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"ENERGY CROPS (ENERGY FARMING)"

For "Biochemical and Photosynthetic Aspects of Energy Production"
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Academic Press, Inc. New York

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Solar energy conversion by the process of photosynthesis in green plants supplies virtually all the energy for living cells on earth. Agriculture, which can be defined as controlled photosynthesis to produce food and materials, has been used by man for millenia, and has caused more modification of the earth's surface than any other of man's activities. Throughout most of history, combustion of photosynthetic products, wood and straw, has supplied a large part of the energy for cooking and heating, and this is still true in some less developed countries (Earl, 1975). In 1850, about 91% of the U.S. energy supply for a population of 23 million came from wood combustion (USBC, 1976) whereas the present U.S. population of 215 million probably relies on biomass conversion for much less than 1% of its energy needs.

During the past 150 years, industrialized nations have depended increasingly on coal and later on petroleum and natural gas for energy and chemicals. These products of photosynthesis in past ages are being rapidly depleted. Within the next 25 years more than half of proven world resources of petroleum and gas are expected to be consumed. It may take another century to approach consumption of half the coal reserves, but severe economic and environmental problems will be encountered in using that much coal. The potential use of other forms of fossil fuels such as those found in oil shales appears to be even more difficult.

The dependence of industrialized nations on the importation of oil from foreign sources is growing at an alarming rate. The U.S., for example, increased the import of oil from 35% of its total consumption in 1973 to 43% in 1976 (FEA, 1976). During the first six months of 1977, the U.S. balance of payments

deficit, largely due to oil imports, was 12.6 billion dollars. While more -2- effective energy conservation efforts may slow this trend, it is unlikely that massive oil importation will cease in the near future without some international crisis resulting in a forced cessation. Although we can hope that the present uneasy peace in the Middle East and other tense parts of the world can be maintained, and even that tensions may somehow be eased, it seems frighteningly evident that within a very few years, the major industrialized nations will be engaged in a severe, even if unwanted, competition for the dwindling supplies of petroleum. Regardless of their motives, the OPEC nations have performed a service of great value to the world by raising the prices of petroleum products to more realistic (in the longer term) values, thus forcing the industrialized nations to examine energy supply alternatives always dismissed by economists as "too expensive." At the same time, less developed countries without their own oil and gas supplies have an increasing interest in developing energy alternatives to expensive imports. Considering the political, economic, and military portents in the present world-wide balance of energy supply and demand, governmental policy makers should feel at least as much dedication towards developing new internal energy supplies as they do for the military defense of their countries.

The problem, of course, is that there are many energy options, fossil, nuclear, geothermal, and the various forms of solar energy. These include wind, heating and cooling, direct conversion by photovoltaic and chemical devices, and finally, direct conversion of light to chemical energy by photosynthesis: energy crops produced by "energy farming."

It is a regrettable fact that energy farming, while much discussed, has received little stimulation in the form of research funds until recently. Perhaps the growing of green plants for energy has seemed simply too prosaic

compared to more exotic methods such as thermonuclear fusion. It appears -3- that attitudes are now rapidly changing, and that various types of energy and chemical plantations (or at least test groves) may soon be planted. The purpose of this article is to review some of the basic considerations that affect the possibilities of success in such projects.

Why is Efficiency Important?

That there has been some pessimism about the possibilities for using energy farms to alleviate our problems of energy shortages can be understood by considering several basic facts. First, enormous amounts of energy are required, so that we need a very large contribution from plants to be of any significance. The U.S. use of fossil energy alone (94% of the total energy use) in one year (1976) was about 72×10^{15} Btu (72 "quads") or 18×10^{15} Kcal (75×10^{15} kj) (FEA, 1976).

Second, although enormous amounts of solar energy reach the earth's surface, the total intensity is rather diffuse, averaging over the conterminous U.S. on a year long basis about 1,450 Btu/ft²day, 3,930 Kcal/m² day or 190 watts/m² (Alich and Inman, 1974). For this area the total incident energy per year is about 4.4×10^{19} Btu or 1.1×10^{19} Kcal per year. Dedication of 1% of this land area to energy farms (an area about one fourth the area of the state of Arizona) would produce, at an energy conversion efficiency of 1%, 4.4 quads, or 6 % of the total energy currently supplied from fossil fuels. Of course, more land could be used, or possibly a higher energy conversion efficiency could be achieved.

This brings us to the third part of the problem: the efficiency of energy conversion by photosynthesizing green plants. It has been estimated that on a global basis, only 0.07% of the solar energy reaching the land surfaces is collected by plants (Lieth and Whittaker, 1975). Even in agricultural areas,

as little as 0.1% is commonly collected on an annual basis. There are many reasons for this low efficiency, including the growing season being only part of the year, conditions of temperature, water supply and nutrient supply that are suboptimal, and so on. As discussed later, photosynthesizing land plants during periods of maximum growth rates sometimes store in the form of chemical energy as much as 3 to 4% of the total incident solar energy. There is reason to believe that efficiencies of 5 to 7% might be achieved, but only at the price of providing conditions optimized beyond current agricultural practice on a year round basis.

The storage of chemical energy by green plants occurs through the conversion of water and carbon dioxide (as well as other minerals, principally nitrates and sulfates) to gaseous oxygen, which is released, and a multitude of chemical compounds, carbohydrates, fats, proteins, etc. which are the substance of the plant itself. There are a number of options for converting this stored energy of biomass to forms useful to man.

One option is to convert the biomass by combustion to heat which can then be used to run steam driven turbines and generate electricity. Any water contained in the biomass will be vaporized in this process, and the heat of vaporization subtracts from the total heat generated, decreasing the fuel value of the biomass in direct proportion to the water content. Assuming a relatively low water content in the biomass, and assuming a 30% efficiency for the conversion of the released heat energy to electricity, an energy plantation converting solar energy to chemical energy at 5% efficiency would deliver electrical energy at an efficiency of 1.5% based on solar energy without taking into consideration the energy cost of running the plantation. Keep in mind the fact that 5% efficiency is higher than any reported biomass production efficiency on an annual basis. An efficiency of 0.5% for primary production is more realistic in terms of reported yields, and this would lead to a 0.15% efficiency for electricity production, always less the cost of running the plantation.

