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Biofuel – The Fifth Utility

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ENERGY RESOURCES

Humanity's way of life is on a collision course with geology and the environment. Ultimately, this is a story about our future, as well as our past.

In the animal kingdom, human beings are one of the species that can most efficiently turn the calories of its food into useful mechanical energy. For example, humans need about half the calories that a horse needs to exert the same physical energy. This astonishing energy-efficient metabolism undoubtedly gave us an evolutionary advantage over other species. Perhaps this advantage also helped give us the big brains we needed to figure out ways to cash out the stream of solar income captured by plants, such as use of fire. By burning plants – especially those we could not eat – humanity leapt beyond the physical limits imposed by its own gastric and metabolic systems to release far more solar energy than by digestion alone. This was a watershed moment because this new means of controlling energy reduced our vulnerability to natural elements, particularly the long ice ages that repeatedly besieged the earth.[1]

Eventually, humans stopped wandering across the land hunting and gathering food. Cultivation and domestication began, a milestone archaeologist generally consider the beginning of civilization. Fire made this settled agrarian life possible: it let humans slash-and-burn – the same method threatening our rainforests today – to clear land for crop cultivation, and made digestible the cereals they planted. In these more permanent settlements, humans developed basic manufacturing skills – ways to make products that would last for societies that would last, at least as long as they had fuel.

From Wood To Cheap Oil

Plants and photosynthetic organisms, both terrestrial and marine, are continuous solar energy converters. More importantly, if properly tapped, they are constantly renewable. Plant photosynthesis alone, for example, fixes about 2×10^{11} metric tons of carbon with an energy content of 2×10^{21} J, which represents about 10 times the world's annual energy use and 200 times our food energy consumption. Unfortunately, the magnitude and role of photosynthesis has gone largely unappreciated because (and fortunately) we use such a small proportion of the fixed carbon. But let it not be forgotten that photosynthesis in the past provided all the present fossil carbon sources, namely coal, oil and natural gas. A series of fortuitous geological events trapped these biomaterials beneath the sediments of ancient seas, and over million of years, the right mix of heat, pressure, and other factors slow-cooked the organic materials into fossil fuel.[2]

Even though more than 70% of the people in less developed countries still use wood for cooking and heating, in the modern society, the fuel is coal, oil and gas. Barring wars and natural disasters, the world can still produce so much crude that the current price of about $50 for a 42-gallon barrel would plummet if the Organization of the Petroleum Exporting Countries (OPEC) did not regulate production. This abundance of oil means, for now, that oil is cheap. In the U.S., where gasoline taxes average 43 cents a gallon (instead of dollars, as in Europe and Japan), a gallon of gasoline can be cheaper than a bottle of water – making it too cheap for most people to bother conserving. This abundance also means the world can now feed on a daily oil habit of nearly 80 million barrels of oil, to make not only fuel for cars, trucks and airplanes, but the synthetic fabric in our wardrobe and the plastics in just everything we touch started out as oil too. Thanks to oil and its cousin, natural gas, foods at supermarkets – grown with the help of hydrocarbon-based fertilizers and pesticides – are cheap and plentiful.

The stark fact is that the earth holds a finite supply of these irreplaceable resources. The flood of crude and natural gas from fields around the world will ultimately top out, and then dwindle. For oil, this could be 5 years from now, or it could be 50, but few doubt that it is coming.

The current "energy crisis" that is reverberating throughout the world has focused attention on the continual depletion and finite nature of these fossil fuel reserves. Taken in association with the projected dramatic rise in global energy demand this century due to population growth and increasing worldwide gross domestic products, standards of living, and the energy intensity of developing economies, this has generated growing economic and trade pressure to start a shift away from fossil fuels and toward an energy path radically different than the one we have been on for centuries.

Amidst this rapidly rising demand, the U.S., having just 5% of the world's population, slurps up a quarter of the world's oil, remaining the undisputed king of consumer economy. This extravagance is equivalent to about three gallons a person every day, and more if the hidden cost of efforts to keep oil price down are taken into account. Whether or not the Bush wars in Iraq (1991 and 2003) was directly motivated by oil, the U.S. clearly hoped it would lay the groundwork for a stable, democratic Middle East, which among other benefits, would in Washington's view put the world's oil supply in more trustworthy hands.[3]

To Kyoto Or Not To Kyoto

The ways we have been using our geological inheritance also exert a toll on the environment. Carbon dioxide (CO_2) is the most abundant greenhouse gas (GHG) in the atmosphere: it absorbs infrared radiation and traps heat in the earth's atmosphere. Based on projected energy use, by the year 2025, U.S. CO_2 emissions could increase almost 40%, and the annual global CO_2 emissions could be 55% higher than in 2001 as a result of accelerated growth in fossil-fuel consumption projected for the developing regions of the world.[4,5] In 2002 global energy use emitted about 7 giga tons of CO_2 into the atmosphere; the CO_2 emissions could be as high as 30GtC per year by 2100.[6] To stabilize the concentration of CO_2 at any level, the global CO_2 emission must peak eventually and begin to decline, ultimately to zero.

