



ECONOMIC FEASIBILITY OF LARGE-SCALE BIOELECTRIC SYSTEMS FOR THE TREATMENT OF ORGANIC MATTER IN WASTEWATER AND ELECTRICITY PRODUCTION

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1 INTRODUCTION

The International Energy Outlook in 2019 forecasted that the global energy demand in 2020 will be doubled as much as demand from 2018 (EIA, 2019). With the COVID-19 circumstances over the past year and a half, in the latest energy outlook for US market, it was reported that there was a steep decline in the energy demand, which further reflected on the country's GDP (EIA, 2021a). Undoubtedly, similar trends were observed in countries around the world that were heavily affected by the current global pandemic. This does not mean the energy consumption or demand will stop increasing within the next year, so, necessary, continuous measures must be taken to reduce the global temperature rise to 1.5 degrees. The goal of Paris agreement, a long term climate action protocol established in 2015, is to bring down the current annual global temperature rise to less than 2 degrees before 2030 (EC, 2016). To achieve this, 90% of the electricity demand in 2050 must be supplied by renewable sources (IRENA, 2021c). With cost of renewable energy solutions falling every year (IRENA, 2021a), emerging economies have an incentive to implement these technologies, carving the pathway to the ultimate goal: net-zero emissions. One such appealing emerging technology is bioelectric systems.

Like solar and wind energy, where the energy is generated from existing resources such as sun and wind, bioelectric systems repurpose bacteria that is abundant in organic waste and wastewater by producing useful energy. The hypothesis of energy production from microorganisms was first identified and experimented by a botany professor, Michael C. Potter, at the University of Durham in 1911 (Potter, 1911). Since then, several methods, materials have been modified and improved through numerous studies. There are many processes that produce energy from waste, like anaerobic digestion (AD) processes, membrane bioreactor (MBR), aerobic digestion and microbial electrochemical cells (MECs), however, till this date, the most dominant field of research and study remains to be microbial fuel cells (MFCs).

Research on MFCs did not emerge till mid-1960s, when NASA invented a system to recycle waste to produce electricity (Canfield, Goldner and Lutwack, 1963). The fundamental function of MFC relies heavily on the use of microbes that are electrochemically active bacteria which are able to break down organic matter to produce electricity or energy (Basri and Kamarudin, 2018). A typical MFC consists of three components: an anaerobic anode, an aerobic cathode and a membrane through which protons can travel (Verma et al., 2021). The electrons released from the anode travel through the external circuit to the cathode. The protons sent to the aerobic cathode reacts with oxygen to form water (Logan et al., 2006b). As a result, we attain both clean water and clean energy that can be reused to lower water and energy consumption onsite.

1.1 OBJECTIVES

Over the years, there has been a huge scientific development in the field of bioelectrochemistry. For example, studies have presented that when microbes can also act as biocatalysts at the cathode, better power generation efficiencies were resulted (Kumar et al., 2019). These studies collectively led to the development of biocathodes in MFC systems (Verma et al., 2021). Similarly, other innovative developments were implemented on lab-scale research to explore the maximum power density, cost-effective, and ideally, the most treatment efficient system. This report will present a literature review of different designs/setup of bioelectric systems and briefly address how factors like materials of the electrodes, design, wastewater type, thus concentration of organic matter, and integration with other biochemical processes may affect the efficiency of the system.

To meet the energy demands and utilise the wastewater available on Earth, these systems needed to be scaled up. Though it is a challenge due to thermodynamic and cost limitations, some companies

have successfully managed to commercialise bioelectric systems as wastewater treatment solution. The report will introduce a set of companies which are active in the market and choose to analyse three companies and their technologies. Their products will be comparatively analysed from an economical aspect, particularly focusing on costs incurred and benefits gained externally. By comparing two MFC systems with one conventional wastewater treatment facility, we aim to present an overview of the feasibility of these bioelectric systems in the global market.

Typically, sustainable development depends on three things: environmental, social, and economic (Purvis, Mao and Robinson, 2018). Environmental impact mainly focuses on the consequences of land use, raw materials, pollution, and emissions. Though it is true that we are saving the environment by treating wastewater to cleaner and more useful products, it is not guaranteed that this technology itself is environmentally friendly nor sustainable. By reducing the 'organic richness' in the wastewater sent to natural waterbodies, we prevent eutrophication. However, there are environmental limitations including CO₂ emissions, logistics issues that may need to be resolved using transportation, use of scarce resources. All of these factors will be accounted as individual indicators and discussion will be presented following the environmental impact quantitative assessment.

2 BACKGROUND

2.1 ANAEROBIC DIGESTION

Amongst various technologies to treat sludge, wastewater, sewage, food waste, or any waste consisting organic matter, anaerobic digestion, at present, remains to be the most well-known biological waste treatment in the market (Tezel, Tandukar and Pavlostathis, 2011). The concept of anaerobic digestion has been around for decades, which has enabled plenty of research and development to take place over the years. The process involves breaking down of solid organic matter, which is typically defined as organic waste consisting of less than 85% water, into carbon dioxide and methane (in large fractions) and other gases such as hydrogen (in smaller quantities) (Mata-Alvarez, Macé and Llabrés, 2000; Tezel, Tandukar and Pavlostathis, 2011). As suggested by the term “anaerobic”, the set of reactions which take place during the process of anaerobic digestion can be within a single reactor, that must be completely deprived of oxygen (Damon et al., 2014).

The process involves breaking down organic molecules to more stable substances, lowering the amount of the solid effluent that needs to be disposed, thereby reducing the overall disposal costs. There are four phases in anaerobic digestion: hydrolysis, acidogenesis, acetogenesis, methanogenesis. The matter in the organic waste can be classified into three main macromolecules: proteins, carbohydrates, lipids. These macromolecules are separated from the main waste through a physical process called disintegration (Tezel, Tandukar and Pavlostathis, 2011).

1. Hydrolysis – rate-limiting step; the long-chain compounds (macromolecules) are split into amino acids, fatty acids, alcohols and sugars in liquid form (Tezel, Tandukar and Pavlostathis, 2011; Damon et al., 2014)
2. Acidogenesis – long-chained fatty acids resulted from hydrolysis are acidified to form short-chained fatty acids; sugars and amino acids undergo this process through fermentation resulting in several organic acids, and alcohols, as well as hydrogen and carbon dioxide (Tezel, Tandukar and Pavlostathis, 2011; Córdova and Chamy, 2019). This process requires fermentative bacteria (Appels et al., 2008).
3. Acetogenesis – alcohols and organic acids produced from previous phase are transformed to acetic acid, and more hydrogen and carbon dioxide are yielded (Tezel, Tandukar and Pavlostathis, 2011). Partial pressure of hydrogen plays a crucial role in this conversion (Appels et al., 2008)
4. Methanogenesis – final step of anaerobic digestion; requires pH-sensitive methanogenic bacteria (Damon et al., 2014; Appels et al., 2008). The type of bacteria suitable for this process is Archean bacterium, which converts the organic acids (mainly acetic acid) to methane (Damon et al., 2014).

The end product of anaerobic digestion (AD) is collectively referred as biogas, which consists of compounds (mainly gases) mentioned above and few side-products. The composition of individual gases varies depending on the feedstock, temperature of the reactor, and retention time (amount of time the compounds spend inside the digester) (Appels et al., 2008). Furthermore, the ratio of sugars, proteins and fatty acids present in the feedstock also determine the amount of methane and carbon dioxide produced (Jarvie, 2018). It is difficult to report exact percentages, however, we can summarise biogas composition as a range. This information is summarised in the following table (Damon et al., 2014) (see Table 1 below).

Table 1: Table presenting a range for gas composition in the biogas produced as a result of AD

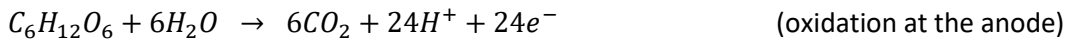
Chemical compound	Compound name	Composition in biogas (%)	Reference
CH_4	Methane	50 – 75	(Damon et al., 2014)
CO_2	Carbon dioxide	25 – 45	(Damon et al., 2014)
H_2O	Water	2 – 7	(Damon et al., 2014)
N_2	Nitrogen	0 – 10	(Damon et al., 2014)
H_2S	Hydrogen sulphide	0 – 3	(Damon et al., 2014)

2.2 BIOELECTRIC SYSTEMS

While anaerobic digestion treats water and produces energy in the form of biogas, there are more innovative technologies that can produce electricity directly from breakdown of organic matter in wastewater. These solutions are collectively known as bioelectric systems (BES).

2.2.1 Typical microbial fuel cell producing direct electricity

One type of BES is microbial fuel cells (MFC), where microorganisms break down organic molecules at the anode. Bacteria produce their own energy through anaerobic cellular respiration, where this bacteria converts sugar to water, carbon dioxide and ATP (energy) (Pop, 2019). Another purpose of bacteria is acting as a catalyst to oxidise organic and inorganic matter (Logan et al., 2006a). This is what happens in wastewater treatment technology. As seen in the figure below, the anode and cathode chamber are separated by a membrane. The anode chamber is anaerobic (oxygen free) and cathode is open to oxygen (aerobic). Wastewater is fed to the anode side of the cell such that the microbes in the wastewater start to grow on the anode. If the organic matter is in the form of glucose, the following reaction may take place (Ford and Brown, 2014).



A more generic equation is given by (Ardakani and Badalians Gholikandi, 2020):

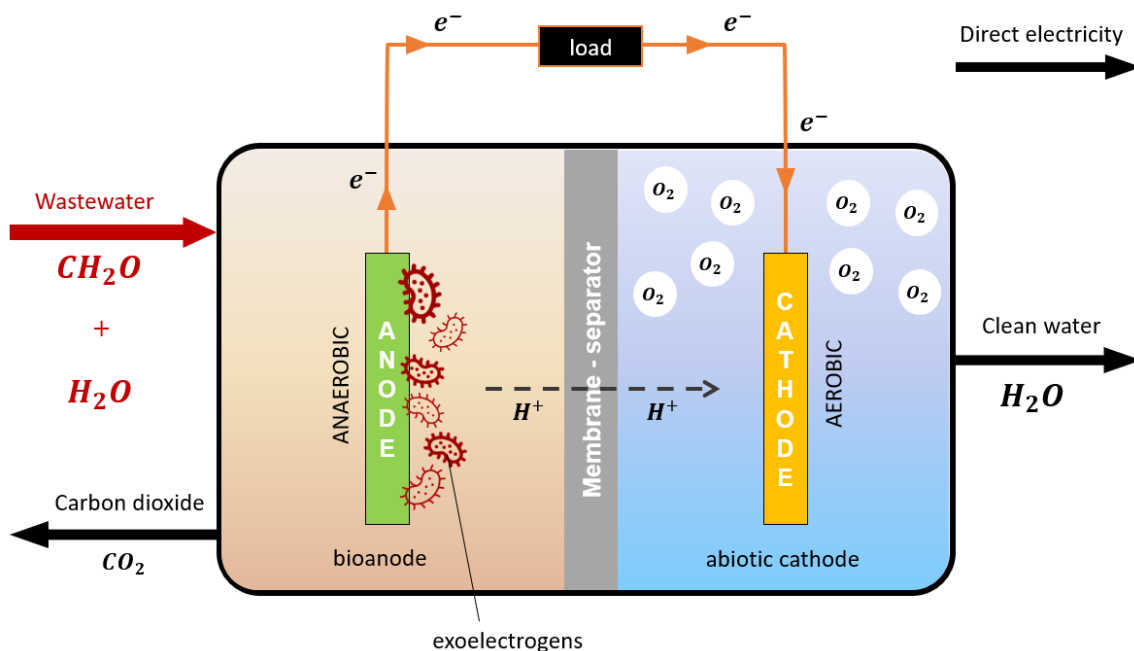
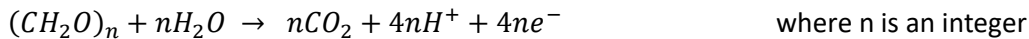


Figure 1: The setup of a typical MFC system producing direct current, comprised of anode, cathode, membrane, illustrating the reactions taking place in both chambers

The electrons produced must first transfer from the bacteria to the anode. There are three ways through which this occurs: 1) transfer through nanowires, 2) transfer on the surface of the cell, and 3) transfer through chemical mediator (Logan, 2008b). Following the electron release from the bacteria to the anode as a result of the oxidation reaction taking place, the electrons move up to the resistor through wires (see diagram – Figure 1).

The protons generated at the anode pass through the membrane to the cathode, while the electrons pass externally through a circuit connecting anode and cathode with a load (resistor) (see diagram) (Logan et al., 2006a). Since the electrons are travelling externally and are generating current, the bacteria from which electrons transitioned from are referred to as “exoelectrogens” (Logan, 2008b). The cathodic chamber has surplus amount of oxygen which reacts with the positive H⁺ ions resulting in water (Pop, 2019), i.e. the treated water effluent.



The current generated as a result of the flow of electrons is referred to as direct electricity, which can be connected to any apparatus that needs electricity, e.g. lights. This electricity is clean, as well as the molecular water produced as the effluent.

2.2.2 Microbial electrolysis cell producing biogas (methane)

A similar design of the microbial cell can be applied for wastewater treatment with different sets of reaction taking place at the anode and cathode, sometimes with the need of power supply. One such variation is the reduction of carbon dioxide to methane (Cheng et al., 2009). A multipurpose technology that emerges from this is wastewater treatment through the process of electro-methanogenesis. The setup of a simple electro-methanogenesis cell is illustrated below (Figure 2).