Such considerations make it apparent that maximizing conversion efficiency on an annual basis may be rather important if production of biomass for fuel to generate electricity is ever to compete with other alternatives. Efficiencies of 15% or more are being claimed for photovoltaic systems and perhaps for direct thermal to electrical systems. -5-

Advantages of Energy Farming

That electricity from biomass production and combustion might be considered at all stems from the following expected advantages: First, biomass can be stored and fed into the boilers at rates dictated by the load on the electrical grid, much as is the case for fossil fuel fired plants. Second, it is expected that biomass combustion would produce less air pollution by sulfur oxides, since biomass generally has a lower sulfur content than coal. Third, planting, harvesting, and other agricultural operations are already being carried out on large areas of land with a well developed technology, and capital investment could be much less than for novel systems which have not been developed. Fourth, the industrial supply of fertilizers, equipment, etc. for agriculture are already available, and may be less energy costly than the systems which would be required to supply, for example, many square miles of mirrors or semiconductors. Finally, most other proposed systems would produce energy only, whereas energy farms could produce a host of valuable by-products including chemical feed-stocks for industry, portable liquid fuels, and food supplies to supplement those from conventional agriculture. It is entirely possible that by-products might have greater economic value than the electricity sold, yet might represent only a small part of the energy stored in the plants.

While it appears that energy farms are not likely to provide all or most of the energy needed in a modern industrial society, they could make significant contributions in certain regions. In the U.S. southwest, for example, coal

technology could turn out to be less feasible because of air quality consideration, while the abundance of relatively low cost land with very high levels of solar energy could make solar technologies, including energy farming, more attractive. Of course farms require water, in short supply in the Southwest, and we will return to this problem later.

Some types of energy "farms," especially the aquatic ones, would produce biomass with such high water content that drying the material to a point where its fuel value for combustion would be adequate seems impractical. In such cases it is proposed that, perhaps after extraction of useful by-products, the material would be fermented in an anaerobic digester to give fuel gasses such as methane (Poole, 1975, Poole and Williams, 1976, McCarty, 1973).

One of the best uses of "energy plantations" may be to produce neither electricity or methane, but rather to produce chemicals to replace those now derived from fossil fuels. One promising example is the production of rubber from guayule (NAS, 1977); another possibility is the production of a variety of hydrocarbons from plant latex (Calvin, 1976, 1977). In such cases, conservation of fossil fuels is the immediate goal, and there is no need to incur the losses involved in the conversion of chemical energy to electricity or gas. The long range implications are perhaps even more important: when we are really out of petroleum it may be easier to let plants make these substances than to make them from coal.

Many of the costs, both economic and energy, of energy produced by plantations will bear an inverse relationship to the solar energy conversion efficiency. Among these may be listed land cost, cultivation, planting and harvesting, and especially, collection of biomass to a central point for processing. Land cost includes not only the present price of land suitable for energy farming, but also some assessment of the future prices when and if

energy plantations should begin to compete on a large scale with other land⁻⁷⁻ uses. In this respect, it may be attractive to utilize land held by governmental agencies but not required for other valuable uses such as for lumber production or recreation.

Efficiencies of Solar Energy Conversion by Plants

In assessing efficiencies of green plants for solar energy conversion, it must be remembered that although the energy conversion efficiency of the photosynthetic process itself, while quite high (23% or more) is only the first factor involved in the overall efficiency. It is equally misleading to suppose that the 0.1% efficiency or less with which some common agricultural crops convert solar energy to biomass on an annual basis is a good guide for evaluating the potential of energy farms. The growth of such plants often has been optimized for production of a specific organ such as the seed or root, rather than for total plant mass. In the temperate zone, growing seasons may be limited to only a few months, after which the plant is programmed to senesce and die. Even perennials may have long periods of relatively low growth dictated by their adaption to seasons of low temperature, water stress, or both. Of course, energy plantations will also be subject to such limitations, depending on location and plant species chosen (unless we elect to provide artificial environments), but it is useful in evaluating various plants and systems to know what can be expected under ideal conditions. Loomis and Hall (1971) estimated potential productivity of land plants to be $71 \text{ g/m}^2 \text{ day}$ under illumination of $500 \text{ cal/cm}^2 \text{ day}$, assuming optimum temperatures and light response and a one-third loss due to respiration. The following discussion makes similar assumptions, but a more optimistic value for the quantum yield is employed.

The first factor limiting solar energy conversion by plants is, of course, the efficiency with which plants can convert sunlight by the process of

photosynthesis. A common way of expressing photosynthesis is by the -8- equation:

If (CH_2O) represents 1/6 of a glucose molecule, then the Gibbs free energy stored per mole of CO_2 reduced to glucose (ΔG) is about 114 Kcal (Bassham and Krause, 1969). Actually, free glucose is not an important product of photosynthesis, but glucose moieties are incorporated into starch, so that the equation is a reasonable approximation. If we are considering starch or cellulose as the principal product, however, we must allow for the fact that the molecular weight of the product is not 30, which it would be for CH_2O , but 27, since one H_2O (MW = 18) is removed for each glucose (MN = 180) incorporated into the starch or cellulose chain.

Carbohydrates are not the only products of photosynthesis, since sugar phosphates can be taken directly from the carbon reduction cycle in the chloroplasts and converted to other products in the cells, including fats, proteins, etc. (Smith, et al., 1961). The amount so used varies with the plant and its physiological condition. Since the energy stored in the formation of sugar phosphates is not so different from that stored in forming glucose, this different allocation of material to biosynthesis can be ignored in the calculation of the efficiency of the primary process of photosynthesis without introducing serious error. The energy cost of the conversion of photosynthate of secondary products is important, but can be included in the respiration/biosynthesis factor considered later.

The reduction of a molecule of CO_2 to the level of glucose or sugar phosphates requires the transfer of four electrons from water, liberating an O_2 molecule. Each electron transferred requires two photochemical steps each with a quantum requirement of one photon absorbed per electron transferred, or eight quanta in total. Concurrent with this transfer of four electrons is the production of about three

molecules of adenosine triphosphate (ATP), the energy for which is derived from the electron flow. This ATP is sufficient for the reduction of CO_2 to sugar phosphates, although additional ATP may be required for further bioconversions in the green cells. To the extent that such additional ATP is required, it would utilize additional light energy to drive a process of ATP formation called cyclic photophosphorylation. This cost is not included in the photosynthetic efficiency factor since requirements will be lumped into the later correction for respiration/biosynthesis.

The reduction of one mole of CO_2 thus requires the absorption of eight "moles" or einsteins of light: two einsteins for each of the four equivalents of electrons transferred from water to carbon dioxide.

Green plants can use only light of wave lengths from 400 nm to 700 nm. This photosynthetically active radiation (P.A.R.) constitutes only about 0.43 of the total solar radiation at the earth's surface at a location such as the U.S. Southwest. All of this light is used as if it were 700 nm light, but since the photosynthetically active radiation includes all wavelengths from 400 nm to 700 nm, the energy input is equivalent to that of monochromatic light of about 575 nm wavelength (Bassham, 1977). An einstein of 575 nm light has a energy of 49.74 Kcal. Multiplying by 8, we get 398 Kcal required per mole of CO_2 reduced to glucose. Since this process stores 114 Kcal as chemical potential, the maximum efficiency of photosynthesis is $114/398 = 0.286$. This would appear to be the maximum possible efficiency of the photosynthetic reaction. Probably the actual efficiency is somewhat less, but measurements of quantum requirements under optimal conditions in the laboratory have given quantum requirements in the range of 8 to 10 einsteins required per O_2 molecule evolved (Ng and Bassham, 1968).

