

CHAPTER 1

Introduction

1.1 Energy needs

There are over six billion people on the planet with 9.4 billion projected for 2050 (*Lewis and Nocera* 2006). Fossil fuels have supported the industrialization and economic growth of countries during the past century, but it is clear that they cannot indefinitely sustain a global economy. Oil will not appreciably run out for at least 100 years or more, but demand for oil is expected to exceed production from known and anticipated oil reserves ten or twenty years from now, or within the 2015 to 2025 time frame (*Rifkin* 2002). This may seem distant to many consumers and businesses that rarely plan for more than three to five years in the future, but this is a very short time frame for society as a whole. Planning a single section of an interstate highway in a city, for example, can take ten years or more. The infrastructure changes needed to address our global energy needs will be far more extensive and will likely require changes not only to our infrastructure but also to our lifestyle. Changes will affect everything from home heating and lighting, to where we prefer to live and work and how we get there. The costs of energy and how much energy we use will come to dominate our economy and our lifestyle in the coming decades.

The total annual energy consumption in the US is ~100 quads of energy (100 quadrillion BTU = 10^{15} BTU), or 1.1×10^{15} J, which is a continuous consumption rate of 3.34 TW (1 TW = 10^{12} W). On a global scale, energy use is 13.5 TW (*Lewis and Nocera* 2006). Thus, the US uses about 25% of the world's energy despite having only 5% of the world's population. Energy in the US is derived from a number of sources, but most are fossil fuels (Fig. 1.1). Approximately 18% of this energy (600 GW) is generated as electricity at power plants that vary greatly in size, with a typical large power plant producing ~1 GW. Power plants are 33% efficient, so energy used to make this electricity is larger by a factor of three.

If we assume a base of 300 million people in the US, each person in the US consumes on average 11.1 kW, or 97 MWh per year. This is not a level of energy utilization that we see in our daily life as much of this energy is used for manufacturing and transportation or is lost as heat in various energy conversion and utilization cycles. At a more local level, an average US house uses 1.22 kW while a home in British

Columbia, Canada uses 1.5 kW (non-electric heating) to 2.5 kW (electric heating) (Levin *et al.* 2004). In comparison, 500 gallons of gas is annually used per person in the US, or an energy equivalent of 2.1 kW.

How much energy will we need in the future? One estimate of population growth, coupled economic growth at current levels, puts a global demand of 41 TW in 2050 at current energy growth rates. However, considering anticipated energy trends, a more reasonable projection is 27 TW by 2050 and 43 TW by 2100 (Lewis and Nocera 2006).

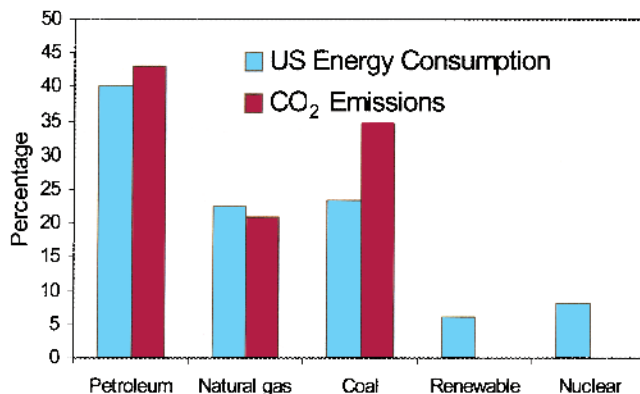


Fig. 1.1 Percent of US energy (98.5 Quad, 2003) by source and CO₂ emissions (5.772×10^9 metric tons). [From Shinnar and Cintro (2006). Reprinted with permission from AAAS.]

