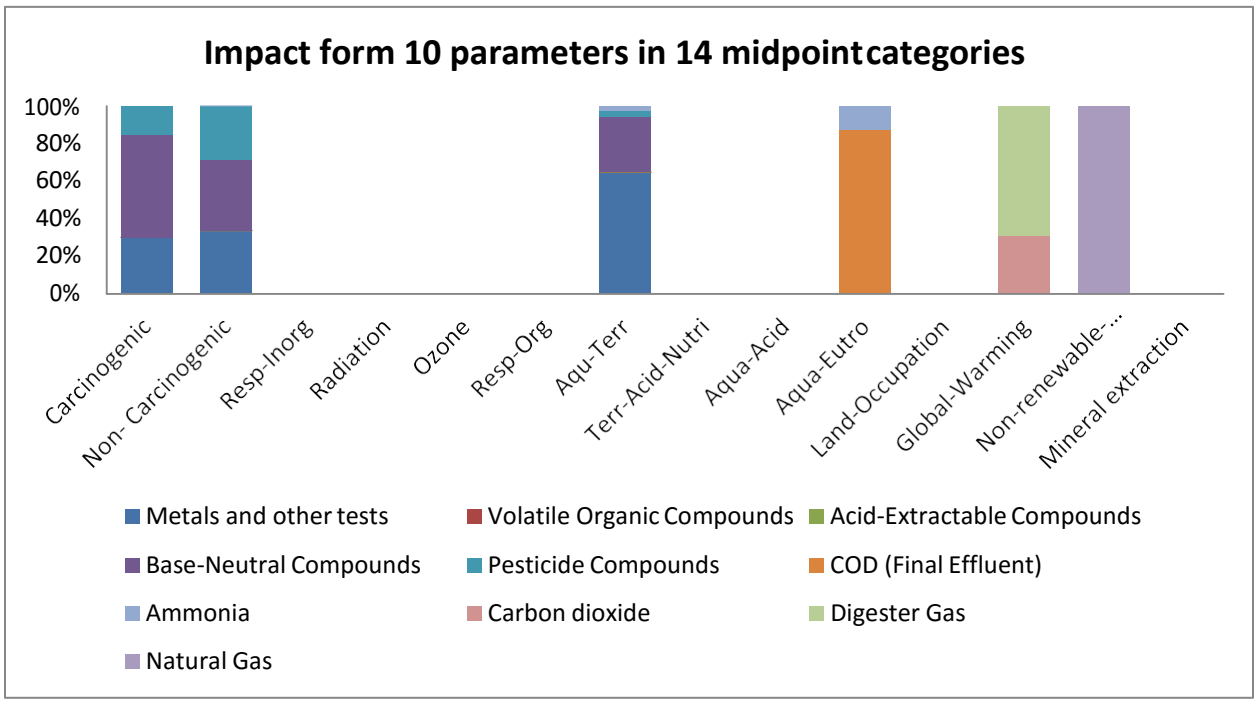


Figure 3.2.5 (g): Total environmental impact from 10 parameters at midpoint level

In this study and under the given conditions, the environmental impact of the ten selected parameters show their contributions on six of the fourteen mid-point categories of the Impact 2002+ LCA methodology.

Table 3.2.5 (h): Total environmental impact from 10 parameters at 4 endpoint level (calculated based on the IMPACT 2002+ Version 2.1 and data from Oregon DEQ)

Normalised damage factor	Human health [pers*yr/kg]	Ecosystem [pers*yr/kg]	Climate change [pers*yr/kg]	Resources [pers*yr/kg]	Total [pers*yr/kg]
Metals and other tests	8.51E+01	8.92E-02	7.98E-03	9.93E+01	7.08E+01
Volatile Organic Compounds	1.01E+01	2.44E-02	1.55E-05	4.68E+00	4.38E-01
Acid-Extractable Compounds	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Base-Neutral Compounds	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Pesticide Compounds	9.52E+01	1.14E-01	8.00E-03	1.04E+02	7.13E+01
COD (Final Effluent)	8.51E+01	8.92E-02	7.98E-03	9.93E+01	7.08E+01
Ammonia	1.01E+01	2.44E-02	1.55E-05	4.68E+00	4.38E-01
Carbon dioxide	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Digester Gas	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Natural Gas	9.52E+01	1.14E-01	8.00E-03	1.04E+02	7.13E+01

