20 Bioenergy Principles and Applications

Marina Islas-Espinoza
Mexico State University

Alejandro de las Heras
Independent Researcher

CONTENTS

20.1 FUNDAMENTALS

20.1.1 FREE ENERGY

The following can be credited to Gibbs and Helmholtz: the internal energy of a system is made up by reactants, where H is the energy contained by the number of chemical bonds in a given volume; G is the available energy to do work (movement, growth, maintenance, reproduction); S is entropy (energy loss); and T is temperature of a reaction (Gaudy and Gaudy, 1980). When a biochemical reaction takes place

$$\Delta H = \Delta G + T\Delta S \tag{20.1}$$

Where ΔG is the change in free energy, or useful energy, and T is proportional to the number of collisions between reactants.

20.1.2 Enzymes and Coenzymes

Consistent with Equation 20.1, biochemical reactions proceed from an initial energy level to a lower energy level, since entropy S augments any reaction. However, reactions are either exergonic (they release energy and proceed spontaneously) or endergonic (they require energy). The rate of reaction is the number of reacting molecules over time. In endergonic reactions, the number of reacting molecules is very low in any given time span, or it can take a very long time for the reaction to occur.

Enzymes are large biochemical compounds that accelerate the rate of reactions, by lowering the energy amount required by an endergonic reaction. Enzymes are energetically very efficient since few of them need to be synthesized, and they remain unmodified by the reaction (Cooper and Hausman, 2015).

Coenzymes are lighter molecules (often made up of vitamins) that also accelerate reaction rates. Again, they are unmodified by the reaction. Among coenzymes, adenosine triphosphate (ATP) stands out as being produced by all living beings.

20.1.3 Electron Carriers and ATP

Most biochemical reactions are redox reactions: electron exchanges between reactants or hydrogen removal by enzymes. Electron transfers between electron donors and acceptors, protons, and ATP are linked: ATP synthesis is driven by a proton electrochemical gradient (a difference of electric charge and chemical concentration) between two sides of a biomembrane. As shown by Mitchell in 1961, the “gradient is produced by the electron transfer and in opposite direction, the proton flow which frees energy to produce ATP” (Cooper and Hausman, 2015).

ATP is ubiquitous in biological energy reactions and diverse in the way different types of organisms obtain free energy: fermenters use organic compounds (nitrate and sulfate) as terminal electron acceptors, while organisms with respiratory metabolism (either aerobes or anaerobes) use oxygen.

In addition to electron donors and acceptors, there are coenzyme electron carriers and phosphate carriers (e.g., ATP). These coenzymes allow for coupled reactions (of the form $A \rightarrow B \rightarrow C \rightarrow D$). In diverse redox exergonic reactions, energy is used to form ATP (Gaudy and Gaudy, 1980).

Although it is true that most chemical bonds are shared electrons, it is not in bonds that the energy is found, and it is not in bond breaking that energy is released; rather, it is in the rearrangement of electrons during reactions. This is consistent with Equation 20.1: energy G is released and entropy S augments (Cooper and Hausman, 2015).

20.1.4 Ion Pumps and Electricity

All living cells have membranes. Ions cannot penetrate, except through open pores and ion channels. Ions penetrate the membrane mostly through ion channels. Their opening and closing drives the transmission of electric signals (Cooper and Hausman, 2015). Ion pumps are responsible for maintaining internal ion concentrations and introducing a substance inside a membrane against its concentration gradient. Sometimes this requires membrane transport proteins, which can follow the concentration gradient (facilitated diffusion) or go against this gradient (active transport carried out by proteins (metabolic pumps) that use an extra source of energy). Ion pumps in particular use ATP.

The transport of calcium across muscle cell membranes uses ATP and results in much lower intracellular calcium concentrations, making the cell very sensitive to small increments in said concentration. Thus calcium has a key role in cell signaling, in particular in muscle contraction (Cooper and Hausman, 2015).

Also, the electron transfer from donor to acceptor induces an electric current. In fact, electric and chemical energy are equivalent:

$$\Delta G = -nF\Delta E_0 \tag{20.2}$$

with n electrons in the reaction, F Faraday (96500 Coulomb required to reduce or oxidize one mol), ΔE_0 the difference in electron potential in volts between two reactants (Gaudy and Gaudy, 1980).

Electric resistance is low when ion channels allow the passage of ions and electric current. When ion channels are closed, resistance is much higher.

20.1.5 MUSCLE

All cells are capable of movement. However, skeletal muscle cells are specialized in allowing animal movement. Each muscle is made of many muscle fibers. Each fiber is a large multinuclear cell. Each of these cells has a larger number of small fibers (myofibrils). Each myofibril is made of many aligned units (sarcomeres), each of which contracts thereby shortening the muscle (Figure 20.1). Sarcomere contraction is a sliding movement of actin protein filaments sliding along myosin protein filaments, according to the 1954 Huxley–Niedergerke–Hanson model. During the shortening of the sarcomere, myosin hydrolyzes ATP (Cooper and Hausman, 2015).

The regulation of muscle contraction starts with a signal from a motor neuron. This stimulation depolarizes the muscle cell membrane, leading to a calcium concentration increment associated with the shortening of the sarcomere. The strength of each muscle cell's contraction is invariable; what varies in muscular workload is the number of cells recruited. In cardiac and smooth muscle cells (located in hollow organs and tubes), contraction strength is modulated by adrenaline (a hormone and neurotransmitter). Adrenaline speeds up and strengthens cardiac contraction; it also relaxes vascular muscle cells. This increases cardiac flow and diminishes resistance in smooth vascular muscles.

The energy for contraction depends on the workload. With moderate ATP demand, supply is handled through oxidative metabolism. When contraction is exhausting, ATP is depleted in about one second, and creatine phosphate stored in muscle cells is used. Skeletal and cardiac muscle cells would also resort to anaerobic ATP generation with blood glucose as feed or feed provided by glycogen degradation (Colby, 1987).