The maximum efficiency of 0.286 is for conversion of P.A.R. The efficiency based on total solar radiation incident on the plants with total absorption of

P.A.R. is $0.43 \times .286 = 0.123$. This is the basis for the statement sometimes made that the maximum efficiency for solar energy conversion by photosynthesis is about 12%.

The maximum net efficiency, over a 24 hr period, and under field or aquatic conditions, depends on two other factors: the amount of incident light actually absorbed in the green tissue, and the cost of energy used in respiration and biosynthesis. For land plants it has been estimated that the maximum absorption to be expected from an optimal leaf canopy may be 0.80 (Loomis and Hall, 1971). This is due to some light being reflected, some reaching the ground or falling on nonphotosynthetic parts of the plant (such as the bark of trees). With aquatic plants such as unicellular algae that are totally immersed there may be less reflection and with sufficient density of algae, absorption could be essentially complete in green tissues. The situation with water plants such as hyacinths probably more closely resembles land plants.

A major loss in stored chemical energy results from respiration which occurs in all tissue not actively photosynthesizing. This includes green cells at night or in dim light, and roots, trunks and other organs that are not green or only a little green. The energy derived from respiration is used for various physiological needs of the plant, transport and translocation, conversion of photosynthate to protein, lipids (including hydrocarbons in some plants), cellulose for structures such as stalks and trunks, and so forth. In the green cells during photosynthesis, some energy from the photosynthetic process itself may be used for such purposes, as mentioned earlier. Like the light absorption factor, the factor for respiration/biosynthesis is extremely variable, depending on the physiological conditions and needs of the plant, but it is estimated that in a typical case respiration and biosynthesis use up one third of the energy stored by photosynthesis (Loomis and Hall, 1971). The factor would thus be 0.67.

-11-

It may be argued that both the absorption factor and the respiration factor are not true maximum values, since there may be cases where each is exceeded. The product of these two factors, $0.80 \times 0.67 = 0.53$ probably is close to the maximum, since there is some trade-off between the two factors. For example, for a land plant to have all brightly illuminated leaves and hence lower respiration compared to photosynthesis would mean that its leaf canopy was probably less perfect than required for 0.8 absorption. At the other extreme, in a dense jungle, little light may reach the ground, but the respiration in the shade plants may nearly equal photosynthesis. Similarly, an algae pond may be nearly totally absorbing, but the average light intensity for the cells would then be so low as to allow a high rate of respiration. Advocates of algae as the most efficient of photosynthetic plants do not always take this into consideration.

If we combine the photosynthetic efficiency, 0.123, with the product of the absorption and respiration/biosynthesis factors, 0.534, we obtain an overall maximum efficiency for photosynthetic/biosynthetic energy storage by green plants of 0.066. This calculated maximum efficiency can be compared with various reported high yield figures from agriculture. Before doing this it is useful to convert the efficiency to expected yield of dry matter.

From the equation and discussion given earlier, the reduction of a mole of CO_2 to the glucose moiety of starch or cellulose stores about 114 Kcal and results in an organic molecular weight of 27. Each Kcal of stored energy thus results in the formation of $27/114 = 0.237$ grams of biomass (dry weight), if the biomass were entirely cellulose and starch. Of course, this is not the actual case, but the assumption provides a reasonable approximation.

Total available solar energy depends on latitude and amount of cloud cover, and it is not surprising that in the U.S., the greatest annual incidence of solar energy is in the southwest in the states of Arizona, Utah,

Nevada, California, and New Mexico. The annual average energy per day in this area is around $4,610 \text{ Kcal/m}^2 \cdot \text{day}$ compared to the U.S. national average of about $3,930 \text{ Kcal/m}^2 \cdot \text{day}$ (Table I). In June, solar radiation incident in the U.S. Southwest at locations such as Ely, Nevada, Fresno, California, or Tuscon, Arizona, can be as high as $6.775 \text{ Kcal/m}^2 \cdot \text{day}$ (Alich and Inman, 1974).

Calculated Maximum Biomass Production and Reported High Yields

From the foregoing discussion, the upper limit for biomass production can be calculated by multiplying the efficiency, 0.066 times the daily total energy times 0.237. This gives $72 \text{ grams/m}^2 \text{ day}$ for the U.S. Southwest on an annual basis, equivalent to 117 tons per acre yr, or 263 metric tons per hectare year (Table II).

Since optimal conditions of temperature, light absorption, etc. are never found during all seasons for crops in the temperate zone, it is obvious that reported crop yields will not approach closely to this maximum on an annual yield basis. Nevertheless, it is instructive to compare reported high yields and maximum growth rates with the calculated values.

What are the actual rates measured? The figures in parentheses (Table II) are rates during the active growing season, not annual rates. For C-4 plants, these maximum rates range from 138 up to 190 metric tons per hectare per year. The highest (190) is about half the calculated maximum. Similarly, the highest reported annual yield, with sugar cane in Texas, is 112 metric tons per hectare--again about 1/2 the calculated maximum (263) for the U.S. Southwest. The energy storage efficiency for these reported yields suggests that 3.3% to perhaps 5% as the best we can hope for with land plants in the future. One reason for going above the highest reported yields of total dry material (3.3%) is that we should be able to make some improvements if we can provide for year round growth and frequent harvesting of organic matter.

The term C-4 refers to certain plants such as sugar cane that evolved in semi-arid tropical or sub-tropical areas, and which have a special added metabolic pathway (Kortshack et al., 1965; Hatch and Slack, 1966). Some of the intermediate compounds in this pathway are four-carbon acids, hence the term, "C-4." Those plants use some of their light energy to drive this extra path, but their overall energy efficiency in air and bright sunlight is higher than for other plants. This is because, by investing energy in the C-4 pathway, the C-4 plants avoid a wasteful process called photorespiration (Reviewed by Zelitch, 1975) that occurs in other plants (called "C-3" plants) at high light intensities. Photorespiration results in the reoxidation of freshly formed sugar to carbon dioxide. The C-4 plants are more efficient under conditions of high light intensities and temperatures and low CO₂ pressures such as in air (0.03% CO₂) where photorespiration occurs in C-3 plants.

At higher levels of CO₂, photorespiration doesn't occur and some C-3 plants become just as efficient. Even in air, some C-3 plants (e.g. sugar beets, alfalfa and Chlorella) (Table II) produce at very respectable rates during maximum growth. On an annual basis, though, the yield drops down. This is in part because many of these plants are not grown year round. A plant such as sugar cane that grows year round can produce a very high annual yield.

