Title
COVERED ENERGY FARMS FOR SOLAR ENERGY CONVERSION

Author
Bassham, James A.

Publication Date
1976-04-01

Presented at the Conference on Capturing
the Sun Through Bioconversion, Washington
Center for Metropolitan Study, Washington,
DC, March 10 - 12, 1976

LBL-4844
c 1

COVERED ENERGY FARMS FOR SOLAR ENERGY CONVERSION

James A. Bassham

April 1976

Prepared for the U. S. Energy Research and
Development Administration under Contract W-7405-ENG-48

LBL-4844
c 1

COVERED ENERGY FARMS FOR SOLAR ENERGY CONVERSION

James A. Bassham
Laboratory of Chemical Biodynamics
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

This work was supported by the U. S. Energy Research and Development Administration.

COVERED ENERGY FARMS FOR SOLAR ENERGY CONVERSION

James A. Bassham

Capturing and converting enough sunlight to have a significant impact on total energy needs of the United States (perhaps 90 quads by 1985) requires a solar energy conversion device that is sufficiently low in cost and maintenance to be used over 10,000 mi^2 (25,900 km^2) or more. Green plants can be used to cover large areas at relatively low cost, but the efficiency of solar energy conversion in plants is usually very low (1%) in most conventional agriculture.

The value of food (biological energy supply) is high enough to make such low efficiencies acceptable. For other energy uses--industrial, transportation, residential electrical--such low efficiencies may be economically unacceptable. Society will pay more for calories as food energy than as a biological energy. It follows that schemes for energy farms (purposeful growing of plants for a biological energy) should be very concerned with conversion efficiency, so that a reasonable yield of the product (energy) per unit area can be realized.

Such energy farms are not likely to be able to compete with even inefficient food-producing agriculture for good land. Forests may be considered, but the expected efficiencies are low (less than 1%). Moreover, as with food production, competing uses as materials (fibre, chip-board, etc.) often have a higher economic value. For steep slopes (where much of the forests grow), ecological damage resulting from removing essentially all organic material during harvesting may rule out such harvesting even where selected timbering for lumber is permitted.

For almost any scheme involving low conversion efficiencies, collection costs make conversion to useful fuels or power economically unattractive. It appears that, as a general rule, whenever collection of forest or agricultural wastes is feasible, higher economic use of the collected products as specialized materials will tend to rule out their use for energy.

Given these considerations, it is worthwhile to examine the factors limiting conversion efficiency in plants, determine what efficiency we might achieve, and define the conditions necessary for achieving it. At the same time, we should try to think of an energy farm that could use land not suitable for conventional agriculture, yet could produce enough material per unit area to bring collection costs to reasonable levels. Finally, a scheme which could provide for an economic byproduct with a value per acre equal to or greater than that of the energy produced might make the first, limited installations more attractive economically.

This discussion will be limited to land plants. There are other schemes involving fresh water plants (for example, water hyacinths) and marine plants (kelp). Probably it is worthwhile to explore all such approaches, but we should recognize that each faces severe economic considerations, as does the scheme I will discuss.

The maximum expected efficiency of solar energy conversion in green plants is directly predictable from our present day knowledge of the detailed mechanism of this process.

Plant photosynthesis makes many organic products, but as a reasonable approximation we can consider the formation of the carbohydrates starch and cellulose, which are composed of glucose subunits. For further simplification let us examine the formation of one sixth of a mole of a glucose subunit from CO_2 and water:

$$CO_2 + H_2O \xrightarrow{\text{Light}} \underset{\text{1/6 glucose}}{[CH_2O]} + O_2$$

The free energy stored by this reaction is about 114 KCal per mole of CO_2

reduced to starch or cellulose. This overall reaction can be considered as the transfer of four electrons from the oxygen atoms of two water molecules to CO_2 resulting in the formation of a water molecule plus carbon reduced to the level of carbohydrate. From knowledge of the detailed mechanism of light absorption and electron transfer, we know that each electron must be transferred through a number of intermediate steps, two of which require light energy. Further examination of this process shows that for each electron transferred through a light reaction, one photon of light is used up. The theoretical quantum requirement is thus four (for four electrons) times two (for two light steps per electron) equals eight. Each mole of CO_2 reduced to sugar requires that eight moles of photons (eight einsteins) must be converted.

