AN ENVIRONMENTAL CRITIQUE OF
SOLAR POWER BY BIOCONVERSION METHODS*

MASTER

by

CHARLES E. CALEF

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

BIOMEDICAL AND ENVIRONMENTAL ASSESSMENT DIVISION
NATIONAL CENTER FOR ANALYSIS OF ENERGY SYSTEMS
BROOKHAVEN NATIONAL LABORATORY
ASSOCIATED UNIVERSITIES, INC.
UPTON, NEW YORK 11973

*Research carried out under the auspices of the United States Energy Research and Development Administration under Contract No. EY-76-C02-0016.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

As supplies of fossil fuels, especially the desirable oil, gas, and low sulfur coals diminish at an accelerating rate, it is natural to consider replacing them with energy derived from the sun. One solar technology to which people are being attracted is the oldest of all: harvesting and burning plant tissues or combustible liquids synthesized from them, a process that has been called bioconversion. There is a pervasive underlying feeling in this country summed up in the bumper sticker that exhorts us to "Split wood not atoms", that bioconversion is a desirable, clean, renewable source of energy that we can eventually fall back on when our present fuels become unavailable. Serious studies of the potential of New England's forests to supply energy for the northeast have been made (1,2). At a meeting of the American Chemical Society on "viable alternate energy sources" last spring the Inter Technology Corporation described their plans for plantations to fuel military bases. During the energy crisis winter of 73-74 state and national forests were opened to individuals wishing to cut firewood. State forests in New York are still open for such purposes upon payment of a small fee. Wood burning stoves are enjoying a comeback.

The idea of returning to a wood or wood products burning economy seems retrogressive at first, but proponents of rejuvenating this dying practice point to its many attractive features.

1. It is a solar technology, depending only upon the inexhaustible radiant energy from the sun.

2. Unlike most other solar technologies, it is proven. The photosynthetic apparatus of the green plant cell has evolved over the past hundreds of millions of years into an extraordinarily complex and efficient convertor of sunlight into energy stored in chemical bonds of carbohydrate molecules.

3. The "hardware" of the technology, i.e. the plant, does not require large quantities of exotic, rare and sometimes toxic materials as do the more sophisticated of man's solar conversion contrivances. In the parlance of the systems engineer, plants are not "materials intense".

4. The plant, unlike man's machines is self-replicating, and does not cause pollution when it is thrown away. It is claimed that the plant, even when burned, which is its fate in the practice we are now discussing, produces relatively little air pollution.

Given all these considerable advantages one tends to overlook the shortcomings of the technology which form the subject of this paper. The failings are of two types. First, man's present world-wide use of energy is so staggeringly huge that it is inconceivable that bioconversion can supply more than a tiny fraction of the total. Its contribution will be limited by lack of some very basic resources: land, water and nutrients. Second, given these limitations on the size of bioconversion's total energy contribution, even modest size application of the process may damage valuable biotic communities and other natural resources, especially soils.

The Energy Plantation

Two general approaches to acquiring biomass for conversion exist. Naturally growing biomass as in forests may be harvested, or special energy farms may be created where the crop, selected for its high production is used as a fuel or feedstock rather than as a food. Higher hopes are held for the latter alternative--the energy plantation--because, it is argued, with man controlling the species composition, the nutritional value of the soil, the times of harvesting and providing for adequate moisture, a much higher productivity will be realized than is found naturally.

One hypothetical energy plantation has been described as follows (3).

A biomass plantation would be relatively large in terms of conventional agriculture, covering perhaps an area of 15 miles square (144,000 acres). A facility for converting the biomass to usable energy (e.g. [a 60 megawatt] electric power plant, gasification plant) would be located at the center of the plantation. The biomass crop would consist of a conglomerate of species selected primarily on the basis of high biomass yield... Conventional farming practices would be used where appropriate or modified to exploit either production potential or energy-costs savings to the fullest extent possible. Examples of such modifications would be the use "no-till" methods, the harvest of roots and crowns in addition to aerial plant parts (annual crops), and the use of understory...crops. Yields of 30 tons of dry biomass per acre-year would be anticipated, providing an annual energy harvest of 450 million Btu per acre.