Muscle contractions occur continually to maintain a body's posture; these tonic contractions do not exhaust muscle energy. Contrarily, muscle soreness takes place 24 h after exhausting exercise, because of diminutive tearing or swelling in the muscle. It was formerly believed that this delayed-onset muscle soreness was due to accumulated lactic acid released by anaerobic metabolism during strenuous effort (Hitchcock, 2007).

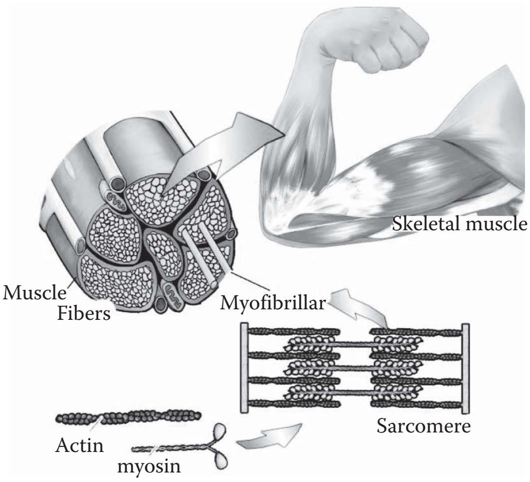

FIGURE 20.1 Human muscle anatomy. (From Tomoki Fukushima, Creative Commons 4.0. https://commons.wikimedia.org/wiki/File:筋肉英語版.png.)

20.1.6 WHAT DISTINGUISHES ORGANISMS

Organisms self-organize at the molecular level (including the genetic level), as well as at the ecological (or trophic) level. At the ecological level, organisms transform their habitat to reach equilibria with their physicochemical environment. They self-regulate, self-repair, self-detoxify (homeostasis), and establish feedback loops with the environment (one example being Table 20.1). Adaptation is transient (through learning) but also evolves irreversibly (through genetic information exchanges). Fitness (rather than efficiency) measures organismal or genetic success. Nondeleterious mutations also may enhance fitness. Enzymes allow work at lower temperatures than artificial chemical processes. Organisms, unlike machines, can work against thermodynamic gradients. Waste is unavoidable, but it is turned into a resource to feed on or mineralized and returned to biogeochemical cycles.

20.1.7 HYBRIDS, INCLUDING HUMANS

High levels of coupling, hybridization, and regulation prevail in organisms to maintain a continuous flow of energy through equilibria in ions, acidity, alkalinity, and redox potentials (Ponizovskiy, 2013).

Striking examples of hybridization are given by chloroplasts, mitochondria, and peroxisomes, reckoned to have a bacterial origin. Chloroplasts are responsible for photosynthesis. The transformation of solar to chemical energy occurs in the reaction center, where the absorbed excitation

TABLE 20.1
hiG Interactions with Geosphere, Biosphere, and DNA

Radiation Type (Energy)	Geosphere-Biosphere Interactions	Human Damages
Alpha (He nuclei, 4–9 MeV)	Keep Earth's iron core molten: vital for magnetosphere and avoid Earth's temperature cooling down. Natural greenhouse gases and solar radiation then bring temperature to an average 18°C, midway through the 5°C–40°C range of optimal enzymatic activity	Hazardous if inhaled/ingested. Large exposures lead to cancer in lining of lung/stomach (IAEA, 2004)
Beta (electron or positron, 0.511 to 938.3 MeV)		Hazardous if inhaled or ingested. Large high-energy beta exposure can cause skin burns/cancer (IAEA, 2004)
Gamma (photon, 0.1–3 MeV)	Filtered by magnetosphere. Magnetosphere deflects solar wind which would erase the O_3 layer	Penetrate the body producing single or double strand break, or base damage (Faraj et al., 2016)
X rays (photons < 25 MeV)	Filtered by ionosphere	
UV (< 24.8 eV)	UVC filtered by the O_3 and by atmospheric O_2 produced by photoautotrophs. O_2 was essential in emergence of O_3 layer. UV ionize the ionosphere, which absorbs extreme UV	UVA and UVB: distortion of the DNA structure avoiding replication. Linked to cancer mainly in skin and eyes, immune system problems (Kim et al., 2014)
Cosmic rays (9/10 H nuclei, 1/10 α particles, highly energetic charged heavy ions like iron nuclei, and β particles, > 100 MeV)	Deflected by the magnetic field. Cosmic rays ionize atmospheric N_2 and O_2 leading to O_3 layer depletion	Penetrate living tissue and are carcinogenic (Ghissassi et al., 2009)

Note: Energy = (1.24)103/λ. 1 eV = (1.602)10–19 J is the energy of a photon in the range visible to humans.

energy is converted into a stable charge-separated state by ultrafast electron transfer events (Romero et al., 2014). Mitochondrial oxidation is associated with the respiratory chain and the tricarboxylic cycle that leads to the production of ATP, while peroxisomal metabolism is associated with mechanisms of detoxification and the biosynthesis of specific fatty acids. Peroxisomes cooperate with mitochondria in lipid metabolism, oxidizing fatty acids, and in reactive oxygen species production (Demarquoy and Le Borgne, 2015).

In a human, around 10 billion mitochondria comprise 10% of the person's body weight (Perlmutter and Loberg, 2015). Human bodies are actually ecosystems whose cells contain symbiotic bacteria, collectively called the microbiome. The microbiome weighs around 2 kg and includes more genes than the whole human genome. Without the microbiome, mostly hosted in human intestines, many vital (immunity, digestion, physical, and microbiological barriers against pathogens, detoxification, enzyme, neurotransmission) functions would not be carried out in the human body. Mitochondria contain 5–10 copies of their own DNA (mitochondrial DNA transmitted in humans by the mother) and exert control over the nuclear DNA of the human cells (Perlmutter and Loberg, 2015).

20.1.8 Nonequilibrium Thermodynamics

An organism keeps away from maximum entropy by continuously extracting energy and matter from its surrounding environment. Metabolism is what allows an organism to get rid of all the entropy it cannot help but produce while being alive (Schrödinger, 1944).