Plant biochemists know that besides the four electrons from water, the reduction of CO_2 to sugar requires the using up of three molecules of the biological energy carrier, adenosine triphosphate (ATP). Fortunately, the three ATP molecules are made from three adenosine diphosphate (ADP) molecules with some of the same light energy absorbed and used to transfer electrons. Therefore, no additional light energy is needed.

Photosynthesis uses visible light from 400 nm to about 700 nm, corresponding in energy per Einstein to seventy to forty kilocalories, respectively. Plants use only a single reaction mechanism for conversion of all of this light, so the extra energy in the shorter wavelengths is wasted. All the absorbed light is used as if it were red light. If we look at the overall process including carbon dioxide reduction, the net energy efficiency is around 30% when red light only is used.

Before attempting to apply this information to a calculation of possible efficiency in land plants, I would like to consider another aspect of photosynthesis on earth. This is the location of various photosynthetic domains. From such information we can perhaps obtain an indication about where we might want to carry out additional large-scale photosynthesis. The continents (Table I) are responsible for about two-thirds of the photosynthesis on earth, even though they only occupy about thirty percent of the area. This is because a great part of the ocean is rather sterile. The open ocean does account for a lot of photosynthesis, but it is very diffuse and does not lead to organic mass accumulation because the small widely scattered microorganisms soon decay and are not harvested to any great extent.

If we look at the land, we see that the forests are by far the predominant places for photosynthesis, accounting for some forty percent of all photosynthesis. This might lead us to think that we should get our energy from the forests, but this is not a simple matter. There are strong ecological considerations. If you cut the forest down too rapidly or in the wrong way, they may not regrow. Particularly the jungle forests are very susceptible to such damage.

The tropical rain forests are mostly jungles which we don't have in the United States. These tropical forests are where most of the forest photosynthesis occurs, although a substantial amount is in other types of forests. Tropical forests such as the Amazon forest are very susceptible to ecological damage when the trees are cut down.

Besides the forests, we see various other domains--woodlands, dwarf and scrub. And then, of course, you see the extreme desert, which covers a considerable part of the earth's land area but which has almost no photosynthesis. Finally, there is cultivated, or agricultural, land.

Given the growing need for food in the world, we're not going to be inclined to use our agricultural land for energy farms. Such land is too valuable as a place for collecting energy in the form of food for human nutrition. The United States is depending heavily now on the export of agricultural products. It's the export of food that's helping us to keep our balance of

TABLE I

PRIMARY PHOTOSYNTHETIC PRODUCTIVITY OF THE EARTH

	Area (total = 510 million Km^2)				Net Productivity (total = 155.2 billion tons dry wt./yr.)			
Total Earth	100				100			
Continents		29.2				64.6		
Forests			9.8				41.6	
Tropical Rain				3.3				21.9
Raingreen				1.5				7.3
Summer Green				1.4				4.5
Chaparral				0.3				0.7
Warm Temperate Mixed				1.0				3.2
Boreal (Northern)				2.4				3.9
Woodland			1.4				2.7	
Dwarf and Scrub			5.1				1.5	
Tundra				1.6				0.7
Desert Scrub				3.5				0.8
Grassland			4.7				9.7	
Tropical				2.9				6.8
Temperate				1.8				2.9
Desert (Extreme)			4.7				0	
Dry				1.7				0
Ice				3.0				0
Cultivated Land			2.7				5.9	
Freshwater			0.8				3.2	
Swamp & Marsh				0.4				2.6
Lake & Stream				0.4				0.6
Oceans		70.8				35.4		
Reefs & Estuaries			0.4				2.6	
Continental Shelf			5.1				6.0	
Open Ocean			65.1				26.7	
Upwelling Zones			0.08				0.1	

Percentages based on data presented by H. Lieth at the Second National Biological Congress, 1971.

payments in the black. And were it not for the huge amounts of grain and other agricultural products that we export, we would be running very serious deficits due to the increased cost of imported oil.

