The Microbial Fuel Cell, is it the power source of the future?

Contents

Introduction

As the human population continues to grow the demand for more energy increases. Currently we rely almost entirely on the non-renewable, un-sustainable and environmentally damaging resource Oil to fuel our hunger for energy, but oil is fast running out along with coal and natural gas. As fossil fuel supplies dwindle and the use of petroleum fuels becomes more and more unsustainable, new alternatives must be considered if we are to continue living in an energy driven age. This new alternative fuel must tick all the boxes before we can implement it into our daily lives. It must be, renewable, carbon neutral, non-polluting, transportable, easy to store, economically viable, and produce enough power to be useful.

Of course, energy is not the only environmental issue that faces us today, the issue of waste is one that is fast becoming a major concern. The more we build and consume in our energy driven lives, the more waste is created. This report aims to evaluate a new developing technology called the Microbial Fuel Cell (MFC). It is still a developing idea, only in its infancy, but already it holds great potential to combat the issues mentioned above.

What is the Microbial Fuel Cell?

For a long time scientists have understood the complicated processes that living creatures undertake to produce energy. A simple glance at most higher-level textbooks will demonstrate this, with complicated metabolic processes such as respiration and photosynthesis being explained clearly in terms of redox reactions, protons and electrons. For example, the charge separation that occurs from the complete oxidation of glucose in a bacterial cell is this:

$C_6H_{12}O_6$ + $6H_2O$ $\longrightarrow$ $6CO_2$

24H+ and 24*e*-

(Bennetto, 1990)

Therefore, the concept that microorganisms can metabolize food, converting it from organic matter to a flow of electrons, is not a new one. In fact, it goes back centuries. The notion of utilizing this electron flow to produce a voltage is also not new, and the very first Microbial Fuel cell can be traced back to as far as 1910, put together by a man called Michael Cresse Potter. However, even though interest in them has grown over the past decade, they still remain in the shadows as an uncertain technology. Ask anyone what a hydrogen fuel cell is and they will almost certainly have some idea of what it is and how it works, but mention the words 'Microbial Fuel Cell' to most people and you will be rewarded with a blank stare.

Despite this general ignorance on the subject though, research into the MFC is ongoing and over the years its performance has improved substantially, so much so that the idea of it becoming a feasible power source, and a solution to our energy problems, is no longer quite so unimaginable.

How do they work?

Fuel cells work like batteries in that they require an anode, a cathode and an electrolyte to run. However, unlike batteries they require a constant input of fuel to continue running. As long as this fuel is supplied they do not need to be recharged and can supply electricity continuously. What distinguishes the Microbial Fuel Cell from other fuel cells is that it runs on the principles of microbial hydrolysis and anaerobic respiration, using live microbes to generate its electricity. (Ieropoulous, 2012) States, “A Microbial Fuel Cell is a bio-electrochemical transducer that can convert organic matter (fuel) directly into electricity, via the metabolism of constituent bacteria.”

The chemical energy (in the form of chemical bonds) in organic compounds is converted to electrical energy through microbial catalysis at the anode under anaerobic conditions. The microbes are usually facultative bacteria, meaning that they can respire without oxygen (anaerobically). These microbes hydrolyze the organic substrate (fuel), and utilize it for anaerobic respiration. Although fermentation is the best-known pathway for the anaerobic respiration of microbes, evidence shows that the reduced products it produces, such as acetate, do not react readily with the anode. (Veeranjaneya Reddy, 2010)

Therefore, mediators, also known as electron shuttles, tend to be required for efficient electron transfer to the anode. These now reduced, and more electrochemically active mediators have effectively stolen the electrons from the reduced products of fermentation. They are able to then cross the cell membrane, shuttling the ‘stolen’ electrons to the anode surface where they are subsequently oxidized and re-used. Reuse of these electron shuttles for microbes that create their own is vital, as biosynthesizing an electron shuttle is energetically expensive. (Veeranjaneya Reddy, 2010)

It has also been shown that cells without a mediator of any kind produce relatively little current. (Benetto, 1987). Of course, the ways in which electron transfer is achieved varies depending on the type of microorganism. Effectively though the key principle behind a successful transfer is always the same, there must be some kind of link to the anode surface that allows the electrons from the inner metabolic pathways of the microbe to pass out across the lipid membrane and onto the anode surface. Whether that is a mediator, a chain of electrically conductive proteins or cytochromes that spans all the way to the organisms lipid membrane, or electrically conductive nanowires or pili grown by the microbes that attach to the electrode surface (Ieropoulous, 2012), an effective link between the microbe and the anode must be established.

Once these electrons pass to the anode, they are conducted along an external circuit/wire that is usually connected to a load or resistor of some kind. So far, the size of the load the MFC can power remains small, however power generation has increased by several orders of magnitude (approximately 10^6 in less than a decade) according to (S. Kim, 2008) who cite (Logan, 2006) and further research is still being conducted into how to increase this power generation even more.