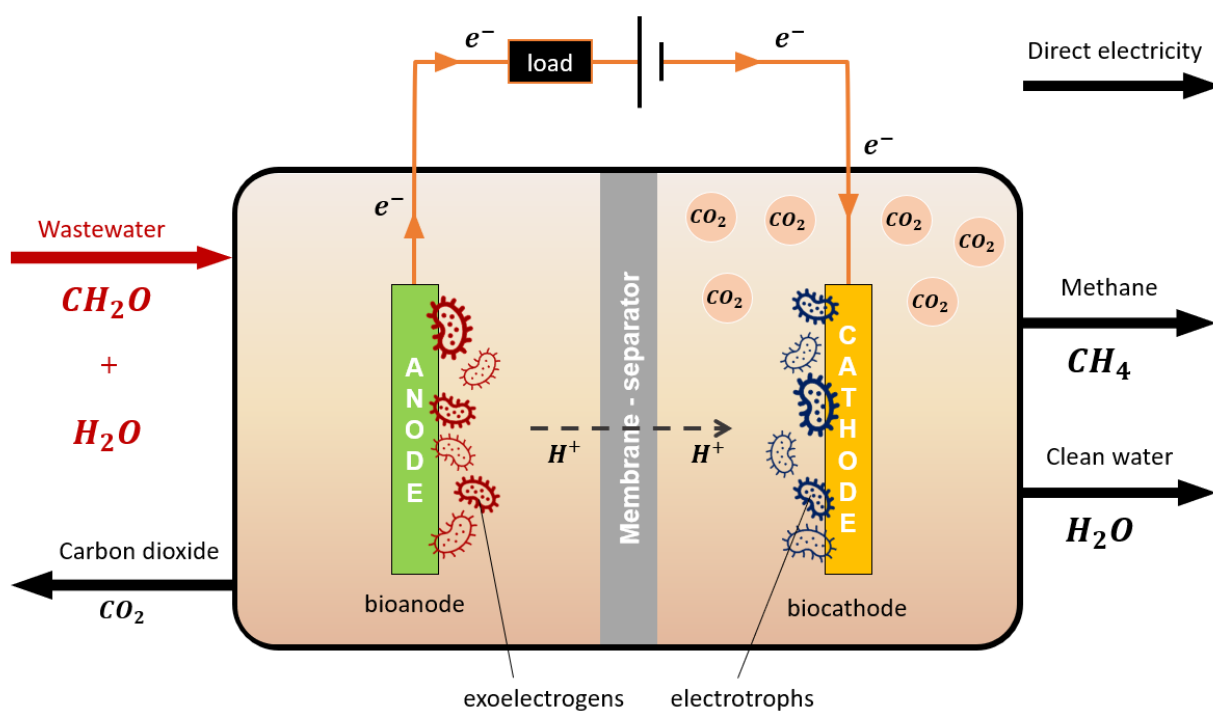


Figure 2: The setup of an electromethanogenesis cell system producing direct current and biogas, comprised of anode, cathode, membrane, illustrating the influents and effluents consumed and produced respectively

This is a type of microbial electrolysis cell (MEC), where a power supply is required to drive the reactions. In some cases, the cathode is filled with microbes, whereas the anode is abiotic (no microbes present on this electrode) (Cheng et al., 2009). We will focus on anode and cathode in a single-chamber system separated by a membrane like shown in Figure 2 (Ishii et al., 2019), where different set of microbes cultivate on both the electrodes (bioanode and biocathode) (Matheson, 2014).

The dirty wastewater containing methanogenic archaea (a specific type of bacteria that can undergo methanogenesis) enters the reactor. The microbes which are electrochemically active grow on the anode through electron transfer, releasing electrons, similar to the anode process in a typical MFC (Matheson, 2014). A possible reaction that may take place at the anode is (Kadier et al., 2016):



Unlike exoelectrogens which are present at the anode, the cathode is coated with a different set of bacteria, called electrotrophs (Matheson, 2014; Pawar et al., 2020). These are the type of bacteria that consume electrons to produce useful products (Logan, 2010). As usual, the protons migrate from the anode to the cathode through the membrane and combines with the electrons and carbon dioxide (Cheng et al., 2009). The carbon dioxide is pumped from an external environment into the reactor which results in the following reduction reaction to take place. This electrochemical reaction can be summarised as direct electromethanogenesis process (Pawar et al., 2020; Logan, 2010):



A study presents that around 0.7-1.3 kWh of energy may need to be supplied to produce 1 m³ of methane (Molognoni et al., 2020). The power can be supplied from renewable energy sources like wind energy. With the use of more appropriate organic substrate to meet the thermodynamic balance, it is possible to eliminate the need for power supply (Cheng et al., 2009). In that case, less energy will be consumed, and we would attain the following benefits: CO₂ capture, direct current flow thus direct electricity, clean methane (biogas) production, and most importantly treatment of wastewater (Lovley and Nevin, 2013; Eerten-Jansen et al., 2012).

2.3 COMMERCIALISED LARGE-SCALE BIOELECTRIC SYSTEMS

Microbial fuel cell technology brings about many benefits compared to conventional anaerobic digestion treatment plant, such as direct energy production from waste, reduced solids production (effluent from the wastewater) and the absence of high energy-consuming aeration equipment (Logan, 2008a). As of now, majority of published research papers and studies on lab-scale MFC technologies are contributed by researchers in China (ISMET, 2021). Scaling up this technology to treat large volumes of wastewater is yet a challenge as there are some limitations that needs resolving. For instance, thermodynamic losses result in lower cell potential than theoretical calculations. Another major limitation is the cost of materials (Koroglu et al., 2018). Carbon materials for anode and cathode are cost-efficient and they function well, however for increased cation transfer, platinum catalyst or expensive membrane (separator) may be required, which increases the total cost of the technology (Koroglu et al., 2018). Lastly, configuration and design of scaled-up system is also being researched on. Compared to the application of large units of MFCs, smaller stacked MFCs yielded a higher power density (Ieropoulos, Greenman and Melhuish, 2008). Thus, the most practical approach for large-scale wastewater treatment solution would be stacking multiple units of MFCs together (Ieropoulos, Greenman and Melhuish, 2008).

Despite these limitations, over the past decade, several companies have stepped up and paved their way for future commercialisation of new hybrid MFC systems. Many of these companies which are in

the process of developing solutions and commercialising are based in United States and Europe. Some of the prominent companies in this industry are Cambrian Innovation Incorporation, Plant-e, MICROrganic Technologies Incorporation, Aquacycl, Fluence, EVOQUA, ElectroChem, Prongineer, Triqua and many more (Singh and Mahapatra, 2019; The Expresswire, 2021). Some of these companies focus only on MFCs like ElectroChem, MICROrganics and Plant-e through the means of either producing materials/kits for MFC setup. Other companies like Cambrian Innovation, Fluence, CASCADE Clean energy (Singh and Mahapatra, 2019), EVOQUA, AquaCycl provide industrial scale bioelectric solutions, as their expertise are broader and extend to MBR and/or anaerobic treatment technologies as well. The table below presents an overview of companies that expertise in microbial fuel cell and/or wastewater treatment solutions which are active in the market.

Table 2: Table presenting a list of companies that are active in the global market categorised alphabetically, with criteria as well as additional information and source.

Company name	Founding year	Provision of treatment solutions	Case studies available	Energy producing solution	Comments	Source
Aquacycl	2016	✓	✓	✓	Leasing and servicing one wastewater treatment solution: BETT®	aquacycl.com
Cambrian Innovation	2006	✓	✓	✓	3 different large-scale bioelectric solutions actively installed; collectively have treated 2 billion gallons of wastewater	cambrianinnovation.com
CASCADE Clean Energy	2008	✓	X	✓	Suppliers of bioreactors, piping, sludge pump and engineering designs, as well as software determining the efficiency of organic treatment	ccleanenergy.com
ElectroChem	1986	X	X	✓	Material, membrane, catalysts, stacks supplier. ECcell™ – hydrogen producing solution but not wastewater as a source	fuelcell.com
EVOQUA	2013	✓	✓	✓	Provides water and wastewater treatment solutions; broad portfolio and products; aerobic and anaerobic technologies;	evoqua.com
Fluence	2017 (operated under the name 'Emefcy')	✓	✓	✓	Specialises in producing water and wastewater treatment solutions that are easily scalable, sustainable, and cost-	fluencecorp.com

	since 2007)				effective	
MICROrganic Technologies	2010	✓	X	✓	Produce bioelectric system: VIVA MFC for wastewater treatment as an alternative for aeration techniques for large-scale production.	microrganictech.com
Plant-e	2009	✓	✓	✓	Manufacture plant based fuel cell where the solution is buried under the soil, and organic matter in the soil breaks down releasing electrons	plant-e.com
Prongineer	2006	✓	X	✓	Produce solutions, designs, feasibility studies, modelling and headworks for both anaerobic and fuel cell technologies.	prongineer.com
Sainergy Tech	2014	X	X	✓	Produce(d) materials, catalysts and small-scale MFCs	sainergytech.com
Triqua	1996	✓	✓	X	Produce membrane bioreactor, anaerobic treatment solutions as well as membrane filtration technologies for small and medium scale wastewater sources	triqua.eu

Due to the drastic development in the use of bioelectric systems for wastewater treatment, both scientifically and commercialisation-wise, the designs and thorough information are usually not provided on company's website for public access. Furthermore, many companies are still yet to be commercialised, whereas well-established Cambrian Innovation and Fluence have clients where their wastewater treatment have been adapted to their brewery/winery for few years already. The companies whose MFC technologies will be reported for cost analysis are Cambrian Innovation, Fluence and AquaCycl.

These three companies were chosen due to multiple individual reasons. Cambrian Innovation Incorporated launched into the MFC market about 15 years ago (Cambrian, 2020), making it one of the first companies to provide such bioelectric systems on a scale larger than laboratory studies and tests. Throughout their remarkable journey, many existing wineries and breweries have adapted their technologies. Their case studies provide an insight on their experiences with EcoVolt (technology in focus from Cambrian), how cost-effective and useful their MFC designs are. Similarly, Fluence has several case studies where their solutions have been implemented. Even though their demanding MABR technology represents the innovative side of the brand, it is only proven to be energy-efficient (Fluence, 2021b), not energy-positive or neutral. Thus, our focus will be on anaerobic digestion solutions (biogas plants) provided by Fluence. Lastly, AquaCycl's solution BETT is a scalable MFC solution, comprised of modular units treating gallons of wastewater per day (Aquacycl LLC, 2018).

Furthermore, there are existing case studies on this technology which are available on their website, which will be useful to analyse its benefits and environmental impacts.

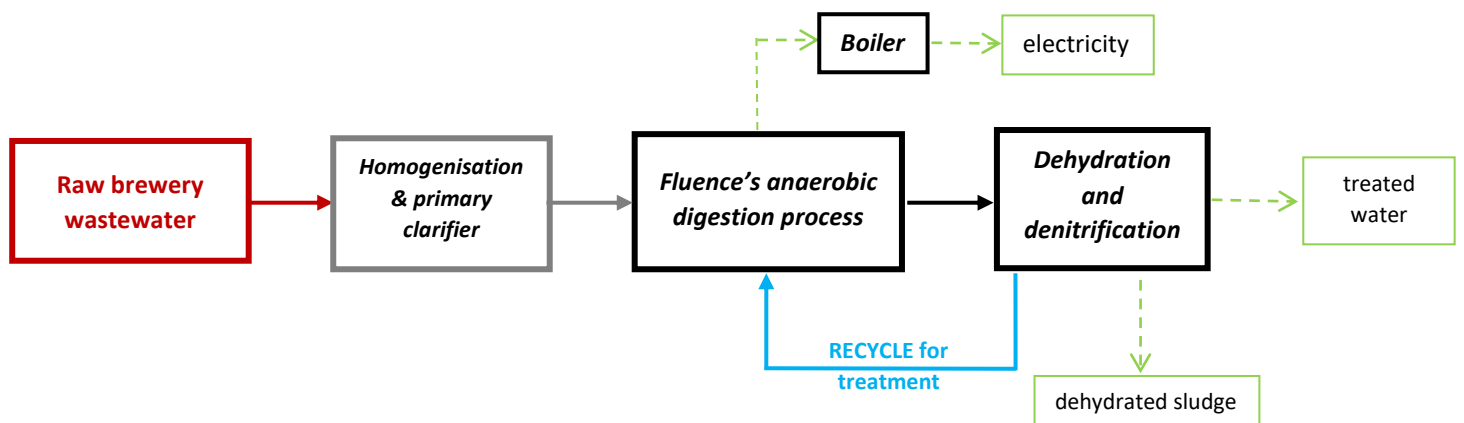
2.3.1 Fluence – Anaerobic digesters

Fluence Corporation is a leader in waste and water management industry, headquartered in New York, USA. Their vision is to provide water treatment technologies that is sustainable, high-quality and affordable (Fluence, 2021a). They focus on decentralised treatment systems that can be easily installed (Fluence, 2021a). One of their remarkable, engineered solution is MABR technology requiring minimal energy requirement for aeration process. Despite these modular containers are able to cut down 90% energy needed (Fluence, 2021c), no net energy can be gained in the form of direct electricity or through biogas production. On the other hand, their current ‘waste-to-energy’ solution: anaerobic digestion plant is able to produce biogas that can be used as energy source for water clarification and pre-treatment, adding value overall (Fluence News, 2020).

Fluence’s anaerobic treatment technologies are engineered such that they can work independently or installed to an existing biological treatment plant (Fluence, 2021d). These digestion reactors range from typical continuously stirred tank reactors (CSTR), membrane incorporated reactor, external forced circulation (EFC) reactor (Fluence, 2021d). These biogas plants have been primarily deployed in different parts in Italy, however there are few plants in countries like Ecuador, Argentina, Spain and Uruguay (EBA, 2020; Fluence, 2021d). A case study (Fluence, 2019) on treatment of wastewater from a dairy farm in Treviso in Northern Italy was conducted. Here, Fluence installed an anaerobic digester CSTR working in conjunction with a biogas scrubber to the existing plant, to treat 180 tonnes of whey each day. At this capacity, the plant was able to generate 12000 kWh and 12500 kWh per day of electrical energy and thermal energy, respectively (Fluence, 2019). Similarly, at a confectionary in Italy, both EFC and traditional sludge digesters (working for 18 hours) (Fluence, 2020) were deployed along with high-quality pre-treatment process (dissolved air flotation system to separate fats and oils) (Fluence Corporation, 2021). EFC purification rate is 85% (EBA, 2020) but the complete process yielded in almost 99% COD removal efficiency: 9600 mg/L for influent and below 80 mg/L for effluent (Fluence, 2020). With the pre- and post-treatment process in addition to the two main digester, solid sludge was reported to be reduced by 70% (Fluence, 2020). Evidently, an anaerobic digester on its own cannot fully treat wastewater, but with few more clarification processes, the plant can work much more efficiently.



Figure 4: Two Fluence large-scale anaerobic digestion products: EFC digester and sludge digester to treat confectionary wastewater at a facility in Ossona, Italy. Image taken from (Fluence, 2020)



Black boxes indicate the processes that make up the necessary elements of the BETT solution
Grey box indicates the recommended but optional pre-treatment
Green boxes indicate the effluents that has benefits in this process
Blue stream indicates that part of effluent from post-treatment re-enters the digestion process

Figure 5: Recommended setup for brewery wastewater treatment plant with Fluence’s AD solution (may differ from plant to plant depending on location and capacity). Adapted from (Fluence, 2021d)

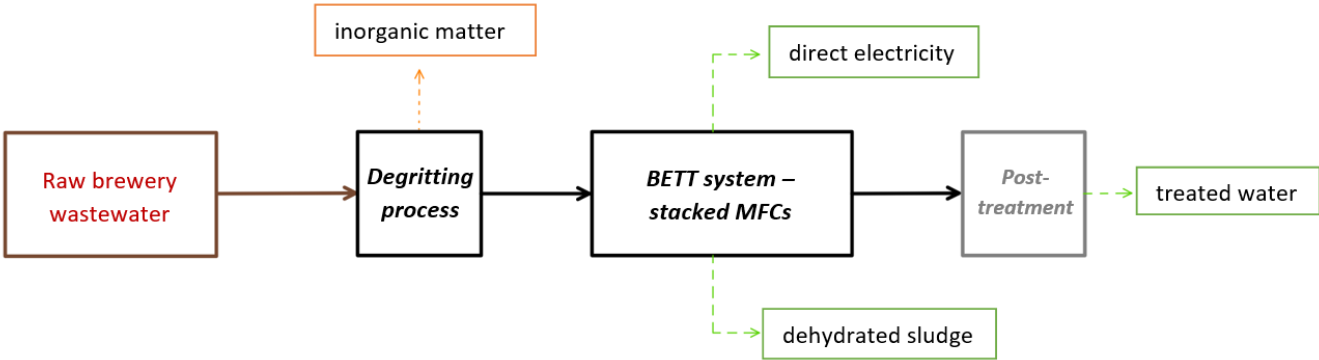
One of the attractive features about Fluence and their solutions is the customisation and selection of products that is best suitable for the facility and type of waste, for example, their proposed solution differs if the client is a brewery from a dairy farm. To briefly explain the treatment chain they generally use, Italian confectionary case study will be looked at. The first step is sending wastewater through a flotator as it facilitates separation of fats (Fluence, 2021d). This is followed by an EFC digester (an UASB type reactor) where the wastewater is pumped upwards, and the dense granules formed by the bacteria is carried with, forming carbon dioxide and methane (biogas), and water (Mullai et al., 2020). The remaining sludge from EFC and flotator is sent to CSTR anaerobic reactor to further reduce the COD concentration. In Figure 5, these digesters are collectively referred as “Fluence’s anaerobic digestion process”. The treated water effluent from this anaerobic plant is aerobically processed where contaminants such as nitrogen, phosphorus and COD are consumed by the oxygen. The sludge is then sent to a separator where solid sludge is separated from liquid (which is sent back to aerobic water treatment) (refer to Figure 5).