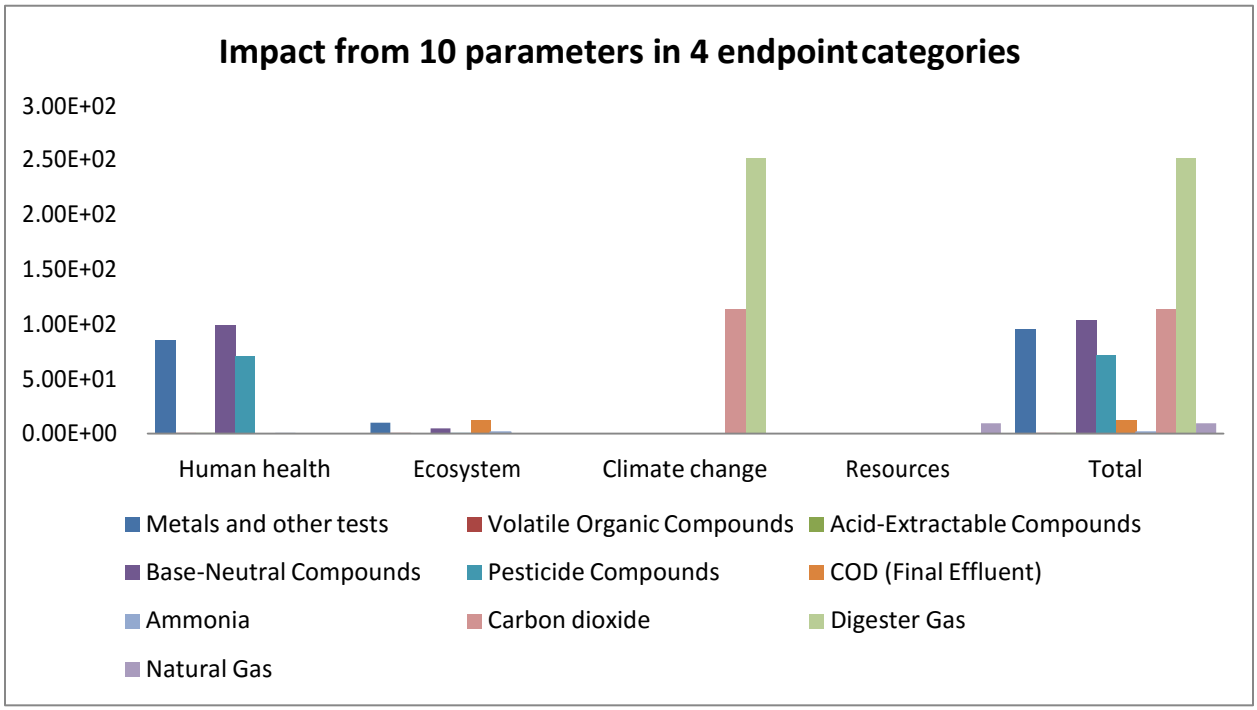


Figure 3.2.5 (h): Total environmental impact from 10 parameters at 4 endpoint level

The total environmental impact from the ten selected parameters was finally quantified by four end-point categories of the Impact 2002+ LCA methodology.

Results and discussion

The LCA for the operational phase of the wastewater treatment processes was conducted by using real data from Oregon DEQ and the Corvallis wastewater reclamation plant. In a sense, the results could show the real environmental impact caused by the conventional wastewater treatment processes to a certain degree. According to the results, wastewater treatment procedures have negative influence in six midpoint categories: Carcinogenic, Non-carcinogenic, Aquatic ecotoxicity, Aquatic eutrophication, Global warming, and Non-renewable energy. With

respect to the negative influences on human health (Carcinogenic and Non-carcinogenic midpoint), the different types of pollutants produced during the wastewater treatment processes obviously played an important role, especially the Base-Neutral Compounds. In regards to Aquatic ecotoxicity, metals had the most contribution on the aquatic system even though they didn't have more items in their category in comparison to the Base-Neutral Compounds. With regard to the aquatic eutrophication category, only ammonia and COD did cause environmental impact. In addition, the damage caused by COD was more than 7 times higher than those by ammonia. About the global warming midpoint category, carbon dioxide and digester gas produced by the anaerobic digester in the wastewater treatment plant were the two sole contributors in the ten parameters. Moreover, the environmental impact from carbon dioxide was 2.22 times higher than those caused by digester gas. In the midpoint category of non-renewable energy, the use of the natural gas did contribute to the consumptions of our limited natural sources. By looking at the total environmental impact part of the figure 3.2.5 (k), we could conclude that the digester gas and carbon dioxide were the number 1 and number 2 parameters that caused more environmental damages than other eight parameters in the wastewater treatment processes.