Finally, the electrons end up at the cathode, which will contain an oxidizing agent for example, Oxygen, that acts as a terminal electron acceptor. This reduced oxygen will combine with the cations (in this case H+) passing through the ion exchange membrane (that separates the two electrode compartments) to form water. This reaction between the electrons and cations with the oxidizing agent is what closes the ‘circuit.’ Without this facilitated reaction between the electrons and the cations, there would be no charge (electron flow) and so the circuit would be ‘open.’ Overall CO_2 is given off at the anode and water is given off at the cathode.

The CO_2 is produced as an oxidation product by the MFC however there is no net gain of CO_2 to the atmosphere as the carbon dioxide produced is carbon dioxide that was initially taken in by the renewable biomass, for example from the photosynthesis of plants.

Typical electrode reactions are shown below using acetate as an example substrate.

Anodic reaction: $CH_3COO^- + 2H_2O \xrightarrow{\text{Microbes}} 2CO_2 + 7H_+ + 8e^-$

Cathodic reaction: $O_2 + 4e^- + 4H_+ \longrightarrow 2H_2O$

(Veeranjaneya Reddy, 2010)

The Overall reaction is the breakdown of the substrate to CO_2 and H_2O with the production of electricity as a by-product.

Figure 1 demonstrates this process in a simple MFC configuration.

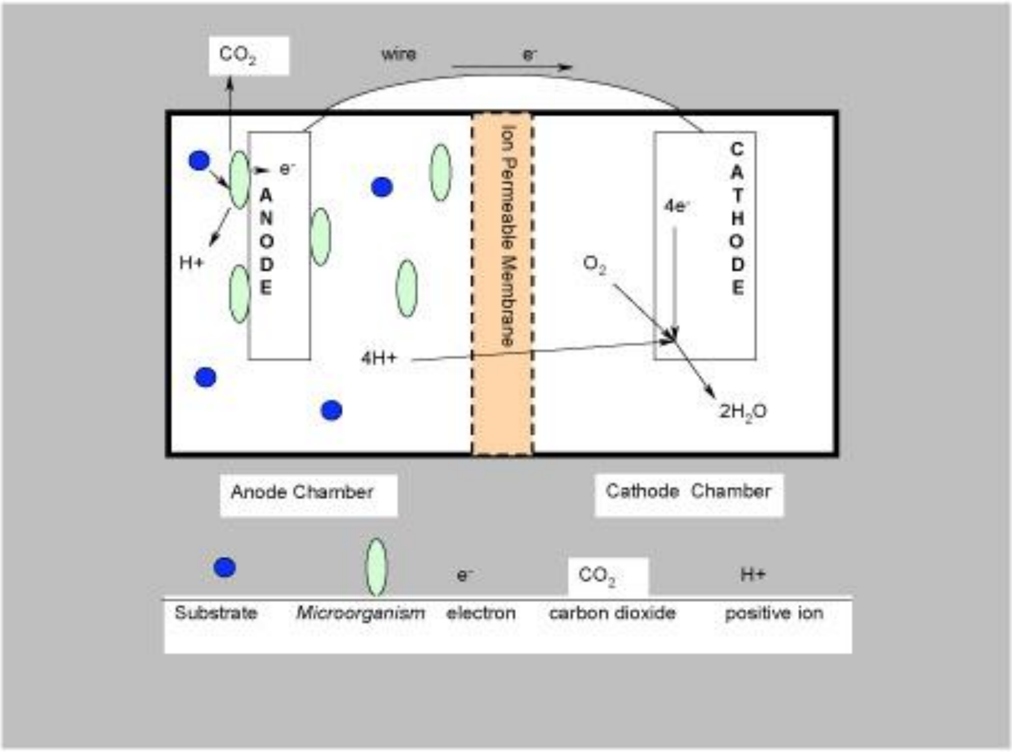

Figure 1: Diagram of working MFC. Reference: (Henslee et al. 2004)

Figure 2 shows some of the microbes being used in microbial fuel cells that utilize Marine sediment, soil, wastewater, fresh water sediment and activated sludge for power generation.