2.3.2 Aquacycl – BioElectrochemical Treatment Technology (BETT)

Aquacycl is a wastewater treatment company based in San Diego, USA, and they are striving to provide wastewater treatment solutions that is scalable and cost-effective, as depicted in their motto (Aquacycl, 2018a). Aquacycl solutions have been tested with various influents such as swine wastewater, soda factories, breweries, dairy farm waste, residential waste and more (Aquacycl, 2018a). Their primary solution is: BioElectrochemical Treatment Technology (BETT), a technology that accomplishes wastewater treatment without the need for oxygen i.e., an anaerobic process, and produces direct electricity (Bretschger, 2020). The amount of electricity produced can be used for other purposes onsite, for example, charging a forklift, (Bretschger, 2020) enhancing the energy neutrality of this treatment solution. Depending on the wastewater type and operating conditions, the systems can produce anywhere between 0.2-0.8 kWh per kg of COD treated (Aquacycl, 2018d). As of COD removal, their product is guaranteed to treat influents with COD content up to 300000 mg/L with hydraulic retention time of 4 hours (Aquacycl, 2020, 2018d). At this point, pilot testing showed 65% removal

efficiency (Aquacycl, 2018c), however the company guarantees 95% removal efficiency with their scaled-up product (Aquacycl, 2020). With additional post-treatment operation, which is considered optional as the efficiency is already high, COD level less than 2 mg/L is achievable.

As mentioned, two pilot systems were installed in San Diego to test BETT solution about 4 years ago. In 2018, Aquacycl launched their first commercial, large-scale, 20-foot container treatment technology at a small brewery in the United States, Joshua Tree Brewery (Armao, 2018). Here, the BETT reactors are stacked up like LEGO bricks on top of each other and arranged inside the container (Bretschger, 2020). This brewery was in need for a robust, high-quality wastewater treatment, given the location was situated above an aquifer (rock layer below which groundwater is present) (Britannica, 2020; Armao, 2018). The Aquacycl’s BETT was installed, and yielded great results in terms of electricity production, however the effluent water had high concentration of nitrates (Armao, 2018). A one-year study of this plant presented better BOD/COD removal efficiency, ranging between 50-93% during the summer months (Bretschger, 2018b). Despite these adequate efficiencies, it was reported that this plant presented better results than laboratory test runs (Armao, 2018). To improve the COD removal and total nitrogen content, Aquacycl partnered with BioLargo and adapted two further polishing processes to ensure that the final discharge meets environmental safety regulations (Armao, 2018; Bretschger, 2018b). After post-treatment using BioLargo reactors, 90-99% BOD/COD removal efficiencies are achievable (Bretschger, 2018b). In more recent interviews and reports (Bretschger, 2020; Labs, 2021), with presumably improvements made to the design, Bretschger claims 95% is achievable with BETT system alone, and then post-treatment or pre-treatment reactors above that can be installed if necessary.



- Black boxes indicate the processes that make up the necessary elements of the BETT solution**
- Grey box indicates the optional process to refine the water effluent**
- Orange box indicates effluents that has no benefit in this process**
- Green boxes indicate the effluents that has benefits in this process**

Figure 6: Generic setup of Aquacycl’s BETT system for wastewater (may differ from plant to plant depending on location and capacity). Adapted from (Aquacycl, 2018d).

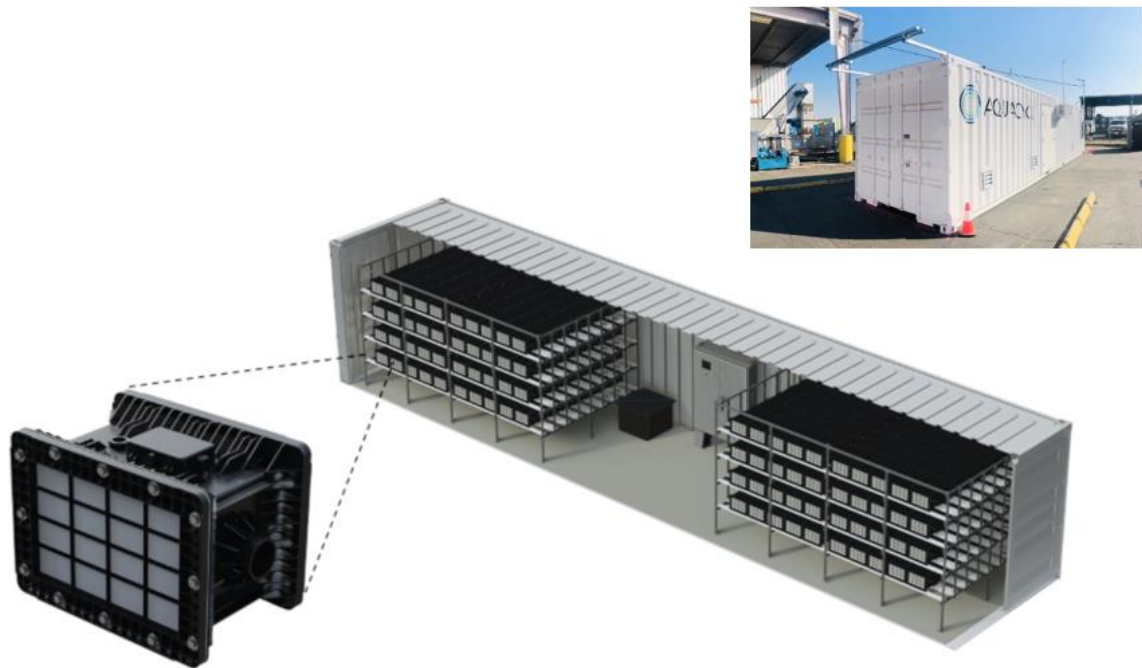


Figure 7: Figures showing real-life container located at one of the client's wastewater treatment facilities (top-right), setup of BETT reactors inside the container (middle), and closer look at one BETT reactor unit (bottom-left). Source: Adapted from (Labs, 2021).

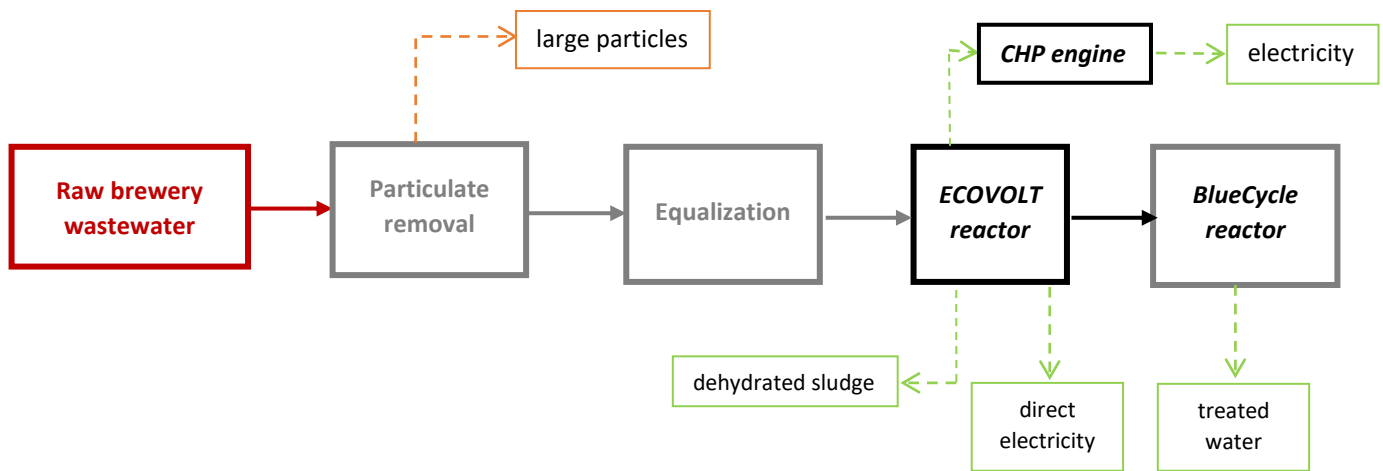
Each of the “black boxes” shown in the figure above are one MFC single-chamber unit cell. At Aquacycl, particular bacteria is not chosen and enriched on the biofilm, instead locally available bacteria is used (Bretschger, 2020). Like a typical MFC, the bacteria break the soluble organic matter down releasing electrons (Bretschger, 2020; Logan et al., 2006b). This is caused due to breathing tendency of bacteria when in contact with a conductive material (Bretschger, 2020). The anode is made of multiple carbon fibre brushes connected in series (Babanova et al., 2020), which is ideal because brushes are reported to generate higher power density, COD removal efficiency than flat mesh (Hays, Zhang and Logan, 2011). As expected from MFC function, clean water is produced due to oxidation, and carbon dioxide is produced along with treated water due to reduction (Bretschger, 2018a). Depending on the conditions, the redox reactions can differ, in this case, oxidation produces both molecular water and hydrogen peroxide (Bretschger, 2018a). Some microbes may develop a biofilm on the cathode and respiration takes place (Aquacycl, 2018d). The hydrogen peroxide will make the conditions less ideal for bacteria growth on the aerobic biofilm (Aquacycl, 2018d), which reduces short-term maintenance costs. At Aquacycl, all tests conducted with BETT solution in real, industrial, outdoor conditions have been running smoothly since 2016 (Aquacycl, 2018d).

2.3.3 Cambrian Innovation – EcoVolt Reactor

Cambrian Innovation was one of the very first companies to commercialise microbial fuel cell technology as large-scale reactors that can treat more than 250000 gallons of wastewater (approximately 954300 litres) (Cambrian, 2021). One of their very first, highly known product is the EcoVolt reactor which effectively and efficiently transforms wastewater to useful, and more importantly clean energy and water (Cambrian, 2021). Depending upon the substrate and the amount of organic matter present in the wastewater used, this technology can produce between 30-200 kWh of energy (biogas production as well as direct electricity) (Global Opportunity Explorer, 2018). To this day, EcoVolt Reactor series, is well known as the ‘world’s first bioelectrically-enhanced wastewater treatment solution’ (Cambrian, 2021). One of the wastewater treatment designs in the EcoVolt series (provided by Cambrian) was first installed at a brewery in western part of USA, in 2016, as the only

wastewater treatment plant onsite. The Sonoma County craft brewery adopted EcoVolt MBR, which is claimed to remove 99% of the organic matter and impurities, and generated clean water (Aviles, 2016).

During the following year, the application of this technology expanded to wineries and food processing factories. Rombauer Vineyards became the first winery to adapt this bioelectric technology (Fehrenbacher, 2017). In 2018, they replaced their existing treatment plant with EcoVolt + BlueCycle MBR integrated treatment facility (Cambrian Innovation, n.d.). EcoVolt is an anaerobic reactor which dominates the organic matter removal, whereas BlueCycle MBR is an aerobic reactor is used to polish (Cambrian Innovation, n.d.) the effluent and produce cleaner water. This solution, therefore, is claimed to treat “100% of the winery’s wastewater”, and under difficult, undesirable seasons, an average 94% removal efficiency is reported (Cambrian Innovation, n.d.). During 2019, 92% removal efficiency was reported in the EcoVolt Reactor, and the remaining 8% was attained through BlueCycle reactor resulting in high quality effluent (Cambrian Innovation News, 2019).



Black boxes indicate the processes that make up the necessary elements of the BETT solution

Grey box indicates the pre-treatment and OPTIONAL post-treatment process

Orange box indicates effluents that has no benefit in this process

Green boxes indicate the effluents that has benefits in this process

Figure 8: Generic setup of Cambrian’s EcoVolt system for wastewater (may differ from plant to plant depending on location and capacity). Adapted from (Matheson, 2014).

The figure above presents a brief blueprint on the transportation and treatment of wastewater using EcoVolt. After solids and particulates are removed, the wastewater is sent to the bioelectric treatment units: EcoVolt. The exoelectrogens undergo the process of electromethanogenesis (Matheson, 2014). Microbes which are coated on the anode convert organic waste and sends off electrons (Matheson, 2014). The cathode (secondary electrode) then transforms this to methane fuel and carbon dioxide, collectively known as biogas (Cambrian Innovation, 2021). The process of electromethanogenesis enables stabilization and automation of the system operation, and enhances biogas production (Aviles, Dean and Gobburu, 2017; Matheson, 2014), which is what makes EcoVolt Cambrian’s “flagship” product.

3 METHODOLOGY

3.1 LITERATURE REVIEW

To carry out a review on state of the art MFC technologies, and categorise the most common systems, I started by choosing an existing review article through Scopus. I used the filter search on Scopus to narrow my search to “wastewater treatment” and “MFC”.

The review found (Ardakani and Badalians Gholikandi, 2020), which presented a wide range of MFC integrated/hybrid systems, which gave me access to analyse various papers on lab-scale experiments. I used an online highlighter on the web to spotlight articles in this review that uses wastewater specifically, rather than sludge from vegetable waste. However, throughout my exploration, I realised a variety of substrate/feedstock is important for analysis, so I chose one or two studies whose substrate are sludge from wastewater treatment plant.

After I filtered out the most relevant articles, the next step was to gather data for current density, power density and COD (chemical oxygen demand) removal efficiency. Since our focus is on energy production from these bioelectric systems, I further narrowed down studies that have measured a parameter that provides an insight on how much energy can be produced. Mainly, we look for studies that provide power densities and current densities such that a comparative analysis between different hybrid systems can be carried out.

The next step was to read through the “results and discussion” section of these articles and tabulate the data needed for the review. The discussion section provided further information on several factors that affected the power generation and removal efficiencies. The design is the important factor that distinguishes one study from another, therefore, significant to report in the review. Moreover, an understanding of anode and cathode chamber; how they are used, and their materials sets the ground for discussing the economic feasibility of the large-scale MFC systems.