A metastable dissipative process is invariable not in the sense of maximum entropy but because new particles are constantly recycled in situ. A metastable process will settle in a stationary state of minimal entropy production, as close to equilibrium as possible (Prigogine, 1991). In particular, a metastable dissipative process is a system open to solar energy subsidies to keep life away from maximum entropy.

Organisms also circumvent entropic degradation through reproduction: the system replicates beyond individual death. Self-perpetuation takes place at the species, genetic, and molecular levels (in an autocatalytic cycle of chemical reactions $A \rightarrow B \rightarrow C \rightarrow D$).

20.1.9 Excess Energy in the Anthropocene

Humans and domesticated animals consume increasing amounts of bioavailable energy in the geosphere (BEG):

$$\mathrm{BEG} = \mathrm{hiG} + \mathrm{loI} + \mathrm{hiC} \tag{20.3}$$

where hiG is the sum of the natural background radiation (Table 20.1; Figure 20.3) and anthropogenic high energy radiation emissions. 1oI are low intensity radiations (noise and vibrations as produced by machines), and infrared. hiC is a carbon compound. hiC is an essential component through which humans consume energy. Although it includes hydrocarbons, carbohydrates and fat are vital. Humans, like any other organism, are endowed with bodily mechanisms to dissipate excess energy. Now however, storage exceeds biological requirements, a process called the global nutrition transition (Popkin et al., 2013) of pandemic proportions due to the lack of physical activity and access to cheap dietary fat and sugar. Excess sugar is converted to fat, which is stored in adipose tissue, inflammatory and hormonally active (Frayn, 2010). Other changes occur in the microbiome, such as dominance of *Clostridium* bacteria in children addicted to sugar and fat, which induces craving for these compounds (Perlmutter and Loberg, 2015). Past a certain body mass index threshold, fat mass exceeds the cardiovascular and musculoskeletal capacity to sustain enough aerobic expenditure to process fat stores. All excess food energy intake further accumulates and at the same time requires energy to be maintained or metabolized. Dietary energy intakes must be based on energy expended, not on nutrient availability (see Chapter 22).

Insulation from loI noise and vibration has to an extent prevented deleterious effects. This has not been so for urban heat waves, which killed thousands of people in the U.S. and Europe in 1995 and 2002.

Of particular biological concern, in the discussion of sustainable energy technologies are the limits to hiG:

$$\lim \text{hiG} = \text{geofilters} + \text{DNA protection} + \text{DNA repair} \tag{20.4}$$

The geofilters are Earth's magnetic field, ionosphere, and atmosphere (Table 20.1; Figure 20.2).

An important component of hiG is the changes in Earth's balance of natural radiation (BNR) where

$$\begin{aligned} \text{BNR} &= \text{Earthbound extra-terrestrial radiation at the top of the magnetosphere} \\ &\quad - \text{absorption by geofilters} + \text{changes in biofilters} + \text{bodily } ^{40}\text{K and } ^{14}\text{C} + \text{lithospheric radiation} \end{aligned} \tag{20.5}$$

In the Anthropocene, three complicating sources of mutagenicity, genotoxicity, and cytotoxicity occur, explaining the difference between the total DNA-altering exposure (TDA) and BNR:

$$\text{TDA} = \text{BNR} + \text{xenobiotics} + \text{pathogens} + \text{artificial radiation} \tag{20.6}$$

so that

$$\text{TDA} > \lim \text{hiG} \tag{20.7}$$

which is possibly the tipping point at which human bodies find themselves in the Anthropocene. Xenobiotics are artificial chemical compounds. Pathogens here refer to those organisms that are linked to carcinogenesis in humans; in the Anthropocene, climate and land changes have modified the exposure of humans to pathogens (de las Heras et al., 2016). As to artificial radiation, it encompasses emissions from coal mining and burning, phosphate fertilizers, nuclear weapons, nuclear power plants and their waste, medical use of radioisotopes and X rays, airplane trips, and tanning devices.

Natural and anthropogenic exposure to radiation is a common cause of damage to the DNA. The double-strand helix of DNA has phosphorylated sugars in the exterior and four nucleotides or bases in the interior united by hydrogen bonds (two purines: A-adenine and G-guanine; and two pyrimidines: C-cytosine and T-thymine). When humans are exposed to radiation, the DNA structure is often broken or altered. Sometimes the DNA is repaired, but if the dose frequency or intensity exceeds the limits of the organism, the endpoints of damage are cancer, inheritable errors, or death. DNA repairs through (a) reversing the chemical reaction responsible for the damage or (b) eliminating damaged bases and restoring them with new synthesized DNA. Excision, recombination, and translesion synthesis are the main repair mechanism in humans. During excision, damaged bases are recognized and eliminated; the empty space is filled with new synthesized DNA

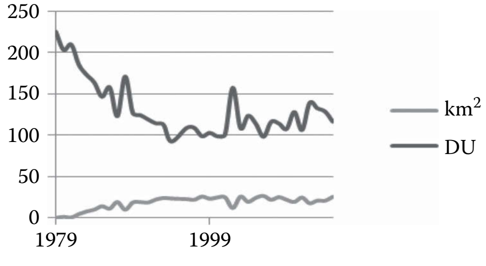

FIGURE 20.2 Extent and density of the Southern Hemisphere ozone layer. Ozone hole mean 7 September-13 October area (million km^2). Minimum 21 September-16 October ozone density (Dobson Units, DU). By definition, DU<220 in the hole; such values did not exist in the historical record. (From http://ozonewatch.gsfc.nasa.gov/meteorology/annual_data.txt.)

using the nondamaged complement strand as a template. Recombination reestablishes the sequence of the broken double strands with homologue sequences of an intact chromosome after replication, while the new synthesized chromatids remain united or reattaches the two broken extremes of each strand, but the latter mechanism is associated with mismatches through deletion of bases in the damaged point. Without a template, cells use the error-prone recovery mechanism known as translesion (Cooper and Hausman, 2015). Also, a cell cycle may stop progress from one phase of the cycle to the next (cell-cycle checkpoints) or go to apoptosis (programmed cell death), protecting the organism at the expense of the individual cell (Sinha and Häder, 2002).