Microbes	**Substrate**	**Applications**
Actinobacillus succinogenes	Glucose	Neutral red or Thionin as electron mediator
Aeromonas hydrophila	Acetate	Mediator-less MFC
Alcaligenes faecalis, Enterococcus	Glucose	Self-mediate consortia isolated from MFC With a maximal level of 4.31 W m−2.
Gallinarum, Pseudomonas Aeruginosa	Starch, glucose	Fermentative bacterium
Clostridium beijerinckii	Starch, glucose, lactate, molasses	Fermentative bacterium
Clostridium butyricum	Starch, glucose, lactate, molasses	Sulphate/sulphide as mediator
Desulfovibrio desulfuricans	Sucrose	Ferric chelate complex as mediators
Erwinia dissolven	Glucose	Ferric chelate complex as mediators
Escherichia coli	Glucose sucrose	Mediators such as methylene blue needed.
Geobacter metallireducens	Acetate	Mediator-less MFC
Geobacter sulfurreducens	Acetate	Mediator-less MFC
Gluconobacter oxydans	Glucose	Mediator (HNQ, resazurin or thionine) needed
Klebsiella pneumoniae	Glucose	HNQ as mediator biomineralized manganese as electron acceptor
Lactobacillus plantarum	Glucose	Ferric chelate complex as mediators
Proteus mirabilis	Glucose	Thionin as mediator
Pseudomonas aeruginosa	Glucose	Pyocyanin and phenazine-1-carboxamide as mediator
Rhodoferax ferrireducens	Glucose, xylose, sucrose, altose	Mediator-less MFC
Shewanella oneidensis	Lactate	Anthraquinone-2,6-disulfonate (AQDS) as mediator
Shewanella putrefaciens	Lactate, pyruvate, acetate, glucose	Mediator-less MFC but incorporating an electron mediator like Mn(IV) or NR into the anode enhanced the electricity production
Streptococcus lactis	Glucose	Ferric chelate complex as mediators

(Veeranjaneya Reddy, 2010)Figure 2

The Experiment.

Demonstrating electricity generation by anaerobic respiration of yeast using a simple Microbial Fuel Cell set up.

Evaluating the Microbial Fuel Cell

What does an MFC run on, what is it made of and how does this benefit us?

(Ieropoulous, 2012) States, "the bacterial communities normally used in our MFCs are those that are naturally occurring in wastewater or indeed in soil, water and sediment." Therefore, MFCs can make use of microorganisms that naturally occur in the environments selected for the MFC work. This means that money does not need to be spent on developing specialized microorganisms for MFC work, unlike in other areas of research such as microbes for renewable oil.

MFCs can be produced from a variety of materials, and energy or environmental problems will arise depending on the materials used to construct and assemble an MFC. However, MFCs can be made from pipette tips, styrene foam and plastic bags. (Ieropoulous, 2012) Therefore, the environmental problems that are encountered by some research groups that use expensive catalysts or toxic chemicals can be avoided by choosing to work with sustainable materials instead. Furthermore, MFCs can use waste materials such as rumen fluid as a source for the biocatalysts, and agricultural byproducts such as manure as a substrate. In this way, MFCs are inexpensive to construct because they depend on materials produced in abundance and conventionally regarded as waste. (Christy, 2012)

The MFC runs on organic waste. Waste is only waste so long as we do not have a use for it, but lots of 'waste' contains significant quantities of energy that if utilized could be an invaluable renewable resource. Just by changing our method of thinking, we can simultaneously begin to solve the problems of global waste and renewable energy.

What is organic waste?

It is organic material such as; food, animal and plant based material and degradable carbon such as paper. The main forms of organic waste are household food waste, agricultural waste, human and animal waste (Rees/ITDG, 2006)

Why is organic waste a problem?

Much of it ends up in landfills where it undergoes anaerobic decomposition, which generates methane into the atmosphere. Methane is 20 times more potent as a greenhouse gas than CO2 (Victoria, 2012). When it is broken down it also forms a liquid 'leachate', which contains bacteria, rotting matter and maybe chemical contaminants from the landfill. This leachate can present a serious hazard if it reaches a watercourse or enters the water table. In industrialized countries, the amount of organic waste produced is increasing dramatically each year. (Rees/ITDG, 2006).

In developing countries, there is a much higher organic content in domestic waste. From Figure 3 we can see that up to 60% (or more in some cases) of all municipal waste is organic matter, much higher than the figure for an industrialized country.

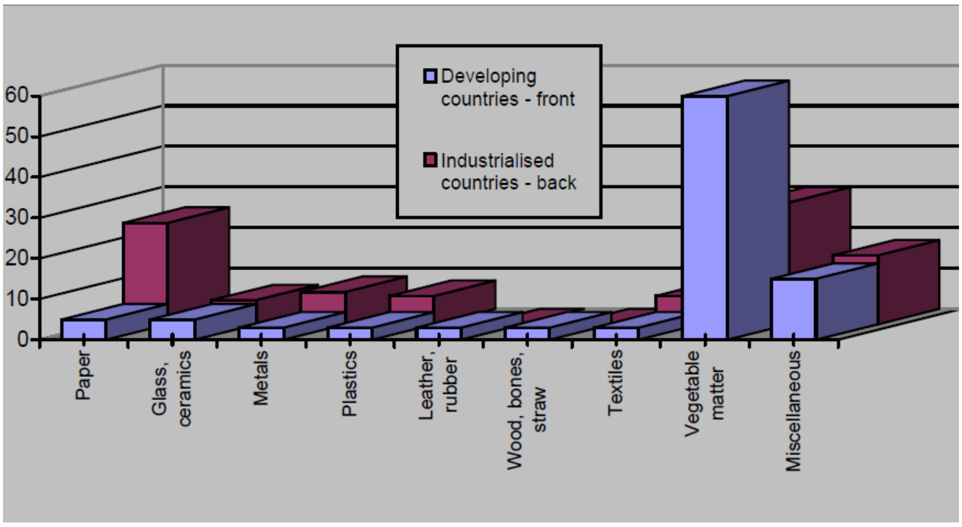

Figure 3 (Rees/ITDG, 2006)

What are the anticipated applications of the MFCs?