1.2 Energy and the challenge of global climate change

There is no “magic bullet” for meeting our current or future energy needs. While oil, natural gas, and coal are the main methods for energy production today (Fig. 1.1), this cannot continue into the future. When the US had its first oil crisis in the 1970s due to demand exceeding production, the solution was simply to find other sources of oil. However, finding new sources of oil, increasing the efficiency of extracting oil from existing source, or using other fossil fuels such as tar sands and shale oil will not address an equally challenging task of addressing climate change. There is no question that the release of stored carbon in fossil fuels is increasing the concentration of carbon dioxide in the atmosphere, with increases from 316 ppmv in 1959 to 377 ppmv in 2004 (Fig. 1.2A). By 2100, it is estimated that CO₂ concentrations will reach anywhere from 540 to 970 ppmv. Without substantial changes to our energy production methods, we will have greatly exceeded any historic level of CO₂ concentrations in the atmosphere. Global CO₂ accumulation over the next 40–50 yr will persist for the next 500–2,000 yr, and thus even the current levels of CO₂ are not likely to soon change. Global mean temperatures have already risen above pre-historic levels (Fig. 1.2B), resulting in melting of glaciers and rising sea levels.

The insufficient availability of oil and natural gas could be augmented by other fuels, such as coal, coal tars, oil shales, and methane hydrates. However, if we obtain energy from these sources using conventional technologies, we will release additional CO₂,

exacerbate environmental damage, and accelerate global climate change. Carbon capture and sequestration could be used, but this will continue to add to releases produced by other fuels. Clearly, we would need a very efficient method of carbon sequestration. We would need to develop a method that did not leak CO₂ into the atmosphere at an average rate (globally!) of more than 1% over centuries (Lewis and Nocera 2006). Of course this approach requires that all countries that release CO₂ are equally committed and effective in carbon capture and sequestration.

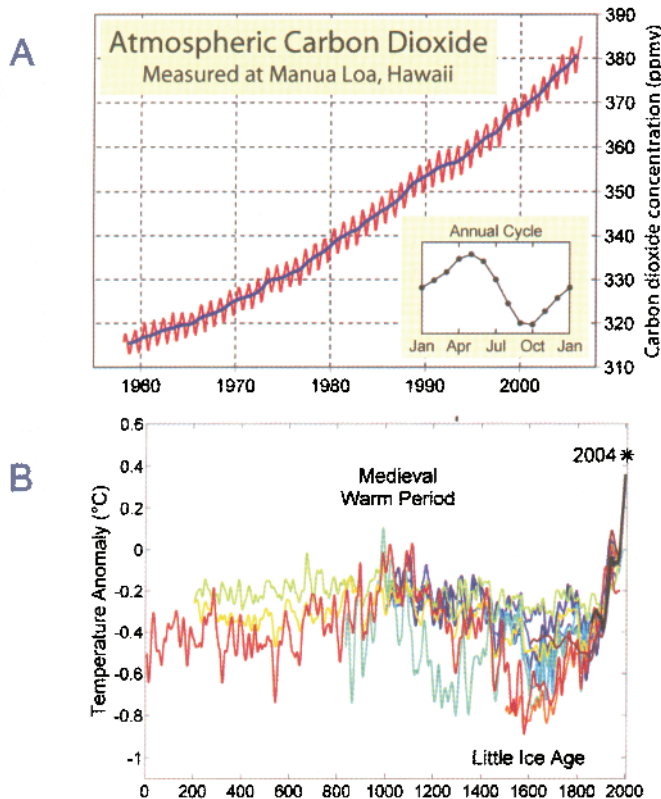


Fig. 1.2 (A) CO₂ concentrations in the atmosphere measured at Manua Loa (Wikipedia-Contributors 2007a); (B) temperatures relative to historic levels (Wikipedia-Contributors 2007b).

Our greatest environmental challenge is to simultaneously solve energy production and CO₂ releases: We must develop a whole new energy platform that produces sufficient energy while at the same time reduces CO₂ emissions. Our goal must be to meet 2050 energy needs on a carbon neutral basis.

