Acknowledgment. Parts of this article are derived from studies done by the author for a UNESCO study on 'Fundamental World Energy Problems', a UNEP project on 'Photosynthesis in Relation to Bioproductivity', and a UN Biomass Panel paper. In addition various research contracts and reviews by the author have been incorporated.

Addendum. Since the completion of this article 4 symposia have been published which are of direct relevance to this article.

a W. Palz, P. Chartier and D.O. Hall, eds, Energy from Biomass. Applied Science Publishers, London 1981. 982 pp.
b T. Chandler and D. Spurgeon, International Cooperation in Agroforestry, ICRAF, P.O. Box 30677, Nairobi 1980. 469 pp.
c Proceedings Bio-Energy 1980 World Congress. Ed. Bio Energy Council, Washington D.C. 20056, USA. 586 pp.
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1 D.O. Hall, Solar Energy *22*, 307-328 (1979); Nature *278*, 114-117 (1979); Outlook Agriculture *10*, 246-254 (1980).
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Higher plants as energy converters

The first paper by S.H. Wittwer describes agriculture as the only major industry that processes solar energy. On one side this happens through photosynthesis and production of biomass. He discusses the possibilities for increasing the biomass yield for food, fiber and fuel as well as the use of sunlight for biological nitrogen fixation. On the other side solar energy can be used for many processes on the farm such as drying grain, heating livestock stables and greenhouses.

E.S. Lipinski and S. Kresovich discuss sugar crops (sugar cane, sugar beet and sweet sorghum) as important energy plants. They outline the features of each in cultivation and detail the procedures for processing and converting the crops into useful products and fuel.

M. Calvin et al. present plants with a high content of hydrocarbons, e.g. *Euphorbia* species, for energy crops on arid land. While these plants have a low requirement for water and nutrients, their production of biomass is relatively high.

F.H. Schwarzenbach and T. Hegetschweiler discuss energy conservation in trees and wood, the oldest form of biomass to be used as fuel by man. They deal primarily with the production of wood in the industrial countries of temperate climates rather than with energy farming in the tropical and subtropical zones.

Finally in the paper by N.W. Pirie, a special biomass product, leaf protein, is proposed as an alternative source of protein for food and fodder.

Solar energy and agriculture*

by Sylvan H. Wittwer

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Agriculture stands pre-eminent as the world's first and largest industry. It is our most basic enterprise, and its products are renewable as a result of 'farming the sun'. Through the production of green plants, agriculture is the only major industry that 'processes' solar energy. The greatest unexploited resource that strikes the earth is sunlight and the green plants are biological sun traps. Each day they store on earth 17 times as much energy as is presently consumed worldwide. The goal of agriculture is to adjust species and cultivars to locations, planting designs, cropping systems and cultural practices to maximize the biological harvest of sunlight by green plants to produce useful products for mankind. Many products of agriculture may be alternatively used as food, feed, fiber or energy. Conflicts over the agricultural use of land and water resources for food, feed or fuel production will arise as resource constraints tighten.

Thus, the greatest use of solar energy in agriculture is in agricultural production itself. All farm practices directed toward increased crop productivity must ultimately relate to an increased appropriation of solar energy in the plant system. And yet, while solar energy is clean, makes no noise, is widely available, requires no fuels, and is renewable, is non-polluting, and cannot be embargoed by nations, few research efforts on photosynthesis have focused on crop productivity and increased biomass production. Photosynthetic efficiency averages less than 0.1% during the entire year for the major food crops. For most crops that efficiency of solar energy utilization during the growing season does not expend 1%. Only under the best of conditions can it be 2–3% for such crops as sugarcane, maize, hybrid Napier grass and water hyacinths. Yields and photosynthesis are affected by varying environmental pressures and diversity among plants themselves. There are many opportunities in research for enhancing photosynthesis. The approaches may be biochemical, genetical or cultural. One way to most immediatly improve photosynthesis for a large number of food crops species is to genetically alter the plant architecture. Verticle positioning of the flag leaves of the rice plant above the panicles of grain rather than having them droop below is an example of recent technological achievement which is improving yields. A better light receiving system is thus created (fig.). Positioning the flag leaves above the panicles of grain in the rice plant is one approach currently being adopted in Southeast Asia and in the People's Republic of China. The current energy establishments (industries), however, tend to downplay the importance of solar energy in the photosynthetic process and for other agricultural uses. This is perhaps to be expected of organizations that would be threatened by the success of new energy systems. Nevertheless, some noteworthy developments are in progress.