Eucalyptus trees are considered by some as possibly a good choice for energy farms (Alich and Inman, 1974) because they grow rapidly. In general, the C-3 plants produce less than C-4 plants, but keep in mind that this is with air levels of CO₂ and low winter temperatures. Field grown plants are limited by air levels of CO₂, and these levels can drop even below the general atmospheric level of 0.035% at plant height on a still day in a densely planted field with bright sunshine and otherwise optimal conditions for photosynthesis.

Achievement of efficiencies approaching the calculated maxima would require higher levels of CO_2 , especially for C-3 plants.

There is in fact a two-fold effect on photosynthetic rate in such plants with increased CO_2 , since the carboxylation rate increases while photorespiration ceases. The detailed study by Gaasstra (1959) showed that for sugar beet, turnip, cucumber, spinach, and tomato increases in photosynthetic rate of two-fold or more could be obtained by increasing the CO_2 pressures from air levels (0.032%) to 0.13%. A more recent study (Witwer, 1974) (Table III) shows similar increases.

When legumes are allowed to photosynthesize with increased levels of CO_2 there is an increase in photosynthesis and a dramatic increase in N_2 fixation. A three-fold increase in CO_2 level resulted in the amount of fixed nitrogen obtained from the soil decreasing from 220 to 85 Kg per hectare (Hardy and Havelka, 1975)

Energy Content of Biomass

In the calculation of maximum efficiency, it was assumed that for the formation of glucose moieties of cellulose, 114 Kcal per molecular weight of 27, or 4.22 Kcal per gram. To be more precise, somewhat more energy is stored when starch or cellulose is formed from glucose, probably about 120 Kcal per carbon gram atom, or 4.44 Kcal per gram. This may be compared with the Gibbs free energy $\Delta G = 3.80$ Kcal per gram for glucose. The heat of combustion, ΔH , of glucose is 3.74 Kcal per gram (6,732 Btu per pound), while for starch, $\Delta H = 4.18$ Kcal per gram (7,524 Btu per pound). Presumably it is similar for cellulose.

Biomass of course is not pure cellulose or starch. Woody materials commonly contain lignin, resins, and other energy-rich compounds that increase the fuel value. These materials even when considered relatively "dry" contain 10-13% water (Table IV). When correction is made for the weight of water and

for the heat of vaporization of water, the heats of combustion of such -15- substances typically exceed that of starch by 10 to 20%, falling in the range of 4.6 to 5.0 Kcal per gram (8,300 to 9,000 Btu per pound).

Types of Energy Farms

Within the past five years, a number of types of energy farms have been proposed, and some are under active investigation. Several studies have been prepared, and conferences held in which information about suitable plants, yields, economic and energy costs, possible technology, etc. have been compiled. There is a wealth of information in such reports and proceedings about such important facts as land ownership and costs, solar intensity at various locations, fuel values of various types of biomass, and technologies for conversion of biomass. (Alich and Inman, 1974; Schauffler, 1976; Mitsui et al., 1977; Salo and Inman, 1977; Cooper, 1973; Henry, et al., 1976 and 1977, Jewel, et al., 1976; Sessler, 1977)

Types of energy farms may be classified according to the kind of land or water area to be used, type of plants, products, etc. (Table V). Clearly, there will be some overlap among these classifications, and certainly other crops and other systems may in time become important, but already there is considerable diversity among the proposals. Research, experimental plantings, model farms and ultimately the marketplace will determine which will succeed. It is likely that a variety of crops and systems may eventually become established for the various environments and needs, just as is the case with conventional agriculture. As we turn more and more to plants for chemicals and materials in the future (as fossil fuel supplies become more costly), we can expect to see an ever increasing number of specialty plants, such as Guayule grown not for fueling power plants but for replacing fossil fuel used for synthesis. The growth in world population, and the ever increasing demand for food may increase the relative importance of crops that can produce both fuel and food.

a. Crops Requiring Good Farm Land

The greatest emphasis to date has been on land crops that require moderate amounts of water, either as rainfall or irrigation. All of the land plants that have high efficiencies for solar energy conversion fall in this category. Growth of plants adapted to arid conditions is generally achieved by physiological mechanisms which of necessity limit photosynthesis rates.

There is considerable debate at present over whether or not good crop land can ever be used for energy crops. The first criterion used is the economic cost of biomass produced compared with the cost of an equivalent amount of a fossil fuel such as coal. A study carried out recently in California (Sessler, 1977) estimated that forage sorghum might be produced at a cost of \$445 per acre based on 1975 production costs in the Imperial Valley (California) and assuming a yield of 21 tons dry weight per acre (47 metric tons per hectare), the highest yield reported in a seven month test in 1962. This gave a cost of \$21 per ton, and \$1.45 per million Btu, assuming a fuel value of 7300 Btu/pound. This was compared with a reported cost of \$1.50 per million Btu for coal delivered in California. The lowest cost for commercially produced forage sorghum was \$2.20 per million Btu, and costs for all other crops produced commercially in California were higher, generally ranging from \$3 to \$6 per million Btu for promising crops. Clearly, production of biomass for fuel by commercial crops on good land with water in California is only marginally competitive with the use of coal at present, although it is recognized that many assumptions are involved in such calculations.

In another study of a hypothetical energy plantation, also in the U.S. Southwest, where a biomass yield of 30 tons dry matter per acre year was assumed, a production cost of \$9.72 per ton was estimated (Alich and Inman, 1974). Assuming a fuel value of 7,300 Btu per pound in this case also, the cost per million Btu would be \$6.66. In this study, costs were broken down as follows:

Labor and Fuel, 20%; Farm Chemicals, 37%; Farm Machinery, 6%; Irrigation -17- Equipment, 10%; Land, 12%; Water, 13% and seed 2%. Obviously, such costs will vary enormously with geographic and political area. In many parts of the U.S. and the world, water is derived from rainfall rather than irrigation, labor and other costs are different, etc.

It is perhaps reasonable to assume that in general there will be severe economic competition for the use of the land to produce food and fiber rather than biomass for combustion. A study summarized above considered whether biomass could compete with coal as a fuel for the generation of electricity, but it is at least as relevant a question to ask whether biomass production can compete with food production. Of course, the two questions are not completely unrelated, since land costs are determined by the value of the land for food production, and in turn this influences the cost of biomass production for energy. Finally, we should not forget that the massive export of food products from the U.S. is a most important economic balance to the cost of importation of fossil fuels. Probably nations such as the U.S. would not find it economically feasible to produce biomass for energy on good farmland as long as the dollar value of food produced and exported per acre exceeds the dollar value per acre of the produced biomass as a fuel for energy. There may be periods when worldwide weather is relatively good in areas of high agricultural production, and wholesale costs of cereal grains would drop to a point where production of biomass for fuel could compete as an economic use of good cropland. Considering the rapid growth of population in the world, it would seem that in the longer term, demand for food will outstrip even the demand for energy.

b. Silviculture

Henry, et al. (1976) have estimated that there is from 100 million acres (the area of the state of California) to as much as 175 million acres of land

in the U.S. that might be devoted to biomass production without irrigation, -18- excluding land presently reserved for commercial or other uses (farm, urban, commercial forests, recreation, etc.). Also excluded from this estimate was land lacking "suitable site, climate and precipitation characteristics."