Nuclear fission alone is not the answer. The expected availability of uranium is estimated to produce only 100 TW-h of electricity, and thus if 10 TW of power was obtained from nuclear energy the supply of uranium would be depleted in less than a decade. Moreover, we would need to build a new 1 GW plant every 1.6 days for the next 45 years (Lewis and Nocera 2006). This scenario doesn't even address the environmental

and human damage caused by uranium mining, or the lack of a safe, long-term solution for the storage of nuclear waste.

Solar energy is ultimately the long-term solution, but it all depends on how we harvest this source of energy. We currently use in 1 hour the energy of sunlight (4.3×10^{20} J) that strikes the planet each year. The sun does not shine all day, nor does it shine equally in all regions. Thus, solar panels can help with daytime electricity needs, but it will not serve as a primary source of energy throughout the day and night without efficient methods of energy storage. Water electrolysis to produce hydrogen is a useful approach as electrolysis can be quite efficient, and regeneration of electricity in hydrogen fuel cells could approach 80% compared to 50% currently achieved (*Grant 2003*).

Biomass energy is another form of captured solar energy, and it has the advantage of solar energy being stored in the biomass for concentrated processing and delivery. *Shinnar and Cintro (2006)* have proposed a roadmap to switch to non-fossil fuels over the next 30 to 50 years that rely on proven and available technologies that include solar, geothermal, wind, hydro and nuclear technologies. Roughly 15% of the land area in the US is currently used for cultivation, and most of that for food (*Grant 2003*). The energy value of these crops is estimated to be 2.6 TW of energy, which clearly is not sufficient to meet existing energy needs alone (and what would we eat?). However, to produce sufficient hydrogen to meet our transportation infrastructure with crops we would need 0.4 TW to make hydrogen via water electrolysis. This is equivalent to an increase in cultivation to 18% of the land (*Grant 2003*).

Costs to replace 70% of the fossil fuels (and most coal sources) would cost \$170 to \$200 billion per year over the next 30 years (*Shinnar and Cintro 2006*). While such economic figures are indeed challenging, they are not insurmountable. Given this long time frame, it is also likely that new technologies could emerge that could change the economic assessment. Thus, our best solution for both energy and climate appears to be heavy investment in renewable energy resources, in terms of both research and development.

1.3 Bioelectricity generation using a microbial fuel cell—the process of electrogenesis

Microbial fuel cell (MFC) technologies represent the newest approach for generating electricity—bioelectricity generation from biomass using bacteria. While the first observation of electrical current generated by bacteria is generally credited to *Potter in 1911 (Potter 1911)*, very few practical advances were achieved in this field even 55 years later (*Lewis 1966*). In the early 1990s, fuel cells became of more interest and work on MFCs began to increase (*Allen and Bennetto 1993*). However, experiments that were conducted required the use of chemical mediators, or electron shuttles, which could carry electrons from inside the cell to exogenous electrodes (see [Chapter 2](#)). The breakthrough in MFCs occurred in 1999 when it was recognized that mediators did not need to be added (*Kim et al. 1999c; Kim et al. 1999d*).

In an MFC, microorganisms degrade (oxidize) organic matter, producing electrons that travel through a series of respiratory enzymes in the cell and make energy for the cell in the form of ATP. The electrons are then released to a terminal electron acceptor (TEA) which accepts the electrons and becomes reduced. For example, oxygen can be reduced to water through a catalyzed reaction of the electrons with protons. Many TEAs such as oxygen, nitrate, sulfate, and others readily diffuse into the cell where they accept