The plantation operation ideally would produce three crops of annuals per year....Before planting, the fields would be cleared of weeds by the application of an herbicide to eliminate competition for water and plant nutrients. Planting the biomass crop could be combined in one operation with the application of fertilizer. At an appropriate interval after planting, a sidedressing of fertilizer would be applied. The biomass crop would be harvested by means of self-propelled combines, which would chop the biomass into small pieces to facilitate drying....Aircraft would apply insecticides and fungicides when and where needed.

It is assumed that an average of two such operations per acre-year would be needed across the entire plantation. In certain instances it would be feasible to apply these pesticides with the irrigation water.... Irrigation water would be applied at two-week intervalsThe plantation would be operated seven days per week, 12 hours per day. Irrigation activities would be performed 24 hours per day.

There have been suggestions to exploit naturally growing biomass for fuel, notably by the States of Maine and Vermont which have low populations and large forests. Similarly agricultural by-products such as stalks, chaff and animal droppings have been considered suitable for conversion to available energy.

The U.S. Energy System

The United States acquire energy principally from fossil fuels, with minor contributions from hydropower and nuclear sources. Figure 1 shows, in very simplified terms, the source and fate of energy within the system (4). Of the 72.16×10^{15} Btu that fuel the system, 56.5 quadrillion, or 78% of the total eventually goes to end uses such as heating homes or making steel. Of the twenty-two percent lost in various transportation and processing steps, eighteen appear as waste heat in the generation of electricity.

Of interest to us at the moment is not the details of the energy system, but rather its magnitude. In particular, the huge number of Btu entering the system, 72.16×10^{15} , is impossible to conceptualize unless cast into terms within our experience. We can accomplish this and, at the same time, give a feeling for bioconversion's contribution to the country's energy supply by

Figure 1. Reference energy system for the year 1972. Figure from reference (4).

asking what resources would be necessary to supply this amount of energy purely by the familiar and natural means of photosynthesis.

Bioconversion as the Sole Supplier of U.S. Energy Needs

Plants, by absorbing radiant energy of the sun and using this energy to drive chemical syntheses, build up a store of organic compounds as plant tissue or biomass. The energy content of these compounds, that is, the energy that is released upon their combustion, usually expressed as kilogram calories, (Kcal) is called net primary production. The rate of net primary production depends on the types of plant species and the hospitability of the environment. Productivity rates are also often expressed in weights, such as 30 tons per acre-year. Some net primary production rates are listed three different ways in Table 1.

Land requirement. To return to our problem of calculating the resources necessary to supply U.S. energy needs by photosynthesis, we read from Table 1 that 1540 Kcal/m²-yr is the net productivity of the cool temperate forest, the type of forest growing in New England and seriously cited as a source of energy for Maine and Vermont. At this rate of productivity, how much land would be required to produce the 72.16 quadrillion Btu = 18.18 x 10¹⁵ Kcal used annually in this country? The arithmetic:

$$\frac{18.18 \times 10^{15} \text{ Kcal}}{1540 \text{ Kcal/m}^2\text{-yr}} = 11.8 \times 10^{12} \text{ m}^2\text{/yr}$$

leads to a land requirement of 2916 million acres or 4.56 million square miles. The area of the U.S., including Alaska is roughly 3.68 million square miles. So, were the entire area of the country covered by this type of forest and each year its total net productivity funneled with 100% efficiency into the U.S. energy system we could not produce as much energy as is now being consumed. The situation is hardly more auspicious for the more productive plants in Table 1. Even sugar cane, one of the most productive of all plants, would have to be intensively grown over 148 million acres, or 6% of the total land surface area to provide the annual Btu used in this country. This is an area only a little smaller than Texas.

