Lawrence Berkeley National Laboratory

Recent Work

Title

SYNTHESIS OF ORGANIC COMPOUNDS FROM CARBON DIOXIDE IN LAND PLANTS

Permalink

<https://escholarship.org/uc/item/0vn1j53p>

Author

Bassham, James A.

Publication Date

1976-11-01

0 0 0 0 4 6 0 5 2 2 2

Presented at the Solar Energy
Conversion Seminar, Miami, FL,
November 15 - 18, 1976

LBL-5580

c. 1

SYNTHESIS OF ORGANIC COMPOUNDS FROM
CARBON DIOXIDE IN LAND PLANTS

James A. Bassham

RECEIVED
LAWRENCE
BERKELEY LABORATORY

JAN 11 1977

November 1976

LIBRARY AND
DOCUMENTS SECTION

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

For Reference

Not to be taken from this room

LBL-5580

c. 1

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal 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 its 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, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

SYNTHESIS OF ORGANIC COMPOUNDS
FROM CARBON DIOXIDE IN LAND PLANTS

James A. Bassham

Lawrence Berkeley Laboratory, University of California

Solar energy conversion by green plant photosynthesis supplies virtually all the energy for living cells on earth. Fossil fuels, on which we depend for a large part of our other energy requirements, are the products of photosynthetic solar energy conversion in past ages. Man has used wood and straw for energy and materials from the beginning, and it has been only about a decade since nuclear power surpassed wood combustion in importance as an energy source in the United States.

Man has modified the earth's surface to a much greater extent with agriculture than for any other purpose. It is economically practical and necessary to cover vast areas of land with selected plants for solar energy conversion when the product is to be used for food, as materials and chemicals, and even as fuel in some cases. There is no doubt about the importance of using plant photosynthesis for solar energy conversion. The only questions are how much plants can contribute to our energy needs that are now being filled by other exhaustible or environmentally unfavorable energy sources, and what is the best technology for increasing our use of plants for this purpose.

Three basic facts have to be faced in any scheme for using plants for industrial energy and chemical needs. Enormous amounts of energy are required, there is a relatively low energy conversion efficiency for the plant photosynthetic process, and energy as a crop has low current market value compared to conventional food and material crops. Solar energy farming shares with some other proposed energy technologies the problem that while it will eventually be feasible and needed, the short range economic prospects appear to be unfavorable. Nevertheless, ten to twenty years of research on plant selection, growth, and utilization for this purpose may be needed in order to be ready by that critical period around the year 2,000 when the supply of petroleum and gas have fallen seriously behind the world requirements for energy. There are indications that other alternative energy sources including coal, shale, and nuclear power will be sufficiently expensive, when the environmental and technological costs are paid, to allow energy farming to become economically competitive. In a shorter time span, photosynthetic solar energy conversion may provide us with portable fuels and chemicals at competitive prices. Some of the systems envisaged might produce basic foods such as protein and sugars at lower energy costs than conventional agriculture.

The total energy needs of a large industrial nation are so great that very large projects have to be considered. However, if the focus is on a specific need and area, such as electrical power generation in the U. S. Southwest, the impact of a system covering even 10,000 Km² can be very great.

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 in 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. It follows that schemes for energy farms (purposeful growing of plants for abiological energy) should be very concerned with conversion efficiency, so that a reasonable yield of the product (energy) per unit area can be realized. Land cost and, to some extent, harvesting cost will be directly proportional to yield per unit area.

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 0.5%). Moreover, as with food production, competing uses as materials (fibre, chipboard, 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 any crop with low conversion efficiencies, collection costs make conversion to useful fuels or power economically unattractive. When 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.

We must therefore 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 conceive of energy farms 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 (food or chemical) 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.

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:

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, oxygen, and 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.

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 (P.A.R.) includes all wave-lengths from 400 nm to 700 nm, the energy input is equivalent to that of monochromatic light of about 575 nm wavelength. 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 this process stores 114 Kcal as chemical potential, the maximum efficiency of photosynthesis is $114/398 = 0.286$.

This is the efficiency of conversion of P.A.R. 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 the maximum for aquatic plants (usually unicellular algae) where it is often assumed that there is total light absorption. For land plants with a well developed leaf canopy, an absorption

of 0.80 of the P.A.R. is considered to be maximal. Using this value for energy absorption, we get an efficiency of $0.123 \times 0.80 = 0.0984$.

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 figure which agronomists say is reasonable, we reduce the efficiency by a third, giving us a factor of 0.667.