Difficulties remain in compounding data on labor, domestic, and environmental exposures, and in relating exposure to damages. But there are at least two trends in damages to future generations of humans: first, lessened quality of human sperm has been documented in the last decades (Sharpe, 2012). Cellular phone radiation is among the factors implicated in this trend (Agarwal et al., 2009). Second, an increased trend in cancers has been observed, even as most of them are preventable (IARC, 2014).

20.1.10 NATURAL AND ANTHROPOGENIC ALTERATIONS TO GEOPHYSICAL SHIELDING AGAINST EXTRATERRESTRIAL RADIATIONS

The biogenically derived stratospheric ozone layer protects life on Earth from UV. Starting in 1979, however, anthropogenic chlorofluorocarbon (CFC) gases seasonally have depleted the ozone layer, mainly in a vast area around the South Pole. Although the depletion process seems to have stabilized, there are no clear signs of recovery (Figure 20.2); in 2014, a record ozone hole reached South America. Furthermore, dichloromethane, a very short-lived substance whose concentrations had diminished in the 1990s, is being used in industrial processes and increasing in abundance in the lower stratosphere. Ironically, it is used in the manufacture of "ozone-friendly" hydrofluorocarbons, which had replaced CFCs. Dichloromethane has more ozone depletion efficiency and a more powerful influence on climate than CFCs (Hossaini et al., 2015).

In addition, Earth's magnetic field has been weakening since at least 1840 (Zhong et al., 2014). Consequences are, first, a lessened filtration of alpha, beta, and gamma extraterrestrial radiation and cosmic rays (Table 20.1 and Figure 20.3). Second, this decaying magnetic dipole will let the solar wind buffet the ozone layer with an ensuing reduction of UV filtration. Third, oxygen will escape Earth with more ease (Wei et al., 2014) possibly leading to higher exposure to UV on Earth's surface.

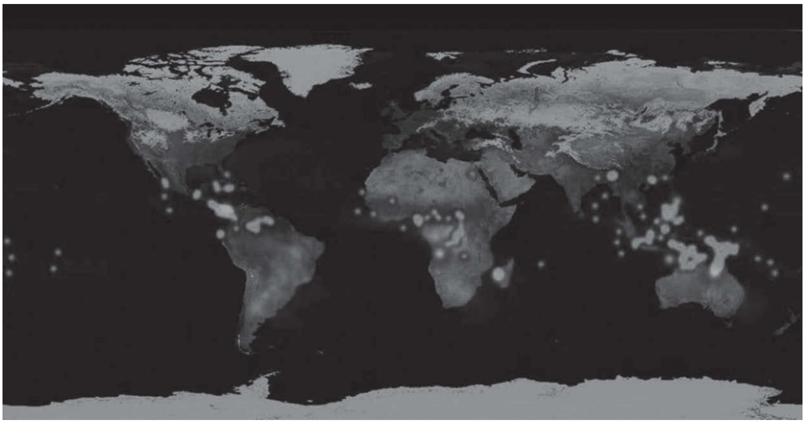

FIGURE 20.3 Distribution of gamma rays around Earth's equator. The red dots show the ~500 terrestrial gamma-ray flashes daily detected by the Fermi Gamma-ray Space Telescope through 2010. (From Goddard Multimedia, NASA/Goddard Space Flight Center. https://en.wikipedia.org/wiki/File:Antimatter_Explosions.ogv.)

20.2 APPLICATIONS

Living organisms can help generate energy sustainably based on their capabilities such as catalysis, energy capture and storage, and fuel synthesis. They can also help save energy in green chemistry via CO_2 fixation, chemosynthesis, and biorefining rare materials. They are also endowed with self-repair, self-replication capabilities, applicable to long-term bioremediation of waste and waste sites. These capacities afford technologies at lower economic and environmental impact costs (Adesina et al., 2017).

Applications with live organisms can further be hybridized with life-inspired (biomimetic) devices: when lighting devices track solar light actively—following the model of sunflower phototropism—collect outdoor light and transmit it inwards, improvement in performance can be 30%–36% over passive light collection technologies (Yuan et al., 2017).

Two sets of applications stand out in their ability to solve sustainability issues in all their conventional environmental/economic/social classes. These are biomechanical and biomass waste recovery applications. Their importance stems from their storability, portability, and dispatchability (ease of use on demand). These applications pertain to self-organizing systems, so rather than large investment and maintenance costs, they require hybridization to close an organic matter cycle. Such a system should aim for self-sustainability: maximal resort to natural processes and minimal or null artificial inputs. In particular, since biomass waste has recently captured atmospheric CO_2, the combustion of biomass-waste-based biomethane is carbon neutral (Chong, 2008). As to biomechanical applications using human power, they are needed to face today's excess energy intake by an increasing number of humans. Animal power should increase too, while meat consumption should decrease due to the large environmental hoofprint of animal husbandry.

20.2.1 Biomechanical Applications

These applications fulfill essential agricultural, medical, and transport goals. Horsepower is a shift to local flow-limited renewable sources, away from a technology supported by nonlocal processes, driven by nonrenewable sources, and beyond the control of the farmer. The horse generates traction and emotional comfort, but also meat, leather, horsehair, and manure (a soil amender after it has gone through biomethane production). Horse inputs are more renewable (60%) than tractor inputs (9%). The farmer is in control of the information needed to help the horse manage its own life (Rydberg and Jansén, 2002).

Most devices implanted in human bodies to correct physiological performance are powered by batteries. But conversion of glucose into electrical energy using implantable glucose fuel cells in the blood vessels could supply energy to small electronic devices such as cardiac pacemakers, implanted biosensors, or artificial urinary sphincters. For this, glucose biofuel cells need improved power and lifetime (Cosnier et al., 2014).