We have in our country a lot of land with high sunlight that falls under such categories as grassland and desert. The areas of highest solar energy in the United States are in Arizona, New Mexico, parts of Texas, California and southern Nevada (Fig. 1). The next highest energy contour includes areas which also have abundant energy--Utah, more of Texas and California.

There is an average energy flux in the U. S. of about 1450 b.t.u./ft^2 day (Table II). The U. S. Southwest is somewhat higher on an annual average basis, and of course in the summer it goes up to a very high level.

These figures can be used to see what quantities we might predict in terms of possible photosynthetic harvesting of energy. First, it is necessary to estimate the possible efficiency of energy conversion to be expected. A brief calculation will show why it is that, while we talk about efficiencies of 30% or so for the primary photochemical events, you commonly hear that agricultural products collect only one or two-tenths percent of the incident solar energy. The first reason is that the agricultural products are very often storage organs, seeds, or potatoes, roots, etc., but not the whole plant. Furthermore, we usually do not use the whole plant nor do we harvest it frequently. Rather, after a harvest we allow it to go into senescence and die. By frequent harvesting of the green leaves as they grow, and selection of the right kind of plant, you can get to a much higher efficiency. There are, however, four factors limiting the maximum possible efficiency.

First, the photosynthetically active radiation (P.A.R.) is much less than the total radiation. Visible light from 400 to 700 nanometers wavelength can be used by green plants. More than half of the solar energy incident to the earth's surface is at wavelengths longer than 700 nanometers, and there's a little bit in the u.v. as well. Only 43% of the solar energy can be used by

TABLE II

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

	B.t.u./ft^{2}day	cal/cm^2 day	Kcal/m^2 day	watts/m^2
U.S. 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

green plants.

Second, the maximum leaf absorption, according to agronomists, is about 80%. In other words, even with an excellent leaf canopy, there would be some reflection of light energy and some loss or scattering of light energy down to the ground, so that not all the light is absorbed into the leaf.

Third, there is the maximum efficiency of the photosynthetic process itself. As already discussed, the conversion of a mole each of CO_2 and water to a mole of O_2 and one sixth mole of glucose requires the absorption of eight moles (einsteins) of light. All the light is used as if it were 700 nm light, but since the photosynthetically active radiation (P.A.R.) is the total solar radiation of wavelengths from 400 nm to 700 nm, the energy input is equivalent to that of monochromatic light of about 575 nm wavelength.

The energy of one light photon is given by $e = hc/\lambda$, where h is Plank's constant, c is the velocity of light, and λ is the wavelength. To get the energy of an einstein (or one mole of photons) we multiply by Avogadro's number, 6×10^{23}. Using appropriate units, we get an energy per einstein, $E = 28{,}600/\lambda$ KCal, when λ is expressed in nm. Thus, an einstein of 575 nm light has an energy of 49.74 KCal.

Multiplying by 8, we get 398 KCal required per mole of CO_2 reduced to glucose. Since, as mentioned earlier, this process stores 114 KCal as chemical potential, the maximum efficiency of photosynthesis is 114/398 = 28.6%.

This is the efficiency of conversion of photosynthetically active radiation actually absorbed. The efficiency based on total absorbed solar radiation is 0.286 multiplied by 0.43 (P.A.R./total radiation) or 0.123, a figure sometimes quoted as maximum for aquatic plants (usually unicellular algae) where it is sometimes assumed that there is total light absorption. For land plants with an estimated 80% absorption maximum, we get an efficiency of 0.123 x 0.80 = 0.0984.