When we multiply all these factors ($0.43 \times 80 \times 0.286 \times 0.67$), we come out with about 6.6% overall maximum daily energy efficiency. From this value, we can calculate the absolute upper limit of stored chemical energy to be expected from land plants. The solar energy incident at the earth's surface, averaged over 24 h and 365 days is 3,930 Kcal/m² day for the United States (average) or 4,610 Kcal/m² day in the U.S. southwest (Table I). In the U.S. southwest during the summer the average is 6,775 Kcal/m² day. Of course, we should realize that the amount of energy changes during the day and with the weather, and there may be too much or too little at various times. This is one reason the actual energy storage under the most optimal conditions will be less than the theoretical.

TABLE I

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
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

Using 4,610 Kcal/m² day and an efficiency of 0.066, we get a daily energy storage of 304.3 Kcal/m², enough to form $(304.3/114)27 = 72 \text{ g/m}^2 \text{ day}$. This is equivalent to 262.8 metric tons/hectare year (Table II). Other values of daily solar energy

in Kcal/m^2 day may be converted to expected maximum dry weight stored in metric tons/hectare yr by multiplying by 0.057.

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 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 maximum (190) is about half the calculated maximum. Similarly, the maximum 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 maximum reported yields is about 3.3%. We can thus set a range of 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. 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 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 such as in air (0.03% CO_2) because they avoid photorespiration.

At higher levels of CO_2 , photorespiration doesn't occur and some plants that are not C-4 plants become just as efficient. Even some non-C-4 plants, sugar beets, alfalfa and Chlorella in air (Table II) at certain times of the year produce at very respectable rates. 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. In general, therefore, the non-C-4 plants produce less than C-4 plants, but keep in mind that this is with air levels of CO_2 and low winter temperatures. Eucalyptus trees are considered by some as a good choice for energy farms because they grow rapidly. Sugar beets grow about as fast as alfalfa.

TABLE II
MAXIMUM PHOTOSYNTHETIC PRODUCTIVITY AND MEASURED MAXIMUM YIELDS
IN SELECTED PLANTS

	gm ² /day	tons/ acre yr.	metric tons/ hectare yr.
<hr/>			
Theoretical max. (Table II)			
U.S. Average annual	61	100	224
U.S. Southwest ave. ann.	72	117	263
U.S. Southwest, summer	106	172	387
<hr/>			
Maximum Measured			
C-4 plants			
Sugar cane	38	(62)	(138)
Napier grass	39	(64)	(139)
Sudan grass (Sorgum)	51	(83)	(186)
Corn (Zea mays)	52	(85)	(190)
<hr/>			
Non-C-4 plants			
Sugar beet	31	(51)	(113)
Alfalfa	23	(37)	(84)
Chlorella	28	(46)	(102)
<hr/>			
Annual Yield			
C-4 plants			
Sugar cane	31	50	112
Sudan grass (Sorgum)	10	16	36
Corn (Zea mays)	4	6	13
<hr/>			
Non C-4 plants			
Alfalfa	8	13	29
Eucalyptus	15	24	54
Sugar beet	9	15	33
Algae	24	39	87

Let us consider next the factor of CO₂ pressure (Table III). At the level of CO₂ 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 temperate zone plants than with corn or sugar cane. This suggests that we should somehow enrich the atmosphere with CO_2 . When CO_2 is released in the open, the wind blows it away. This leads to the idea of using covered agriculture, using inexpensive desert land, where it is necessary to save water.

In conventional covered agriculture we grow tomatoes or flowers in the winter, and they can be sold at a high price to justify this expensive installation. What I have in mind (Fig. 1) 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 isn't lost to the earth.

In these greenhouses we could grow some crops, such as alfalfa that can be harvested ten or twelve times a year. It's been found that five tons or more of protein per hectare can be grown in the form of leaf protein of alfalfa. This is possibly the highest amount of protein known to be produced per acre by any land plant.

To make the process more economical, we'll remove some of 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.

The supply of CO_2 for covered greenhouses could come from a powerhouse. As fuel for this powerhouse, we would burn all of the residue of the cells, after we've taken out about 15% of the dry weight of protein. The other 85% is mostly cellulose, sugars, lipids, and unextracted protein. The carbon taken from the system as protein could be made up as CO_2 from some fossil fuels that would also be burned in the powerhouse. All the CO_2 and the water vapor from combustion would go back into the greenhouse. The heat from combustion would be used to generate electricity which would be sold to the city.

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

Figure 1. Alfalfa Energy Farm

fixation of nitrogen increases by a factor of five. Presumably this is because the 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 and fixing N_2 . This means that 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.

TABLE III

RATE OF PHOTOSYNTHESIS AT AIR LEVELS AND ELEVATED LEVELS OF CO_2 (milligrams CO_2/dm^2 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

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. If you put a transparent cover over fields, the system absorbs all of the solar energy and the plants are using only a small part of it for photosynthesis (3-5%). 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. A preliminary engineering calculation indicates that with certain assumptions made about meteorological conditions in the U.S. southwest and humidity in the greenhouse, a volume of air some 200 meters high would have to be enclosed in order that the temperature would not rise above an acceptable limit for plants during one daylight period. Perhaps an equally serious problem could be the failure to lose enough heat across the plastic barrier during the night, with radiation to the desert sky, to allow the temperature to return by morning to the starting level.