Human-powered nebulizers to treat respiratory diseases (Hallberg et al., 2014) require only the manual energy of a health worker or caregiver to generate an airflow while the patient is being treated; they are virtually fail proof. A biomechanical energy harvester allows a recharge of prosthetics or medical devices, with a little extra effort (5W) when walking. The use of negative muscle work resembles the use of hybrid car brakes that recharge a battery. The electricity generated is 10 times that of devices installed in shoes. The additional metabolic cost is 1 W (1/8 of conventional human energy generation) (Donelan et al., 2008).

Even tiny, continued efforts can recharge portable electronic devices with the energy, otherwise dissipated, of another energy harvester using a computer keyboard and typing > 100 characters/min. This scheme uses triboelectricity: when a positively charged human finger approaches a key, free electrons flow toward the upper electrode. Then, as the finger lifts, it produces another current, from the lower to the upper electrode (Chen et al., 2015). Other technologies to harvest energy from human motion include, but are not limited to, piezoelectric materials, electromagnetic generators, and dielectric elastomers (Partridge, 2014).

In human-powered vehicles, improved aerodynamics and reduced friction are paramount. The effective frontal area is the coefficient of drag times the frontal surface. Effort efficiency depends on the vehicle (i) holding the body by the saddle, preventing the muscles from making an effort to maintain posture and balance, (ii) allowing the muscles to always operate in the optimal direction (iii). Cycling is particularly efficient in generating energy, since it draws on the most powerful muscles of the body. Rowing in turn uses a kinematic chain that involves the whole body, and not just the legs. It is therefore not surprising that cycling and rowing have allowed flight across the British Channel or ocean circumnavigating (Figures 20.4 and 20.5) using only human energy: the Moksha boat crossed several oceans in 1998–2007.

20.2.2 Waste Recovery Applications

20.2.2.1 Biorefineries

Biorefineries are facilities for fractioning and refining biomass to increase its value through conversion from several substrates to several products, preferably using all resource components. The most common substrates are still sugar, straw, wood, and starch for ethanol, lignin, and organic acids; plant and algae oil; cellulose and lignocellulose (Al-Kaidy et al., 2015). This concept goes beyond the exhaustion of biomass into a range of products based on four principles: sustainability, cascading, nonconflict with food, and neutral carbon footprint (Escamilla-Alvarado, 2017).

Living systems manage their chemistry more efficiently than manmade chemical refineries, and most of the wastes they generate are recyclable or biodegradable, operate at lower temperatures, and produce less toxic waste and fewer emissions than conventional chemical processes to produce energy (Erickson et al., 2012).

Biorefinery might develop the use of lignin, celluloses, and hemicelluloses that do not compete with food or land and are massive agricultural, forestry, and municipal residues, as substrates for the synthesis of biofuels with the help of novel enzymes improved by metabolic engineering, the implementation of pretreatments, recombinant technology, biocatalyst design, and reaction engineering and chemicals (Seibel et al., 2014).

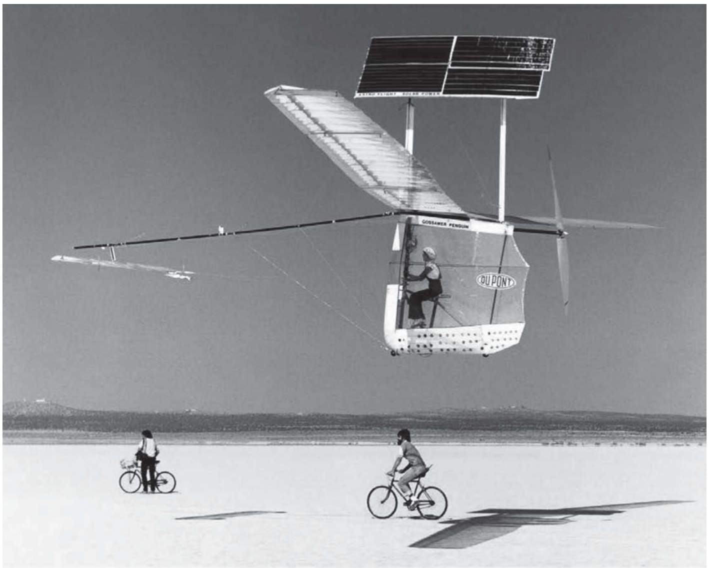

FIGURE 20.4 The Gossamer Albatros crossed the Channel in April 1979. (From NASA on The Commons. From https://commons.wikimedia.org/wiki/File:Solar-powered_Gossamer_Penguin_in_flight.jpg.)

FIGURE 20.5 Hybrid pedal/row kayak/sail/boat. (From "Mike" Michael L. Baird. Creative Commons Attribution 2.0 Generic license. https://commons.wikimedia.org/wiki/File:Hobie_Mirage_Adventure_Island_Trimaran_sail_yak.jpg.)

Engineered metabolic pathways have been developed to produce butanol, oleaginous fuels, branched-chain alcohols, medium-chain fatty acids, alkanes, gasoline-like molecules, biodiesels, and aviation fuels (Adesina et al., 2017). The use of algae, microalgae, and aquatic biomass as feedstock for biofuel production is an interesting option due to fast-growth rates, efficient CO_2 capture, a short harvesting cycle, absence of lignin, low hemicellulose content, and growth in areas unsuitable for agricultural purposes, which may be cultured with nutrients emitted from marine animal aquaculture in manmade open ponds and closed systems to exclude the heterotrophs that graze on the algae (Harish et al., 2015).

Mineralization of substrates by microorganisms can construct nanostructured porous materials for electrodes of batteries. Electroactive microbes can transfer electrons over long distances between the cell surface and external substrates by using conductive pili (bacterial nanowires). The use of nanostructured electrode materials is also attractive to improve the capacity, cycling life, and safety of batteries. Viruses have the potential for templating carbon nanotube electrodes at ambient temperatures, and bacterial biofilms can be used for the design of nanofibers (Adesina et al., 2017).