Conclusions and recommendations:

The demonstration of conducting this LCA for the operational phase of wastewater delivered many significant messages. Any individual contribution to the environmental impact in a system can be easily shown by performing a LCA. The results of a LCA can provide the public with a comprehensive way to see what is going on in a complicated or dynamic system such as wastewater treatment system. Although only six of the fourteen midpoint categories could

have results for us to analyze in this LCA study, this research itself already showed the power and convenience of performing LCAs for wastewater treatment procedures. However, the issues for lacking of available data to continue and the time/energy-consuming process of collecting data need more attention and support from the public and authority. As a matter of fact, this LCA research could be further performed to support other research and better protect our environment if the law makers or the authority see the value and meanings of this type of study seriously. For example, EPA doesn't monitor and model the greenhouse gases (GHG) emissions from the wastewater collection system. As a result, the Oregon DEQ and wastewater treatment plants in Oregon won't quantity or monitor these GHS. Hence, there is no such database to use for this type of LCA. In this study, the results of the LCA were supposed to be further utilized to see the feasibility of using a CEA-MFC system to replace the activated sludge basins in conventional wastewater treatment plants. Without this type of data to conduct this LCA to support our next research, our conclusions for that study may be less convincing.

Chapter 4: CEA-MFC v.s. Activated sludge basins

4.1 Background, objective and scope:

According to research conducted by the Electric Power Research Institute (EPRI), about 4% of the United States' electricity consumption is used to treat water and wastewater systems. The Pacific Gas and Electric Company's research shows that the municipal wastewater treatment alone consumes around 1.5% of the nation's electricity usage. In the conventional wastewater treatment processes, the secondary treatment is the most energy-intensive which can consume from 30% to 60% of the total plant electricity usage. The activated sludge basins are the largest electricity consumer in the secondary treatment. The objective of this research is to explore the feasibility of using cloth electrode assembly microbial fuel cell (CEA-MFC) to replace activated sludge basins in terms of Life Cycle Assessment (LCA) methodology. If the CEA-MFC can convert the wastewater treatment industry from energy consumption to energy generation, it will be a meaningful milestone in the scientific history.

4.2 Materials and Methods

The results of the LCA for the operational phase of the wastewater treatment processes in the chapter 3 are used as a foundation to compare the two systems: CEA-MFCs and activated sludge basins. Some assumptions are made to run this simulation model based on the results of the research of Fan et al in 2007.

- The CEA-MFC system for this wastewater treatment plant only generates electricity, water and carbon dioxide.
- The value of the COD is considered equal to the value of the BOD in this model.
- The COD removal rate for this CEA-MFC system is assumed 80%.
- The remaining COD in this wastewater treatment plant is thoroughly converted into carbon dioxide in the model.

Results:

The results are calculated based on the data used in the previous LCA chapter and the above assumptions. Under this condition, only the production rate of COD and carbon dioxide of the two systems will have differences; that is, the two different systems will have different environmental impact on aquatic eutrophication and global warming categories.

Table 4.2 comparison of Activated sludge basins and CEA-MFC systems

	COD removal rate	COD (Final Effluent)	Produced CO_2
Activated sludge basins	60.61%	2.11E+02 (Kg/Day)	1.56E+03 (M^3/Day)
CEA-MFC	80%	1.07E+02 (Kg/Day)	1.62E+03 (M^3/Day)