All the gathered information were tabulated. A total of 10 different studies and corresponding data were collected. Studies that focused on two relevant experimental runs were both tabulated, as the variation in results between a typical MFC and an MFC hybrid system (using an MFC of the same kind) can be crucial to note. The review is followed by a thorough discussion on ‘MFC-MBR technology’, ‘MFC-anaerobic treatment technologies’, and ‘other MFC hybrid systems’ that mainly focuses on use of biohydrogen reactor as pre-treatment.

3.2 COST-BENEFIT ANALYSIS

3.2.1 Generic assumptions

Wastewater treatment plants are extremely important solutions that we must possess all around the world, whether it may be to treat local domestic wastewater (toilets, sewage waste), or municipal wastewater (household wastewater and precipitation included), or industrial wastewater from farms, dairies, breweries etc. The technologies selected are most efficient in treating high COD concentration wastewater, therefore, it is only sensible to perform our cost-benefit analysis on such high strength wastewater. The following table summarises different wastewater types and their typical range of COD and BOD values.

Table 3: Table presenting the organic matter concentrations in different wastewater sources

Type	COD (Total chemical oxygen demand)	BOD	Source
Typical domestic sewage	600-900 mg/L	300 mg/L	(BMS, 2013)
Beer brewery wastewater	2500-6500 mg/L	1500-3500 mg/L	(Choi, 2016)
Rice wine distillery wastewater	82000 mg/L	-	(Ling, de Toledo and Shim, 2016)
Milk candy wastewater	29600 mg/L	-	(Ling, de Toledo and Shim, 2016)
Petroleum refinery	250 mg/L	-	(Guo et al., 2016)
Dairy wastewater	2000-4000 mg/L	1000-2500 mg/L	(Kolev Slavov, 2017; Tawfik, Sobhey and Badawy, 2008)

Two most commonly accessible facilities with steady effluents are: domestic sewage and dairy wastewater, as the demand for milk products fluctuates very little, and there is an abundant amount of municipal wastewater available in sewers. The next resource that is quite commonly popular is alcohol. Its high demand leads to steady production rate which benefits as the influent in energy-producing wastewater plants. Winery wastewater treatment is shown to result in incredibly high COD/BOD removal efficiencies is because of their high organic matter content: 85% of total contaminants is organic matter from grapes and wine (Skornia et al., 2020).

Whether it may be distillery or brewery, the COD levels are high because the wastewater is rich with organic substances. It has a high content of dissolved sugars, fatty acids that can easily vaporise, ethanol and soluble starch. Ultimately, we want to use the source that has very high concentration, however, we need to know whether commercialised systems introduced earlier is suitable for facilities like rice wine distillery or milk candy production. As for this research goes, there are no such evidence of the company installing their treatment plants at these facilities. However, at all three companies, Aquacycl, Cambrian and Fluence have implemented their respective technologies on breweries, and they yielded substantial results that both the client and company were proud of. Furthermore, brewery wastewater contains high COD concentration compared to domestic wastewater or dairy waste.

There are many parameters like COD concentration that define the wastewater quality. The data in the third column in Table 4 were chosen and decisions are based on literature, previous studies.

Table 4: Range of organic component concentrations and fixing values based on this for our analysis

Parameter	Units	Typical range	Value chosen	Sources for range
COD	mg/L	2500-6500	5000	(Choi, 2016)
BOD	mg/L	1500-3500	2750 (typical BOD/COD ratio is 0.5-0.6) (Modic et al., 2017)	(Choi, 2016)
TS	mg/L	1300-8750	7000	(Rao et al., 2007)
TSS	mg/L	200-3000	2000	(Brito et al, 2007; Rao et al., 2007)
TKN	mg/L	25-85	81.6 (calculated)	Calculated from

				Fluence Energy consumption calculator (Brito et al, 2007; Bakare and Khumalo, 2019)
VSS	mg/L	804-1278	1090 (average estimate)	(Díaz et al., 2006)
Temperature	°C	18-40	20 (low temperatures – lower energy consumption)	(Rao et al., 2007)

The energy produced as a result of the treatment will be used to supply power within the plant for other purposes like pumping, boiler (for methane) and other monitoring devices. The remaining electricity or electrical energy, if any, is best sold to the national electricity grid at current prices. Consequently, the electricity generated from waste can be supplied to power households. This revenue is accounted as one of the major benefits attained through the use of these treatment plants.

The location of each wastewater treatment facility is different from one another. This is because the location is chosen such that it is similar to where existing case studies are based on. Similar geographical location/region allows us to make more reasonable estimates and assumptions when calculating costs and benefits. Moreover, at most times, location of study is where company is based at, thus any financial information available (for public access) regarding that company and their solution will have based their numbers on that location (unless stated otherwise). Therefore, the monetary values placed to define the costs and benefits in this study will be in appropriate currencies and prices, depending on the location.

For all three studies, we will base the calculations for on-site wastewater treatment for a brewing facility where the inlet wastewater flowrate is 600 m³/day. We will assume that all three systems will operate 8000 hours per annum (Carlini et al., 2017).

3.2.2 Cost and benefit parameters

Cost-benefit analysis is a type of economic analysis to determine the feasibility of a project or initiative by weighing both gains and losses (assessed based on monetary values) as a result of implementing that project. There are two main methods for this assessment: 1) monitoring the net present value (NPV) throughout technology's lifetime, or 2) using a benefit-cost ratio (Molinos-Senante, Hernández-Sancho and Sala-Garrido, 2012). This report will use the latter method, and the preferable technology will be determined by the highest benefit-cost ratio.

The cost-benefit analysis will be executed for the three large-scale wastewater treatment applications presented above: one anaerobic treatment and two bioelectric systems. The costs will take into account of 1) investment costs which involves the initial capital costs of the system, 2) operating and maintenance costs, 3) tipping fees for disposing sludge effluent where necessary. The benefits for this study will mainly focus on the attributes that would have been 'costs of no action'. For example, if wastewater had been discharged directly from the brewery to natural waterbodies, electricity, water (for reuse) and dehydrated sludge would not have been reclaimed. Thus, the prices for these effluents will be accounted as the benefits in this study.

The prices of electricity, water, sludge sales and disposal costs vary from country to country, due to demand-supply market in that region. Anaerobic treatment plant by Fluence has a few case studies on plants located in Italy, thus it is best to perform the study using Europe or Italy prices. On the other hand, both bioelectric system companies are based in United States. Similarly, the respective case studies are also in the same country: EcoVolt's case study on Lagunitas Brewing Company and Aquacycl's BETT case study on Joshua Tree Brewery are both based in California. Disposal, electricity, and sludge prices are specific to the region, and will therefore be identical for both bioelectric technologies.

3.2.2.1 Liquid water effluent for discharge/reuse

The recycled water can be utilised before it enters the natural water cycle again. Its applications are mainly non-potable; this includes washing, cleaning, irrigation, and industrial uses (Watereuse, 2021). On the other hand, over the years, Cambrian has improved its clean water effluent efficiency. Most recent article (Moutenot, 2019) reports that for every 3 units of wastewater treated, one unit of clean water can be gained. As of Aquacycl, approximately two-fifths of total wastewater is waste and sludge (as well as water lost due to evaporation), while the remaining volume is the effluent reusable water, says their sales department (Crowell, 2019).

According to one of Fluence's case studies, the output flowrate of treated wastewater is the same as inlet flowrate (Fluence, 2018a). However, this may not be accurate as this may be the total effluent rate of both water (liquid sent for post-treatment) and solid sludge product. A study (Ozgun et al., 2012) reveals that a typical conventional wastewater plant treats 77% of wastewater sent and based on their data of influent and effluent of anaerobic digestion plant alone, only 16% of the total wastewater is discharged as clean water. This estimate will be used to calculate the amount of water attained in an AD plant.

3.2.2.2 Price of electricity

The recent most estimate, based on second half of 2020, the price of electricity in Italy was 0.2153 EUR per kWh of electricity (Eurostat, 2021). The treated wastewater can be directly discharged into the nature as it will meet the quality criteria and requirements to be approved as unarmful for the environment, and this is accounted as a benefit.

The price of electricity in the United States is slightly cheaper than European prices, at an average of 10.73 cents (all sectors average) (EIA, 2021b). Fortunately, the US Energy Administration provides an insight for electricity prices for each state. As of California, the price is at 19.16 cents, as of April 2021 (EIA, 2021b).

3.2.2.3 Price of recycled water for potential irrigation purposes

We will account clean water production as a benefit and set the monetary value as the amount the client would have gained if they sold the resource at local prices or amount the client could save by using it for irrigation purposes within their facility. According to (City of San Diego, 2021), in California, the price of recycled water is \$1.734 per 100 ft³. This is equivalent to \$ 0.6124 for every m³ treated water effluent from the plant. This is approximately 29% of typical potable water rates there. Other sources (Shen, 2020) also present that recycled water prices are less, roughly one-third of normal clean water rates. Knowing that tap water prices in Italy range from 0.40-1.90 EUR (based on 4 cities) (IBNET, 2021), average estimate for tap water price is 1.16 EUR per m³. Thus, we will assume that recycled water price rate in Italy is 0.3867 EUR per m³.

3.2.2.4 *Sludge price for agriculture and farm uses*

The biosolids can be sold as livestock bedding for local farms. Typically, these biosolids are sold at a price much lower than product substitutes, to make them competitive. The cost at which dried sludge can be sold ranged from \$34-64 per tonne (EPA, 2018), and we fixated the price at roughly \$50 per tonne. Due to low demand for this at local farms, we will assume that half of sludge remains are sold for agricultural purposes, whereas the other half is disposed to landfills.

3.2.2.5 *Tipping fees for sludge disposal*

Tipping fee is an amount of money that must be paid by the client to disposing their wastewater sludge to a landfill. These tipping fees are rising around the world as the need for environmental preservation grows. As of Italy, in 2019, the tipping fees increased to 115 EUR (previously 75 EUR), for every tonne of dewatered sludge (solid) disposed to landfills (ECSM, 2019). In the United States, EREF has presented the fluctuations in these prices for specific regions as well. In California, where Aquacycl and Cambrian technologies are based, the current price as of 2020 is \$58.48 per tonne (EREF, 2021).

3.2.2.6 *Sludge removal efficiency*

Fluence has the capacity to cut down the solid sludge disposal by 70%, indicating the total tipping fees over a year can be cut down by the same amount compared to if an anaerobic digestion plant had not been installed. The BETT solution guarantees 80% sludge reduction rate (Aquacycl, 2018b), which means the cost spent on tipping fees is cut down by 80% than if no treatment plant was installed at the brewery. (Gobburi, 2016) presents that 70% of sludge can be reduced with their EcoVolt technology.

3.2.3 *Technology specific data/information gathering*

Information regarding energy production, energy consumption, capital costs and operational and maintenance costs are sometimes found for each company specifically or through their case studies. In other cases, assumptions needed to be made based on existing scientific research. The findings for these parameters are further explained below, for each solution.

3.2.3.1 *Fluence's AD plant as 'waste-to-energy' solution*

The cost of an anaerobic digester depends highly on its size and its design, and it usually ranges anywhere from \$400000 – 5000000 (Montana State University Extension, 2011). This would be the cost at which the plant is bought and installed, i.e. the investment cost. Assuming a digester at a brewery costs 2 million USD with post-treatment for phase separation of digestate, and pre-treatment (and recycle) processes within the chain to make the sludge more concentrated, a suitable approximation is approximately 1.69 million EUR. The lifetime of an anaerobic digestion plant is 20 years (Gebrezgabher et al., 2010).

Anaerobic digestion is a common procedure to treat wastewater. For a conventional procedure as such, there are several maintenance aspects to be taken into account. These include use of electricity for any pre-treatment or post-treatment, water requirements, labour costs and any other maintenance equipment. An average estimate based on monetary values given on (Tassart et al., 2017) around 8.13% of the total capital cost is needed for annual running cost. This is for a typical biogas plant, irrespective of the wastewater type being treated. This is similar to (USDA, 2007), where it was reported operating costs for anaerobic treatment of livestock wastewater (from farms and dairy farms) ranged between 5-7.5%. With increased COD concentrations (see Table 4), it is justifiable that more energy and sophisticated post-treatment may be required, thus higher operating cost. Thus, a suitable approximation for maintenance cost is 10% of total capital costs. The difference may also be due to

time, and how more maintenance is required nowadays due to the complexity of the treatment chain, like shown for typical Fluence's solutions.

While there is not a full case study available for implementation of Fluence's anaerobic digesters as treatment process for a brewing client, we can make assumptions for energy production using other case studies. The plant at chicken slaughterhouse in Teramo, Italy, generated 3600 Nm³/day of methane (Fluence, 2018b). The COD level in the influent at this plant was 5300 mg/L, which is very similar to the value we chose. However, the flowrate is set at 4180 m³/day (Fluence, 2018b), compared to 600 m³/day for our assumption. Another case study, where the volumetric flowrate is 2200 m³/day (Fluence, 2018a) and with COD influent concentration at 3000 mg/L, the total methane production was 1800 Nm³/day. Based on these two studies, we derive that between 0.82-0.86 Nm³ of methane can be produced for every m³ of wastewater treated. The higher conversion rate was achieved when the COD influent level was 5300 mg/L. Since this is the closest representation of brewery wastewater levels, we will use the higher conversion rate, 0.86 Nm³ methane per m³ of wastewater treated. Since the data is given for methane (not biogas), we use the conversion 1 Nm³ = 10 kWh of energy (Suhartini, Lestari and Nurika, 2019). Distribution of electrical and thermal energy are given on two case studies (Fluence, 2018a; b), which was also taken into account to determine potential net electrical energy generation through AD plant.

Fluence claims that the energy produced can meet the demands, and sometimes even result in a surplus amount of energy left. This can be sent to the national grid. A recent statistical analysis on many Italian wastewater treatment plants (Ranieri, Giuliano and Ranieri, 2021) presents that suitable value for energy consumption is 0.53 kWh/m³ on average for high flowrates of wastewater at large wastewater treatment. While a suitable approximation for on-site anaerobic digestion at a facility like a brewing company could not be found, we can use the correlation identified in (Ranieri, Giuliano and Ranieri, 2021). With this, we identify that for a plant with a flowrate of 600 m³/day, approximately 6.8 kWh of energy for every m³ wastewater treated is utilised in a powerplant.

3.2.3.2 *Aquacycl's BioElectrochemical Treatment Technology (BETT)*

Aquacycl offers their solution, BETT, on a leasing based plan. One of the founders of Joshua tree brewery, Dario Guerra, says that this novel technology which Aquacycl provides is "about half the price of conventional treatment technologies" (Armao, 2018). As established, a conventional treatment plant can easily be an anaerobic digestion processing plant. According to (Bretschger, 2018a), they have secured a fixed revenue of \$190000 from this brewery, and also will acquire the operational and maintenance costs for 5 years. This package solution leased out to this small brewery was only able to handle 76 m³/day. In our case, we want to find a suitable solution to treat 600 m³/day. This is equivalent to 4 BETT-40 systems, each allowing 150 m³/day. Estimating that the fixed payment for one of their largest systems is \$300000, we can predict the overall cost. The lifetime for this treatment solution is 10 years (Fan, Han and Liu, 2012).

