Chapter 5
Energy Storage in Organic Fuels

5.1 Introduction

The Preface included a discussion of the several types of natural materials that can be obtained from the earth and used as fuels. The major ones are wood and the several fossil fuels, including the various types of coals, crude oil, and natural gas. The fossil fuels, which now play such a major role in the energy supply, will surely gradually become less important as they become depleted. But the recent development of fracking technology, as discussed in the Preface, will result in the access to substantial additional sources of crude oil in some locations.

There are also some organic materials that can be considered to be renewable. These include the agrofuels, which contain significant amounts of vegetable oil, and the crops that are high in sugar or starch. These are often discussed in terms of *biomass*, and *bioenergy*.

While these materials are basically fuels, and therefore energy carriers, they can also be thought of as energy storage media, for as they grow they accumulate energy that can be utilized in the future. But in addition, some of them have other characteristics, such as being nutrients, or serving as raw materials for a number of industries.

Another aspect of biomass is that this category should also include living materials, including animals. There is, of course, crossover between these categories, for animals consume agrofuels, and also contribute energy in the form of food. They can also provide mechanical energy.

5.2 Storage of Energy in Living Biomass

It has been estimated that the energy storage densities of living plants and animals are 10–30 MJ kg^{-1} of dry weight [1]. The question is how this energy can be usefully acquired. In the case of dry wood and straw, it can be converted to heat by burning. But most organic material contains a significant amount of water, and the

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energy that has to be furnished to dry it can exceed the amount that is obtained by its burning.

There are other methods by which the energy contained in biomass can be retrieved, however. One of these is the consumption of biomass by a wide variety of living organisms as food without having to dry it.

The total amount of energy stored in living biomass on the earth is roughly 1.5×10^{22} J, and its average living residence time is about 3.5 years. There is a difference between living biomass in the oceans and on the land. Growth is generally more rapid in the oceans, mostly in the form of phytoplankton, which has a very short lifetime, of the order of a few weeks. On land the biomass growth rate is much lower than in the oceans, but the average residence time is longer.

For biomass to be considered as a renewable energy storage mechanism, the rate of growth must be at least as rapid as the rate of the extraction of the energy by harvesting. This can be influenced in various ways, such as by the use of fertilizers and/or artificial irrigation or lighting. Growth typically involves the consumption of CO_2, which is generally also considered positive for other (environmental) reasons. It has been shown that increasing the concentration of CO_2 in the air can enhance the rate of growth of many plants, in some cases up to a factor of two [2]. This is done in commercial greenhouses in some places. Pest control can also be important.

The rapid growth of plants can be very impressive. The efficiency of the use of solar radiation to produce stored energy by a number of plant types is shown in Table 5.1 [2]. The efficiency is defined as the energy content of the crop divided by the accumulated incident solar energy for a given land surface area.

These data are general averages, and actual yields can be increased by the use of fertilizers, well-designed irrigation, etc. The matter of irrigation is a critical worldwide problem, for the needs are growing more rapidly, partly because of the increase in human population, than sources are being developed.

As mentioned earlier, the situation is somewhat different for aquatic plants. Open ocean photosynthesis is dominated by phytoplankton. The limiting factor determining production is the availability of nutrients, particularly nitrogen and phosphate. Where these are readily available, for example from agricultural runoff, the growth in nearby waters can be remarkable. This is not always desirable, however.

Table 5.1 Examples of high-yield plant species

Plant	Short-term efficiency	Annual average efficiency	Annual yield ($kg\ m^{-2} years^{-1}$)
Sugarcane		0.028	11.2
Napier grass	0.024		
Sorghum	0.032	0.009	3.6
Corn	0.032		
Alfalfa	0.014	0.007	2.9
Sugar beet	0.019	0.008	3.3
Chlorella	0.017		
Eucalyptus		0.013	5.4

The author saw this happen in Clear Lake in Northern California, where there was evidently a lot of agricultural fertilizer runoff. He was there to participate in small sailboat racing. The water was so full of green algae marine growth that it was essentially opaque. It was like sailing through thick pea soup. This problem has evidently been subsequently alleviated by controlling the runoff.

The organic energy production in the North Atlantic ocean is about 0.05 Wm-2 [3]. But in coastal areas the productivity typically rises to about 0.5 Wm-2. For coral reefs and areas where currents bring nutrient-rich water, such as along the Peruvian coast, the conversion efficiency can be 2–3 % of the incident solar energy. Under ideal conditions, with an artificial nutrient supply, energy conversion efficiencies can reach 4 % [4].

Despite these attractive data, the annual marine plant harvest is only about 1 million metric tons. Most of this is consumed as food in Japan and Korea. Most algae are rich in protein, and it would seem to make sense to increase their use in food. Unfortunately, pollution interferes with this in many areas.