Assuming a yield of 9 oven-dry tons of biomass per acre, with a fuel value of 5,600 Btu per oven dry pound of biomass, these authors calculated that 100 million acres could produce 10×10^{15} Btu of fuel (10 quads) per year, about 12% of the 1977 U.S. energy use. Salo and Inman (1977) estimated a currently attainable yield of 4 quad-equivalents and a future yield of 7 quad-equivalents from 10% of the area of the U.S. identified as pasture, forest, and range land.

Henry, et al., 1977, propose the growing of woody deciduous trees in plantations. Species employed are those which sprout from stumps after the tree is cut. Also, clones (live sticks) would be planted rather than seeds. Cottonwood, sycamore, and poplar are examples of the kind of trees to be used. Plantings are to be rather dense--5,000 to 10,000 trees per acre, and growth periods between harvests would be short, from 2 to 4 years. In a study performed by this group for California (Henry, et al., 1977), the most favorable case energy plantation is estimated to produce oven dry biomass at a cost of \$17.67 to \$23.78 per ton, corresponding to a cost of only \$1.03 to 1.38 per million Btu of fuel. We should keep in mind, however, that there is little in the way of field data for the production of high yields of these species of trees in some of the areas being considered. In the "best case" just cited near Redding, California, there is ample rainfall in the winter months, but virtually none in the summer at the time when maximum growing temperatures prevail. This is why irrigation is required for most crops in the U.S. Southwest. Evergreen forests, mostly conifers, are extensive in this area, but are generally limited to mountainous regions with higher elevations. The silviculture plantation without irrigation would seem to be better suited to eastern and

northwestern areas of the U.S. where there is summer rain. Of course, the -19- incidence of solar energy is not as high in those areas. In some parts of the southwest, such as the coastal ranges of California, the limited rainfall may be sufficient to support the rapidly growing species of Eucalyptus, which are able to survive long dry summers.

Energy Crops in Semi-Arid and Arid Regions

It is an unfortunate fact (from the standpoint of energy farming) that the regions of the earth with the highest solar incidence are also the driest. In the U.S., a large area including most of Arizona, southeastern California, and western New Mexico has an annual solar incidence of 500 langley (500 calories per cm^2/day , 1,830 Btu per ft^2/day). The 450 langley or higher region includes additional large areas of California, Nevada, Utah, New Mexico and Texas (Alich and Inman, 1974). Of perhaps even greater importance, the western part of this region has many areas with 300 days or longer growing season--essentially year round. Given irrigation and good soil, as in the Imperial Valley of California, very high yields of crops are possible. Unfortunately, the possibilities for irrigation of additional area in this region are remote, requiring transfer of water into the area from other water basins thousands of miles away.

For this reason it is of interest to consider plants native to semi-arid areas and deserts which do not require irrigation. Not surprisingly, many such plants have evolved very long root systems for collecting water from considerable depth and over large areas. They have also developed physiological mechanisms for avoiding water loss. Such mechanisms can limit photosynthetic productivity. For example, plants with thick waxy cuticles and with stomata that can be closed during the heat of the day are not able to take in carbon dioxide rapidly; thus photosynthesis is limited. Many desert plants exhibit

Crassulacean Acid Metabolism (CAM) in which CO_2 is taken in through stomata⁻²⁰⁻ open at night and incorporated by a carboxylation of phosphoenolpyruvate (PEP), a three carbon acid, to give dicarboxylic acids with four carbon atoms. During the night this PEP is made from sugars stored in the plant. In the daytime, the stomata are closed, limiting water loss but also CO_2 ingress. The four carbon acids are decarboxylated, the CO_2 released is reduced to sugars by photosynthesis, and the PEP is also reduced back to sugars. Not all desert plants have CAM, but for most, survival requires mechanisms that limit photosynthetic productivity.

Nevertheless, it is worthwhile to consider the growing and harvesting of plants in the dry regions. For one thing, there is much governmentally controlled land in this region, and land costs for unirrigated land are generally low. Two quite different possibilities suggest themselves for energy farms in arid to semi-arid regions. The first, which already is practicable in some cases is the growing and harvesting of plants which produce chemicals or other useful materials of high economic value and replacing materials now derived from fossil fuels. The second, more distant, prospect, is to employ some form of covered agriculture on a very large scale to obtain photosynthetic conversion efficiencies far beyond any achievable with conventional agriculture. While this idea is rather visionary at the present time, there are so many advantages to such a system, discussed later, that it seems realistic to consider it seriously and to begin research leading to the eventual development of regional covered agriculture.

a. Natural Environments

Several types of plants well adapted to semi-arid environments and capable of producing useful chemicals appear to have considerable potential. Guayule has been raised in Mexico, and at times in the U.S. for many years as a source of natural rubber (NAS, 1977). From 1910 to 1946, the U.S. imported more than

150 million pounds of guayule rubber from Mexico. Much of this came from wild stands, which eventually could not support such sustained harvesting. During the 1920's, large plantations were planted in the U.S., and rubber from these plantations competed with Hevea rubber from Indonesia. Such developments stopped during the Depression in the 1930's, and in 1942 when the Japanese cut off the supply of Indonesian rubber, it was necessary to launch a massive new project in guayule production in the U.S. and in Mexico. Over three million pounds of resinous rubber were produced. By 1943, synthetic rubbers were being produced from fossil fuels, and at the end of World War II these synthetics plus large supplies of Hevea rubber which became available from Indonesia again removed the necessity for producing Guayule rubber. The leased farmland in the U.S. was needed for other crops, and in 1946, 26,000 acres of guayule, containing an estimated 21 million pounds of rubber were burned.

In Mexico, however, guayule development has continued, and agencies of the Mexican government are embarking on rubber production from guayule plants growing wild over about 4 million hectares (10 million acres). There is considerable technology available for the production of Guayule, harvesting, extraction and deresination. From work done in Manzanar, California in 1942-44, it is clear that good yields of Guayule can be grown in semi-arid regions without irrigation. Thus, Guayule production may serve as a model for the production of other dry land plants capable of supplying useful chemicals. Yokayama (1977) has been able to increase the rubber content of harvested guayule by a factor of 2 to 3 by treating the 4-week old seedlings with 5000 ppm each of 2-(3,4-dichloropenoxy)-triethylamine and 2-diethylaminethanol plus a wetting and harvesting three weeks later.