So far we have the maximum daylight efficiency in the green cells of leaves. However, plant cells also use up stored chemical energy when not photosynthesizing, and this introduces the fourth factor.

At night, plants carry out respiration which means they're burning glucose with oxygen. Also, the stems and roots respire during the day as well as night. The amount of such respiration varies greatly, depending on the weather, the temperature, the species of plant, and many other factors. Taking an overall, ballpark figure which agronomists say is reasonable, we reduce the efficiency to a factor of a third, giving us a factor of 66.7%.

When we multiply all these factors (0.43 x 0.80 x 0.286 x 0.67, we come out with about 6.6% overall maximum daily energy efficiency. Using the theoretical calculation, based upon the efficiency just calculated, we might predict a maximum production of nearly 120 tons of dry weight per acre year in the U.S. Southwest. I'm considering the dry weight now as if the plants made only glucose units. Of course, the dry weight actually includes fats and proteins and other substances, but glucose is a reasonable approximation on a dry weight basis. The most abundant single constituent in plants is cellulose, composed of glucose subunits. What we have done so far, of course, is to establish the upper (and doubtless unobtainable) limit, based on theoretical constraints. What are the actual rates measured? The figures in parentheses (Table III) are rates during the active growing season, not annual rates. For C-4 plants, these maximum rates range from 60 up to about 85 tons per acre year.

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. 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

TABLE III

MAXIMUM PHOTOSYNTHETIC PRODUCTIVITY AND MEASURED MAXIMUM YIELDS IN SELECTED PLANTS

	g/m^2 day	tons/ acre yr.	metric tons/ hectare yr.
Theoretical max. (Table II)			
U.S. Average annual	61	100	223
U.S. Southwest ave. ann.	71	117	262
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	10	16	36
Corn (Zea mays)	4	6	13
Non C-4 plants			
Alfalfa	8	13	29
Eucalyptus	15	24	54
Sugar beet	9	15	33
Algae	24	39	87

investing some energy in the C-4 pathway, the C-4 plants avoid a wasteful process called photorespiration that occurs in other plants at high light intensities. Photorespiration results in the reoxidation of freshly formed sugar to carbon dioxide.

The C-4 plants are more efficient at high light intensities and temperatures and low CO_2 pressures because they avoid photorespiration. They are more efficient only at the low levels of CO_2 in air, that is, at 0.03% CO_2. At higher levels of CO_2, photorespiration doesn't occur and some other plants that are not C-4 plants become just as efficient.

Even some non-C-4 plants, sugar beet, alfalfa and Chlorella (Table III) at certain times of the year produce at very respectable rates--up to fifty tons per acre per year--and that's very encouraging. 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. Actually the rate achieved in cane is a reasonable rate to expect under good conditions if we look at the growing rates that can occur with many plants over a shorter period of time.

A yield of 50 tons of dry weight per acre-year is a very substantial amount of material. Some of the non-C-4 plants produce less, of course--we can see that alfalfa produced only thirteen tons. Keep in mind, however, that this is with air levels of CO_2 and low winter temperatures. Eucalyptus trees are considered by some as a good candidate for energy farms because they grow rapidly. Sugar beets grow about as fast as alfalfa. Chlorella, a unicellular alga that grows in tanks, has a higher rate. This Chlorella is an example of an aquatic plant.

Let us consider next the factor of CO_2 pressure (Table IV). At the level of CO_2 in air, corn and sugar cane grow faster than the non-C-4 plants such as soybean and sugar beet. But when the level of CO_2 in a greenhouse is raised by a factor of three or so, one observes higher rates with some of these

TABLE IV

RATES OF PHOTOSYNTHESIS AT AIR LEVELS AND ELEVATED LEVELS OF CO_2

(milligrams $CO_2/dm^2\cdot$hour)

Plant	Air	Elevated CO_2
Corn, grain, sorghum, sugar cane	60-75	100
Rice	40-75	135
Sunflower	50-65	130
Soybean, sugar beet	30-40	56
Cotton	40-50	100

temperate zone plants than with corn or sugar cane. This suggests that we should somehow enrich the atmosphere with CO_2. But how do you do that? If you put CO_2 on the land, the wind blows it away, and you can't maintain a CO_2 level above 0.03%. This leads to the idea of using covered agriculture, using inexpensive desert land.