Water requirement. The amount of water that must be added to soil by irrigation or rainfall to support plant growth depends on the water holding capacity of the soil, the local climate (temperature, humidity, distribution of precipitation during the year) and the plant's physiological tolerances. Five acre-feet per acre-year is a typical water need for crops grown intensively in the southwestern U.S., an area suggested as ideal for an energy plantation because of its high insolation rate and vast areas of public land available as a government subsidy. (Actually seven acre-feet must be added, because some water runs off or percolates downward out of reach.) Multiplying the sugar cane plantation acreage in Table 2 by five feet, we obtain 740 million acre-feet, water consumption. By comparison the mean annual discharge of the Colorado River, the largest river in the region,

Table 1

<u>Plant community</u>	<u>Productivity</u>		
	Kcal/m ² -yr	10 ⁶ Btu/Acre-yr	Tons/Acre-yr
Cool temperate forest	1540	25	1.5
Old Field	4950	79	5.0
Corn Field	6500	104	6.5
Scots Pine plantation	7670	123	7.7
Tropical forest	18000	289	18.0
Sugar Cane plantation	30000	450	30.0

Conversion factors: Btu/lb. x 0.556 = Kcal/Kg

Kcal/m² x 16058 = Btu/Ac

Kcal/m² x 0.001 = Tons/Ac

Note: rounding errors cause some numbers to slightly disagree when calculated by different paths. Figures from Refs. 3, 5, 6.

Table 2

Plant community	Productivity Kcal/m ² -yr	Millions of Acres	Millions of Square miles	% of US land area
Cool temperate forest	1540	2916	4.56	124
Old field	4950	914	1.43	39
Corn field	6500	692	1.08	29
Scots pine plantation	7670	593	0.93	25
Sugar cane plantation	30000	148	0.23	6

Total US energy use in 1972 = 72.16×10^{15} BTU = 18.18×10^{15} Kcal.
 Total land area of US, including Alaska = 3,675,545 square miles.

Table 3

<u>Fertilizer</u>	<u>Millions of tons</u>	<u># of rail cars</u>
K_2O	7.5	125,000
NH_3	5.0	83,000
P_2O_5	27.5	458,000

under natural conditions is 13.5 million acre feet.

Nutrient requirements. Everyone knows that plants require for growth, in addition to sunlight and water, relatively small amounts of nitrogen, phosphorous and potassium, as well as other elements and organic substances in trace quantities. On the scale of supplying national energy needs by bioconversion, these mineral requirements become huge.

It is known (7) that a 50 ton cane crop removes from the soil 75-90 pounds of N, 50-60 pounds P_2O_5 , and 150 pounds K_2O . To produce 18.18×10^{15} Kcal at 4 Kcal per gram of cane requires 5 billion tons of cane. Using K_2O as an example, we have:

$$\frac{50 \text{ tons cane}}{150 \text{ lbs } K_2O} = \frac{50 \times 10^8 \text{ tons cane}}{150 \times 10^8 \text{ lbs. } K_2O}$$

Fifteen billion pounds of K_2O fertilizer must be delivered to the fields every year. If we take into account harvest inefficiencies this quantity would have to be increased. Table 3 lists some other annual nutrient requirements.

To give some idea of these quantities we can calculate the annual number of 60 ton hopper cars required to deliver all these fertilizers. The total is 666,000 cars or about 18 trains per day discharging their contents into our hypothetical super-plantation.