The Anticipated applications for the Microbial Fuel Cell seem to be virtually endless, however much of the literature on the subject seems to all point to the same conclusion; that the MFCs technology is not yet sufficiently advanced to reach these goals. One journal (Veeranjaneya Reddy, 2010) states that at present, the MFCs can only produce enough current to power small electronic devices for short periods, or can only trickle charge capacitors for applications with higher power demands. Therefore substantial further optimization of the MFC is required if they are to have any impact on the issues that face us today. The good news is that if they succeed a noticeable dent should be made in the oil industry due to the replacement of oil for fuels, residential applications such as heating, and electricity generation. Not to mention the benevolent effects they would have on the environment and the people that populate it.

Applications being considered for this technology are as follows; household electrical generators, powering small portable electronic devices, boats, automobiles, electronics in space, self-feeding robots, biosensors, conversion of sewage and other organic waste to electricity, wastewater treatment and the bioremediation of contaminated environments. Furthermore, the MFC may even have a role to play in applications beyond electricity generation. An example of this would be electrohydrogenesis. MFCs can be modified to produce hydrogen instead of energy. Therefore, even if hydrogen fuel cells end up being our main power source of the future, MFCs may still have an important role to play in power generation. (S. Kim, 2008)

Although the application of the MFC for electricity generation in transport would have the biggest impact on the oil crisis, the most likely applications emerging so far appear to be wastewater treatment and biosensors/bioremediation of contaminated environments.

Wastewater treatment is an area that frequently crops up in the literature and as (Ieropoulous, 2012) states “a particular benefit of there application here is that they can help remove organic loading from wastewater by generating energy instead of consuming energy.”

What is wastewater and why is its treatment so important?

Wastewater is used water. It includes substances such as human waste, food scraps, oils, and chemicals.

Wastewater has many negative effects on the environment such as harming fish and wildlife populations, for example, decaying organic matter and debris can use up the dissolved oxygen in a lake so fish and other aquatic biota cannot survive (Perlman, 2012). Furthermore, around 700,000 children die every year from diarrhea caused by unsafe water and poor sanitation - that is almost 2,000 children a day. (Water Aid 2012/WHO 2008/The Lancet 2012). Therefore, its treatment is extremely necessary.

The current treatment of wastewater however, is a laborious process that involves many stages of treatment before the water is considered safe to be put back into general circulation. It contributes to about 30% of energy costs in the United States. (USEPA & Water, 2008). The Microbial Fuel Cells offers a solution to this problem. Thus the application of the MFC for wastewater treatment brings about many obvious benefits to not only the environment but also to alleviating energy demands and economic strains.

What could its impact be on the oil crisis?

Firstly, to understand what its impact could be, an understanding of the oil crisis is required.

Oil is running out

Peak Oil is a theory that was first developed back in the 1950s by American Geologist M King Hubbert who worked for Shell. (Dunn, n.d.) Describes peak oil as the “point in time when crude oil production reaches its maximum level”.

That is, if we continue to produce and consume oil at our current rate we will reach a point where oil production goes into terminal decline, with prices climbing steeply to match the increased demand, as shown in figure 4.