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 removal from the system as protein. Fortunately, research on effects of CO_2 and SO_2 (an expected contaminant) on greater 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 an extensive examination throughout the plant kingdom for plants with appropriate characteristics. The environment in the covered energy farm would be very different from that in which most temperate zone plants grow. The humidity and temperature could undergo large daily variations with very high levels in the late afternoons. Disease resistance would be most important, along with high growth rates at elevated CO_2 pressures, good leaf canopy characteristics, and high leaf protein content. This might suggest plants from certain tropical areas, but the selected plants would have to use high light intensities efficiently. Plant breeding or genetic manipulation of cells growing in tissue culture might be required.

The system should show some promise of becoming economically viable in the next 20 years or so. Conventional covered agriculture has usually been limited to frame and glass greenhouses which produce crops with values running to hundreds of thousands of dollars per hectare per year. An "energy crop," with the best efficiencies we can expect will bring in only a few percent of that amount. Thus we need to give serious consideration to possible valuable byproducts that might help in the economics.

Let us assume that we can achieve somewhat better than the best measured energy conversion efficiencies of about 3% but of course below the maximum of 6.6% I have calculated earlier. Allowing for expected improvements to come from CO₂ enrichment and continuous growth and harvesting, let us assume about 75% of the 0.0666 conversion efficiency calculated above, or a 0.05 conversion efficiency. This would result in the production of 200 metric tons dry matter per hectare year. The energy stored would be 0.05×2230 (kilowatts/hectare) $\times 24 \times 365 = 9.77 \times 10^5$ kilowatt-hr/hectare year. If we extract 15% of the dry matter as protein, and assume a 30% conversion efficiency of the residue to electricity, each hectare would produce $(9.77 \times 10^5) \times 0.85 \times 0.3 = 2.49 \times 10^5$ Kw-hr per year. At the 1975 Southern California Edison price of \$0.02 per kw-hr, this energy crop would be worth \$5,000 per hectare. Obviously this is a very poor yield compared with even conventional agricultural crops, and much worse compared with present day covered agriculture crops. Let us therefore consider also the possible value of the protein.

The 15% of 200 metric tons would be 30,000 Kg. Green leaf protein, because of its higher nutritional value, should in time have a higher value than soy protein, so let us assume a value of \$1.00 a Kg. We could then obtain \$30,000 a hectare for the protein, which added to the \$5,000 for the energy gives a \$35,000 crop. Of course, the market for protein might not match the amount produced when we get into really large scale energy production, but perhaps by then the economics for pure energy production will have improved.

Let us next consider the impact of 10,000 Km² of such agriculture (an area 100 x 100 Km or 60 x 60 miles). At 2.49×10^5 Kw-hr/hectare year we would have 2.49×10^{11} Kw-hr/year. The total electrical sales in the state of California for the year 1975 was 1.39×10^{11} Kw-hr, and is projected to reach 2.67×10^{11} Kw-hr/year by the year 1995, according to a recent study by the California Energy Conservation and Development Commission.

What would it cost? Perhaps too much, if we accept figures like \$20 per m² of plastic cover, plus all the costs of fabrication, inflating mechanism, cooling, farming, power plants, etc. With a huge market for plastic and other materials the cost should

come down. In time we might have to learn how to use some of the leaf substance as a starting material for the plastic synthesis.

At this point, we should take the view that this scheme is as worthy of further study as most of the other long range energy farr 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.

At the present time, residual material after removal of protein from alfalfa leaves has a higher market value as cattle fodder than as fuel for a power plant. As the production of grain and cotton for world markets continues to displace forage crops, there will be a growing demand for some time for this cellulosic residue from leaves. The current market price in California is about \$80 per metric ton, so that the 170 tons of dry matter left after protein extraction is worth \$13,600. This suggests that in the early stages of development, it would be more economic to sell all the product of covered agriculture as agricultural commodities. In this case, of course, the CO_2 for enrichment would have to come entirely from fossil fuel combustion. Even on this basis, the system is worth developing for the purpose of water, land and energy conservation. In time, as fossil fuel becomes more expensive, the system could change to one generating electricity from biomass.

While covering of large areas of desert with plastic greenhouses may not be practical at this time, there is an intermediate type of project that can act as a forerunner by providing information about the feasibility of solar energy conversion via covered agriculture with CO_2 enrichment and water conservation. This is to use waste gases and heat from fossil fuel combustion at plants in the U.S. Southwest. Such programs already are being proposed and would appear to be very deserving of support. The initial focus would be on high value crops such as tomatoes in the winter as well as algae which could be fed to other organisms, harvested for their food value directly. Such projects might very well prove to be economic in the near future. At the same time, through such projects, information about plastic or other inexpensive structures, about heating and cooling, diseases in plants under such artificial environments, productivity, etc. will be obtained.