5.3 Storage via Animals

Domesticated animals are fed mostly by plant material that has grown by accepting energy from the sun. Animals convert and store energy acquired from the consumption of plants. This energy can be delivered in the form of food, both to humans and in some cases to other animals.

Roughly one-third of the total harvested plant material is fed to animals; yet it is estimated [1] that animal production constitutes only 14 % of the total food production. The difference between the 33 % input and the 14 % output shows that the use of plant food to raise animals is actually not a very efficient use of the energy in the plants. There are, however, other arguments why this is done. These involve concerns about the desired distribution of meat, vegetable, and milk products in the human diet, which varies with location in the world. Thus energy efficiency is not always the dominant concern.

In the past animals also have contributed mechanical energy to a number of important applications, such as transportation and the tilling of soil to assist agriculture. In the more affluent countries these applications have been mostly taken over by mechanical alternatives, such as tractors, which consume fossil fuels.

There are also some other ways in which the stored energy in animals is utilized. When travelling in the Black Forest region of Germany one notices that the older buildings were typically constructed so that the animals were kept underneath the living quarters of the farming families. This was done to utilize the heat from the animals to increase the temperature of the living quarters in the winter.

Jensen [1] provided some interesting figures on several aspects of energy consumption, storage and output related to domestic animals. He estimated that there are some 1.5×10^9 domesticated large animals in the world (cattle, horses, yaks, buffalo, donkeys, camels, etc.). About 400 million of these may be contributing mechanical work, at an average power level of 375 W per animal for some 6 h a day. If the average food intake is 600 W per animal, the efficiency of the conversion of the food energy to mechanical energy would be 16 %. In many applications, however, only a fraction of the animals' mechanical power is actually used for a useful purpose. For example, there is no useful energy output, although there is energy consumption, when a horse or cow merely walks around.

5.4 Hard Biomass

The growth of wood and other hard biomass by the absorption of solar energy, and its consumption, after at least some level of storage, by oxidation to provide heat for cooking, space heating, and other purposes, is important in many relatively less highly developed societies. But much of this heat is actually wasted. For example, in cooking, less than 10 % of the fuel's heat of combustion actually reaches the contents of a cooking pot. In addition, some of the energy that does reach the pot is given off as heat to the surroundings. As a result, only a fraction of the heat energy involved in cooking can be actually used, although this depends to a considerable extent upon the design and operation of the stove. Some of the cast iron stoves used in Europe in the past were actually quite good at converting and storing the heat of combustion, partly for cooking, and partly for space heating.

5.5 Synthetic Liquid Fuels

A number of fuels can be made by the modification of species found in nature. The most interesting of these are methanol (CH_3OH), ethanol (C_2H_5OH), methane (CH_4), ammonia (NH_3), and methylcyclohexane (C_7H_{14}).

The production of methanol involves the *steam reforming reaction*,

$$CH_4 + H_2O = CO + 3H_2 \tag{5.1}$$

followed by further reaction of CO with hydrogen

$$CO + 2H_2 = CH_3OH \tag{5.2}$$

Alternatively, it is possible to react CO_2 with hydrogen to form methanol and water

$$CO_2 + 3H_2 = CH_3OH + H_2O \tag{5.3}$$

Ethanol can be produced from CO_2 and H_2 in a similar way as methanol by upgrading the hydrogen content.

5.6 Gaseous Fuels Stored as Liquids

Some liquid fuels can readily be stored in small high-pressure tanks. This is often done in cases where a fuel is used for small scale heating or cooking, e.g., in recreational vehicles, boats, or when camping. The fuel is kept as a liquid under pressure, but as soon as the pressure is reduced by opening a valve, it emits as a gas.

The approximate pressure at ambient temperature can be calculated from the boiling point at one atmosphere pressure, T_{bp}, by use of the ideal gas equation

$$PV = nRT \tag{5.4}$$

where V is the volume, n is the number of mols, and R is the gas constant. So for a fixed volume and amount of material the pressure at ambient temperature, assumed to be 298 K, is given by

$$P_{298} = 298/T_{bp} \tag{5.5}$$

Some common examples are shown in Table 5.2.

5.7 The Energy Content of Various Materials Used as Fuels

To put some of these data in perspective, the specific energies of a number of materials that are used as fuels are shown in Table 5.3. It is interesting to compare these numbers with the specific energy of the well-known explosive TNT, which is only 3.6 MJ kg^{-1}, which, when converted to electrical units, is about 1 kW-hr kg^{-1}.

Table 5.2 Data on materials commonly used for small-scale heating

Material	Boiling temperature (K)	Pressure at 298 K (atm)
Butane	272.5	1.1
Propane	231	1.3
Methane	111	2.7

Table 5.3 Specific energy of various materials used as fuels

Fuel	Specific energy (MJ kg^{-1})
Crude oil	42
Coal	32
Dry wood	15
Hydrogen gas	120
Methanol	21
Ethanol	28
Propane	47
Butane	46
Gasoline	44
Diesel fuel	43

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