1000 Megawatt Equivalents

Clearly no one is suggesting satisfying all our energy requirements by photosynthesis but there is great interest in

generating sizable amounts of electricity by burning bio-fuels. For this reason we calculate the resource requirements for fueling a 1000 megawatt (MW) electric power station, a huge facility, but nevertheless the size that is now favored. It is easy to show that a 1000 MW plant working at a load capacity of 80% and an efficiency of 33% requires about 72×10^{12} Btu of fuel every year. This is almost exactly one-one thousandth of the total U.S. energy used each year. Therefore we may obtain the resource requirements of a biomass burning 1000 MW plant by merely multiplying all the figures in the preceeding tables by 0.001. The land requirement ranges from 4560 square miles for the cool temperate forest, an area almost the size of Connecticut down to about 230 square miles for the intensively grown and harvested sugar cane plantation. Water requirement, assuming five acre-feet/acre-year for a sugar cane powered electric plant would be 740 thousand acre feet, or about 74 times the amount consumed in cooling the plant. Annual nutrient requirements, were cane the crop, would be, ammonia-5,000 tons, phosphate-27,500 tons, potash-7,500 tons.

Discussion of the Magnitude Problem in Bioconversion

We have calculated the minimal resource requirements for growth of different plant communities for two cases: 1- the resulting biomass will supply all our energy requirements, 2- the biomass will be used to fuel a single 1000 MW electric plant. If the reader will consider the resource requirements of the first case, he should immediately see that to supply these

resources is impossible; they are simply too huge. The energy consumption of the U.S. at present is roughly the same as the net primary production of the country as a whole (8). In this case all the productivity of the country, that is from all the plants covering the entire land surface, would have somehow to be harvested each year. As this is unacceptable and impossible intensive plantations are suggested as a means of lowering the land requirement. But is 6% of the U.S. land surface (what would be required for sugar cane plantations of sufficient size) really reasonable? Once we concentrate productivity then the other resources also become limiting. Intensive agriculture demands that man supply resources that are naturally dilute. It is unfeasible to deliver the required millions of acre feet of irrigation water per year to our plantations. Similarly problems of supplying the required 666,000 rail cars of fertilizer appear insuperable.

Given the size of these resource needs the reader may well wonder that naturally growing plants actually use them each year with no "environmental impact". It may seem unimaginable that the equivalent of half a million boxcars of nutrients can be processed by plants, or that Mississippi sized rivers of water pour into vegetation, but such is the case. The process goes unnoticed because it is diffuse. Plants are everywhere, capturing sunlight, pumping water and cycling nutrients. Natural growth may be slow, but as it is everywhere it sums to a mighty natural

force in the world.

It can be argued that the resource requirements for a biomass fueled 1000 MW plant though much less are no more reasonable than those for supplying all our power. We would only need a thousandth of the resources, but then we would get only a thousandth of the power. The natural resource requirement per kilowatt is roughly constant. One critical factor in power plant siting now is availability of water for cooling. This is why coastal sites are among the few available for large installations. But as we have pointed out, the cooling water requirements are dwarfed by the quantity of water required to grow the fuel for the plant. If Vermont wishes to produce a 1000 MW of electricity by bioconversion, it will have to harvest the annual productivity of roughly 4,500 square miles of its forest; about half its area. It is hard to believe that Vermont land or any other land would not have greater value fulfilling a function other than producing Btus. No matter what the amount of energy being cultivated, the value of the land, water, nutrients, and biomass itself will be higher for other purposes than producing Btus.

An exception to this rule might be the small-size wood lot. A family may be unable to exploit the wood in its lot for lumber--its greatest dollar value--because they lack the trucks, sawmills, etc. to convert it. Its use as firewood, or feedstock is possible because it requires but a small investment of capital. This economic argument for bioconversion remaining a "people's power" neglects certain unavoidable impacts to

which we now turn.

Generic Impacts

No matter what the size of the energy plantation, as usually conceived it is simply an extension of intensive agriculture, with its reliance on pesticides, combines, irrigation, and airplanes. The Stanford Research Institute Report

notes that "The objective of such a plantation would be to produce the greatest amount of biomass possible per unit of time and space, at the lowest possible cost, and with a minimum of energy expenditure." The concept of the biomass plantation embodied in these words is but a distillation of the general goals of a technocratic society as described by Lewis Mumford (9).