The Kyoto Protocol, negotiated in 1997 and adopted by 36 industrial nations, established a mechanism aimed at finding the cheapest way to curb emissions of GHGs that contribute to global warming. The protocol requires the signatory nations – with varying targets – to reduce their emissions of greenhouse gases below their 1990 levels, in the five years from 2008 to 2012. For the European Union (EU), the target is to reduce emissions to 8% below 1990 levels; currently the EU is 6% above its 1990 levels. The U.S., which generates a fifth of GHGs but has not joined the Kyoto Protocol, is currently 19% above its theoretical limits. The Protocol is a small step in the right direction, not nearly enough actually to stop the build up in GHG levels in the atmosphere.[7]

President Bush of the U.S. rejected the Kyoto Protocol in 2001, citing the high cost to American industry. Without the support of the world's largest emitter of GHG (and the largest economy), it is unlikely that other nations will extend the treaty beyond 2012. Companies face a dilemma of whether it is worth investing millions of dollars to comply with an international regulatory regime that may not be enforced after 2012, and one that may collapse even before then.

RENEWABLE BIOFUEL ECONOMY

Non-renewable resources cannot be replaced; these include fossil fuels, such as

- L Crude oil has hydrocarbons, oxygen, sulfur and nitrogen compounds in it. The world's crude oil has a life expectancy of about 42 years.
- L Natural gas is a mixture of methane, propane and butane. Propane and butane may be liquefied for use and storage.
- L Approximately 68% of the world's coal reserves and 85% of untapped sources are located in the U.S., Eastern Europe and China. 80% of the coal is used to produce electricity.

Renewable resources include energy from the sun, wind, flowing water, the earth's internal heat, and biomass. For example,

- J Passive solar heating captures sunlight directly within a structure and converts it into low-temperature heat for heating.
- J Hydroelectric power supplies 20% of the world's power and 6% of the total commercial energy.

Wind and solar power represent an ultimate in environmental sustainability. However, there is a problem with reliability: the sun does not necessarily shine and the wind may not blow exactly when needed. Electricity is a product with essentially no shelf life; it must be generated to meet demand exactly as it arises because we have not come up with a practical way of storing it. Coal can be handily piled up next to power plants; when a severe heat wave strikes, we can just shovel the coal in faster and keep ourselves in a state of climate-controlled comfort. In so doing, we wittingly increase the risk of the next heat wave because these power plants emit GHGs into the atmosphere.

An alternative renewable and environmentally friendly (thus “green”) source of energy is biomass. Biomass are organic material from living organisms, typically plant matter including trees, grasses, and agricultural crops that can be burned or converted to liquid or gaseous fuels for energy. Currently it supplies about 11% of the world’s fuel. It is renewable as long as the material is not used faster than it can be replenished. Biofuels, derived from renewable biomass, include biodiesel, ethanol, methanol, methane and hydrogen.[8]

There are three main directions that can be followed to achieve biomass supplies:

- Cultivation of so-called energy crops.
- Harvesting of natural vegetation.
- Utilization of agricultural and other organic wastes.

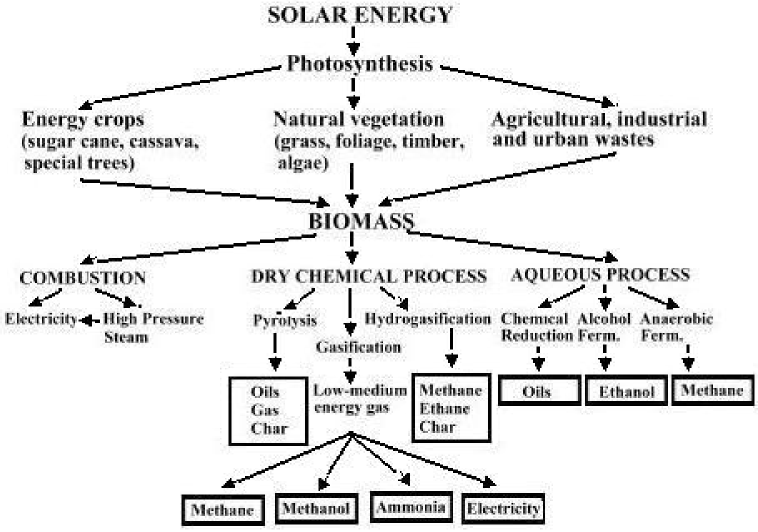

Figure 1. Different options for converting biomass into bioenergy. (Figure adapted from J.E. Smith, *Biotechnology*).