Operational costs for a treatment plant differ from one another as the equipment used and maintenance involved greatly impacts these costs. Compared to a single unit MFC on own, stacked MFCs lower the overall operational costs. When three MFCs are connected in series, a cost of \$2.01/day for every percent of COD removal percentage (Mehranfar, Mahdavi and Gheshlaghi, 2019). This was the most economically friendly result out of the different configurations, as well as the most practical one. However, we do not have clear estimate on how many MFC units are comprised in the huge BETT system, thus we cannot use this estimation. A suitable estimation for operational costs for bioelectric systems in general, is 0.05 EUR for every kg of COD removed (Sleutels et al., 2012). This is

equivalent to about \$0.06 per kg-COD removed. The maintenance cost includes labour costs, regular checks on equipment and instruments (for data collection).

A case study used two pumps (for inlet flowrate: 76 m³/day) and data collection equipment; when combined, requiring 3.62 kWh of energy per day (Aquacycl, 2018b). We assume flowrate is proportional to power required. Moreover, we know that the largest plant design they provide for food and beverage industry, where maximum flowrate is 600 m³/day, i.e. 4 BETT-40 systems, around 16 pumps may be necessary (Aquacycl, 2018d, 2020). We shall assume an inlet flowrate at 600 m³/day and energy consumption of 29 kWh per day. As of energy production, Aquacycl claims it can range between 0.2-0.8 kWh for every kg-COD removed. We assume that on average, the rate of energy production is at 0.5 kWh for every kg-COD removed, for our calculations.

3.2.3.3 Cambrian's EcoVolt solution

One of Cambrian's biggest applications is at a brewery in California, Lagunitas brewery, where 50000 gallons of wastewater is treated every day (Knapschaefer, 2014). This is equivalent to about 189 m³/day. According to their latest brochure (Cambrian Innovation, 2021), they have 5 types of reactors of various sizes which are able to intake larger flowrates than 189 m³/day. Their largest reactor, EVR5, can intake flowrates up to 1250000 gal/day (4730 m³/day) (Cambrian Innovation, 2021). EcoVolt solution installed at Lagunitas Brewery, involved equal number of EcoVolt reactors (anaerobic process) and MBR aerobic solution, as well as a disinfection system. The combined system were able to remove 99.9% COD, resulting in clean water (Gobburu, 2016). Since the information is based on EcoVolt solution as a whole, we will assume that cost information and estimations made are for the whole process (refer to Figure 8).

Cambrian follows an agreement called WEPA (waste energy purchase agreement), where the facility hiring the products only pay a monthly fee to the company in order to use their wastewater treatment (Cambrian, 2021b), similar to Aquacycl's servicing protocol. This allows their clients to save a lot of money in terms of purchasing the treatment solution, and the useful effluents are sold to their clients instead of accessing them for free (Cambrian, 2021b). Though this monthly cost is not disclosed (even for case studies) as this is relatively a new initiative, we can make an estimate for the overall cost without WEPA implementation. For consistency in the comparative analysis, we can base the benefits of electricity, water, and sludge sales as gains for the client (brewery), rather than the company providing the solution. The brewery paid \$1.24 million (Knapschaefer, 2014) for reactor that allowed flowrate of 189 m³/day, and assuming the cost of the installation/capital cost is proportional to the flowrate, a rough estimate for capital cost can be derived. The lifetime of this technology is 15 years (Hardcastle, 2017).

Since their solutions are usually deployed onsite, we do not account for transportation costs. A suitable estimation for operational costs for bioelectric systems is \$0.06 per kg-COD removed. The energy consumption rate for a typical MFC treating wastewater can be assumed 0.0547 kWh per kg-COD removed (Zhang et al., 2013b). However, most of the energy requirement, around 70% is required for aeration of cathode chamber in a typical MFC system (Zhang et al., 2013a). In the case of EcoVolt, the cathode is a biocathode with microbes, which eliminates aeration energy requirements (Cambrian, 2021a). Therefore, energy consumption is reduced to 0.01641 kWh/kg-COD removed.

Information regarding energy production is available as a range, not fixed ratios (relating to COD removal). However, we know that wastewater contains energy potential of 3 kWh per kg of BOD removed (Gobburu, 2016). Cambrian's solutions use cogeneration unit, which are combined heat and power (CHP) systems that produces both electrical energy and heat energy using biogas. Typical CHP

units are 60-80% efficient (US EPA, 2021). For this study we will assume, 70% efficiency, which leads to 2.1 kWh of electricity potential per kg of BOD removed from wastewater. Maximum BOD removal efficiency for all EcoVolt solutions is 90% (Cambrian Innovation, 2021).

3.3 ENVIRONMENTAL IMPACT QUANTITATIVE ASSESSMENT

Due to the abundance of wastewater and sewage in the world, and the increasing demand for global energy, large-scale wastewater treatment plants that can produce electricity from microbes and contaminants will help attain some of SDGs (sustainable development goals) established by the UN. The sustainability of a process, product, or even an economy is typically defined by three aspects: economic, social, and environmental impacts. There are indicators for each category that are measured and recorded to determine the overall sustainability. To analyse the feasibility, i.e., the extent of viability of this technology to produce energy, economic and environmental impacts need to be explored.

A quantitative assessment will be performed for each technology based on a criterion comprised of environmental impact indicators. The indicators can be both positive and negative, thus the qualitative measurement will be in the form of colours. There will be a set of 4 colours ranging from red (high negative impact) to green (high positive impact). The indicators we will use to measure the impact on the environment are as follows: land use, direct CO₂ production, CH₄ production, treated water effluent quality, sludge disposal in landfills, material use and disposal impact, energy use, constant electricity fuelling, heavy metal ions, use of transport, inefficiency of wastewater treatment, eutrophication potential, particulate matter removal (suspension of inorganic matter in pre-treatment), source sustainability, odour emissions, noise pollution.

The technologies will be referred as: 1) anaerobic digestion, 2) typical MFC system and 3) electro-methanogenesis cell, representative of Fluence, Aquacycl and Cambrian technologies respectively.

4 RESULTS

4.1 LITERATURE REVIEW

Table 5: Review of lab-scale MFC hybrid systems and designs for improved efficiencies

Description of the MFC system study	Wastewater type	Current density	Max. power density	COD removal efficiency	Reference
AD+MFC integrated system – long-term treatment of primary sludge.	Primary sludge (before AD treatment) - obtained from a water reclamation in Milwaukee, USA	20.5 A/m ³	6400 mW/m ³	68.4 ± 17.9%	(Ge et al., 2013)
AD+MFC integrated system – long-term treatment of digested sludge	Digested sludge (post AD treatment) - water reclamation in Milwaukee, USA	34 A/m ³	3200 mW/m ³ (of wastewater treated)	36.2 ± 24.4%	(Ge et al., 2013)
Anaerobic fluidized bed (AFB) + MFC – AFB acts as the anode chamber	Wastewater from an alcohol distillation factory in Sichuan, China	1.64 mA flow	124.03 mW/m ² (of anode area)	89.95%	(Huang et al., 2011)
Up-flow anaerobic sludge blanket reactor MFC with biological aerated filter (UASB-MFC-BAF)	High strength molasses wastewater	4947.9 mA/m ²	1410.2 mW/m ²	53.2% (raw wastewater – no dilution)	(Zhang et al., 2009)
Two-chambered MFC with aqueous cathode	Raw food processing wastewater (cereal, plant discharges)	0.6 mA	80 mW/m ² (of anode area)	95%	(Oh and Logan, 2005)
Biohydrogen reactor, producing hydrogen, and effluent which is sent to MFC	Pre-fermented food processing wastewater (cereal, plant discharges)	53.5 mA/L of wastewater	371 mW/m ²	-	(Oh and Logan, 2005)
Single chamber MFC with graphite felt anodes	Cheese whey	1.37 A/m ²	0.34 mW/m ²	41% (theoretical)	(Wenzel et al., 2017)
Biohydrogen reactor effluent sent to MFC	Effluent from biohydrogen reactor	1.71 A/m ²	439 mW/m ²	100% (theoretical)	(Wenzel et al., 2017)
Membrane bioreactor (MBR) integrated with	Synthetic domestic	1.9 mA of current flow	6.0 W/m ³ (of wastewater)	89.6%	(Wang et al., 2012)

MFC using activated carbon fibre as anode and carbon felt for cathode	wastewater		treated)		
MFC-MBR system that uses air-biocathode (no aeration)	Domestic wastewater collected from a local treatment plant in Jeddah, Saudi Arabia	2.0 A/m ²	380 mW/m ² (cathode area)	97%	(Malaeb et al., 2013)
Electrochemical membrane bioreactor (EMBR) with biocathode and graphite felt anode	Synthetic wastewater from municipal	4.7 A/m ³	1.2 – 7.6 W/m ³	87.4 – 91.2%	(Wang et al., 2013)
MFC-MBR with graphite particle anode and phytic acid modified membrane serving as cathodic chamber (MBR)	Secondary sludge from wastewater treatment in Dalian, China	-	44.80 mW/m ² (anode area)	85%	(Li, Liu and Yang, 2014)
Dual chamber MFC integrated with anoxic/oxic membrane reactor (MBR-MFC)	Synthetic wastewater	-	36.08 mW/m ² (cathode area)	96.3%	(Cheng et al., 2017)

As said, MFC technologies on their own present low energy production, hence several studies have been conducted on lab-scale to test the perform of MFC hybrid systems. MFC integrated with membrane bioreactor (MBR), anaerobic digestion (AD) processes and other designs involving biohydrogen reactor, anaerobic fluidized bed are some of the bioelectric system designs whose results and efficiency data has been gathered and presented in Table 5 above. There are two noteworthy, state of the art hybrid technologies that have presented improved efficiencies: MFC and MBR integrated system; and MFC and anaerobic treatment (particularly AD).

4.2 COST-BENEFIT ANALYSIS FOR ANAEROBIC DIGESTION – FLUENCE’S ‘WASTE-TO-ENERGY’ SOLUTION

Table 6: Defining parameters and carrying out calculations to determine energy, treated water and sludge production from anaerobic digestion solution

Parameters	Values (with respective units)
Lifetime of anaerobic plant	: 20 years
Total number of working hours	: 8000 hours
Number of working days in an annum	: 335 days
Volumetric flowrate of wastewater	: 600 m ³ /day
Total volume of wastewater treated per annum	
	: $600 \times 335 = 201000 \text{ m}^3$
TSS concentration	
	: $2000 \times 10^{-3} = 2 \text{ kg/m}^3$
Amount of TSS in the effluent in tonne	
	: $2 \times 201000 \times 10^{-3} = 402 \text{ tonne}$
Sludge removal efficiency	
	: 70%
Dehydrated sludge effluent	
	: $0.3 \times 402 = 120.6 \text{ tonne}$
Amount of sludge effluent sent for agricultural purposes	
	: $0.5 \times 120.6 = 60.3 \text{ tonne}$
Amount of sludge effluent sent for disposal to landfills	
	: $0.5 \times 120.6 = 60.3 \text{ tonne}$
Energy consumption rate	
	: 6.8 kWh/m ³
Total energy consumption rate	
	: $6.8 \times 201000 = 1366800 \text{ kWh}$
Daily biogas production rate	
	: 8.6 kWh per m ³
Daily biogas production	
	: $8.6 \times 600 = 5160 \text{ kWh}$
Total energy production through biogas	
	: $5160 \times 335 = 1728600 \text{ kWh}$
Net energy produced	
	: $1728600 - 1366800 = 361800 \text{ kWh}$
Average electrical to thermal energy ratio (based on existing Fluence case studies (Fluence, 2018a; b))	
	: 9 : 10
Net electrical energy production	
	: $\frac{9}{19} \times 361800 = 171379 \text{ kWh}$
Amount of recycled water from this plant	
	: $0.16 \times 201000 = 32160 \text{ m}^3$

Table 7: Defining the costs and benefits involved for anaerobic digestion using monetary values and calculating total costs and benefits over its lifetime, and benefit-to-cost ratio

COSTS	Amount (in Euro)
Cost of biogas plant (estimated)	1690000
Total fixed cost	1690000
Tipping fees (sludge disposal)	115
Total cost for sludge disposal	$115 \times 60.3 = 6934.5$
Operating and maintenance costs	$0.1 \times 1690000 = 169000$
Total maintenance cost per annum	175934.5
Total maintenance cost	$175934.5 \times 20 = 3518690$
Total cost	$1690000 + 3518690 = 5208690$
BENEFITS	
Price of electricity in EUR per kWh	0.2153
Amount gained from net electricity produced	$0.2153 \times 171379 = 36898$
Sale price of dehydrated sludge in EUR per tonne	42
Amount gained from sludge sales	$42 \times 60.3 = 2532.6$
Price of recycled water in EUR per m³	0.3867
Amount saved from recycled water use	$0.3867 \times 32160 = 12436.3$
Total benefit per annum	51866.9
Total benefit	$51866.9 \times 20 = 1037338$
Benefit to cost ratio	0.1991
Cost of producing electricity	1.520 €/kWh
Cost of producing electricity in USD (based on 1 EUR = 1.18 EUR)	1.793 \$/kWh

4.3 COST-BENEFIT ANALYSIS FOR MFC SYSTEM GENERATING ELECTRICITY – AQUACYCL’S BETT

Table 8: Defining parameters and carrying out calculations to determine energy, treated water and sludge production from Aquacycl’s solution

Parameters	Values (with respective units)
Lifetime of BETT Package Plant	: 10 years
Treatment time for one operational cycle	: 4 hours
Total number of working hours	: 8000 hours
Number of working days in an annum	: 335 days
Volumetric flowrate of wastewater	: 600 m ³ /day
Total volume of wastewater treated per annum	: $600 \times 335 = 201000 \text{ m}^3$
TSS concentration	: $2000 \times 10^{-3} = 2 \text{ kg/m}^3$
Amount of TSS in the effluent in tonne	: $2 \times 201000 \times 10^{-3} = 402 \text{ tonne}$
Sludge removal efficiency	: 80%
Dehydrated sludge effluent	: $0.2 \times 402 = 80.4 \text{ tonne}$
Amount of sludge effluent sent for agricultural purposes	: $0.5 \times 80.4 = 40.2 \text{ tonne}$
Amount of sludge effluent sent for disposal to landfills	: $0.5 \times 80.4 = 40.2 \text{ tonne}$
Energy consumption rate	: 29 kWh/day
Total energy consumption rate	: $29 \times 335 = 9715 \text{ kWh}$
Daily electricity production rate	: 0.5 kWh per kg of COD
COD concentration	: $5000 \times 10^{-3} = 5 \text{ kg/m}^3$
Amount of COD present in the influent in kg	: $5 \times 201000 = 1005000 \text{ kg}$
COD removal efficiency	: 95%
Total amount of COD removed	: 954750 kg
Amount of electricity produced	: $0.5 \times 954750 = 477375 \text{ kWh}$
Total electrical energy production	: 477375 kWh
Net electricity production	: $477375 - 9715 = 467660 \text{ kWh}$
Amount of clean water effluent	: $\frac{3}{5} \times 201000 = 120600 \text{ m}^3$