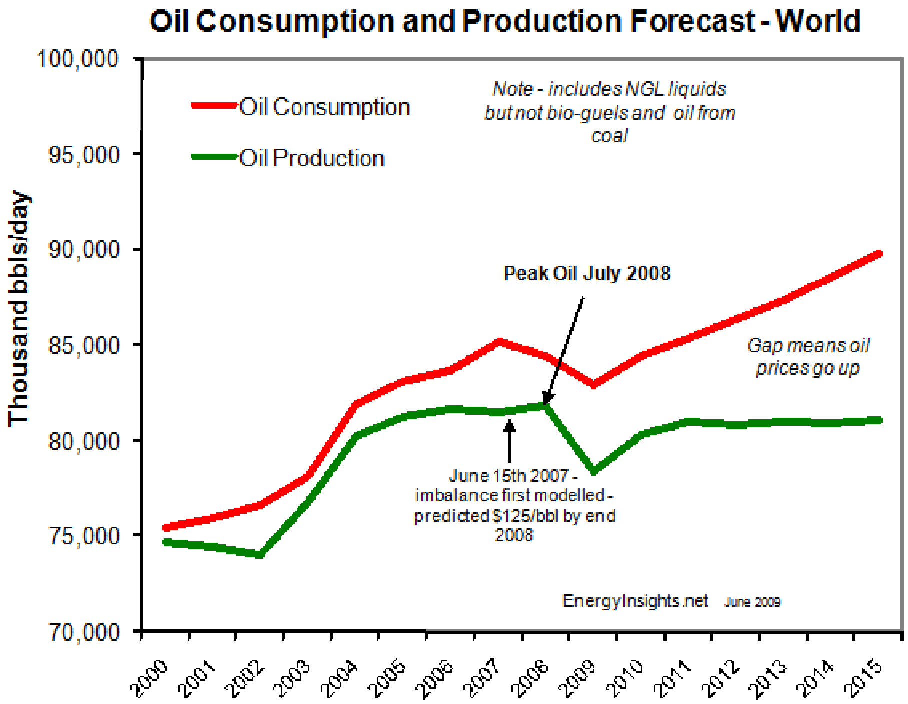

Figure 4 June 2009 Energy.net

Oil pollutes

Burning oil releases carbon dioxide, a greenhouse gas that contributes to global warming. The US Energy Information Administration says levels of important greenhouse gases, such as carbon dioxide, have increased about 25 percent in the past 150 years, with the rise of modern industry. The burning of fossil fuels to create energy accounts for 82 percent of man-made greenhouse gas emissions in the United States, making it the top source of emissions in the country. ((EIA), 2012)

Why Oil?

If we know that it is running out and that it damages the environment, why do we continue to use it? The reason is that the energy stored in oil is significantly greater than in any other currently available source and that at the moment it is the cheapest source of energy we possess. We use Oil for Heat, Electricity, Transportation, Agriculture, and Industry. Before we can make the break from oil, we need to develop technologies that can produce the same amounts of power at a similar or even lower cost.

What would have the biggest effect?

The biggest use of oil is for petroleum fuels for transport. The internal combustion engine (ICE) runs on petroleum fuels. As seen above the use of crude oil is unsustainable and damaging to the environment, therefore in order to tackle the problem, electric vehicles are being developed to replace the ICE. As seen in Figure 5 the transport sector is the biggest drain on oil resource and thus if electric vehicles were to successfully replace the ICE the demand for oil would drop drastically. This would have a beneficial effect on the environment and could avoid the strain that peak oil would place on countries' economies.

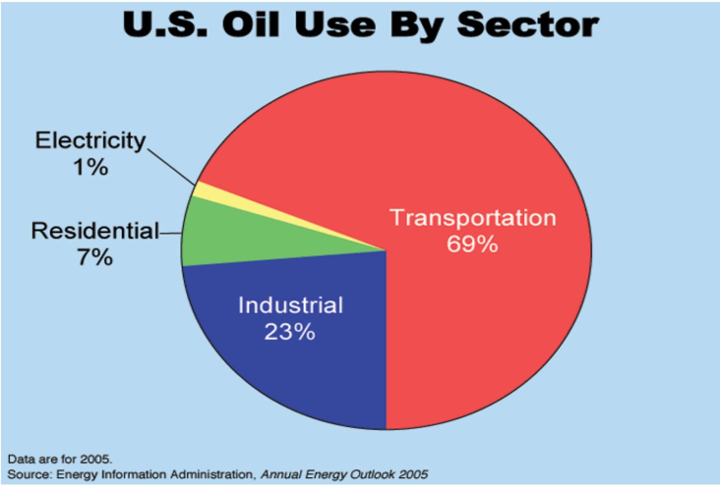

Figure 5, Source: Energy Information Administration, Annual Energy Outlook 2005

The benefits of switching to electric over gasoline are obvious as show in figure 6-