Another example of a specialty dry land plant is Jojoba. This plant is now being grown on Indian reservations and in other areas in Arizona as a source of a valuable lubricant with properties which allow it to replace oil obtained from whales.

The direct production of hydrocarbons as liquid fuels and chemical feedstocks by the extraction of latex bearing plants of the Euphorbia family has been proposed and is being studied by Calvin (1976, 1977). Test plots of several species are now being grown in southern California. Preliminary yield figures suggest that the hydrocarbon content of the biomass produced could supply as much as 5 to 10 barrels of oil per acre per year. These species can grow on semi-arid lands in the U.S. Southwest. Such direct production of liquid fuels is very attractive since it bypasses the conversion of biomass to heat and then to electricity, with the resulting losses in efficiency. Moreover, the time will come when supplies of petroleum will be exhausted, and it may well be necessary to obtain chemical feedstocks from plants as a replacement. Even if that time is 50 years in the future, it is hardly too soon to begin to develop the technology to guarantee continued supplies so vital to modern civilization. Preliminary analyses of the hydrocarbon and lipid materials in the latex of plants suggest a wealth of useful chemicals may become available (Calvin, 1977).

Another dry-land plant which has been suggested as a useful source of materials is the common Mesquite, found growing wild in many parts of the U.S. Southwest (Felker and Waines, 1977). The pods of this plant have a high food value and were used by American Indians as an important dietary supplement. Possibly this plant could be used to supply both fuel and food.

b. Artificial Environments: Covered Agriculture.

One way to take advantage of the high solar incidence and low land cost of the U.S. Southwest would be to employ covered agriculture (Bassham, 1975, 1976, 1977a, 1977b). The proposal is to cover large areas with high greenhouses. The canopies would be made from tough, sun-resistant plastic. The structures might be 1 Km² in area and 300 meters high (at maximum extension), perhaps with a capacity to go up and down daily. A requirement would be to maintain growing temperatures year round. Under this canopy would be grown a high-

protein forage legumes such as alfalfa. It would be harvested periodically during the year, leaving after each harvest enough of the plant to produce quickly a good leaf canopy. Growth would be year round. The atmosphere would be enriched in CO_2 and neither water vapor nor CO_2 would be allowed to escape, although some CO_2 would diffuse through the plastic canopy.

While there are serious problems to be overcome with this system (economic, engineering, and physiological), there are a number of important advantages.

1. With year round growth and CO_2 enrichment (photorespiration eliminated), maximum photosynthetic efficiency should be possible. At a 5% conversion efficiency the yield would be 200 (89 tons/acre-year) metric tons/hectare-year. The whole plant except for roots would be harvested and used.

2. Most or perhaps all of the nitrogen requirements in legumes would be met by N_2 fixation, due to stimulation at these high photosynthetic rates. Enrichment with CO_2 can result in a five-fold increase or more in N_2 fixation in the root nodules of legumes (Hardy and Havelka, 1975).

3. Alfalfa grown under optimal conditions has as high as 24% protein content based on dry weight. It is feasible and economic to remove a part of this protein as a high value product using the methods developed at the Western Regional Research Laboratory of the U.S. Department of Agriculture at Albany, California (Spencer, et al., 1971). The residue is a feed for ruminants. Most of the feeding of expensive cereal grains to cattle could be replaced by this alfalfa, and the cereal grains could be sold for human nutrition in the U.S.A. and abroad where there is a rapidly growing market. The protein extract of the alfalfa has a high value as animal (poultry, for example) feed. An interesting alternative is to convert part of it to a protein product for human consumption (Edwards et al., 1975). Nutritionally it is as good as milk

protein (Stahmann, 1968) and far superior to soy protein. From the 15 -24-metric tons of dry matter removed as juice from the leaves, it might be possible to recover 5 tons of protein, worth \$5,000 at \$1 per Kg.

4. Land with relatively low value at present because of lack of water could be used because of water recycling. With water vapor containment, only a few percent of the present irrigation requirements for desert land would have to be met.

5. Carbon dioxide could be obtained from flue gasses from fossil fuel power plants, thus decreasing the amount of such CO_2 discharged to the atmosphere. Projected increases of CO_2 in the atmosphere when fossil fuels are all burned is a matter of considerable concern with respect to the future temperature and climate of the earth (Revelle, 1977). Alternatively, CO_2 from CO_2 gas wells might be used (Witwer, 1974).

6. The modular nature of the system would help in the prevention, containment, and elimination of plant diseases.

7. Once the needs for cattle feed are satisfied, additional capacity could supply fuel for power plants. The material left after removal of some of the protein could be burned in the power plants along with the fossil fuels. Ash might be recycled as mineral fertilizer. Calculations suggest that all the electric power needs of California in 1995 might be met by an area of $10,000 \text{ Km}^2$, or 1 million hectares (Bassham, 1977). At 5% conversion efficiency, the energy stored in biomass in the U.S. Southwest would be $9.77 \cdot 10^5 \text{ Kw hr/hectare year}$ (3,332 million Btu per hectare year, worth \$5,000 per hectare; or \$2,000 per acre, at \$1.5 per million Btu). Assuming 20% removal for protein extraction and plastic production, 30% efficiency for conversion of the remaining 80% of the biomass to electrical power, and a net sale of 80% of the electricity, (with 20% used to run the farm) power sold would be $1.88 \cdot 10^5 \text{ Kw-hr per hectare yr}$. An area 100 mi

x 100 mi, with 80% devoted to covered farms ($8,000 \text{ mi}^2 = 20,720 \text{ Km}^2$) would be able to sell 3.89×10^{11} Kw-hr per year. Major utilities sales of electrical power in 1975 were $1.39 \cdot 10^{11}$ kw-hr and are projected to be $2.67 \cdot 10^{11}$ Kw-hr in 1995. The U.S. requirement for electrical power should be about 10 times as large as for California.

Of course, there are many problems; some very serious. The greenhouse effect would have to be controlled, perhaps by allowing daily expansion of the canopy. Contraction of the canopy at night would tend to maintain a greater temperature gradient across the plastic between inside and outside, allowing faster heat transfer out through the plastic. Expansion by day would reduce the daytime temperature excursion. The plastic would have to be tough, sun-resistant, not too permeable to CO_2 , perhaps capable of synthesis from materials grown under the canopy, and inexpensive. In fact, use of fossil fuels to synthesize the plastic could be avoided by making the plastic from some of the solid biomass residue, after protein extraction. Cellulose could be converted to glucose by treatment with enzymes from the fungi (Wilke, 1975) and the resulting glucose could be fermented to give ethanol. Ethanol in turn could be converted to ethylene and thence to polyethylene or other suitable plastic. The insoluble material of plants also contains polymers of xylose. After acid hydrolysis, the xylose can be converted to furfural (Sheppard, 1977) a possible starting material for other plastics.