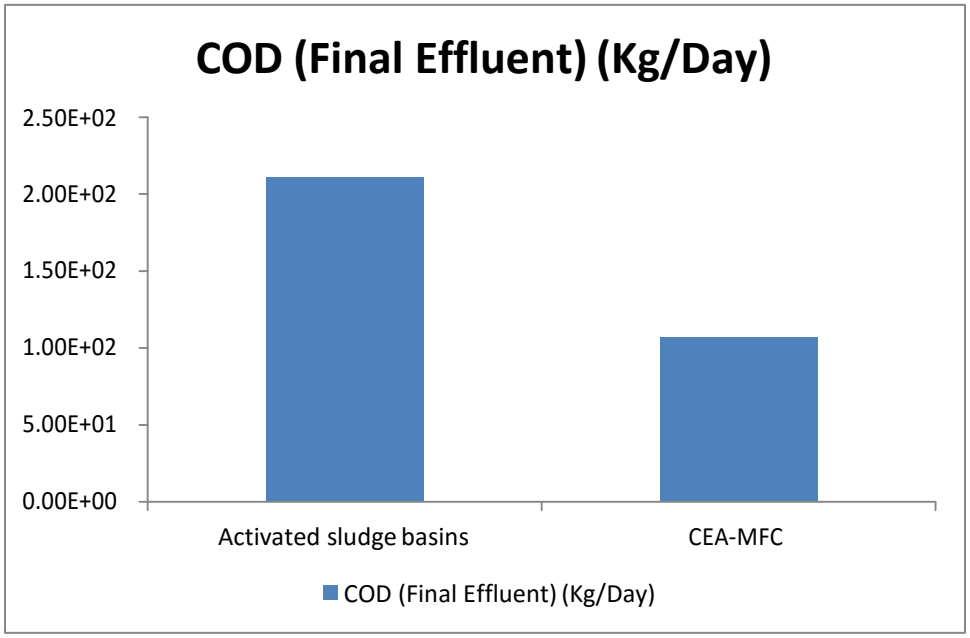


Figure 4.2 (a) the comparison of the final COD effluent between the activated sludge basin and CEA-MFC systems

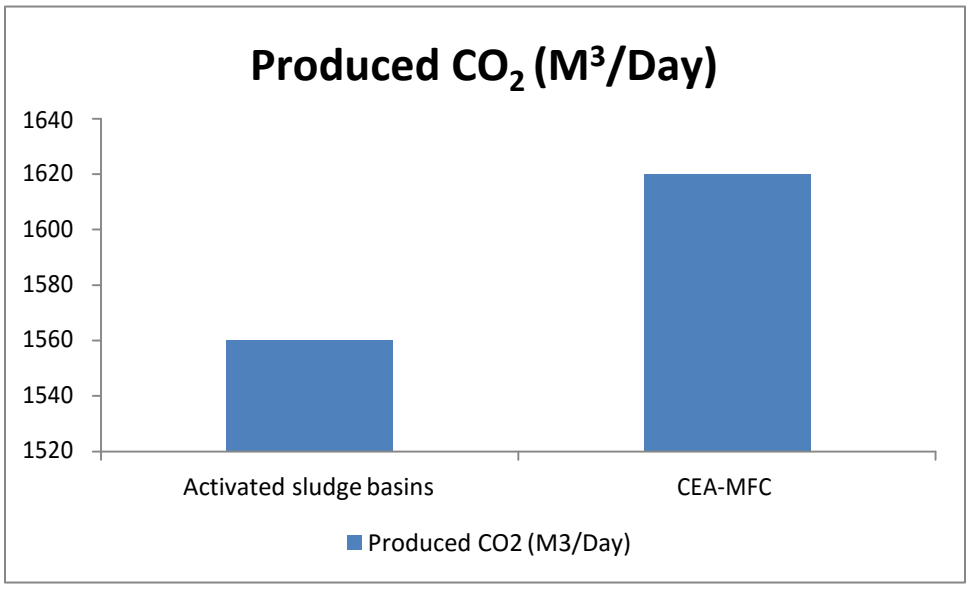


Figure 4.2 (b) the comparison of the produced carbon dioxide between the activated sludge basin and CEA-MFC systems

4.3 Capital and operational cost for activated sludge basins

The construction cost for the wastewater treatment plant with activated sludge basins was calculated according to the EPA's guidance "Construction Costs for Municipal Wastewater Treatment Plants (1973-1977)". Based on the research of the EPA, the cost of an activated sludge basin (10.0 MGD) which included equipment, concrete, steel and inter-processing pumping was $1,683,000 in 1977. The following assumptions are made to run this simulation model.

- The inflation rate was considered 5% per year.
- The wastewater treatment plant was built in 2014.