How do you grow plants in the desert without water? Obviously you've got to save the water. You can't allow it to be transpired from the leaves and disappear into that sink of low humidity that exists over the desert. You've got to put a cover over it and keep the water in. In conventional covered agriculture we grow tomatoes in the winter, flowers in the winter, and they yield a couple of hundred thousand dollars per acre, justifying the cost of this expensive installation.

What I have in mind (Fig. 2) is a much less costly installation, namely inflatable plastic covers such as are already used for temporary warehouses. Perhaps these can be coated in special ways to help control the flow of heat in and out. The greenhouse may have to have a floor under the soil--a plastic layer of some kind so the water doesn't trickle out the bottom.

In these greenhouses we could grow some crops, such as alfalfa that can be harvested ten or twelve times a year. To make the process more economical, we'll remove the protein from the leaves and sell this as an economic product. The scientists at the USDA Western Regional Laboratories found that they can remove protein from alfalfa leaves by presses. They can clean up this protein and deodorize it and take bad tastes out. It has very high nutritional value, better than soy protein, better than most cereal proteins, and is, in fact, as good as milk protein, according to nutritional studies with various animals. It doesn't have to be enriched with amino acids. Also, as prepared by the process developed at the U. S. Department of Agriculture, the purified protein is essentially free of the flatulence factors, stachyose and raffinose.

It's been found that you can grow two tons or more of protein per acre in the form of leaf protein of alfalfa, and this is the highest amount of protein you can produce per acre by any known agricultural means. The atmosphere in the greenhouses can be enriched with CO_2, thus taking advantage of the fact that we've already covered the plants to preserve the water. We can put in, CO_2 from a powerhouse. In this powerhouse we're going to burn all of the residue of the cells, after we've taken out about 15% of the dry weight of protein. The other 75% is mostly cellulose, sugars and lipids. We can make up the necessary added CO_2 with some fossil fuels that we will also burn in this powerhouse, and the CO_2 and the water vapor from that combustion will go back into the greenhouse.

If the CO_2 is enriched to a tenth of a percent or so, studies have shown that for nitrogen-fixing plants, such as alfalfa, the fixation of nitrogen increases by a factor of five. Presumably this is because photosynthesis rate has gone up and more of the photosynthate gets down to the roots to feed the bacteria that are living in root nodules there and fixing N_2. This means then with CO_2 enrichment we may not have to put in any fixed nitrogen made by the combustion of fossil fuels. Instead, the root nodules may be able to fix all the nitrogen required for this production of protein by using nitrogen from the atmosphere in the greenhouse.

The heat from combustion would be used to generate electricity which would be sold to the city. Just possible, this could turn out to be an economic process. At the moment, the market for plant protein (presently soy protein) is rather limited. Given the growing world population, as well as the development of new vegetable protein products in the U. S., and the escalating cost of animal protein, the market for plant protein for human nutrition should expand. Eventually, though, the energy generation, if successful, might grow to a point where there would be no possible market for all the protein produced.

Of course, there are some serious problems with such a scheme. First, we might boil the spinach, because of greenhouse effects. If you put a transparent cover over fields, the system absorbs all of the solar energy and you're only using a little bit of it for photosynthesis (3-4%), all the rest is converted to heat. Thus, there is a tremendous heating effect. This is a very serious problem, but it may not be insurmountable. Perhaps these covered energy farms could be placed in some of the high deserts, such as exist in Nevada and California at high elevations where the temperature at night drops down very low. The hope would be that by using a very large structure with a large volume of air to warm up, there would be enough heat capacity in that air to be able to absorb the input of heat during the course of one day without the temperature rising above a permissible level. Also, the transpiration of water from the plant leaves during the day would absorb a large amount of heat. Then at night the water vapor which has been transpired during the day would condense and rain back down on the plants.