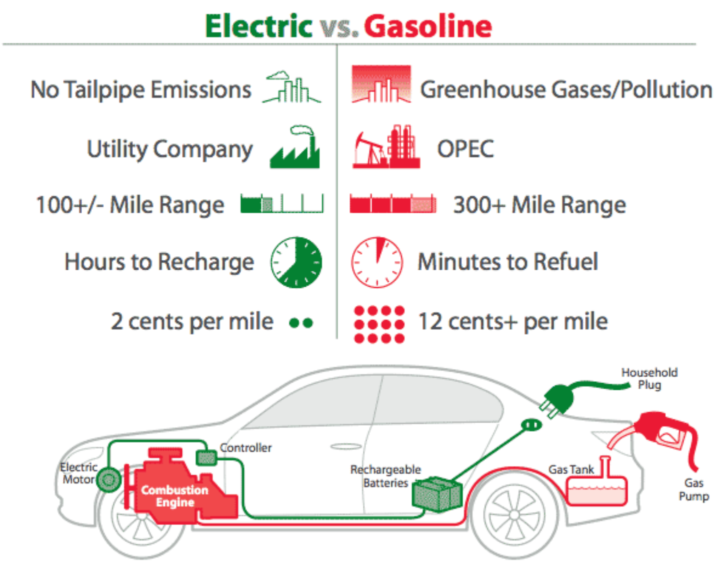

Figure 6, 2012 Circuits today.com 1

However, an article (Strahan, 2012) evaluating the current success of the electric vehicle for replacing the ICE showed that ultimately it will be a long time before electric vehicles have any major impact on the transport industry, although, the ICEs days are certainly numbered. The reasons put forward are as follows; cost, amount and efficiency of the ICE. Cost: The cost of the lithium-ion battery that powers the electric car is so expensive that electric cars cost far more than their petrol-powered counterparts do. Amount: there are currently not enough electric cars in circulation to have a big impact on oil demand, and finally, increased efficiency of the internal combustion engine, for example the improvement of catalytic converters to remove pollutants from the exhaust stream.

Where does the MFC come in?

The concept of fuelling cars with carbohydrates is not unheard of; the energy that can be obtained from the complete oxidation of a monosaccharide such as glucose is 5-kilowatt hours of electrical energy. Although this is less than half of the energy that can be obtained from burning a fuel like octane, the efficiency of effectively, 'cold burning' the carbohydrate in a MFC is potentially much greater than that of burning petrol. (Benetto, 1987). For example, the typical internal combustion engine of a car is about 25% energy efficient (Energy, 2012), whilst according to the U.S. Department of Energy, fuel cells are generally between 40–60% energy efficient. (Energy, 2011).

A far off vision of this is that the MFC may even be used alongside the internal combustion engine. (Ieropoulous, 2012) States that "the microbial fuel cell could work alongside the internal combustion engine, in a similar manner to how electric vehicles work today. Only in this instance, electricity will be produced by waste, food waste or even urine." In this way the car would still be running with an ICE but would release less carbon emissions, run more efficiently thus reducing the need for more oil, and would also be making use of fuels commonly thought of as waste.

However, this vision may not be so far off as it seems. A key factor for the success of the electric car is its efficiency compared to that of the ICE's as well as its considerably low Carbon emissions (zero when running). (Strahan, 2012) States, "The Nissan Leaf is responsible for just 99 grams of CO_2 per kilometer even when charged on electricity generated by the average mix of coal, natural gas nuclear and renewables. This makes it 40% cleaner than a typical petrol car in Europe."

As seen above, the efficiency of the MFC is potentially much greater than that of the ICE's and as fuel economy and emissions policies (see Figure 7) grow stricter further reductions to CO2 emissions produced by the production of electric cars may be demanded. Therefore, if the electricity that charged electric cars was generated by the MFC, a carbon-neutral power source, these carbon emissions would fall even further. Potentially leading to a boost in funding for MFC research, and consequently a reduction in the amount of time before the implementation of the MFC in transport becomes a feasible consideration, either directly or as a power source for electric vehicles.

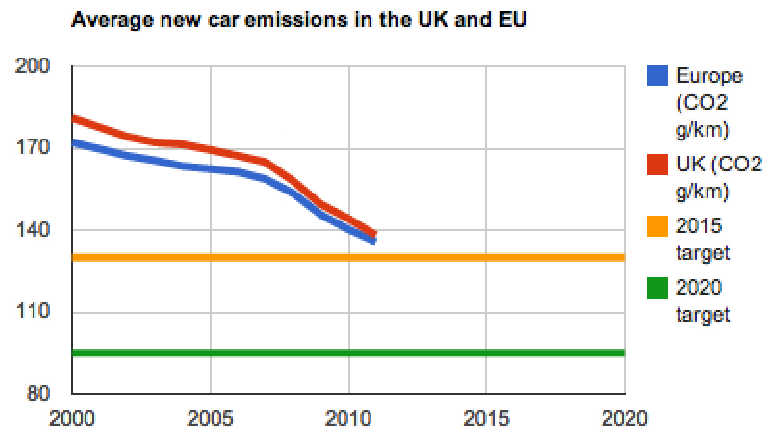

Figure 7 The Guardian 2012

In addition, if the MFC were to be used as a battery in the electric car it would remove the need for the expensive lithium-ion batteries currently being used, reducing the overall cost of the electric car and so increasing sales. Cost is not the only issue with these batteries however; lithium is fast becoming an endangered element. Therefore, use of MFCs as batteries, which can be configured using only renewable materials, would not only be reducing the amount of time before electric vehicles really make an impact on oil demand, but would also be reducing the amount of time before lithium supply plummets as well.