New applications with networks made of nucleic acids have been used to program, calculate, and store events such as molecular interactions and facilitate regulatory circuits; these have been combined with logic-gated nanorobots, solid-state nanochannels, or switchable nanovalves and artificial aptamer-lipid-receptors (Al-Kaidy et al., 2015). In situ use of nanomaterials seems to be a must, lest nanoparticles in the environment continue to accumulate.

20.2.2.2 Biomethane

Organic residues and nonfood agricultural and forestry residues are recommended when converting biomass to energy. Certain microalgal species seem to be good substrates for anaerobic fermentation, resulting in the production of biogas with relatively high methane content (Mussgnug et al., 2010).

Biomethane seems to be cost-effective, less toxic, and more efficient than other biofuels in life cycle assessment studies (Islas-Espinoza and Weber, 2014). Methane combustion is carbon neutral since it emits only one molecule of CO_2 per molecule of CH_4, compared to other fossil fuels. Details about methane generation and purification are explained in Chapter 21.

20.2.2.3 Biohydrogen

Fuel combustion for water electrolysis aiming at hydrogen production contaminates the air, is toxic, and is difficult to store. Hydrogen as a fuel does not seem to have significant impacts on climate at this time, but its large-scale use is suggested to lead to increased leakage of hydrogen into the atmosphere. Currently, the atmospheric lifetime of hydrogen appears to be controlled by soils. Hydrogen is an indirect greenhouse gas that would affect the lifetime of methane in the atmosphere, and if concentrations in the atmosphere increase, then migration to the stratosphere could enhance ozone depletion (Schauer, 2015).

Recent research has been carried out to imitate nature: the chlorophyll of plants absorbs solar light to produce H_2O and O_2, but instead of chlorophyll, nanoparticles of rhodium and ruthenium are being evaluated to produce hydrogen from water (Takeuchi, 2011). There are three methods of biohydrogen production: splitting water to hydrogen and oxygen by green algae and cyanobacteria (direct biophotolysis); photodecomposition of the accumulated biomass enriched by carbohydrates during the process of photofermentation by photosynthetic bacteria (indirect biophotolysis); and dark fermentation of organic compounds (Voloshin et al., 2016).

In dark fermentation, hydrogen is produced by anaerobic bacteria on carbohydrate-rich substrates. The effluent from the dark fermentation is usually rich in organic acids and can be used for photofermentative biohydrogen production using photosynthetic bacteria (Harish et al., 2015).

20.2.2.4 Beyond Hybridizing: Designing Human-Natural Cycles

Considerable heat is dissipated by transport (see Figure 1.2, p. 4), and transportation of food from rural breadbaskets to urban markets is a major component of this issue. This has inspired the local food movement and more recently sparked interest in urban food production in green roofs and reclaimed empty lots. The city of Detroit after the demise of the car manufacturing industry is exemplary in this respect.

Those innovations leave plenty of room for improvement, along two converging hybridization lines: on the one hand, the microbiological and molecular level represented by biorefineries and biomethane production. On the other hand, the ecosystem-level transition where isolated water bodies and islands of greenery in a sea of asphalt give way to green-and-blue corridors and then to mixed rural and urban spaces with maximal solar gain by natural and human communities.

Hybridization starts with standalone devices, in particular devices using the sun and waste to produce energy and recycling heat (Figure 20.6); at this early stage of hybridization, the goal is to recycle all waste, which then becomes a valuable resource, following the principles of biorefinery. Wastewater for instance becomes—through (an)aerobic bioremediation—biomethane, soil amender, while water is reclaimed via hybrid solar-biomethane disinfection (Figure 20.6). Urban environments where this started taking place included Hammarby in the vicinity of Stockholm; the idea then diffused to the Bo01 neighborhood of Malmö, also in Sweden.

The hybridization of devices then has to become part of a cycle where primary production by vegetables is promoted by the use of solar and waste-based energy (Figure 20.7). Solar energy, even at the latitude of the Netherlands is more than enough for greenhouse vegetable production, as shown more than a decade ago by Zonneterp, which recirculated excess greenhouse heat into a housing block. Zonneterp's idea can be expanded in many ways. For instance, two half-spheres (a triple-glazed greenhouse at the top and a parabolic solar concentrator at the bottom) make up the outer envelope of an anaerobic reactor. The apparatus is partially belowground to minimize advective wind cooling and radiation heat losses to the cooler atmosphere. The apparatus is further protected on the less sunny sides by a building or orchard trees. Below the solar concentrator, heat-trapping materials (like zeolites) slowly release heat at night. Hot (55°C) effluent from the reactor flows through a drained field that fertirrigates the orchard or the nursery trees in a minitunnel greenhouse. Dissolved methane in the effluent water is trapped by the soil and acts as greenhouse

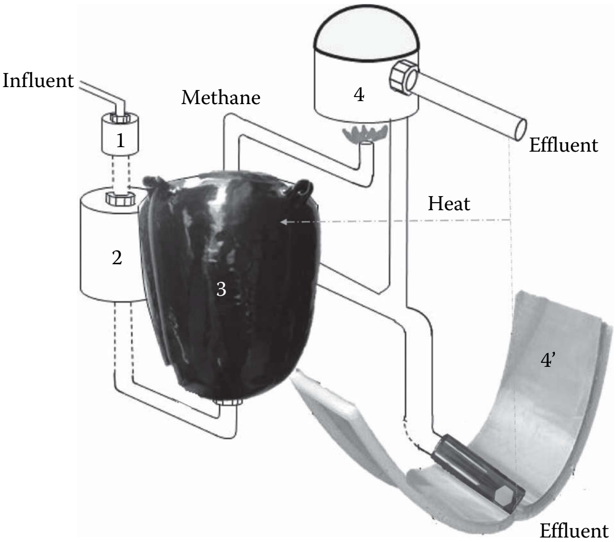

FIGURE 20.6 Hybrid system for biomethane production using food/animal wastes or wastewater. (1) Primary filtration (zeolite), (2) Secondary filtration (biofilm), (3) Anaerobic digestion, (4) Methane heat generation, (4′) Solar heat and waste disinfection.

gas, heating the soil of the orchard. Methane combustion is done belowground so that carbon dioxide emissions also act as greenhouse gases in the soil and promote microbial life. In this scheme, agro waste and wastewater are recirculated (Figure 20.7). Efficiency enhancements can proceed along several paths, such as the use of a dome-shaped Fresnel Köhler concentrator instead of a greenhouse, in colder climes.