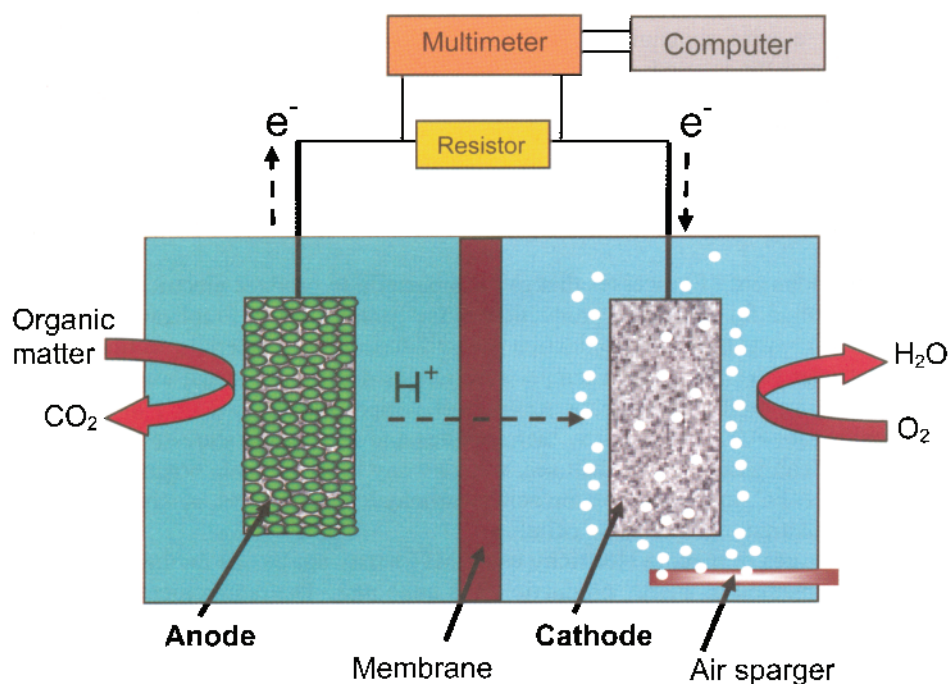


Fig. 1.3 Schematic of the basic components of a microbial fuel cell (not to scale). The anode and cathode chambers are separated by a membrane. The bacteria grow on the anode, oxidizing organic matter and releasing electrons to the anode and protons to the solution. The cathode is sparged with air to provide dissolved oxygen for the reactions of electrons, protons and oxygen at the cathode, with a wire (and load) completing the circuit and producing power. The system is shown with a resistor used as the load for the power being generated, with the current determined based on measuring the voltage drop across the resistor using a multimeter hooked up to a data acquisition system.

electrons forming products that can diffuse out of the cell. However, we now know that some bacteria can transfer electrons exogenously (*i.e.*, outside the cell) to a TEA such as a metal oxide like iron oxide. It is these bacteria that can exogenously transfer electrons, called *exoelectrogens*, that can be used to produce power in an MFC. The nomenclature used for categorizing process, microorganisms, and reactors for methane generation is: methanogenesis, methanogens, and anaerobic digesters. Similarly, we classify this method of electron-generating process as *electrogenesis*, with the bacteria *exoelectrogens* and the reactor a *microbial fuel cell (MFC)*.

A schematic of an MFC system is shown in **Fig. 1.3**. Oxygen in the anode chamber will inhibit electricity generation, so the system must be designed to keep the bacteria separated from oxygen (the catholyte in this example). This separation of the bacteria from oxygen can be achieved by placing a membrane that allows charge transfer between the electrodes, forming two separate chambers: the anode chamber, where the bacteria grow; and the cathode chamber, where the electrons react with the catholyte. The cathode

is sparged with air to provide dissolved oxygen for the reaction. The two electrodes are connected by a wire containing a load (*i.e.*, the device being powered), but in the laboratory a resistor is used as the load. In principle, the membrane is permeable to protons that are produced at the anode, so that they can migrate to the cathode where they can combine with electrons transferred via the wire and oxygen, forming water. The current produced by an MFC is typically calculated in the laboratory by monitoring the voltage drop across the resistor using either (a) a voltmeter (intermittent sampling) or (b) a multimeter or potentiostat hooked up to a computer for essentially continuous data acquisition.