Table 9: Defining the costs and benefits involved for Aquacycl's solution using monetary values and calculating total costs and benefits over its lifetime, and benefit-to-cost ratio

COSTS	Amount (in US dollars)
Cost of one BETT reactor (estimated)	300000
Total initial cost of the system	$300000 \times 4 = 1200000$
Total fixed cost	1200000
Tipping fees (sludge disposal)	58.48
Total cost for sludge disposal	$58.48 \times 40.2 = 2350.9$
Operating & maintenance costs	$0.06 \times 1005000 = 60300$
O&M cost per annum	$60300 + 2350.9 = 62650.9$
Total operational and maintenance cost	$62650.9 \times 10 = 626509$
Total cost	$1200000 + 626509 = 1826509$
BENEFITS	Amount (in US dollars)
Price of electricity in USD per kWh	0.1916
Amount gained from net electricity produced	$0.1916 \times 467660 = 89603.66$
Estimated sale price of dehydrated sludge in USD per tonne	50
Amount gained from sludge sales	$50 \times 40.2 = 2010$
Price of recycled water in USD per m ³	0.6124
Amount of avoided cost due to recycled water use	$0.6124 \times 120600 = 73855.44$
Total benefit per annum	$89603.66 + 73855.44 + 2010 = 165469.1$
Total benefit	$165469.1 \times 10 = 1654691$
Benefit to cost ratio	0.9059
Cost of producing electricity	0.391 \$/kWh

4.4 COST-BENEFIT ANALYSIS FOR MFC SYSTEM GENERATING BIOGAS – CAMBRIAN’S ECOVOLT

Table 10: Defining parameters and carrying out calculations to determine energy, treated water and sludge production from Cambrian’s solution

Parameters	Values (with respective units)
Lifetime of ECOVOLT	: 15 years
Total number of working hours	: 8000 hours
Number of working days in an annum	: 335 days
Volumetric flowrate of wastewater	: 600 m ³ /day
Total volume of wastewater treated per annum	: 600 × 335 = 201000 m ³
TSS concentration	: 2000 × 10 ⁻³ = 2 kg/m ³
Amount of TSS in the effluent in tonne	: 2 × 201000 × 10 ⁻³ = 402 tonne
Sludge removal efficiency	: 70%
Dehydrated sludge effluent	: 0.3 × 402 = 120.6 tonne
Amount of sludge effluent sent for agricultural purposes	: 0.5 × 120.6 = 60.3 tonne
Amount of sludge effluent sent for disposal to landfills	: 0.5 × 120.6 = 60.3 tonne
Energy consumption rate	: 0.01641 kWh per kg of COD
COD concentration	: 5000 × 10 ⁻³ = 5 kg/m ³
Amount of COD in the influent in kg	: 5 × 201000 = 1005000 kg
COD removal efficiency	: 90%
Total amount of COD removed	: 904500 kg
Total energy consumption rate	: 0.01641 × 1003995 = 14842.8 kWh
Biogas energy production rate	: 3 kWh per kg of BOD
CHP efficiency (electrical energy)	: 70%
Electrical energy production rate	: 2.1 kWh per kg of BOD
BOD concentration	: 2750 × 10 ⁻³ = 2.75 kg/m ³
Amount of BOD in the influent in kg	: 2.75 × 201000 = 552750 kg
BOD removal efficiency (EcoVolt only)	: 90%
Total amount of BOD removed	: 497475 kg
Amount of electrical energy produced	: 2.1 × 497475 = 1044698 kWh
Net electricity production	: 1044698 – 14842.8 = 1029855 kWh
Amount of clean water effluent	: $\frac{1}{3} \times 201000 = 67000$ m ³

Table 11: Defining the costs and benefits involved for Cambrian's solution using monetary values and calculating total costs and benefits over its lifetime, and benefit-to-cost ratio





COSTS	Amount (in US dollars)
Initial cost of ECOVOLT solution	3936500
Total fixed cost	3936500
Tipping fees (sludge disposal)	58.48
Total cost for sludge disposal	$58.48 \times 60.3 = 3526.34$
Operating & maintenance costs	$0.06 \times 1005000 = 60300$
Total operational and maintenance cost per annum	$3526.344 + 60300 = 63826.34$
Total operational and maintenance cost	$63826.34 \times 15 = 957395$
Total cost	$3936500 + 957395 = 4893895$
BENEFITS	Amount (in US dollars)
Price of electricity in USD per kWh	0.1916
Amount gained from net electricity produced	$0.1916 \times 1029855 = 197320.16$
Sale price of dehydrated sludge in USD per tonne	50
Amount gained from sludge sales	$50 \times 60.3 = 3015$
Price of recycled water in USD per m ³	0.6124
Amount of avoided cost due to recycled water use	$0.6124 \times 67000 = 41030.8$
Total benefit per annum	$197320.16 + 41030.8 + 3015 = 241366$
Total benefit	$241366 \times 15 = 3620490$
Benefit to cost ratio	0.7398
Cost of producing electricity	\$0.3168 /kWh

4.5 QUANTITATIVE ENVIRONMENTAL IMPACT ASSESSMENT

Table 12: Table presenting the environmental impact indicators and ranking each technology using colours to determine the overall positive/negative impact

<i>Environmental indicators</i>	Anaerobic digestion	Typical MFC system	Electro-methanogenesis cell
<i>CH₄ production</i>	High negative impact	High positive impact/no negative impact	Low negative impact
<i>COD removal efficiency</i>	Low positive impact	Low positive impact	Low positive impact
<i>Constant supply of electricity</i>	Low negative impact	Low positive impact	High negative impact
<i>Direct CO₂ production</i>	High negative impact	High negative impact	Low negative impact
<i>CO₂ reduction/capture</i>	Low negative impact	Low negative impact	High positive impact/no negative impact
<i>Energy consumption</i>	High negative impact	Low negative impact	Low negative impact
<i>Eutrophication potential</i>	Low positive impact	Low positive impact	Low positive impact
<i>Heavy metal pollution</i>	Low positive impact	Low negative impact	Low negative impact
<i>Land use</i>	High negative impact	Low negative impact	Low negative impact
<i>Material use – availability</i>	Low negative impact	Low negative impact	High negative impact
<i>Material disposal – lifetime</i>	Low positive impact	Low negative impact	Low negative impact
<i>Noise pollution</i>	Low positive impact	High positive impact/no negative impact	High positive impact/no negative impact
<i>Odour emissions</i>	Low negative impact	Low negative impact	Low negative impact
<i>Particulate matter removal</i>	High negative impact	High negative impact	High negative impact
<i>Sludge disposal in landfills</i>	High negative impact	Low negative impact	High negative impact
<i>Source sustainability</i>	High positive impact/no negative impact	High positive impact/no negative impact	High positive impact/no negative impact
<i>Treated water effluent quality</i>	Low negative impact	Low positive impact	Low positive impact
<i>Use of transport</i>	Low negative impact	High positive impact/no negative impact	High positive impact/no negative impact

Key:

-  High negative impact
-  Low negative impact
-  Low positive impact
-  High positive impact/no negative impact

5 DISCUSSION

5.1 LITERATURE REVIEW

5.1.1 MFC + MBR technology

Some of the disadvantages of MBR technology are power consumption, membrane fouling and high cost of membrane material (Makisha and Nesterenko, 2018). Although MFC has its own disadvantages such as low energy production (Franks and Nevin, 2010) and logistics issue with power collection, it has the ability to reduce the impact of membrane fouling and energy requirements for the operation of a MBR system. This, therefore, resolves some of the limitations of MBR technology (Liu et al., 2018) enabling synergetic results when MBR is coupled with MFC technology.

Relative to other treatment technologies, the quality of clean water produced as a result of this integrated MBR-MFC system is much higher (Liu et al., 2018). This reflects on the removal efficiency of impurities and bacteria that defines the quality of the water. The systems with highest COD removal efficiencies (in Table 5) are attained with MFC-MBR system. The COD removal efficiencies for all MFC-MBR hybrid systems presented in Table 5 ranged between 85-97%. (Malaeb et al., 2013) and (Cheng et al., 2017) presented overall COD removal efficiencies of 97% and 96.3% respectively, compared to anaerobic treated waste as feedstock for MFC where efficiencies ranged between 35-90%. A majority of case studies' results were around the lower bound of this range (see Table 2).

When the same wastewater type, synthetic wastewater (in this case) was sent to a standard MBR system, the end result presented only 93.1 % COD removal efficiency (compared 96.3 % achieved with MBR-MFC unit). Furthermore, it was reported that both designs for MFC-MBR system setup in (Cheng et al., 2017) present very low composition of ammonium nitrogen in the effluent (85.3 – 86.2 % removal efficiency). Thus, it is evident that MFC-MBR has a positive impact on the quality of the water production, which is beneficial as it can be reused for dilution (if needed) or sent to purification plant for further processing.

The power densities and current densities produced by these systems vary from design to design. In (Li, Liu and Yang, 2014) study, four different combinations of anode and cathode material were tested at lab-scale. The one that presented the greatest maximum power density (44.8 mW/m²) is when anode material was made of graphite granules and the cathode was made of modified filter cloth membrane (see Table 5). Whereas, in (Cheng et al., 2017) study, COD efficiency was very high, and it did not reflect too well on power density – 36.08 mW/m². There are two possible justifications for this: design and substrate type. (Li, Liu and Yang, 2014) used real domestic wastewater from a local plant, whereas (Cheng et al., 2017) had produced wastewater using a variety of chemicals to conduct their study. Since (Li, Liu and Yang, 2014) yielded a greater power density, we see that real wastewater treatment is more feasible than synthetic wastewater which presents a hopeful insight for scaling up MFC-MBR system for large-scale wastewater treatment.

Comparing (Wang et al., 2012) and (Wang et al., 2013), whose substrates are both synthetic wastewaters, we observe that their power densities do not present a large difference. Best run in (Wang et al., 2013), presented 7.6 W/m³, which corresponds a net energy production of 0.0766 kWh for every m³ of wastewater treated with this design. This system did not require aeration as biocathode was used, which reduced the amount of energy consumption, thereby facilitating greater energy recovery. On the other hand, (Wang et al., 2012) required an aeration tank to serve as the cathode

chamber, thus requiring some energy input. As intended, this is offset with the direct electricity produced by the MFC part. Even though a lower power density corresponds to lower energy production (given that scale-up is considered for this study (Wang et al., 2012)), the material cost for carbon anode and cathode material is lower than graphite felt anode and biocathode used in (Wang et al., 2013; CeraMaterials, 2021).

5.1.2 MFC + anaerobic treatment technology

Both low and high concentrated COD wastewater are known to work with MFCs, but the real problem is identifying, which one works the best. The problem with feeding high strength wastewater directly to MFC is related to economic and logistics feasibility (Ardakani and Badalians Gholikandi, 2020). Furthermore, high bioconversion gained from anaerobic treatment to produce useful energy is more desirable than the adequate direct electricity produced in typical MFCs (Ardakani and Badalians Gholikandi, 2020). This is why integration of anaerobic treatment plant (to treat high COD wastewater) and MFCs (for low COD wastewater treatment) is explored on lab-scale to find the most efficient designs.

(Ge et al., 2013) conducted a study on how electricity generation and treatment efficiency differ between a primary sludge fed-MFC and another MFC where sludge that was anaerobically digested was used as feedstock. The result presented that primary sludge, which contained a higher percentage of active microbes, showed a higher COD concentration which led to a greater removal efficiency at the MFC unit (68% for primary sludge compared to 32% for digested sludge) (Ge et al., 2013). This tells us that the energy production at MFC will be significantly low as there are not enough microbes which can undergo anaerobic respiration. This is indeed true, as only 3.2 W/m³ can be produced from digested sludge, whereas primary sludge MFC can produce twice as much (refer to Table 5) (Ge et al., 2013). All in all, we understand that implementing anaerobic digestion as a pre-treatment for wastewater may have feasibility advantages, however, efficiency wise, it may be less ideal than MBR-MFC integrated systems.

Another anaerobic treatment method is using an anaerobic fluidized bed reactor as the anode chamber in a conventional MFC design. To maximise the bacteria growth within the anode chamber, (Huang et al., 2011) used porous polymer carriers. The discussion presented that aeration (cathode side) plays an important role in the energy production (Huang et al., 2011). However, most of the factors experimented in this study presented very little impact on the removal efficiency. The removal efficiency with this design (Huang et al., 2011) is reported 89.95%, which is higher than of a typical MFC. Thus, we can say that this integrated design is the most feasible and efficient technology to treat high concentrated COD wastewater (Huang et al., 2011). The source of wastewater, therefore, the geographical region also plays an important role. For instance, (Ge et al., 2013) study on primary sludge was conducted in USA, whereas (Huang et al., 2011) conducted tests in China which yielded very different COD removal efficiencies (refer to Table 5).

There have been many studies on anaerobic treatment integrated with MFC systems, however very few have researched on implementing both aerobic and anaerobic technologies to MFC. (Zhang et al., 2009) conducted such study by using an anaerobic unit (UASB); followed by a MFC, then, an aerobic reactor (BAF). Their hypothesis revolved around the wastewater type: high strength molasses wastewater has high concentration of COD (organic matter) (Zhang et al., 2009) that will potentially yield substantial electricity production. The results presented that when raw wastewater was used, power density produced was indeed high, 1410.2 mW/m² (Zhang et al., 2009) approximately ten times greater than (Huang et al., 2011), however the total COD removal efficiency for this UASB-MFC-BAF system was significantly low. Since this study experimented with different dilutions of wastewater over the course

of their study, it was found that the more diluted the molasses wastewater, the greater total COD efficiency yielded (Zhang et al., 2009). Furthermore, in all scenarios, whether dilution or no dilution, UASB removed the most organic matter (Zhang et al., 2009).

Overall, both anaerobic and aerobic-anaerobic systems presented an overall positive result in either power density and/or total COD removal efficiency. The use of an anaerobic reactor in all three studies (Ge et al., 2013; Zhang et al., 2009; Huang et al., 2011) suggests that the integration of anaerobic-MFC innovation works on different levels, however, each design has its own advantage, as discussed above.

5.1.3 Other MFC systems – biohydrogen reactors + MFC

Apart from ‘anaerobic treatment + MFC system’ and ‘MBR + MFC system’, there are other new innovative designs and hypothesis that are being tested to develop the current, state-of-the-art review. Hydrogen producing reactors integrated with MFC is one way towards energy-positive solution. (Oh and Logan, 2005) attempted this integrated system on lab-scale, which resulted in 371 mW/m². While this is relatively higher compared to some MBR+MFC integrated system (Li, Liu and Yang, 2014; Cheng et al., 2017), this study was performed more than 15 years ago. A more recent study (Wenzel et al., 2017) performing the experimentation using similar methodology used cheese whey as the substrate for the biohydrogen reactor, and the resulting product was sent to a MFC. This resulted in a maximum power density of 439 mW/m² (Wenzel et al., 2017). Furthermore, this study also concluded that when cheese whey was directly used as the substrate for MFC, it yielded a very low power density: 0.34 mW/m² (Wenzel et al., 2017). This presents the potential room for scaling up this integrated process for treating wastewater, like cheese whey which is abundant in dairy industry dominating regions of the world.