The evolution of hybrids then takes over whole landscapes (Figure 20.8), so that human-dominated ecosystems transition toward nature-dominated cycles. Urban heat islands disappear as rooftop and balcony gardens dominate and CO_2 fertilizes plants. Entropy in these cycles is reduced as heat is absorbed by plants and soil and landscapes, and transportation of produce to urban markets is forgone. Energy gain is maximized via photosynthesis. An application of these ideas might follow the model of aquaponics in Inle Lake in Myanmar, where crops are grown on a floating vegetal mat, underneath which a subaquatic ecosystem feeds on detritus. This ecosystem can also harbor methane production in the sediment: rather than letting it diffuse to the atmosphere, the trophic chain started by methanotrophs is used in biorefinery to make fish feed and further increase the productivity of the ecosystem.

FIGURE 20.7 Waste-based energy for high-latitude permaculture.

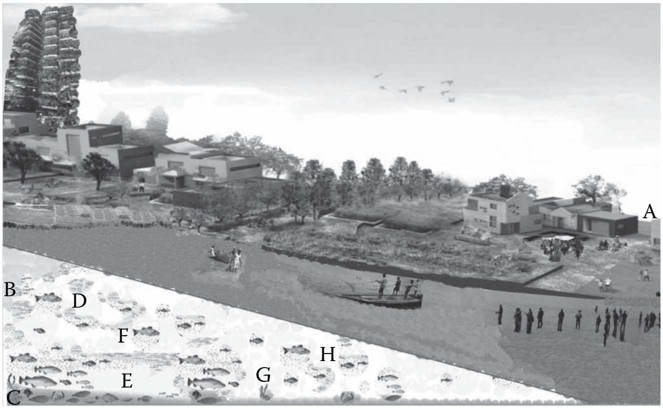

FIGURE 20.8 Urban-Rural hybridization. (A) Urban-Rural mixed uses: energy farm and agriculture close by (web-based) market or interchange, (B) Underwater aquaponics, (C) Sediment, (D) Fish, (E) Methanogenic activity, (F) Detritus, (G) Methanotrophs, (H) Fish feed. (Adapted from Hora dara. Creative Commons 3.0. https://commons.wikimedia.org/wiki/File:The_Social_Ecology.jpg.)

REFERENCES

Adesina, O, IA Anzai, JL Avalos, and B Barstow. 2017. Embracing biological solutions to the sustainable energy challenge. *Chem* 2: 20–51. doi:10.1016/j.chempr.2016.12.009.

Agarwal, A, NR Desai, K Makker, A Varghese, R Mouradi, E Sabanegh, and R Sharma. 2009. Effects of radiofrequency electromagnetic waves (RF-EMW) from cellular phones on human ejaculated semen: An in vitro pilot study. *Fertility and Sterility* 92: Elsevier Ltd: 1318–25. doi:10.1016/j.fertnstert.2008.08.022.

Al-kaidy, H, A Duwe, M Huster, K Muffler, C Schlegel, T Sieker, R Stadtmüller, N Tippkötter, and R Ulber. 2015. Biotechnology and bioprocess engineering – From the first Ullmann' S article to recent trends. *ChemBioEng Reviews* 2 (3): 175–84. doi:10.1002/cben.201500008.

Chen, J, G Zhu, J Yang, Q Jing, P Bai, W Yang, X Qi, Y Su, and ZLWang. 2015. Personalized keystroke dynamics for self-powered human-machine interfacing. *ACS Nano* 9: 105–16.

Chong, J. 2008. Methane: A natural gas. *Microbiology Today* 35 (3): 124–27.

Colby, DS. 1987. *Compendion de Bioquimica*. First. Mexico City: El manual moderno.

Cooper, GM, and RE Hausman. 2015. *The Cell: A Molecular Approach*. Seventh. Sunderland, MA: Sinauer.

Cosnier, S, AL Goff, and M Holzinger. 2014. Towards glucose biofuel cells implanted in human body for powering artificial organs : Review. *Electrochemistry Communications* 38. Elsevier B.V: 19–23. doi:10.1016/j.elecom.2013.09.021.

de las Heras, A, M Islas-Espinoza, and A Amaya-Chavez. 2016. Pollution: The pathogenic and xenobiotic exposome of humans and the need for technological change. *Encyclopedia of Environmental Management*, 1–10. doi:10.1081/E-EEM-120052926.

Demarquoy, J, and F Le Borgne. 2015. Crosstalk between mitochondria and peroxisomes. *World Journal of Biological Chemistry* 6 (4): 301–9. doi:10.4331/wjbc.v6.i4.301.

Donelan, JM, Q Li, V Naing, JA Hoffer, DJ Weber, and AD Kuo. 2008. Biomechanical energy harvesting. *Science* 319: 807–10. doi:10.1126/science.1149860.

Erickson, B, JE Nelson, and P Winters. 2012. Perspective on opportunities in industrial biotechnology in renewable chemicals. *Biotechnology Journal* 7: 176–85. doi:10.1002/biot.201100069.

Escamilla-Alvarado, C. 2017. An overview of the enzyme potential in bioenergy-producing biorefineries. *Journal of Chemical Technology and Biotechnology* 96 (5): 906–24. doi:10.1002/jctb.5088.