The development of processes that can use bacteria to produce electricity represents a fantastic method for bioenergy production as the bacteria are self-replicating, and thus the catalysts for organic matter oxidation are self-sustaining. Bacterial reactions can be carried out over several different temperature ranges depending on the tolerance of the bacteria, ranging from moderate or room-level temperatures (15–35°C) to both high temperatures (50–60°C) tolerated by thermophiles and low temperatures (<15°C) where psychrophiles can grow. As we shall see, virtually any biodegradable organic matter can be used in an MFC, including volatile acids, carbohydrates, proteins, alcohols, and even relatively recalcitrant materials like cellulose.

While the idea of making electricity using MFCs may not be new in theory, certainly as a practical method of energy production it is quite new. The requirements for making MFCs economically viable as a method of energy production are demanding. The cost of oil currently remains low, and there are many different alternative methods of energy production that have reached a high level of development making them competitive for energy production. MFCs are so new that relatively little effort has been put into practical architectures using affordable materials. As highlighted in this book, however, that is already changing and many new approaches for MFC design are yielding promising results. When a new technology is developed, the fastest way to bring it to the market is to apply it in an area most likely to yield the greatest profit. As the technology further develops, it can then reach new markets. Computer hard drives needed many years of development, for example, before they could be small enough to be portable as music players. Similarly, MFCs should be developed for application in the area that will likely produce the greatest profit. For many reasons described below, it appears that the first and most useful widespread application of MFCs will be as a method of energy recovery to make the water infrastructure sustainable.

1.4 MFCs and energy sustainability of the water infrastructure

Over two billion people on the planet lack adequate sanitation, and one billion do not have sufficient access to potable water. Energy demands for conventional water and wastewater processes are a large part of the problem. In the US, we use approximately 4–5% of our electricity production for the water infrastructure, which includes water treatment and distribution, and wastewater collection and treatment. Approximately 1.5% of our electricity goes to wastewater treatment alone. The costs for maintaining the infrastructure are significant, with an annual cost for wastewater treatment of \$25 billion. It is expected that over the next twenty years an additional \$45 billion will need to be expended to maintain and improve this infrastructure (*WIN* 2001).

Wastewaters contain energy, in the form of biodegradable organic matter, that we expend energy to remove rather than trying to recover it. At a conventional wastewater

treatment plant in Toronto, Canada, it was estimated that there was 9.3 times as much energy in the wastewater than was used to treat the wastewater (*Shizas and Bagley 2004*). Domestic, animal and food processing wastewaters are estimated to contain a total of 17 GW. This is about the same amount of energy that is currently used for the whole water infrastructure in the US (*Logan 2004*). Thus, if we could recover this energy we could make the water infrastructure self sufficient. Such an achievement would be a huge benefit to the health and well being of the US in the coming years of energy uncertainty. More importantly, such treatment processes could improve the quality of human life globally, as well as contribute to the reduction of the spread of waterborne disease through untreated sewage. Anaerobic digestion processes, based on methane generation can be an important part of energy generation from waste materials. However, they require relatively elevated temperatures (36°C) and long detention times, making them suitable only for high-strength wastewaters.

1.5 MFC technologies for wastewater treatment

Microbial fuel cell (MFC) technologies are a promising and yet completely different approach to wastewater treatment as the treatment process can become a method of capturing energy in the form of electricity or hydrogen gas, rather than a drain on electrical energy. In the late 1990s, Kim and coworkers demonstrated that bacteria could be used in a biofuel cell as a method of determining the concentration of lactate in water (*Kim et al. 1999d*), and then that electricity generation in an MFC could be sustained by starch using an industrial wastewater (*Kim et al. 1999c*). However, the power production was low and it was not clear whether the technology would have much impact on reducing wastewater strength. In 2004, this changed and the link between electricity using MFCs and wastewater treatment was clearly forged when it was demonstrated that domestic wastewater could be treated to practical levels while simultaneously generating electricity (*Liu et al. 2004*). The amount of electricity generated in this study, while low (26 mW/m²), was considerably higher (several orders of magnitude) than had previously been obtained using wastewater. Research led by Reimers (2001) a few years earlier had demonstrated that organic and inorganic matter in marine sediments could be used in a novel type of MFC, making it apparent that a wide variety of substrates, materials, and system architectures could be used to capture electricity from organic matter with bacteria. Still, power levels in all these systems were relatively low. The final development that sparked the current interest in MFCs was provided by Rabaey *et al.* (2003) when they demonstrated power densities two orders of magnitude greater was possible in an MFC using glucose, again without the need for exogenous chemical mediators.