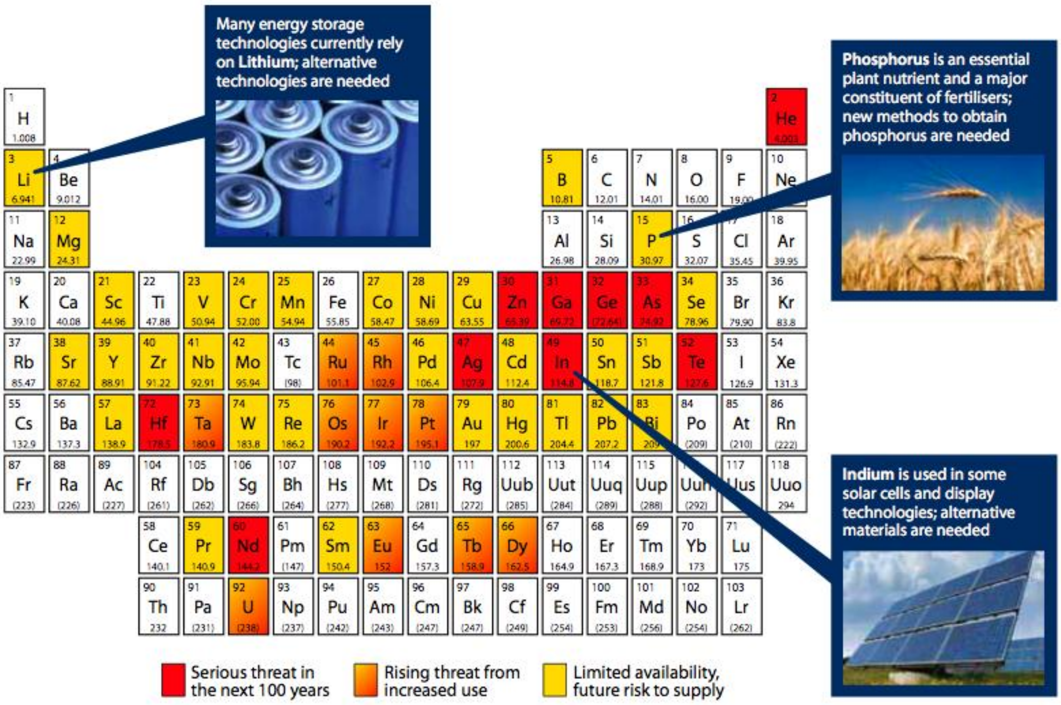

Figure 8 Royal Society of Chemistry1 and the Chemistry Innovation Knowledge Transfer Network's Sustainable Technologies Roadmap, as taken from: http://www.thesolutionsjournal.com/node/1107

These applications however are all still theoretical, and the MFC has a long way to go yet before scientists can even begin to start inserting the MFC into vehicles. In addition, electric vehicles will not have a major impact on the oil industry for some time and so the MFCs current value as a future energy source in regards to the Oil crisis is minimal.

That is not to say we should completely disregard it as an option to help deal with the crisis, but as stated by an expert in the field, (Ieropoulous, 2012) they will only be able to help if adopted on a global scale. “The engineering of the technology's scale-up is an ongoing process.” Different approaches can be taken when scaling this technology up, and some groups work on making individual units larger although according to (Ieropoulous, 2012) larger sizes have been found to suffer higher internal losses.

Others aim to miniaturize individual units, small scale MFCs can be about 1ml total volume, and stacking them can increase power output. This method of stacking has already shown some success for (Ieropoulous, 2012) research group, for practical applications such as digital wristwatches. In this way, the size of the MFC varies depending on the research group working with it and depending on the particular application.

What will be its impact on waste and the environment?

The first and most obvious point here is that the MFC is carbon-neutral and produces only water as a product (other than electricity). The second is that it is potentially self-sustaining and will not run out of 'juice' so long as there is a constant fuel supply. This is supported by evidence that Geobacteracae have been shown to be capable of conserving energy to support growth by completely oxidizing acetate and other organic compounds to CO_2 and electricity (Lovely, 2006). See Figure 9 comparing the properties of the MFC with the properties of a simple alkaline cell (battery). The third is that it runs on renewable fuels, which simultaneously attacks the issue of organic waste (see above) and the fourth is that it can treat contaminated environments whilst doing so.

Additionally, the MFC can provide in situ power for electronic devices in remote locations such as environmental sensors in the ocean. They can harvest the matter from organic sediments, and could replace traditional batteries that are expensive and technically difficult to routinely access and replace (Lovely, 2006). Moreover, what makes the MFC even more valuable as a power source is its use in third world and developing countries that may not have access to a developed and centralized power grid (Veeranjaneya Reddy, 2010).

The overall benevolent environmental impact of MFCs is perhaps the ability to treat waste without consuming any energy, but producing electricity instead. This can help power certain applications in remote locations, but perhaps more importantly alleviate some of the energy and financial costs currently invested in state-of-the-art wastewater treatment.