Faraj, KA, MM Elias, AH Al-Mashhadani, and S Baatout. 2016. Effect of x- and gamma rays on DNA in human cells effect of x- and gamma rays on DNA in human cells. *European Journal of Scientific Research* 53: 470–76.

Frayn, NK. 2010. *Metabolic Regulation: A Human Perspective*. Third. Oxford, UK: Wiley-Blackwell.

Gaudy, AF, and ET Gaudy. 1980. *Microbilogy for Environmental Scientists and Engineers*. First. New York: McGraw-Hill.

Ghissassi, FE, R Baan, K Straif, Y Grosse, B Secretan, V Bouvard, L Benbrahim-tallaa et al. 2009. Special report : Policy a review of human carcinogens—Part D : Radiation. *Lancet Oncology* 10 (8): 751–52. doi:10.1016/S1470-2045(09)70213-X.

Hallberg, CJ, MT Lysaught, CE Zmudka, WK Kopesky, and LE Olson. 2014. Characterization of a human powered nebulizer compressor for resource poor settings. *BioMedical Engineering OnLine* 13: 1–11.

Harish, BS, MJ Ramaiah, and KB Uppuluri. 2015. Bioengineering strategies on catalysis for the effective production of renewable and sustainable energy. *Renewable and Sustainable Energy Reviews* 51. Elsevier: 533–47. doi:10.1016/j.rser.2015.06.030.

Hitchcock, ST. 2007. Skeletal muscle. In *Body: The Complete Human*, edited by ST Hitchcock, 106–23. Washington, DC: National Geographic Society.

Hossaini, R, MP Chipperfield, SA Montzka, A Rap, S Dhomse, and W Feng. 2015. Efficiency of short-lived halogens at influencing climate through depletion of stratospheric ozone. *Nature Geoscience* 8 (3): 186–90. doi:10.1038/ngeo2363.

IAEA. 2004. *Radiation, People and the Environment.* Edited by J Ford. Austria: IAEA.

IARC. 2014. *World Cancer Report 2014.* Edited by BW Stewart and CP Wild. Lyon, France: IARC.

Islas-Espinoza, M, and B Weber. 2014. Bioenergy solutions. In *Sustainability Science and Technology: An Introduction*, edited by Alejandro de las Heras, 157–71. Boca Raton, FL: CRC Press.

Kim, S, S Jin, and GP Pfeifer. 2014. Formation of cyclobutane pyrimidine dimers at dipyrimidines containing 5-hydroxymethylcytosine. *Photochemical and Photobiological Sciences* 12 (8): 1409–15. doi:10.1039/c3pp50037c.Formation.

Mussgnug, JH, V Klassen, A Schlüter, and O Kruse. 2010. Microalgae as substrates for fermentative biogas production in a combined biorefinery concept. *Journal of Biotechnology* 150. Elsevier B.V.: 51–56. doi:10.1016/j.jbiotec.2010.07.030.

Partridge, JS. 2014. Human energy harvesting in the urban environment. EngD Thesis. University College London Faculty of Engineering, London.

Perlmutter, D, and K Loberg. 2015. *Brain Maker : The Power of Gut Microbes to Heal and Protect Your Brain-for Life*. First. New York: Little Brown and Company.

Ponizovskiy, MR. 2013. The central regulation of all biophysical and biochemical processes as the mechanism of maintenance stability of internal energy and internal medium both in a human organism and in cells of an organism. *Modern Chemistry and Application* 1 (1): 1–2. doi:10.4172/2329-6798.

Popkin, BM, LS Adair, and SW Ng. 2013. Now and then: The global nutrition transition: The pandemicof obesity in developing countries. *Nutrition Reviews* 70: 3–21. doi:10.1111/j.1753-4887.2011.00456.x.NOW.

Prigogine, I. 1991. The behavior of matter under nonequilibrium conditions: Fundamental aspects and applications. Austin, TX.

Romero, E, R Augulis, VI Novoderezhkin, M Ferretti, J Thieme, D Zigmantas, and R Van Grondelle. 2014. Quantum coherence in photosynthesis for efficient solar-energy conversion. *Nature Physics* 10: 1–7. doi:10.1038/NPHYS3017.

Rydberg, T, and J Jansén. 2002. Comparison of horse and tractor traction using emergy analysis. *Ecological Engineering* 19: 13–28.

Schauer, JJ. 2015. Design criteria for future fuels and related power systems addressing the impacts of non-CO_2 pollutants on human health and climate change. *Annual Review of Chemical and Biomolecular Engineering* 6: 101–20. doi:10.1146/annurev-chembioeng-061114-123337.

Schrödinger, E. 1944. *What Is Life – The Physical Aspect of the Living Cell.* Cambridge, MA: Cambridge University Press.

Seibel, J, U Bornscheuer, and K Buchholz. 2014. Enzymatic degradation of (ligno) cellulose. *Angewandte Reviews* 53: 2–20. doi:10.1002/anie.201309953.

Sharpe, RM. 2012. Sperm counts and fertility in men: A rocky road ahead. *EMBO Reports* 13 (5). Nature Publishing Group: 398–403. doi:10.1038/embor.2012.50.

Sinha, RP, and D-P Häder. 2002. UV-induced DNA damage and repair : A review UV-induced DNA damage and repair : A review. *Photochemical and Photobiological Sciences* 1: 225–36. doi:10.1039/B201230H.

Takeuchi, N. 2011. *Nanociencia Y Nanotecnología: La Construcción de Un Mundo Mejor Átomo Por Átomo.* First. Mexico City: FCE, CN y N-UNAM, SEP, CONACYT.

Voloshin, RA, MV Rodionova, SK Zharmukhamedov, and T Nejat Veziroglu. 2016. Review: Biofuel production from plant and algal biomass. *International Journal of Hydrogen Energy* 41 (39). Elsevier Ltd: 17257–273. doi:10.1016/j.ijhydene.2016.07.084.