To summarize, covered agriculture for solar energy conversion leading to electrical energy production may be some years in the future, but there are practical, forerunner projects that can be started now. It will be imperative, given the economic considerations, to maximize photosynthetic efficiency. What may be ultimately achieved is not certain, but careful consideration of plant physiology and biochemistry suggests that we can reasonably expect conversion efficiencies of 5%, given optimal

conditions₂ including CO₂ enrichment. Rather large projects (10,000 km²) could have significant impacts on the electrical energy requirements in the U.S. Southwest.

One way to improve the economics of energy farms may be, as just suggested, to produce a valuable byproduct. Another approach is to use plants to produce an energy product of greater value than power from a stationary source. One such proposal, discussed by Calvin, is to raise plants as suppliers of hydrocarbons. An indirect method of doing this is to produce sugars and cellulose, convert the cellulose enzymatically to sugars, and ferment all of the sugars to alcohol. Since sugar cane and sugar beets are among the fastest growing plants, even the fermentation of sugar alone may be attractive in some situations. In Brazil, for example, sugar-containing residues left after crystallization of sugar as a commercial product, are being converted to alcohol which is in turn being used as an extender or additive to gasoline. Something like 5% of the total volume of gasoline engine fuel in Brazil is or soon will be ethanol. In general, though, sugar has a higher value as food than as a precursor for alcohol for fuel.

A more direct approach is to raise plants that produce hydrocarbons convertible to portable fuels. As Calvin points out, productivity of Hevea trees in Indonesia has been increased from 200 Kg per hectare in 1945 to 2000 Kg per hectare in 1965, and there are expectations, based on experimental plots, etc., that the yield could go as high as 8 metric tons per hectare. While latex would not be useful as fuel, other hydrocarbon producing plants might be found among the thousands of species, that would yield large quantities of lower molecular weight polyisoprene compounds. As Calvin suggests "...there are genuine possibilities for harvesting economic amounts of crude-oil like hydrocarbons from land in dry, sunny regions such as Southern California or Southwest Texas which today cannot be easily used for food or fiber production." A search for such compounds and plants has been undertaken in Calvin's laboratory, and already species of Euphorbia have been found which produce sizable quantities of non-latex (lower molecular weight) "hydrocarbon" compounds. Some of this material has proved to be sterols, which, though derived from isoprene units, are perhaps not useful as potential fuels. Probably we are going to need to learn a lot more about the regulation of biosynthetic pathways leading to various end-products made from isopentenyl pyrophosphate, the biochemical form of isoprene.

While the yield per hectare of hydrocarbons from plants is not likely to be as great the yield of cellulose and other materials, we can again envisage a dual productivity, in which the hydrocarbons are extracted and sold as a valuable product, while the residue is burned in a power plant.

A knowledge of the regulation of the pathways of biosynthesis in plants from CO_2 to end products will be useful in selection of optimal physiological conditions, and selection and breeding of plants for energy farms. Clearly, if in some processes the byproduct is more valuable than the energy product, it will be helpful to optimize for the byproduct (protein, hydrocarbon, or other material of commercial value.) At the same time, the preceding discussion illustrates the importance of maximizing overall efficiency. It is therefore necessary to understand the metabolic consequences of physiological variables such as CO_2 pressure.

Many of the early sites of metabolic regulation of CO_2 uptake by photosynthesis and conversion of photosynthate to secondary products have been identified, and some are shown in Fig. 2. There are important points of regulation at the carboxylation of ribulose 1,5-diphosphate and its formation, and at the conversion of hexose and heptose diphosphates to monophosphates. We have postulated that a balance between the rates of these conversions helps to regulate the pool sizes of intermediate compounds of the photosynthetic reductive pentose phosphate cycle. The enzymes at these sites also function to turn off the reductive cycle in the dark, when respiratory metabolism sets in. It is also necessary to control the flow of carbon away from the photosynthetic cycle to secondary products. One example of this is the regulation of the reaction converting phosphoenolpyruvate to pyruvate. As we examine the further conversion of intermediates to fats, amino acids, polyisoprenes, carbohydrates, etc., we will have to learn about many more sites of regulation. In short, a look into the future suggests that as we attempt more and more to use plants as factories to produce specific products in high yield, we will need more than ever to learn how the production is regulated in the plants and how it might be turned more to our advantage.

The preparation of this paper was sponsored by the U. S. Energy Research & Development Administration.

Storch, Cellulose, etc.

This report was done with support from the United States Energy Research and Development Administration. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the United States Energy Research and Development Administration.

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