Special coatings on the plastic to facilitate the flow of heat from inside to outside (since there will always be a temperature gradient) might help. Finally, solar-energy driven heat pumps could be employed, although this would be costly.

Another problem is the possibility of poisoning of the plants by gaseous contaminants from combustion of both the plant material and the fossil fuel that would be added to produce make up CO_2 to compensate for carbon removed from the system as protein. Fortunately, research on effects of CO_2 and SO_2 (an expected contaminant) on green leaf photosynthesis suggests that the deleterious effect of low levels of SO_2 are to some extent mitigated by elevated CO_2. This is due to the fact that SO_2 at low levels causes partial closure of the stomata through which the CO_2 enters the leaves. Higher levels of CO_2 can overcome this effect.

The choice of plants for such a system may require extensive searching through the plant kingdom since the environment would be different from that of most temperate zone plants. The humidity and temperature could go very high, with considerable daily variation. This might suggest plants from certain tropical areas, but the selected plants would also have to use light at high intensity efficiently. Plant breeding or genetic manipulation through cells growing in tissue culture could be required.

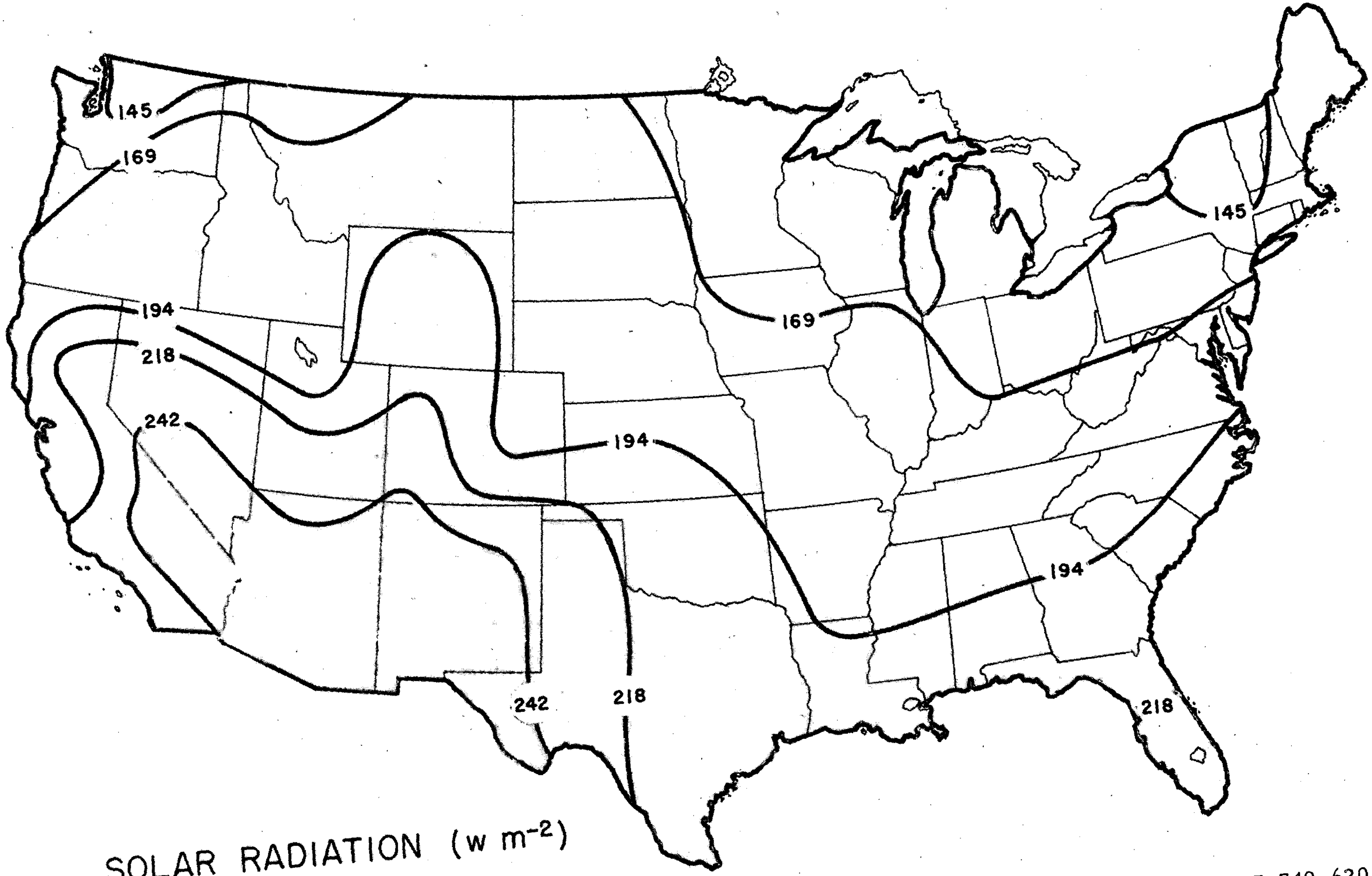
Finally, the system has to show some promise of becoming economically viable, at some time in the next 20 years or so. Conventional covered agriculture has been limited to frame and glass greenhouses with crops such as flowers in the winter, where the crop value runs in to two-hundred thousand dollars per acre or more. An energy "crop", with the efficiencies we can aim for based on the limitations already discussed will bring in only 1-2% of that amount. At 1,700 Btu/ft^2 day there is 1700 x 43,560 x 365 = 2.7 x 10^{10} btu/acre year. If we could achieve 30% of the theoretical maximum efficiency (in addition to the protein production), we could sell 0.3 x 0.066 x 2.7 x 10^{10} = 5.346 10^8 or 535 million btu. At $2 per million btu, this is worth only $1,070 per acre, which immediately illustrates one of the severe economic problems faced by "energy farms". The problem, of course, is that we are getting only about 2% overall efficiency of energy conversion from solar energy to electricity.