Following these demonstrations, the race was on to develop practical applications of MFCs, with the first goal being development of a scaleable technology for the treatment of domestic, industrial, and other types of wastewaters (*Logan et al. 2006*). While the energy that could be captured from wastewater is not enough to power a city, it is large enough to run a treatment plant. With advances, capturing this power could achieve energy sustainability of the water infrastructure. As an example of the power that can be derived from wastewater, consider the example that follows for energy recovery for a modest-sized town.

Example 1.1

What is potential energy benefit of maximum energy recovery using domestic wastewater to a town of 100,000 people? (a) Calculate the maximum energy production for assuming 500 L/d per capita, 300 mg/L of COD, and 14.7 kJ/g-COD (based on wastewater solids (*Shizas and Bagley 2004*)). (b) How much is this electricity worth at \$0.44/kW-h? (c) How many homes would this power, assuming 1.5 kW/home.

(a) We can calculate power in megawatts (MW) from a simple unit conversion calculation with the given assumptions as:

$$P = \left(300 \frac{\text{mg COD}}{\text{L}} \right) \left(\frac{500 \text{ L}}{\text{d-cap}} \right) (10^5 \text{ cap}) \frac{\text{g}}{10^3 \text{ mg}} \frac{14.7 \text{ kJ}}{\text{g-COD}} \frac{1 \text{ kWh}}{3600 \text{ kJ}} \frac{1 \text{ d}}{24 \text{ h}} \frac{\text{MW}}{10^3 \text{ kW}}$$

$$P = 2.6 \text{ MW}$$

(b) The result above is for continuous power generation, so converting it to kWh and using the given electricity cost, we calculate the value of this power as

$$\text{Value} = (2.6 \text{ MW}) \left(\frac{\$0.44}{\text{kWh}} \right) \frac{10^3 \text{ kW}}{\text{MW}} \frac{24 \times 365 \text{ h}}{\text{yr}} = \$10 \times 10^6 \text{ yr}^{-1}$$

Thus, we see that the power could be worth as much as \$10 million per year, although the value of electricity varies widely across the US.

(c) The number of homes (h) served with this power is just the ratio of the power generated to electricity needed per home, or

$$h = (2.6 \text{ MW}) \left(\frac{\text{homes}}{1.5 \text{ kW}} \right) \frac{10^3 \text{ kW}}{\text{MW}} = 1700 \text{ homes}$$

These calculations all assume 100% energy recovery, which as we will see later is not reasonable. As a goal, it is hoped to recover 25–50% of the energy and thus the above numbers should be reduced by one half or more to obtain more practical results.

As we can see from the above example, the amount of power that can be generated from wastewater treatment for a large number of people is substantial, although on a per-person basis the energy is not particularly impressive. For the above case, the wastes from one person could generate a maximum of only 25 W, which is the power needed for a small light bulb. For a family of four, this is 100 W or that of a large incandescent light bulb. Thus, the value of the energy that can be captured from domestic wastewater is not substantial on a single home basis, but for a large plant the energy can become significant even for relatively dilute domestic wastewater.

The most significant energy savings associated with the use of MFCs for wastewater treatment, besides electricity generation, result from savings in expenses for aeration and solids handling (see [Chapter 9](#)). The major operating costs for wastewater treatment are wastewater aeration, sludge treatment, and wastewater pumping. Aeration alone can account for half of the operation costs at a typical treatment plant. Eliminating these costs can save an appreciable amount of energy. The MFC process is inherently an anaerobic process, although, as we shall see, oxygen can diffusive into the system resulting in some aerobic organic matter removal. The sludge yields for an anaerobic process are approximately one-fifth of that for an aerobic process. Thus, using MFCs could

drastically reduce solids production at a wastewater treatment plant, substantially reducing operating costs for solids handling.