Therefore, the construction cost for this wastewater treatment plant was

$1683000 X (1+5%) $^{(2014-1977)}$ =$ 10,235,007.88

The operational cost of this wastewater treatment plant was calculated by extrapolating the operational cost for the Corvallis Wastewater Reclamation Plant from 2008-2012 since data for 2013 and 1014 were not available.

Table 4.3 Operational cost for the wastewater treatment plant with activated sludge basins from 2008-2014

	2008	2009	2010	2011	2012	2013	2014
Operational cost ($)	1.13E+06	1.17E+06	1.17E+06	1.22E+06	1.35E+06	1.35E+06	1.40E+06

4.4 Capital and operational cost for CEA-MFC station

The construction cost for the wastewater treatment plant with CEA-MFC system was calculated according to the predictions and results of the research of Fan et al in 2007. The following assumptions were made to run this simulation model.

- The CEA-MFC system consists of 2,856,000 basic CEA-MFC units. The capacity of each single CEA-MFC is 1 liter. The total capacity of the system is 2,856,000 liters.
- The three dimensions of the CEA-MFC system are 140, 15 and 170 basic units.
- Each single CEA-MFC unit produces a power density of 1 W m^{-2}.
- Each single CEA-MFC unit has a total effective surface area of 6670 cm^2 (66.7 cmx100 cm). The distance between anode and cathode is 0.15 cm.
- \$50 per m^2 for cathode materials
- \$10 per m^2 for anode materials
- \$0.2 per m^2 for separator materials
- \$5000 per m^3 for reactor and other materials
- Operational cost is 5% of the capital cost