If we assume that our dry matter production is at a level of 60 tons/acre-year (51% of the 117 tons maximum rate), and that 15% of the dry weight can be extracted as protein, we could obtain nine tons of protein concentrate. In a few years this should be worth at least as much as soy protein concentrate by that time--say 50¢ a pound. Thus, the value would be $9,000 per acre. Of course, the market would not match the production, if really large amounts of energy are produced this way, but it could help in the economics of the initial stages.

Eventually, we might consider 10,000 mi^2 of covered agriculture. At 2% overall efficiency, and 1700 btu/acre-year in the U.S. Southwest, this would produce 3.4 quads, or 3.8% of our nation's total energy needs in 1985. If such a project proved to be practical, there would be room for several in the U.S. Southwest, and the impact on energy production of that region would be quite substantial.

What would it cost? Too much, if we accept figures like $1 to $2 per ft^2 for plastic, plus all the costs of the fabrication, inflating mechanisms, farming, power plants, etc. With a market as large as thousands of mi^2 of plastic, the cost should come down. In time we might have to learn how to use some of the leaf material as the starting material for plastic synthesis.

At this point, we should take the view that this scheme is as worthy of further study as most of the other seemingly impractical energy farm proposals. We are entering a new era in which the economic factors of the last century (very inexpensive energy and food) may be poor signposts to the future.