Type	Vo/c	Capacity	Energy	Weight	Energy Density	Cost	Durability
Alkaline Cell (AA)	1.5V	2.8Ah	4.2Wh	25g	604J/g	£0.30	Will run out
Microbial Fuel Cell	0.8V	1.05Ah (~120uA for 1 year)	1Wh (~100uW for 1 year)	10g	360J/g	<£1	Will keep on going

(Ieropoulos, 2012)Figure 9-Comparison Table 1

What are the current issues with the MFC?

The performance of an MFC is affected by a variety of factors such as; its physical and chemical operating conditions, the choice of microorganism and the optimization of microbial metabolism to increase electron-donation to electrodes (S. Kim, 2008), electrode material, PH buffer, electrolyte, and operating conditions in the anodic chamber. Further investigations into improving such factors would undoubtedly lead to significant improvements for the MFC.

Currently, as mentioned before, the technology is not sufficiently advanced to provide any sort of immediate solution to the problems facing us. There are many technological challenges still facing scientists before it can be considered on a large scale. One such challenge is the use of MFCs as an In-situ power source for remote areas where the MFC 'recovers' its electricity from sediments. The issue here being that there is a low power density for the MFC due to both the low organic matter concentration and high intrinsic internal resistance (S. Kim, 2008).

Further issues with the actual configuration of the MFC in relation to the type of membrane used to separate the anodic and cathodic chambers are highlighted in (S. Kim, 2008) journal; oxygen back diffusion, substrate loss, cation transport and accumulation rather than protons and biofouling. Further problems for full-scale applications are also highlighted such as the need for suppression of competitive metabolisms and the reduction of capital costs. However, problems arising from the configuration and components of the MFC are not finite and can be addressed quite straightforwardly by adaptions being made to the design and alternative materials being sought out.

In addition, the highest outputs of current are still less than several watts per square meter of anode surface (S. Kim, 2008). Even with a pure substrate like glucose. However, significant progress has been made to increase the power output of systems and their conversion efficiency, and as a result, MFC power production has increased by several orders of magnitude over the last few years.

Ultimately, what needs to be taken away from this is that although many challenges remain for the MFC, improvements are constantly being made and the progress of the MFC does not seem to be in any hurry to come to a stop. Challenges remain for all the different types of alternative power systems, for example, wind turbines are not viable for electricity generation in the transport sector, hydrogen fuel cells still need an effective method of storing hydrogen for use (to name but one problem), nuclear power generates toxic waste and biofuels still produce CO_2. The point is that the MFC still has a wealth of options available for its improvement. One such option could be the use of Mutagenesis and rDNA technology to obtain some kind of ‘super bug’ for the MFC, which could tackle the issue of power output. (ref journal).

In summary the pros and cons of the MFC are as follows.

Pros
Using waste and sustainable materials to construct the MFC means that it can be inexpensive to make
It is Carbon-neutral
It is Self-sustaining and renewing as it can conserve energy to support growth from electron transfer.
It can oxidize ‘dirty fuels’ that don’t often seem to have much value
It can tackle the issue of global waste whilst simultaneously tackling the problem of renewable energy
It has none of the usual pollutants associated with other energy sources
Water is the only by-product
It is more efficient than the Internal Combustion engine for example, it is possible that it could extract over 90% of electrons from organic compounds
It does not need extensive pre-processing of the fuel or expensive catalysts
It could remove the need for lithium (as needed for conventional batteries)
It can be used to produce hydrogen which tackles the issue of expensive processing currently required for hydrogen fuel cells
It can be used on a small scale (biomass burnt in bioreactors cannot be used for powering a battery)
It can treat wastewater without consuming energy
It can be an In-situ power source for remote locations where it could monitor pollutants and weather without the need for difficult and expensive battery changes.
The harmless properties of the fuels it uses removes need for complex and highly regulated distribution systems that are required for other types of fuel cells

Cons
There are many technological challenges still to face
It is not advanced enough to produce substantial quantities of energy in a cost-effective manner
It has an uncertain future-i.e., even if the MFC *can* be constructed from sustainable materials, these may not be effective in increasing power output, in which case unsustainable or toxic materials may be needed. Such as those currently being used by some research groups now, which if subjected to life cycle analysis are not sustainable and will result in a net negative impact.

Conclusion

In my opinion, the Microbial Fuel Cell offers enough potential environmental benefits to be considered a strong candidate for renewable power. Despite the challenges Scientists still face before the MFC can become a viable part of the energy portfolio of the future, the benefits that will be reaped if they succeed in overcoming them far outweigh any issues that may arise whilst pursuing the MFC as a sustainable energy source. Moreover, there are plenty of other renewable energy sources being considered that have their own mix of pros and cons. Even if the MFC falls short to another energy source as the main solution, it could still offer a considerable amount of help in tackling environmental issues such as the oil crisis, global waste and global warming. Consequently, I think it should continue to be an avenue for clean energy research; however, attention should be divided between all alternatives and not solely concentrated on the microbial fuel cell as there are still many uncertainties to be tackled.

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