There are other problems, but they may all be solvable. These very serious engineering and economic problems are not to be lightly dismissed, but a discussion of possible solutions will require considerable engineering study to be meaningful.

An extensive discussion by Dalrymple (1973) of the use of greenhouses in various countries clearly shows that the economic problem is quite severe:

food production in greenhouses has both high capital and labor costs. Nevertheless, greenhouse agriculture is being practiced in a number of countries, though of course only for very high value crops such as lettuce, tomatoes and cucumbers. Oil rich nations such as Kuwait and Abu Dabi have highly sophisticated greenhouse units utilizing desalted water for irrigation.

Since covered agriculture in very large greenhouses, using inflated plastic is a fairly new technology, limited to a few largely experimental applications, it is reasonable to expect that considerable cost reduction could be achieved on a large scale. The cost of the production of plastic may turn out to be the most severe economic obstacle. This is why much will depend on finding an inexpensive process for producing plastic from biomass. Conceivably, such a scheme may not become feasible for many years. Considering the advantages of the system if it becomes feasible, it seems worth further study.

Aquatic plants have several advantages for energy farming: they require no irrigation or rainfall, temperatures of bodies of water tend to vary less than land temperatures, light absorption can be nearly complete, and efficiencies quite high, and mineral nutrients often concentrate in lakes, rivers, and ponds due to runoff from the land, so that fertilizer would not have to be supplied. The areas available, are, however, somewhat limited so that the total contribution to the energy needs of the country may not be so large. Nevertheless, regional impact of energy produced from aquatic plants in areas with large or numerous bodies of fresh or brackish water could be considerable.

a. Ponds with Algae

A critical analysis of bioconversion with microalgae has been made by Oswald and Bennemann (1977) who contend that there is great promise in the idea of growing algal biomass using the nutrients in sewage and then harvesting and digesting the biomass for methane production. The basic plan is to use waste water from municipal sewage treatment plants. The oxidation ponds of such plants already commonly employ algae at an early stage of sewage treatment to generate oxygen by photosynthesis in order to speed the oxidative degradation of organic compounds by bacteria. The effluent from this stage, rich in inorganic nutrients, is then fed into ponds containing the algae to be harvested.

Harvesting the algal biomass has proved to be the most difficult stage of the process, since algal harvesting methods are generally not economic. Oswald and Bennemann propose to solve this problem by species control leading to the production of filamentous species such as Spirulina. These filamentous algae can be removed by filtration or settling. The control of species in algal ponds is a complex undertaking, and considerably more work needs to be done before such control will be reliable and economic.

Production of algal biomass promises to be economic only in the context of waste water treatment where there is an economic credit for the disposal of the sewage and the recovery of useable water. The latter appears to be particularly important in areas such as northern Mexico and the U.S. Southwest where water supply is very limiting to industry and agriculture. Pond construction costs are high for ponds of uniform shallow depths required for efficient photosynthesis. It appears that, while algal ponds may be useful and economic for the treatment of waste water, their total impact on energy needs will be rather limited.

b. Lakes, Rivers, and Estuaries

In many warm regions, waterways, lakes, rivers, canals, etc. are subject to infestation by "weeds," plants growing in or on the surface of the water. A good example is the water hyacinth, Eichornia crassipes Solms, a perennial, mat-forming, floating aquatic plant found in the southeastern U.S. and in California. These plants reproduce vegetatively and grow very rapidly. In growth tests (Yount and Crossman, 1970) an average of 16 tons dry weight per acre/year have been produced, and maximum growth rates of 780 pounds per acre/day have been measured, equivalent to 87 tons per acre/year (195 metric tons per hectare/year), if such maximum growth rates could be extended year round. These rates compare favorably with the maximum rates for land plants shown in Table II. It is proposed that these plants could be harvested and the biomass could be used in fermentors to produce methane.

Marine: Giant Kelp

The oceans of the earth offer vast areas for the collection of solar energy by plants, if an economic technology could be developed to grow and harvest plants in that environment. Much of the open ocean is, however, much more productive than the land of biomass formation through photosynthesis.

The surface layers of the ocean are deficient in mineral nutrients, especially phosphate, except in areas of upwelling of waters from the ocean depths, and in the continental shelf areas receiving runoff from the land. Those areas that are highly productive are the worlds' fisheries and could hardly be dedicated to plant growth for energy. Thus, some scheme is needed whereby the surface layers could be enriched by artificial upwelling of the deep waters which are rich in nutrients.

One rather ambitious proposal is to grow giant kelp, Macrosystis pyrifera, on floating grids (Wilcox, 1976). Small transplants of the kelp are attached to the grids at close intervals, and growth is observed. At the center of each grid system, deep water is to be raised to the surface through a pipe and a pump driven by wave action.

Early experiments done with surface water flowing past the grid showed that the plants grew slowly (North, 1976). Batch experiments with water from deep layers gave variable results, suggesting a buildup of inhibitors. Studies with flowing deep water and test plants gave good growth. In later studies, the deep water was obtained as planned using a wave-energized pump and a 300 meter vertical pipe. At times a growth of 14% per day (based on biomass at the beginning of the day) was observed. The results even with deep water were variable, however, and it appears that further research on growth requirements and possible inhibitors of this organism will be required (North, 1976).

Like some of the other proposals for energy farms already discussed, the growing and harvesting of huge amounts of biomass over vast areas of the ocean would appear to be fraught with a number of problems, both physiological and engineering. There is the question of whether or not enough deep water can be pumped to support rapid growth over a large grid, the problem of destruction of the facility by storms, the economics of harvesting and conversion of biomass to methane (possibly at sea), the transport of the methane to land,

etc. While this type of marine energy farm is an interesting and exciting concept, it appears to be a long way from fruition.

Biomass Residues from Agriculture and Forestry

Although this article is focussed on the purposeful production of biomass for energy and chemicals, it should be noted that there are substantial quantities of biomass produced in connection with conventional agriculture and forestry that might be available as energy and material resources. These potential sources of biomass are receiving considerable attention as possible contributors to our energy needs in the near future. The harvesting of specific plant organs such as seeds and roots leaves the rest of the plant: stalks, leaves, cobs, etc. Particularly attractive are residues produced after the plant material has been collected at a central point--residues left in the field are apt to be too costly to collect, and in some cases are deemed to be of more value when turned back into the soil. Examples of collected residues are rice hulls, bagasse (the residue from sugar cane after sugar extraction), manure from cattle feed lots, and sawdust, wood scraps, etc. at lumber mills. Of course, such materials in many cases have already been put to other economic uses and are not available for energy or gas generation. Some are available, and their conversion to energy or gas is already underway or imminent. In Hawaii, bagasse is burned to heat the boilers in the can-processing plants. Fuel gas from fermentation of animal wastes seems feasible and will make a useful local contribution (Wise et al., 1977). Overall, there does not appear to be enough "wastes" or residues available from conventional agriculture to make a very large contribution to our total energy needs. Wherever there is a waste disposal problem, and economic credit can be gained from the disposal, conversion to energy or gas is particularly attractive.