From these general postulates a series of subsidiary ones are derived: there is only one efficient speed, faster; only one attractive destination, farther away; only one desirable size, bigger; only one rational quantitative goal, more. On these assumptions the object of human life, and therefore of the entire productive mechanism, is to remove limits, to hasten the pace of change, to smooth out seasonal rhythms and reduce regional contrasts--in fine, to promote mechanical novelty and destroy organic continuity.

Because the goals of the energy plantation, like those of society itself, are more, faster, cheaper, it is not surprising that environmental impacts have been given little attention. The lack of ecological awareness on the part of some bioconversion advocates is exemplified by a proposal to diminish fertilizer costs in the Stanford Research Institute Report (10). "A possible

method of decreasing the price [of nitrogen fertilizer] to the plantationmight be to couple an ammonia production operation to the biomass plantation, utilizing a portion of the [synthetic natural gas] produced from the biomass as a raw material for ammonia production." This proposal implies that plantations are mysteriously exempt from the laws of thermodynamics, that a fraction of the nitrogen in biomass, after conversion to fertilizer can be returned to the soil where it will grow into more nitrogen thus completing the perpetual motion cycle.

Disguised as clean, solar power and guided by technocratic ideals, biomass plantations could cause unobtrusive, ecological damage of great magnitude. One form this damage will take, unless great care is taken to prevent it, is the gradual deterioration of soil quality under intensive cultivation. In ordinary agriculture the inedible part of the plant may be returned to the soil in order to maintain a supply of organic matter which decays into humus. But in bioconversion the whole plants (sometimes even the roots) would be harvested and ultimately oxidized by combustion. What will be the long-term fate of soils in energy plantations where there is no return of organic matter to the soil? That there will be no, or only minimal return is guaranteed by the necessity of harvesting, i.e. removing as much biomass as possible; this is the whole point of the plantation concept.

Humus has many functions in soil (11). It is a source of nutrients for plants; it improves soil structure, drainage and aeration; it increases water holding, buffering, and ion exchange capacity of the soil; enhances mineral weathering thus releasing nutrients; and finally, serves as an energy source for the entire community of organisms living in the soil. All of these functions will falter if the consumption of humus outstrips its production.

One of the major services of soil humus is as a supplier of nitrogen to growing plants; in a natural state more than 80% of soil nitrogen is in humus. Experience has shown that continuous applications of inorganic nitrogen fertilizers are no substitute for the natural reserve of organic nitrogen in humus. If soil humus gradually disappears, as it will under a policy of no organic return to the soil, then soil structure is impaired and oxygen diffusion through the soil is retarded. As a result of this oxygen depletion, plant roots become less efficient at absorbing soil nitrogen even when applied in massive doses as inorganic fertilizer (12). This may explain the declining crop yield per unit of fertilizer that has been observed over the past thirty years.

So, we are faced with choosing alternative uses for biomass. We can use it to turn steam turbines or, as humus, to support a diverse and stable soil community, prevent erosion, build soil, and support birds and mammals ultimately dependent on the soil.

During combustion it is not only organic matter that is

lost. The nitrogen incorporated in the woody tissues being burned goes up in smoke, while the furnace ash retains much of the phosphorous and potassium. It would be of some nutritive value to return the ash to the fields. Nevertheless, for sugar cane "the proportions [of valuable nutrients] are not large and the plant foods owing to the partial fusion of the ash, are not readily available to the crop" (13).

The loss of nutrients and organic matter by combustion emphasizes the infinite superiority of digesting biomass over directly burning it. Digestion produces liquid or gaseous fuels and leaves a solid sludge containing most of the original nutrients. The sludge, though awkward to handle, is rich fertilizer.