SOLAR RADIATION $(w\ m^{-2})$

Annual Average

CBB 749-6206

Figure 1

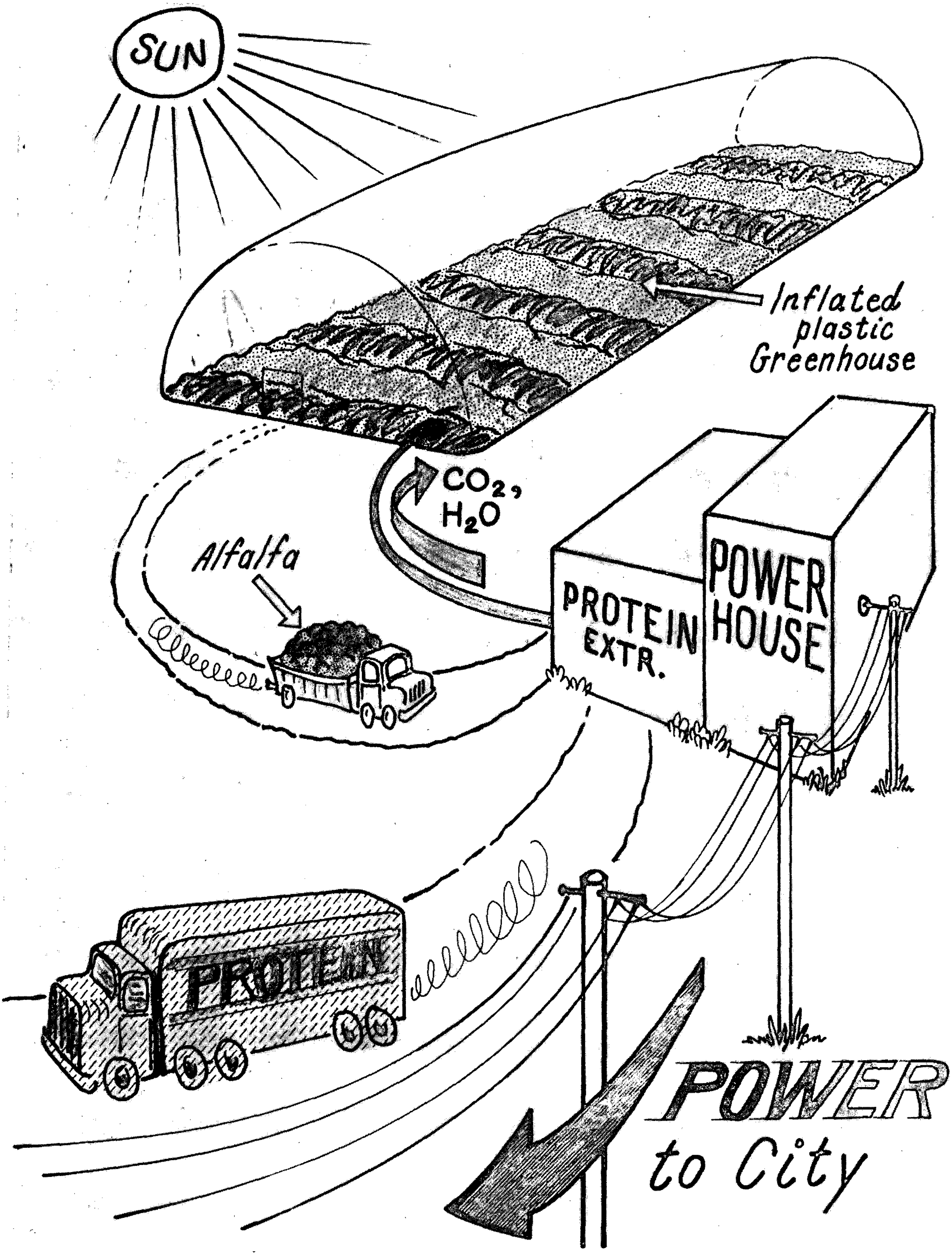

SUN
Inflated plastic Greenhouse
CO$_2$, H$_2$O
Alfalfa
PROTEIN EXTR.
POWER HOUSE
PROTEIN
POWER to City

Figure 2

TECHNICAL INFORMATION DIVISION
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720