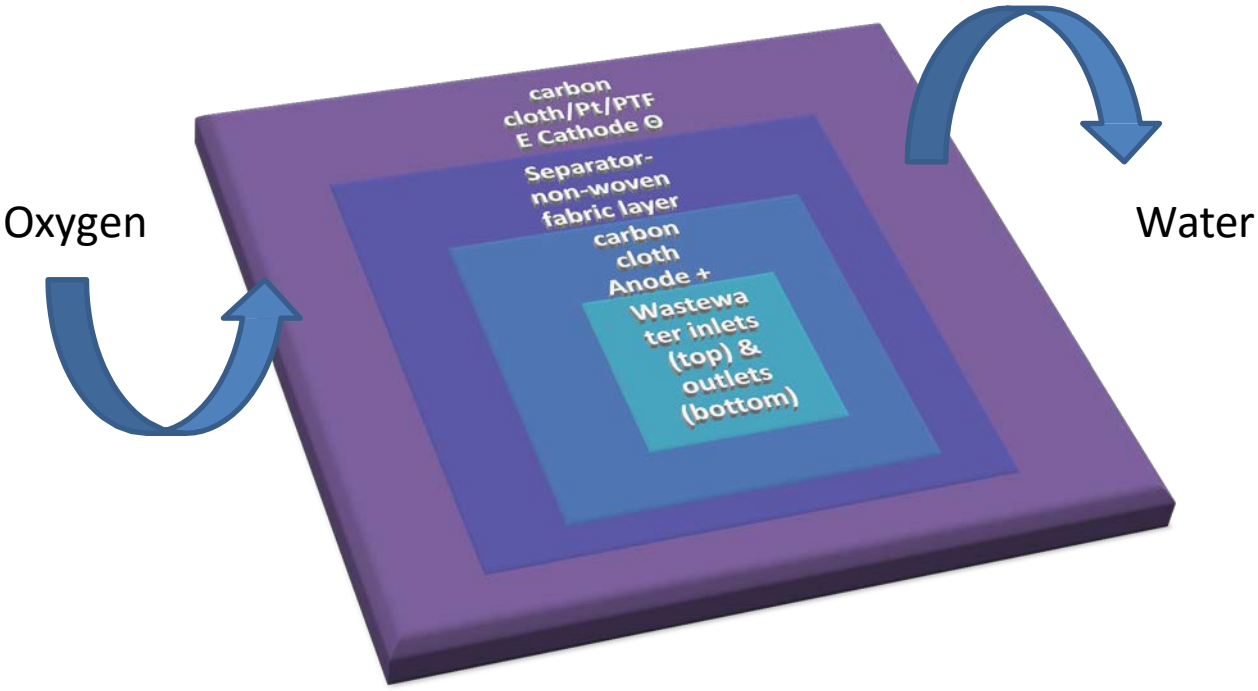


Figure 4.4 (a) Structure of the basic CEA-MFC unit of the system

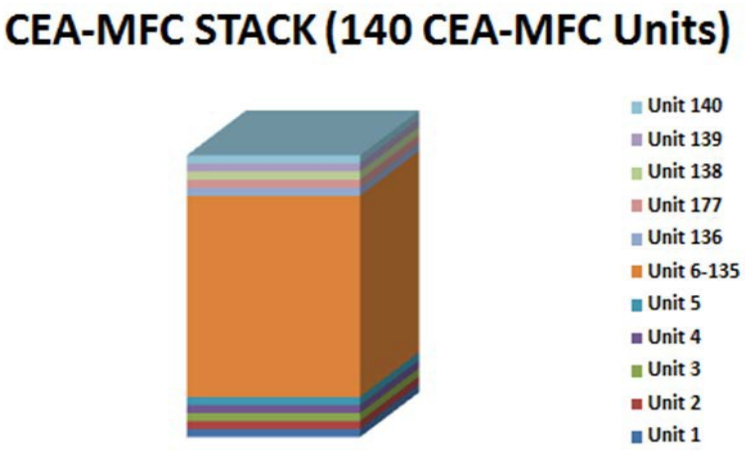


Figure 4.4 (b) The CEA-MFC stack (Height of the CEA-MFC station)

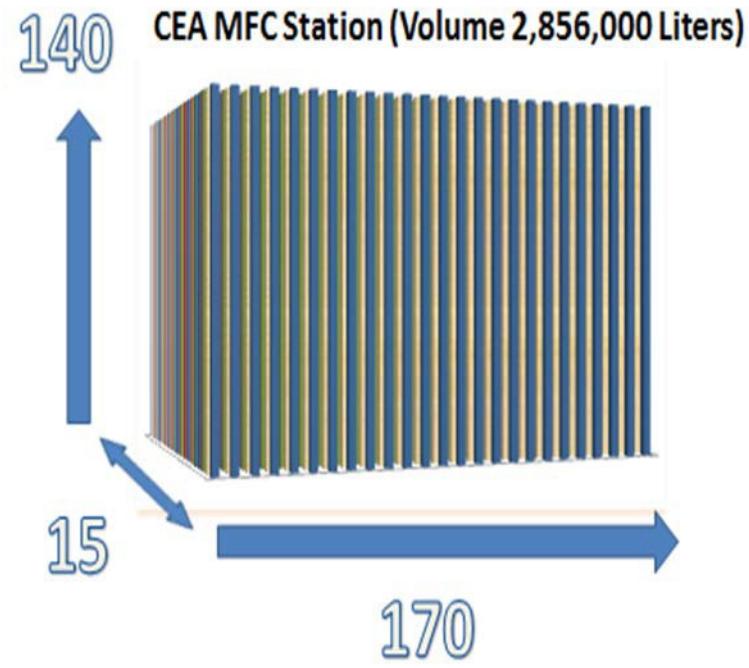


Figure 4.4 (c) The CEA-MFC station for the simulation model

4.5 Results:

Based on the above assumptions, the capital cost of the CEA-MFC station is only 1.6 times higher than the activated sludge basins. With respect to the operational cost of the CEA-MFC station is approximately 58 % of the expense of the activated sludge basins. In addition, the CEA-MFC station generates electricity 1904.95 kWh per day which brings extra $109 income per day.

Table 4.5 (a) Comparisons of CEA-MFC and Activated sludge basins in light of costs and electricity

	Activated Sludge Basin (ASB)	CEA-MFC Station	Ratio (ASB/CEA-MFC)
Capital Cost $	1.E+07	2.E+07	0.63
Operational Cost $	1.E+06	8.E+05	1.73
Total Cost $	1.E+07	2.E+07	0.68
Electricity Production	None	1904.95 kWh/Day = $109	N/A