5.2 COST-BENEFIT ANALYSIS

5.2.1 Benefit to cost ratio

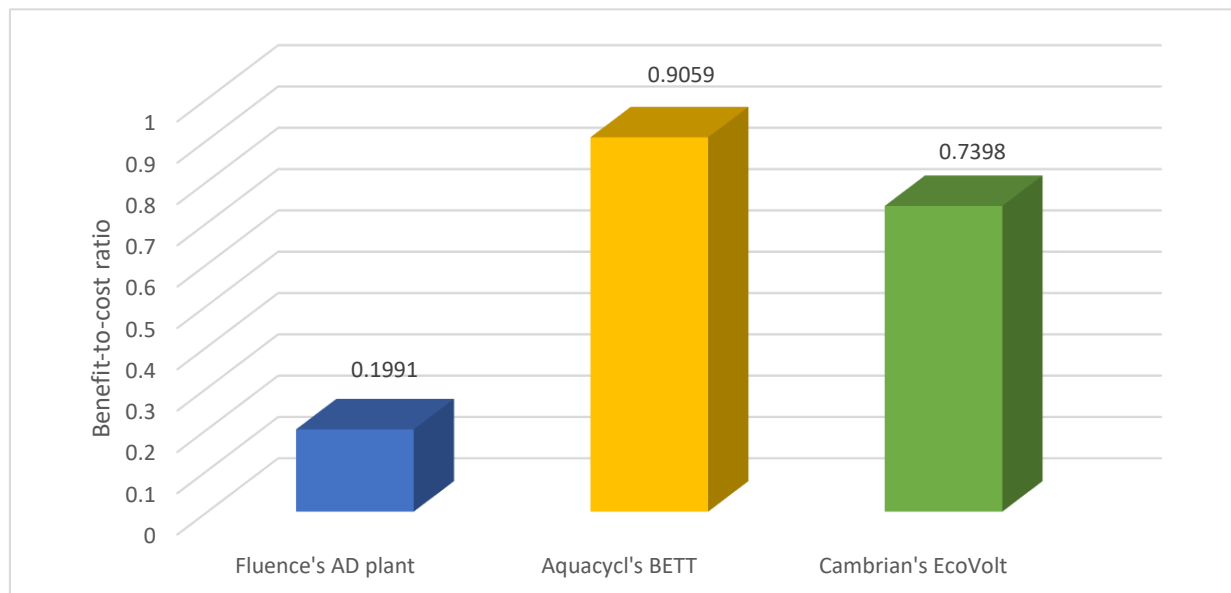


Figure 9: Chart presenting benefit-to-cost ratios (BCR) for each solution addressed in this economical study

Due to the limitations and low electrical efficiency achieved when converting biogas to electricity, the monetary value placed on benefits of anaerobic digestion biogas plant was significantly low, thus a low

ratio. Even though Fluence’s AD solution was not the most expensive technology (based on capital costs), operating costs were very high. This contributed further to a very low benefit-to-cost ratio (BCR). While the technology of both bioelectric systems is similar, the assumptions made regarding the service for individual solutions are different, one of them was assumed to be on lease (benefits gained by the on-site client) while the other was assumed to be bought at a fixed price. This played a significant role in the difference between BCR for EcoVolt technology and Aquacycl’s technology. Since BETT systems are provided to breweries and other clients in need for wastewater treatment on service lease agreement, their fixed cost was less compared to EcoVolt. This led to Aquacycl achieving the highest BCR value out of the three solutions, hence the preferable option for treating brewery wastewater.

5.2.2 Cost of electricity – compared to other renewables

Another way to analyse the three solutions economically is by determining levelized cost of electricity, which gives an overview of the minimum cost required per unit of electrical energy (per kilowatt-hour). This is calculated based on costs and electricity gained throughout its lifetime (Raikar and Adamson, 2020). Comparing these levelized cost of electricity produced from other renewable energy sources such as wind, solar and hydropower, a much broader picture can be illustrated with regards to bioelectric systems’ feasibility (see figure below).

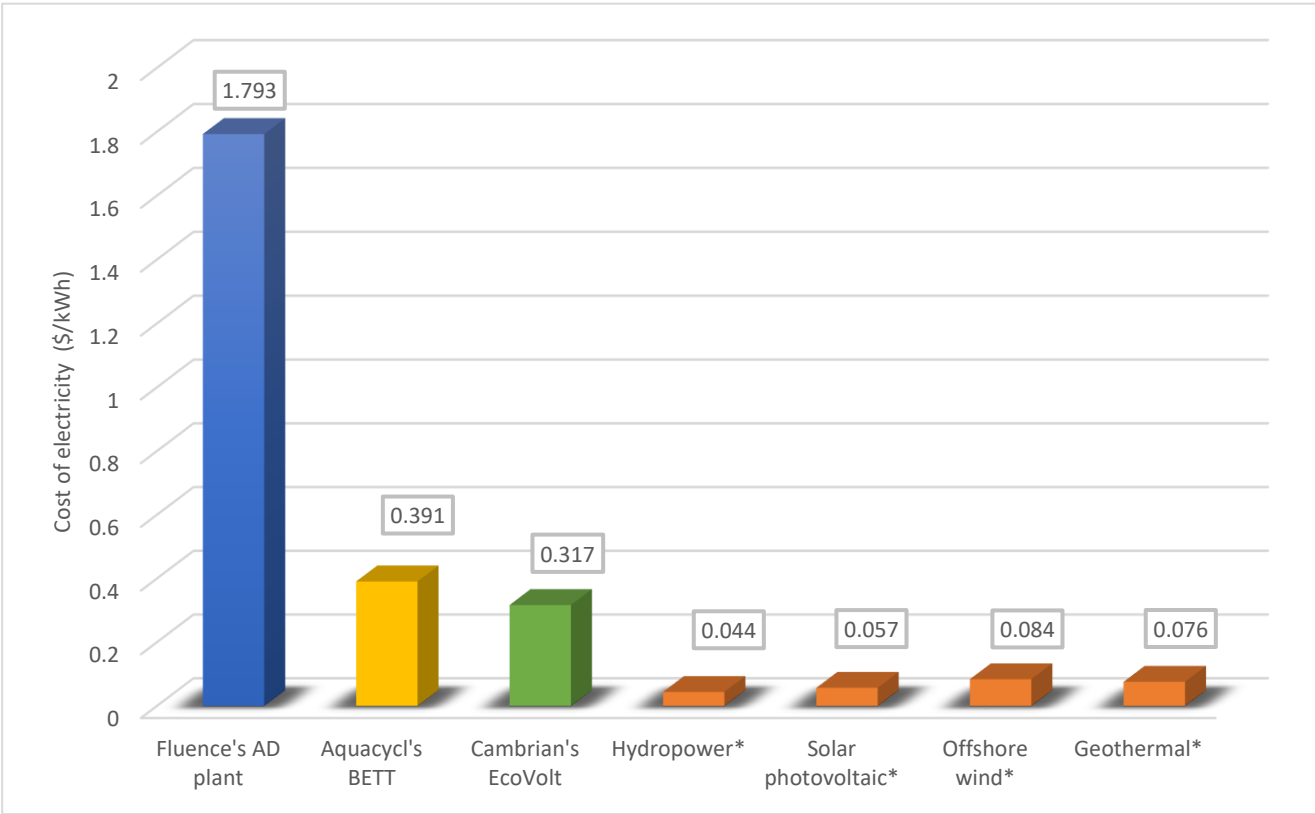


Figure 10: Chart presenting levelized cost of electricity for each solution addressed in this economical study, as well as other renewable energy technologies. * Data taken from IRENA Renewable Cost Database (IRENA, 2021b)

The amount of electricity generated from bioelectric systems are much higher, between three to nine times greater than power generation from anaerobic digestion. A low electricity production and high cost yielded in a high levelized cost of electricity. This high costs mainly arises due to the high maintenance feature of anaerobic digesters. With such high cost of electricity production, it suggests that anaerobic digestion plants are not best suited for the purpose of extracting electrical energy.

Whereas, both microbial cells have lower levelized cost of electricity. This portrays the potential for bioelectric systems in the field of renewable energy. Additionally, all other renewable energy costs are much lower than the three microbial sourced systems. Based on existing data (IRENA, 2021b), the cost of producing renewable energy from solar photovoltaic technology was much higher in 2010, 0.381 \$/kWh, compared to 0.057 \$/kWh (2020 data). This may suggest that with more commercialisation and improvements implemented, as well as its popularity, thus its demand, the technology significantly developed, and costs fell. In the global market, microbial fuel cells intended to extract electricity on a large-scale is simply emerging at the moment. Within the next few decades, we can expect a similar decline in costs, as its breakthrough in the market will be appealing, especially to industries such as breweries and other food and drink production facilities.

5.2.3 Distribution of benefits gained – as a measure of total revenue

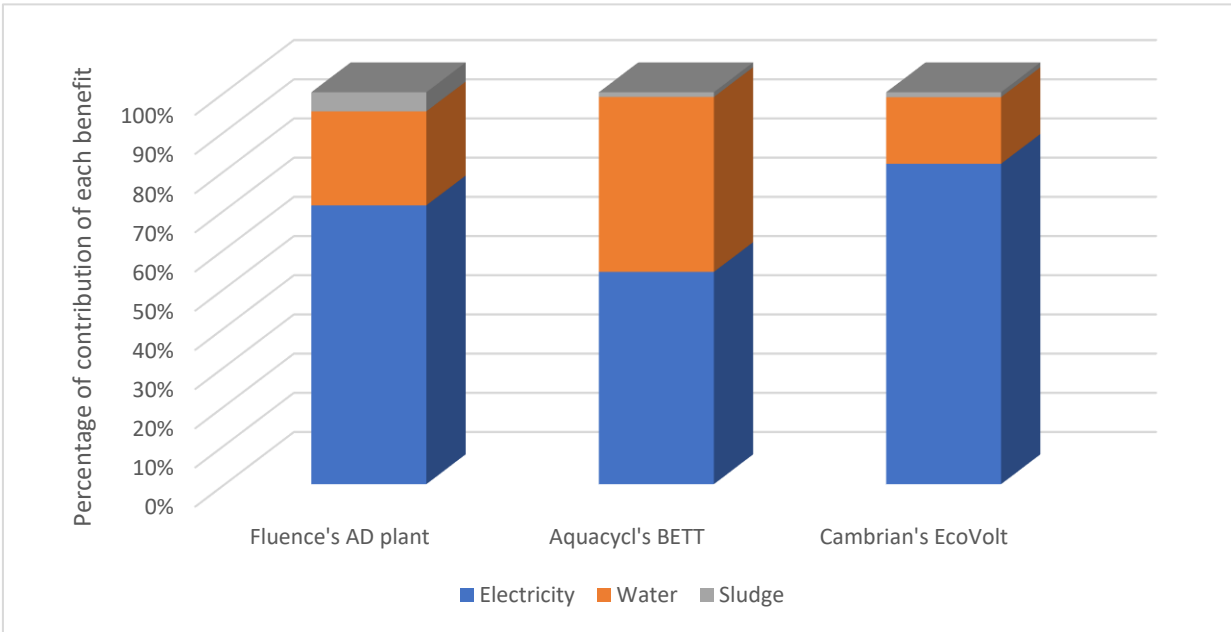


Figure 11: Presenting contribution (in percentage) of three main elements of benefits from each solution - electricity, water, sludge benefits

We can further analyse this prospective by comparing how much of the total revenue is attained from each of the benefits. Ideally, we aim to identify the suitable large-scale MFC system that is able to produce net energy through wastewater treatment. Based on the illustrative figure (Figure 11), electricity achieved from EcoVolt technology contributes the most to its total benefits, as well as produces the most electricity compared to Aquacycl’s BETT or anaerobic digesters (see data in Table in Results section). The contribution of sludge sales to the total benefit is relatively similar as the amount of sludge production as effluent does not differ much in these three technologies. Furthermore, since sludge is intended for disposal, its value in the market for agricultural purposes is very small. The contribution of clean water to the total benefits of the technology is smaller in EcoVolt than it is in BETT solution. Treated water production is generally low in AD treatment, however due to its biogas production, water contribution is comparatively less to that of energy. Even though the bar chart presents energy production in AD contributes most to overall benefits, the data in Results section showcases that the actual amount of electricity is far less than the two bioelectric systems. Overall, EcoVolt is the best option if we consider the aim of the solution is only to produce maximum electricity. However, Aquacycl’s BETT solution which relies on the fundamental design of a typical MFC, the two main effluents, water and electricity contribute almost equally. This suggests that Aquacycl benefits are

more widespread, whereas the electricity generation in EcoVolt on its own contributes to about 80% of the total potential revenue (see Figure 11).