The MEC process for hydrogen production. An MFC is designed to generate electricity based on electrons generated by bacteria from the oxidation of organic matter. However, instead of producing electricity, the potential generated from the electrolysis of the organic matter by the bacteria can be used to produce hydrogen. The details on how this is accomplished using a microbial electrolysis cell (MEC), also known as a bioelectrochemically assisted microbial reactor (BEAMR), are described in [Chapter 8](#). The basic idea is that the potential generated at the anode in a typical MFC can be augmented with an additional voltage to generate hydrogen gas at the cathode. Thus, if we omit oxygen at the cathode, and add in about 0.23 V or more in practice (0.11 V in theory), we can form H₂ gas at the cathode.

The concentration of organic matter in wastewater is usually evaluated on the basis of the amount of oxygen used to oxidize organic matter, in terms of biochemical oxygen demand (BOD) in a five-day biodegradation test, or via chemical oxygen demand (COD) in a chemical test that fully oxidizes all organic matter whether it is biodegradable or not. On the basis of COD, it is easy to determine the potential for hydrogen production as one mole of COD indicates that one mole of O₂ is needed for the reaction. Thus, each mole of COD (or O₂) oxidized produces 4 electrons, or the potential for 2 moles of H₂ (1 mol-COD = 2 mol-H₂). As oxygen has a molecular weight of 32 g/mol and H₂ has a molecular weight of 2 g/mol, this means that one gram of COD produces 0.125 g-H₂.

Example 1.2

How much hydrogen could potentially be generated from the domestic wastewater for a town of 100,000 people? (a) Calculate the hydrogen in kg for one year using information in the above example. (b) What would be the worth of the hydrogen assuming \$6/kg-H₂?

(a) We can calculate mass using with the above results for one year as

$$m_{\text{H}_2} = \left(300 \frac{\text{mg COD}}{\text{L}} \right) \left(\frac{500 \text{ L}}{\text{d-cap}} \right) (10^5 \text{ cap}) \left(\frac{0.125 \text{ g-H}_2}{\text{g-COD}} \right) \frac{\text{kg}}{10^6 \text{ mg}} 365 \text{ d}$$

$$m_{\text{H}_2} = 6.84 \times 10^5 \text{ kg}$$

(b) The value of this hydrogen, based on the given information, is:

$$\text{Value} = (6.84 \times 10^5 \frac{\text{kg}}{\text{yr}}) \left(\frac{\$6}{\text{kg}} \right) = \$4.10 \times 10^6 \text{ yr}^{-1}$$

Thus, we see that the hydrogen could be worth \$4.10 million per year. This calculation, however, does not include the energy needed to be put into the process or costs for gas purification and compression, and it is a maximum assuming no loss of substrate to cell mass or other processes and complete recovery of the hydrogen produced.

1.6 Renewable energy generation using MFCs

In order for MFCs to compete with other technologies in renewable energy generation, the costs of making the reactors and the source of the material must in the near term be competitive with fossil fuels. If carbon taxes are included in the costs of making energy

using fossil fuels, then MFCs and other renewable energy methods will become competitive. The cost to build an electric power plant is \$1,000 per kW (*Grant 2003*). The costs for making an MFC reactor are unknown, as a commercial system has yet to be built. We can look to comparisons to trickling filter media, which costs ~\$530 per m³, with a total surface area of 100 m². Assuming we achieve 1 W/m², this would translate to cost for the media of \$530/0.1 kW or \$5300 per kW. Electrically conductive media could cost more than trickling filter media, but it may be possible to achieve much higher surface areas than with traditional TF media (see [Chapter 9](#) on wastewater applications). This estimate also does not consider the cost of the cathode, electrical systems for DC-DC or DC-AC conversions, and other factors.