Energy crop plantations produce fast-growing plants such as cottonwoods, poplars, sycamores, shrubs, and water hyacinths; and plants that store energy in hydrocarbons (which can be refined as gasoline) such as oil palms and varieties of Euphorbia plants. The concept of cultivating plant biomass specifically for energy supply is based on the fact that much higher yields of fixed carbons are attainable from well-planned plantation methods than from harvesting natural vegetation or collecting agricultural or industrial wastes. Programs of this type are now being extensively planned and practiced in many countries throughout the world. Sugar cane and cassava are two principal crops that are being developed (primarily for ethanol production) in Brazil, Australia and South Africa, whereas more lignocellulosic materials are being developed in Sweden and America. In the latter case plans are being made to grow forest for conversion into liquid fuels.

The problem of water deficiency is very real, however, and rainfall is most often the limiting factor operating in otherwise ideal conditions of solar radiation intensity, such as Africa. In certain areas of the world, such as Malaysia where sunshine and rainfall are plentiful and the soil is fertile, it is possible that such plantations will rapidly become a reality; but for most countries, development will center on the use of organic wastes, namely agricultural, municipal and industrial. Conversion to biofuels could well serve as substitutes for petroleum energy and as a chemical feedstock.

BIOENERGY ALTRENATIVES

Most biological processes that produce energy require solar energy either directly or indirectly via photosynthesis, a complex biochemical pathway in which solar energy is used to drive the chemical conversion of low-energy inorganic molecules (such as water) and carbon dioxide into energy-rich organic molecules. The organic products of photosynthesis are used to build biomass (proteins, fats, carbohydrates, and cellulose) and store chemical energy needed to drive cellular processes. The biomass of photosynthetic organisms can be used directly as a burnable fuel or converted to such high-value energy sources as ethanol, biodiesel, methanol, hydrogen, or methane.

Ethanol (liquid). The production of alcohol by fermentation of sugars and starch is an ancient art:

$$C_6H_{12}O_6 \rightarrow 2CH_3CH_2OH + 2CO_2$$

Ethanol is something that humans can drink, but we can also use it as a fuel. In fact, ethanol is currently the most widely consumed biofuel in the U.S., used as a substitute (such as E85, which is derived from corn, barley or wheat, and is 15% gasoline, 85% ethanol; gasohol is 10% pure ethanol mixed with gasoline) or octane booster for gasoline. A gallon of this biofuel has about 2/3 the energy content of gasoline. Some 4 billion gallons of ethanol were produced from cornstarch in 2005, equaling about 3% of U.S. gasoline consumption.[9]

Brazil's undoubted success in pioneering this production of "green petrol" is creating worldwide interest, particularly among poorer Third World nations with the climate and land to grow their own fuel crops, but with limited currency to buy oil. Whether oil-importing or not, biofuel production from indigenous and renewable sources (such as sugar cane and oil palm in Malaysia) is very attractive. To make available the necessary fermentable sugars, most raw materials require some degree of pretreatment, depending on their chemical composition. With sugar cane this treatment is minimal and consists mainly of the usual milling operation; cellulosic raw materials such as timber and straw require more expensive pretreatment.

Methanol (liquid). In the U.S., about a billion gallons of methanol – a high-octane liquid that has half the energy density of gasoline – are produced each year, primarily from methane. Engine modifications are required to improve cold starts and prevent corrosion.

Biodiesel (liquid). Biodiesel is made by combining alcohol (usually methanol) with vegetable oil, animal fat, or recycled cooking greases. It can be used as an additive to reduce vehicle emissions (typically 20%) or in its pure form as a renewable alternative fuel for diesel engines. In its pure form, biodiesel reduces fuel economy and power by about 10% when compared with diesel. Biodiesel blends perform similarly to diesel and can be used in unmodified engines. Only about 30 million gallons of biodiesel are produced each year in the U.S. alone. This is a tiny fraction of the billions of gallons of diesel consumed each year.

Hydrogen (gas). The energy content per kilogram of hydrogen is three times that of gasoline, but it does not occur free in nature. Thus, hydrogen is an energy carrier, not a primary energy source. Before it can be used, it must be produced using energy from a primary energy source. Currently, most hydrogen is derived from steam reformation of nonrenewable natural gas and used primarily for industrial chemicals production. Only a small fraction is used as an energy carrier. Each year in the United States about 9 million tons of hydrogen are produced, enough energy to power 20 to 30 million hydrogen cars or 5 to 8 million homes.