5.3 ENVIRONMENTAL IMPACT ASSESSMENT

5.3.1 Overall environmental impact

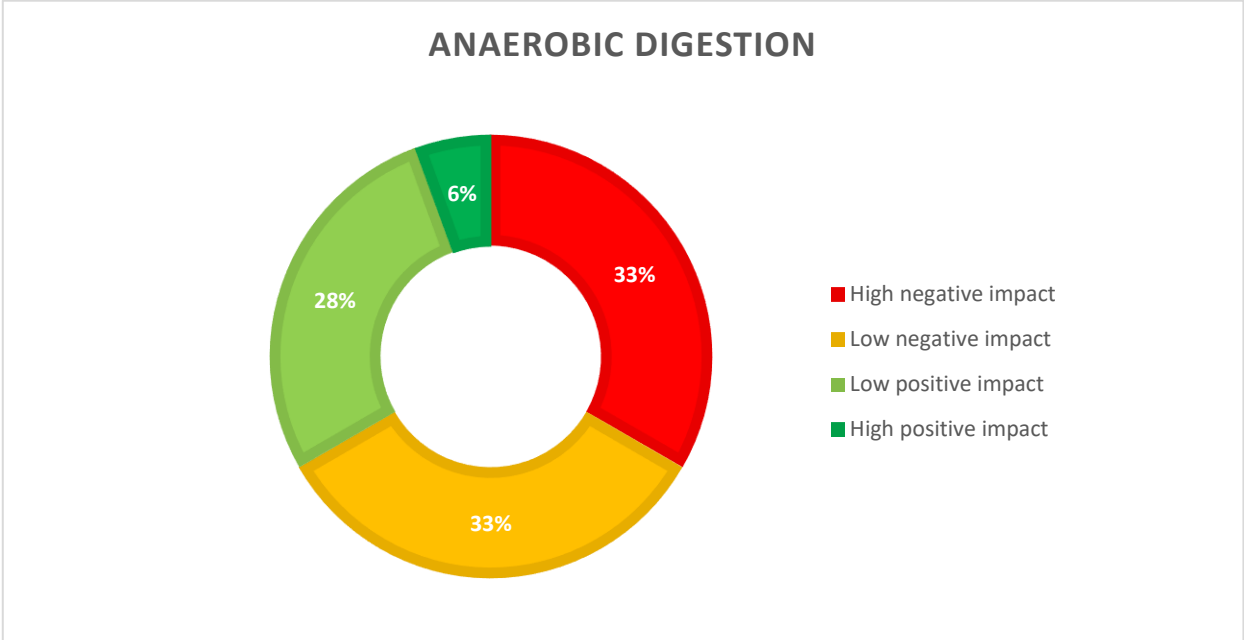


Figure 12: Chart presenting distribution of the total environmental impact based on the ranking for anaerobic digestion

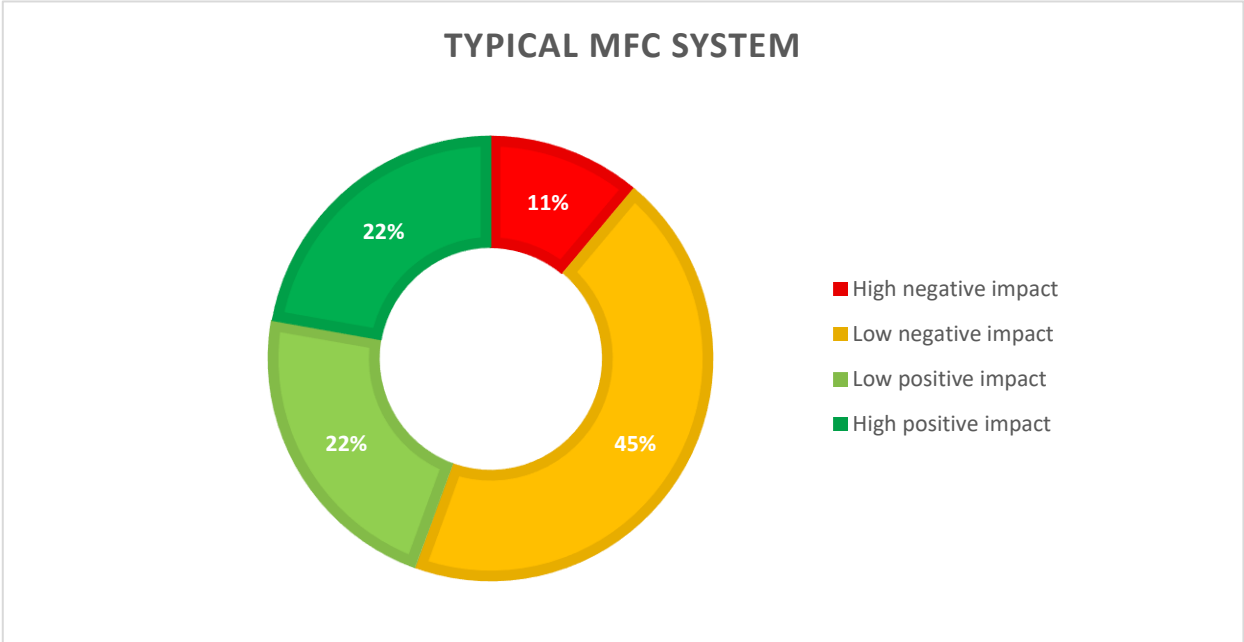


Figure 13: Chart presenting distribution of the total environmental impact based on the ranking for a typical large-scale MFC stacked system

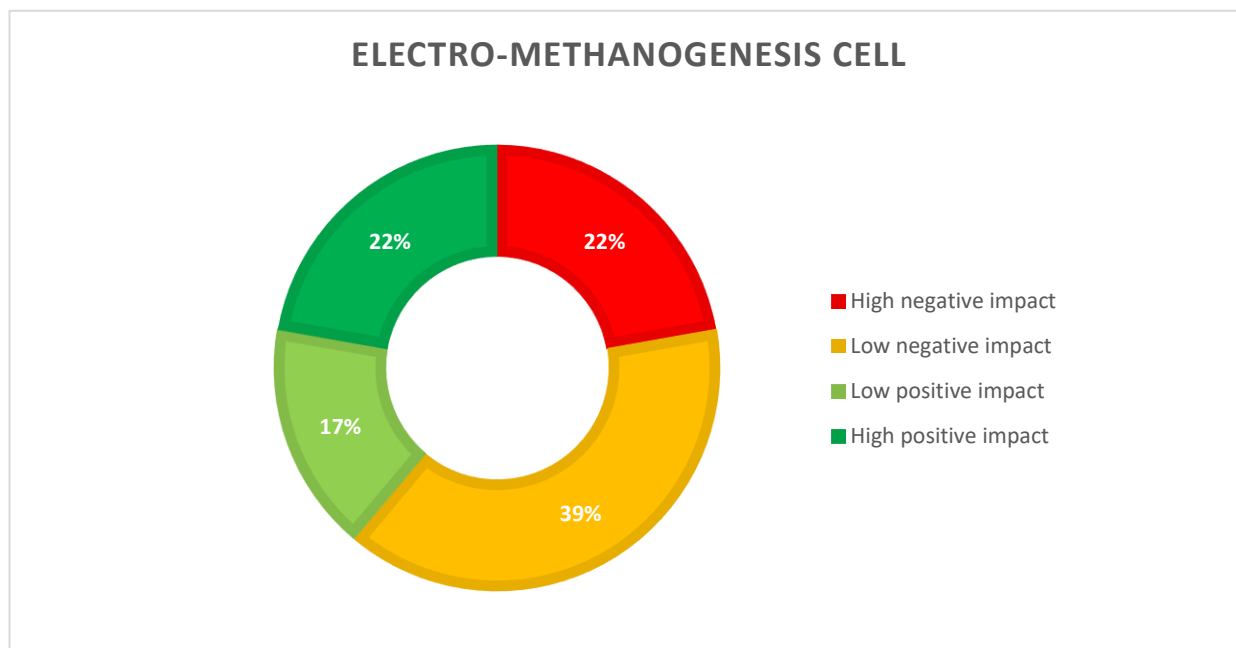


Figure 14: Chart presenting distribution of the total environmental impact based on the ranking for electromethanogenesis cell

By separating the impacts into two aspects: positive and negative, it can be concluded that the negative impacts contribute 66%, 56%, 61% for anaerobic digestion, typical MFC system and electromethanogenesis cell respectively (Figures 12, 13 and 14). The difference here is almost insignificant, moreover all three technologies is inputted with same raw wastewater and produce very similar products. From Figure 12, it is evident that the severity of negative impacts is higher as red and orange section share equal percentages. Whereas in the case of both bioelectric systems, red area is less than orange region, and any other colour area as a matter of fact. From this, we gather that anaerobic digestion influences the environment more severely than bioelectric systems. This could be due to sludge production, high energy usage, and use of transport to send methane to CHP unit (for conversion) and low energy production.

On the contrast, the extent to which anaerobic digestion impacts the environment is very little as the dark green region presents only 6% (Figure 12), compared to 17-22% for bioelectric systems (Figure 13 and 14). The difference in distribution of positive impacts, i.e., light, and dark green area for bioelectric systems is insignificant. This is most likely due to similar energy use, lifetime, and lack of transportation as the technologies will be located where client facility is located. Since, the typical MFC system has lowest percentage for total negative impact, it is evident that this technology is the most desirable option.

5.3.2 Environmental impact category analysis

By combining two or more indicators together to define an environmental impact aspect, for instance, land changes, we can get a more precise idea of where the negative/positive impacts affect. These categories are land and aquatic environment, water reuse and management, social inconveniences, GHG emissions, energy, raw materials. It is to be noted that some indicators can fall into more than one category. For the purpose of this discussion, the indicators are categorised as follows:

- Land and aquatic environment – eutrophication potential, land use, particulate matter removal, sludge disposal in landfills
- Water reuse and management – COD removal efficiency, treated wastewater quality
- Social inconveniences – noise pollution, odour emissions

- Energy – need for constant electricity supply, total energy consumption
- Greenhouse gas emissions – direct CO₂ production, CO₂ capture and reduction, CH₄ production, use of transport
- Raw materials/source – material use (availability), material disposal, heavy metal ions, source sustainability

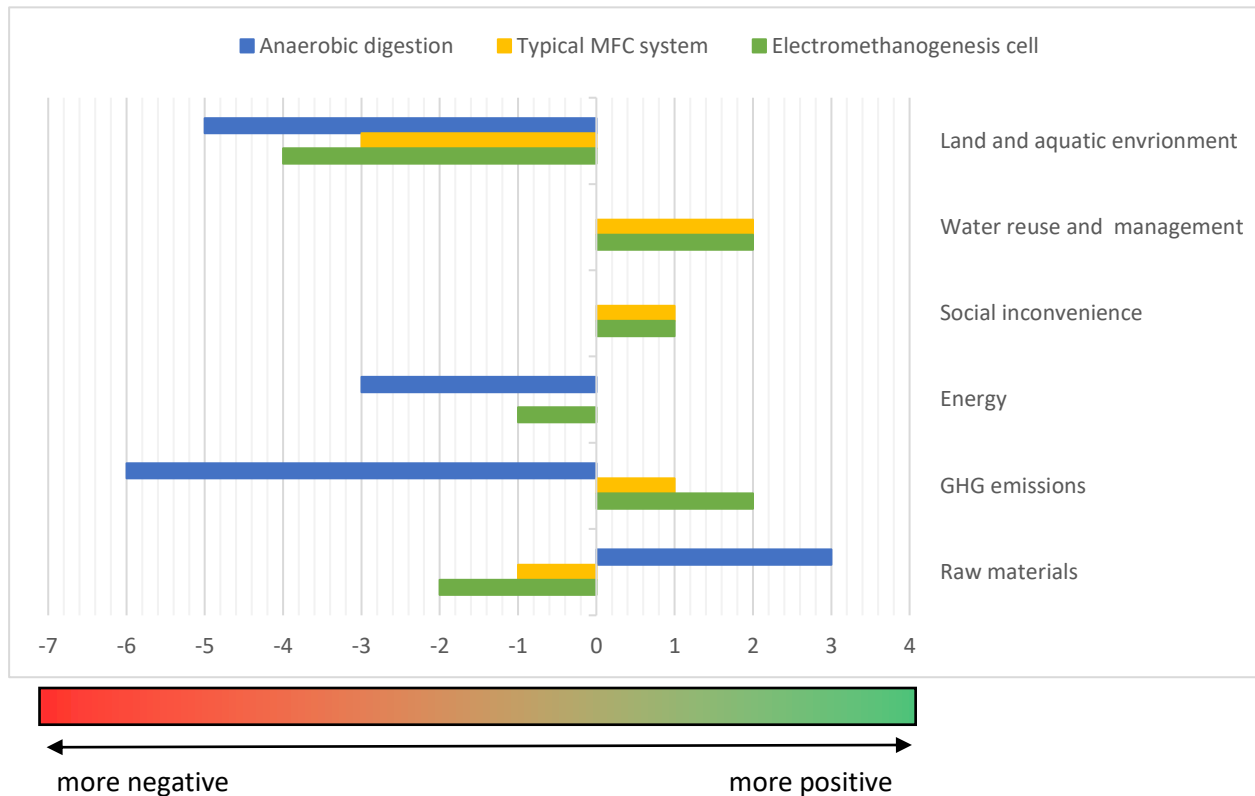


Figure 15: A clustered bar chart presenting the extent of negative (left-side) impacts and positive (right-side) impacts on different environmental aspects for each technology addressed

From the chart (Figure 15), we see that all three technologies have no negative impacts for water reuse and management and social inconvenience. While there may be odour emissions and noise from reactors, it should not affect the local people too much as the facility (in this case, a brewery) will not be located in densely populated area. Furthermore, the use of wastewater as the source, where treated water is then recycled, the positive outcome is enhanced.

Out of the three technologies, anaerobic digestion heavily influences the environment, in most cases, negatively with the exception of raw materials. As of raw materials usage, bioelectric systems may reduce heavy metals rather than oxygen if the wastewater is highly contaminated (Ezziat et al., 2019). Additionally, they are shown to be more thermodynamically favourable (Wang and Ren, 2014) so large-scale operations may opt to this alternative. In such case, the heavy metals will cause pollution.

Even though all three technologies are net energy-positive, relative to one another, anaerobic digestion needs most energy than bioelectric systems. Similarly, between the two bioelectric systems, electromethanogenesis cell requires constant power supply to 'ignite' the reactions taking place in the chamber. Thus, a typical MFC system has the least impact on the energy aspect out of the three. Based on direct production of greenhouse gases (CH₄ and CO₂) Figure 15 suggests that anaerobic digestion has the greatest impact. Due to no CH₄ production in a typical MFC system, and application of CO₂ capture in an electromethanogenesis cell system, we see these advantages contribute to an overall positive impact for bioelectric systems.

6 CONCLUSION

Based on lab-scale experiments and findings, MFC systems when combined with another wastewater treatment procedure such as MBR or AD technology had a synergetic effect. The key conclusion that was drawn from the literature review is that a large-scale bioelectric system operating solely on the concept of MFC will neither be sustainable nor achieve maximum extraction of energy from the wastewater. This leads to the need for pre-treatment and post-treatment (possibly aerobic) in a real-life wastewater facility when incorporating MFC technology. The effluent of an AD plant can be sent a MFC system allowing to remove the remaining organic matter and produce cleaner effluent and direct electricity. While AD plant as a pre-treatment may not be economically favourable nor energy-positive, it is important to achieve the maximum power generation, as far research today goes, and accounting for scale-up considerations.

Practically, the benefits attained from the use of bioelectric systems like MFCs should be higher than the costs (Sleutels et al., 2012), i.e., benefit-to-cost ratio is greater than 1. However, this was not the case with any of the technologies, based on our calculations. This may be due to estimation errors and lack of transparency between companies' profiles and the public. Despite this, Aquacycl's BETT solution was identified as the probable option as it yielded the highest benefit-to-cost ratio. On the other hand, Cambrian's EcoVolt technology achieved the lowest cost per kWh of electricity, which did not present a big difference from Aquacycl's cost. All in all, it was evident that large-scale bioelectric systems are far more economically feasible and desirable than conventional anaerobic digestion wastewater treatment plants.

With rising energy demand and need for climate action, there are expectations for bioelectric systems to play an important role in achieving sustainable energy production. Compared to other renewables, there is still long way to go with research and cost reduction, and most importantly, more commercialisation. However, assessing the direct environmental impact of bioelectric systems based on judgement and prior knowledge, there are negative impacts to the environment due to CO₂ production and energy consumption. However, if the severity of these impacts were assessed by placing a certain value using a better method, we would discover that the positive outcome outweighs the negatives. This environmental impact assessment may be biased as not all rankings are based on numerical evidence, and assumptions were made. Thus, a thorough life-cycle assessment needs to be executed on bioelectric systems (typical MFC and electromethanogenesis cell). This extension will provide a more detailed insight into environmental impact as the information will be collected from a reliable database.

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