Assuming costs can be reduced for building MFCs, what are the potential applications for using biomass for energy recovery? Biomass has already surpassed hydropower as the leading source of renewable energy in the US, providing 3% (2.9 Quads per year, or 97 GW) of the energy in the US equal to 47% of the renewable energy (*Perlack et al. 2005*). Hydroelectric (45%), geothermal (5%), wind (2%), and solar (1%) form the remainder. A recent study for the US Department of Energy concluded that it is possible to obtain 1.3 billion dry tons of biomass per year, more than sufficient to replace over 30% the present petroleum consumption in the US which was estimated to require 1 billion dry tons (*Perlack et al. 2005*). The goal is to provide 5% of the nation's power, 20% of transportation fuels, and 25% of chemicals by 2030.

Example 1.3

How much energy is in the food that you eat? Determine the power generation in watts possible from a 2000-Calorie per day diet.

To answer this question, we must first realize that a “Calorie” used by nutritionists is not the same as “calorie” used for engineering calculations. One Calorie is equal to 1000 cal, or 1 kcal. Thus, a daily diet of 2000 Calories is equal to 2000 kcal. Thus, the power is

$$P = \left(\frac{2000 \text{ Cal}}{\text{d}} \right) \frac{1 \text{ kcal}}{\text{kcal}} \frac{10^3 \text{ Wh}}{860 \text{ kcal}} \frac{\text{d}}{24 \text{ h}} = 97 \text{ W}$$

Thus we see that the food you eat, if converted with 100% efficiency to electricity, would only provide about ~100 W per day, or the amount of power in a large light bulb. Considering that each person uses 11.1 kW of energy as a part of their daily lifestyle, we can see that food as fuel has large challenges to sustain our society. Thus, we need to look to biomass, not just food, as energy sources.

One promising method of energy recovery from biomass is to use corn stover biomass, or the stalk, husk, and leaves remaining after the harvesting of corn. There are 250 million dry tons of corn stover produced annually (*Atchison and Hettenhaus 2004*), with 90% left unused in the fields and 150 million tons that could easily be recovered for reuse (*Glassner et al. 1999*). Energy can be biologically derived from the cellulose and hemicellulose portion (70%), although the lignin (15–20%) is thought only to be useful as energy based on chemical combustion processes. A steam explosion process can convert particulate corn stover into a liquid (hydrolysate) (*Datar et al. 2006*). Hydrogen can be generated by fermentation of the hydrolysate from the sugars, but fermentation yields can

never exceed 4 mol-H₂/mol-glucose, and typically it is 2 mol/mol or lower (*Logan and Regan 2006b*). Electricity can be generated in a type of MFC based on fermentation of cellulose to produce hydrogen, with the hydrogen reacting on a Pt catalyst (*Niessen et al. 2005*). However, electricity can be directly generated in an MFC using corn stover hydrolysates (*Zuo et al. 2005*). Ongoing work at Penn State has further demonstrated direct electricity generation from cellulose in an MFC. By analogy, any process that produces electricity in an MFC should work for hydrogen production in a BEAMR process. Assuming 70% of the corn stover is recovered as sugar, this represents a potential energy source of 52 GW, although current energy recovery is only 10% to date (*Zuo et al. 2005*).

1.7 Other applications of MFC technologies

MFCs may have other applications in the future besides wastewater treatment and renewable energy. By emplacing the anode electrode in marine sediments and emplacing the cathode in the overlying water, it is possible to generate electricity from the bacterial decomposition of the organic matter in the sediment. There is not sufficient electricity generated to make it economically feasible as a source of renewable energy, but it could be sufficient for powering devices in remote marine and estuarine locations. These devices, known as sediment fuel cells, are discussed in greater detail in [Chapter 10](#). It is also possible that MFCs can be modified and used as a method of bioremediation. Although this application is far less developed than other applications, so far it has been shown that MFC-based technologies could be used to remove nitrate (conversion to nitrite) and U [conversion from soluble U(VI) to insoluble U(IV)] from water. This application is also further addressed in [Chapter 10](#).