Extensive research on clean, renewable hydrogen production is progressing along two directions: either released from the breakdown of biomass by microorganisms, or produced directly from water and sunlight via photobiological processes that do not require biomass as an intermediary.[10]

Figure 2. How the solar hydrogen cycle works: electricity from photovoltaic panels is used to power an electrolyzer to split water (H_2O) into hydrogen (H_2) and oxygen (O_2). The oxygen is released into the air and the hydrogen is pumped into storage tanks, where it can be kept on site or transported to sites that need energy. At use site, the hydrogen is recombined with oxygen from the air in a fuel cell, which directly converts the chemical energy in hydrogen into electricity. The only byproduct of this process is pure water.

Methane (gas). The conversion of organic matter to methane by fermentation is a natural process, which occurs in marshes, landfill, peat bogs and organic sediments in aquatic systems:

$$C_6H_{12}O_6 \rightarrow 3CH_4 + 3CO_2$$

The most efficient and complex methane-producing system in nature is the ruminant. This anaerobic (without oxygen) system has never been fully reproduced outside the cow, and is known to be a complex interaction of large numbers of bacteria, protozoa, and fungi.

Figure 3. Wetlands, agricultural and grazing lands, and other anthropogenic sources such as landfills, are major sources of methane, whereas the ocean, grasslands, and desert form major methane sinks. The cow depicted in the figure represents diverse ruminants. Methane is oxidized either photochemically in the atmosphere or biologically in terrestrial and aquatic systems. Anthropogenic inputs of nitrogen in the form of ammonia compete for MMOs (methane monooxygenase), reducing methane oxidation and leading to the formation of nitrous oxide, another greenhouse gas. (Figure adapted from *PLoS Biology*, 2004).

There are several possible ways by which methane can be produced in a planned economy: from sewage, from agricultural and urban wastes, and in biogas reactors. Using urban wastes it should be possible to convert 30-50% of the combustible energy to methane, while with the use of certain other vegetable materials or forages it may be possible to achieve a 70% conversion.

Methane currently makes up about 20% of the energy supply in the U.S., where an extensive infrastructure is already in place for widespread distribution and use. There have also been some considerations of large-scale energy crop plantations to provide a “methane economy.” High-yielding crops in terms of $MJha^{-1}h^{-1}$ cultivated on massive land or water areas have been proposed. An estimate shows that 65% of the current gas consumption in the U.S. could be provided by an energy plantation of area 260,000 km^2 using water hyacinth of energy content 3.8 MJ kg^{-1} dry material.

A traditional way of producing methane is by the fermentation of animal dung. In such systems the animal dung is mixed with water and allowed to ferment in near anaerobic conditions. The gaseous products are usually referred to as biogas and the installations called biogas plants or bioreactors. Production of biogas by such methods goes back to antiquity and is of particular importance in India, Pakistan and China. China has more than 6 million biogas digesters.

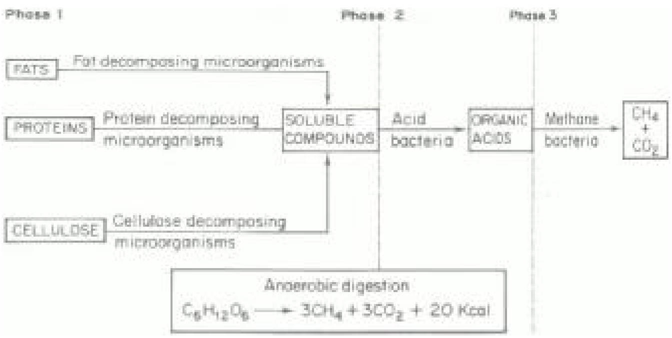

Figure 4. The three phases in the microbiology of methane production: 1) solubilization of complex molecules such as fats, proteins and cellulose; 2) the resultant soluble, low molecular weight products are converted to organic acids; 3) these acids (primarily acetic) are specifically decomposed by the methanogenic bacteria to methane and CO_2.

The overall economics of methane production must recognize the process can convert malodorous and pathogenic wastes into innocuous and useful materials. Valuable by-products generated by the process, namely the effluent and residue rich in ammonia, phosphates, and microbial cells, may be used as fertilizers, soil conditioner or even animal feed.