Given the enormous energy needs of an industrialized nation such as the U.S., the diffuseness of solar energy, and the relatively low efficiency of conversion of solar energy to biomass, it is not likely that energy farming will ever satisfy the major part of our energy demands. Nevertheless, energy farms could make an important contribution to our energy needs, could have a major impact in some areas, and could produce chemicals to replace those now derived from fossil fuels. Economic energy farms may prove to be those which produce both energy and either chemicals or food. The maximum efficiency of solar energy conversion by green plants on a long term basis is about 6.6%, and some plants grown under conventional agricultural conditions have reported efficiencies of about 3 to 4%. In the U.S. Southwest, where solar radiation is high, a 5% efficiency would produce about 200 metric tons dry biomass per hectare-year, or 89 tons per acre/year. A fast growing crop on good farmland, such as sorghum might produce 15 to 21 tons per acre-year, and the fast growing woody crops, such as certain hardwoods produce in the range of 4 to 9 tons per acre/year. Eucalyptus, however, has been reported to produce as much as 24 tons per acre/year.

Economic studies suggest that it is marginally attractive to grow energy crops on good farmland with either summer rainfall or irrigation. Probably a higher economic use for such land will remain for the production of food for domestic use or for export to pay for imported fossil fuels (while they last). There are reported to be large areas of marginal land with sufficient rainfall to support energy farms in the U.S. In the U.S. Southwest, which has the greatest incidence of solar energy and the longest growing season, however, water supply is severely limiting. In this area, it may be more feasible to grow "dry-land" plants, capable of producing useful chemicals and liquid fuels, even though their solar energy-conversion efficiency is not expected to be as high as for fast growing plants. A long-

range alternative may be to create an artificial environment through the use of plastic canopies which would conserve water, permit CO₂ enrichment and consequently enhance photosynthetic efficiencies (and greatly increased nitrogen fixation in legumes), as well as having other advantages. It is too early to say whether such system could ever be economic or practical at this time.

Aquatic plants offer further possibilities. These include algal ponds for waste water treatment, harvesting of water hyacinths and perhaps other water "weeds," and even growing kelp in the ocean. Most such proposals require further study and engineering and economic evaluation.

Conversion of existing crop and forest residues, where already collected or economic to collect is attractive as a source of biomass for energy, but this source is limited.

TABLE I
SOLAR ENERGY AT EARTH'S SURFACE IN U.S.

	Btu/ft ² day	cal/cm ² day	Kcal/m ² day	watts/m ²
Average (annual basis)	1,450	393	3,930	190
U.S. Southwest (annual basis)	1,700	461	4,610	223
U.S. Southwest (summer)	2,500	678	6,775	329

From Alich and Inman (1974)

TABLE II

-33-

MAXIMUM PHOTOSYNTHETIC PRODUCTIVITY AND MEASURED MAXIMUM YIELDS
IN SELECTED PLANTS

	gmm^2/day	tons/ acre yr.	metric tons/ hectare yr.
Theoretica. max. (Table II)			
U.S. Average annual	61	100	224
U.S. Southwest ave. ann.	72	117	263
U.S. Southwest, summer	106	172	385
Maximum Measured			
C-4 plants			
Sugar cane	38	(62)	(138)
Napier grass	39	(64)	(139)
Sudan grass (Sorghum)	51	(83)	(186)
Corn (Zea mays)	52	(85)	(190)
Non-C-4 plants			
Sugar beet	31	(51)	(113)
Alfalfa	23	(37)	(84)
Chlorella	28	(46)	(102)
Annual Yield			
C-4 plants			
Sugar cane	31	50	112
Sudan grass (Sorghum)	10	16	36
Non C-4 plants			
Alfalfa	8	13	29
Eucalyptus	15	24	54
Sugar beet	9	15	33
Algae	24	39	87

From Alich and Inman (1974)

TABLE III
RATE OF PHOTOSYNTHESIS AT AIR LEVELS AND ELEVATED LEVELS OF CO₂
 (milligrams CO₂/dm² hour)

Plant	Air	Elevated CO ₂
Corn, grain, sorghum,		
Sugar cane	60-75	100
Rice	40-50	135
Sunflower	50-65	130
Soybean, sugar beet	30-40	56
Cotton	40-50	100

From Witwer (1974)

TABLE IV

HEATS OF COMBUSTION OF SOME BIOMATERIALS

(From Alich and Inman, 1974)

Plant	Part	% water	Btu/lb	Btu/lb without water (calc.)	Kcal/gr without water (calc.)
†Beech (<i>Fagus</i> sp.)	wood	13	7,506	8,636	4.80
†Birch (<i>Betula</i> sp.)	wood	12	7,578	8,617	4.79
†Oak (<i>Quercus</i> sp.)	wood	13	7,182	8,263	4.59
†Oak (<i>Quercus</i> sp.)	bark	7	8,139	8,755	4.87
†Pine (<i>Pinus</i> sp.)	wood	12	7,956	9,048	5.03
†Sugarcane	bagasse	12	7,281	8,281	4.60
†Buckwheat (<i>Fagopyrum esculentum</i>) hulls		10	7,594	8,442	4.69

†From Alich and Inman (1974).

* Starch	7,524	4.18
*Glucose	6,732	3.74
*Terpeneol	17,176	9.54

*From Handbook of Chemistry and Physics (1960).

TYPES OF ENERGY FARMS

Terrestrial

Moderate of High Rainfall or Irrigated

Field Crops (generally requiring good farm land)

Forage Crops: Sorghum, silage corn, Sudan Grass

Kenaf

Sugarcane

Sunflower

Alfalfa

Siviculture (generally can use marginal crop lands)

Eucalyptus

Hardwoods: Alder, poplar, sycamore, cottonwood, etc.

Conifers: pine, etc.

Semi-arid and arid (desert)

Natural Environment (cellulosic fuel plus)

Rubber producing: Guayule

Special lubricant: Jojoba

Hydrocarbons: Euphorbia species

Carbohydrates: Mesquite

Artificial Environment: crops with both fuel and high value food (e.g. alfalfa, etc.)

Ponds and Fresh-water or Brackish-water Bodies

Ponds: Unicellular and filamentous algae and blue green algae, especially when combined with sewage treatment

Lakes, Rivers and Estuaries: Water Hyacinths, etc.

Marine

Giant Kelp (Macrocystis)

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