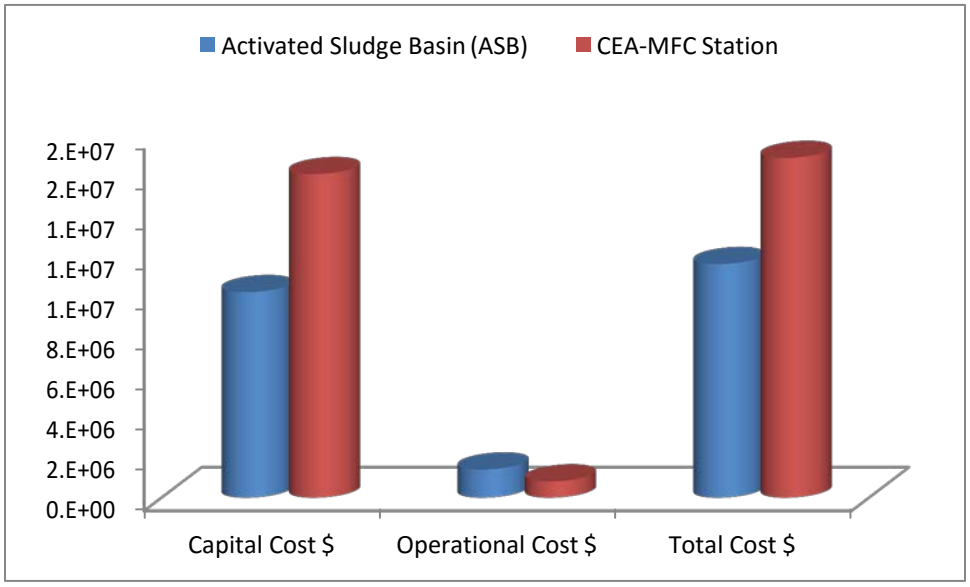


Figure 4.5 (a) Comparisons of CEA-MFC and Activated sludge basins in terms of capital and operational costs

4.6 Conclusions and future work

Conclusions:

In this simulation model, using the CEA-MFC system to replace activated sludge basins in conventional wastewater treatment plants showed a promising result in terms of its operational and capital cost. If we take a close look at these data, we will find that the CEA-MFC system indeed has the potential to replace the activated sludge basins. First, the capital cost of the CEA-MFC system is only about 1.6 times higher than the activated sludge basins. The difference on the costs can be expected to be offset because materials usually become better and cheaper. Second, the produced electricity 1904.95 kWh/Day can bring the wastewater treatment plant yearly revenue for $39,785. Besides, in this simulation, a very conservative method was used to calculate the produced electricity; that is, the real production of electricity could be much higher than what we obtained from this research. For example, we didn't discuss the necessary increase of voltage and current when we made the CEA-MFC stacks and then formed the CEA-MFC station. In a word, by connecting the basic CEA-MFC units in parallel and series in special designs should be able to easily create more than 10 times electricity than this study. In other words, it is possible for us to convert the wastewater treatment industry in to an electricity generation industry. Best of all, CEA-MFC station won't consume so much energy and electricity as the activated basins do. Third, the CEA-MFC usually has a much higher COD removal rate (80% vs 60.61 %), it can significantly reduce the environmental impact on the aquatic ecosystem. Although it does generate carbon dioxide to cause the global warming effect, the quantity is relatively much lower in comparison of those produced in the activated sludge basins.

Future work:

This research has successfully demonstrated that the Impact 2002+ Life Cycle Assessment (LCA) methodology can be combined with the National Pollutant Discharge Elimination System (NPDES) Permit Program to show an overall environmental impact for wastewater treatment plants, and use the LCA results to further compare different unit processes in the targeted systems. However, the LCA study for the two systems (activated sludge basins and CEA-MFC station) was not perfect. At the outset, the constructional phase of the LCA research couldn't be conducted due to a lack of real data. It is necessary for the public work and agencies to start collecting data from now on. Next, the CEA-MFC research must be further conducted to build a database system to better evaluate the feasibility of using CEA-MFC system to replace the activated sludge basins. In this research, only the COD and carbon dioxide could be used to run this simulation model. It would be better if there were data regarding other pollutants removal rate such as heavy metals. Unfortunately, this type of CEA-MFC research has not been widely performed yet. Finally, a liter level CEA-MFC is expected to be made and used for a wastewater treatment plant for at least a year. The data collected from such a research project will be able to better explore the possibility of using CEA-MFC system to replace activated sludge basins when conducting a LCA for the wastewater treatment processes.

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