SUMMARY AND OUTLOOK

In the past, biology played a key role in producing the fossil fuels so critical to meeting today’s world energy demand. Fossil fuels were once living biomaterials synthesized eons ago by photosynthetic and biochemical processes. These energy resources are nonrenewable.

In the future, biology will play an equally key role. As renewable alternatives that can be harvested on a recurring basis, bioenergy crops (e.g., poplar trees, switchgrass, cassava, oil palm, sugar cane) and agricultural residues (e.g., corn stover and wheat straw) can provide farmers with important new source of revenue. Consumption of biofuels produces no net CO_2 emissions, releases no sulfur, and has much lower particulate and toxic emissions than fossil fuels.[11]

If biomass from agricultural surpluses, forestry wastes, and urban wastes can be used to create biofuels, could the world's waste – peanut shells from the U.S., coconut shells from the Philippines, husks of oil palms from Malaysia, pig-farm waste from China, grease from MacDonald's French fries, or even left-over gas from Japanese-beer kegs – be the answer to the next energy crisis? Probably not yet, but a number of companies and countries are touting the benefits in a variety of ways. Talk abounds about fuel cells and the "hydrogen economy;" talks about planned economy: from sewage, from agricultural and urban wastes, and in biogas reactors; talks about planned energy crop plantations…[12]

E85, using ethanol made in the U.S. from corn, is not a science experiment or pipe dream. It is real fuel, sold now. The drawback is it contains less energy than gasoline, so you will have to fill your tank more often. And you'd almost certainly have to buy a new car or truck to use it. All modern vehicles can burn a widely sold fuel – gasohol that is 10% ethanol and 90% gasoline; but only specially outfitted cars and trucks can use E85. They are called flexible fuel vehicles or FFVs, and are designed to burn straight gasoline, E85 or any gas/ethanol blend in between. There are now 5 million FFVs already on the road in the U.S. In the U.S., where labor cost is expensive, the goal is to make biofuels competitive by 2012, and by 2030, to have a well-established, economically viable bioenergy and biobased products industry.

In parts of the world such as Brazil and countries of similar climatic conditions (Malaysia is on the same latitude), biomass will surely attain wider exploitation and utilization. In Brazil, poster child for ethanol use, FFVs are routine and the nationwide standard is E25, 25% ethanol. Fuels range up to E100, which is all ethanol. Ethanol there is made from sugar cane, which requires less work and fertilizer to grow than corn. In Brazil, there is a much cheaper cost of labor, much looser environmental regulations, a whole litany of things that make it easier and cheaper to produce and sell ethanol fuel. Because Brazil is warm, motorists there do not have the cold-start problems that people in colder climate do with pure ethanol. The higher the alcohol concentration, the harder it can be to ignite the fuel in cold weather.

The technical and agronomic problems are still considerable but biotechnology research is making valuable inroads to further understanding. With biotechnological innovations, biology once again can play an important role in producing high-energy fuels. Plants and photosynthetic microorganisms are masters at harvesting chemical energy from sunlight – a virtually inexhaustible supply of energy. By harnessing their photosynthetic and other biochemical capabilities, we can use biological systems to satisfy a great portion of the energy demand. Methanotrophic (methane eating) bacteria, for example, have the unique ability of being able to convert methane to biomass. A protocol has been developed for mixing *Methyloccocus capsulatus* with methane, ammonia and oxygen in a fermentor, where they grow. The process converts one ton of methane to 0.7 tons of biomass (70% protein, 12% carbohydrate, 10% fat and 8% minerals).

So what is in store for biofuel? When biofuel technology is fully developed, it will become the fifth utility, following the pattern of gas, electricity, water, and telecommunication, which began as disconnected networks in the 19th century and were eventually standardized, integrated, and became ubiquitous. As an alternative fuel, biofuel will cut down unnecessary wars, fought, hypocritically enough, in the name of democracy. It is time to stop beating around the Bush.

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Dr. Hwa A. Lim, Ph.D. (science), M.A. (science), and MBA (strategy and business laws), B.Sc. (Hons.), ARCS, is sometimes also known as "The Father of Bioinformatics." Most of his early work on bioinformatics was performed at a U.S. Department of Energy (DoE) supported supercomputer institute, where he was program director, and tenured state-line faculty. Hal has served as a bioinformatics expert for the United Nations, a review panelist for U.S. National Cancer Institute, and as a consultant for prominent firms. Currently he is Adjunct Professor (Math. Sc., and Mole. and Cell Biology) at the University of Texas at Dallas. He was appointed a member of the Expert Panel for BioValley Malaysia in March 2004. Dr. Lim resides in Silicon Valley, California, USA. He can be reached at hal@dtrends.com, hal_lim@yahoo.com.

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