One of the first principles students of natural history learn is the idea of energy transfers down a food chain. Some small fraction of the sun's energy captured by a forest is harvested by, say, herbivorous insects which are in turn consumed by birds. A few larger predators may then prey on the birds. When man cuts the trees, for his own use as lumber or fuel, he removes the resource base of all the animals and plants in the forest community. By replacing the prairie with cornfields or sugar cane plantations, the incredibly diverse biota dependent on prairie plants vanishes. In short, by channeling a large fraction of the primary production of the earth to satisfying only his needs, man destroys the diversity of the earth. There is an important difference between exploiting

the top and bottom of the food chain, between landing a pickerel and clear cutting a forest. In the former case you have plucked off the top leaving the edifice largely intact, but in the latter you have destroyed the foundations themselves. It is not only species diversity that suffers when primary production is prevented from passing through the community. All the other natural flows, processes, and "public service functions" are short circuited as well. The prairie prevented erosion and built the soil. Can we expect as much from the cornfield? The forest mitigates floods, supplies timber, shelters animals, and cleans polluted air, but only if the trees are there.

As E.P. Odum has pointed out (14), the tendency in natural ecosystem development is toward less production per unit of biomass, greater stability of communities, and, in general, a more finely tuned organization. Man's strategy, on the other hand, as expressed by agriculture, intensive forestry, or bio-conversion, is in the opposite direction, toward maximum production via monocultures, with their well known susceptibility to disease, a manifestation of instability.

To summarize, there are natural uses of natural resources, namely to support a diverse and stable community with all its attendant functions. Before man diverts the resources to his own ends he should first be aware of two things: the biotic edifice they were supporting will be destroyed, and services that community was providing, perhaps unnoticed to man, will evaporate.

REFERENCES

1. J. P. R. Associates, Inc., The feasibility of generating electricity in the state of Vermont using wood as a fuel, Stowe, Vermont,
2. Governor's Task Force on Wood as a Source of Energy, State of Vermont, 1975.
3. Stanford Research Institute, Effective Utilization of Solar Energy to Produce Clean Fuel, June 1974, p. 47.
4. A National Plan for Energy Research, Development and Demonstration: Creating Energy Choices for the Future, ERDA-48, June, 1975.
5. Whittaker, R.H, F. H. Bormann, G. E. Likens, and T. G. Siccama, (1974) The Hubbard Brook Ecosystem Study: Forest Biomass and Production, Ecological Monographs, vol. 44, pp. 233-252.
6. Smith, R.L. Ecology and Field Biology, Harper and Row, New York, 1966, p. 37.
7. Barnes, A.C., The Sugar Cane, Leonard Hill, London, 1964, p. 167.
8. This can be shown by applying the global average rate of primary production to an area the size of the United States. See Leith, H., Primary Production, Terrestrial Ecosystems, in: The Primary Production of the Biosphere, Plenum Publishing Co., New York, 1973.
9. Mumford, L., The Myth of the Machine, The Pentagon of Power, Harcourt Brace Jovanovich, Inc., New York, 1970.
10. Stanford Research Institute, Effective Utilization of Solar Energy to Produce Clean Fuel, June 1974, p. 13.
11. Stevenson, F. J. (1972), Role and Function of Humus in Soil with Emphasis on Adsorption of Herbicides and Chelation of Micronutrients, Bioscience, vol. 22, no. 11, p. 643-650.
12. Commoner, B., (1970) Threats to the Integrity of the Nitrogen Cycle: Nitrogen Compounds in Soil, Water, Atmosphere and Precipitation, in, S. Fred Singer, ed. Global Effects of Environmental Pollution, D. Reidel Publishing Co., Dordrecht-Holland, p. 74.
13. King, N. J., R. W. Mungomery, and C. G. Hughes, Manual of Cane Growing, American Elsevier Pub. Co., New York, 1965.
14. Odum, E. P., (1969), The Strategy of Ecosystem Development, Science, vol. 164, p. 262-270.