New rice varieties with flag leaves positioned above the panicles of grain. This type of architecture creates an improved light receiving system for capture of solar energy in photosynthesis.

A shift from food production to fuel production is being encouraged in many parts of the world as motor fuel prices soar. Alcohol derived from grain and to be used for fuel is the latest rage. This may have serious repercussions not only for the resource economy of fuel production from grain, but also as land and water resources are siphoned away from food production. Energy crops not only compete for land and water but also for investment capital, fertilizer, farm management skills, farm to market roads, agricultural credit, and technical advisory services[1,2].

Maize is the primary raw material being considered for alcohol production in the USA. It is also widely adopted for temperate and subtropical agriculture, and has the highest genetic potential productivity of any major food crop. Maize also has many other productive uses – as a food stuff, animal feed, starch, cooking oil and as a basis for sweeteners. In Brazil, sugarcane is the key raw product, and that nation has a 2-year goal for achieving independence with respect to imported oil.

The potentials for food and feed from biomass, and energy from biomass are enormous. Cellulose is the world's most abundant organic compound, followed by lignin. The biochemistry of lignin's degradation and conversion to food and fuel is much more challenging than that of cellulose.

Vegetable oils, particularly sunflower, rapeseed and soybean oil, are not only useful as foods, but will power diesel engines by direct injection[3] and require only one third the processing energy of ethanol extraction from grain or cellulose. Photosynthesis through the green plant is a remarkable resource which produces an abundance of raw materials which may alternatively be used or converted to fuel, feed, or food. Aside from solar energy through photosynthesis there are many other existing and potential solar energy inputs for agriculture[4–6]. These include nitrogen fertilizer fixation – both biotic and abiotic, grain and crop drying, heating of poultry and livestock housing units and drying of wastes therein, irrigation pumping, water heating for low temperature food processing, biogas generation, greenhouse heating and cooling, solar stills in arid lands, and as solar collectors in protected cultivation utilizing various plastic covers and mulches. Many projects are under development in each area.

Nitrogen fertilizer fixation. Approximately one-third of the fossil energy required for agricultural production in the United States comes from the use of nitrogen fertilizer, and up to 35% of the total productive capacity of all crops is ascribed to this single input. Massive amounts of energy are required for nitrogen fixation whether chemical or biological. The limiting factor in the biological fixation of nitrogen for the *Rhizobium*-legume association is photosynthate production[7]. One of the great gaps in current agricultural research is the lack of integration of studies in photosynthesis with biological nitrogen fixation in crop production.

Biological nitrogen fixation research throughout the world has produced and published enormous amount of valuable information during the past 20 years, but this information has had little significance for practical application under the field conditions of traditional agriculture. A unique approach toward nitrogen fertilizer fixation for developing countries would be an abiotic technology utilizing renewable energy resources - solar, wind or water power. A scaled down electric arc system for atmospheric nitrogen fixation that was displaced over 50 years ago by the Haber-Bosch process is now under review[8].

Farm-size units are now being tested that have the potential of making even the poor small farmer self-sufficient in nitrogen fertilizer. This unit could be inexpensive and easy to operate and maintain. It would utilize nitrogen from the air, and modest electric current from a generator powered by wind, water, or sunlight freely available on many farms. It is now being tested on a farm in Sandpoint, Idaho, at the Solar Energy Project of the University of Nebraska's field laboratory near Mead, and in Nepal with its plentiful supply of fast-flowing water and very little nitrogen. Similarly, the unit appears well suited for adaptation in The People's Republic of China given that country's vast and as yet largely untapped hydroelectric power resources.

Grain and crop drying. Drying requires over 60% of the total energy needed for on-farm corn production in the northern corn belt of the USA as well as the humid south. Solar energy or sun drying in the open offers the only alternative in many developing countries. Considerable interest has now also emerged among industrialized countries, and many sophisticated technologies have been described which use variously designed solar collectors including inflated plastic structures. Their economic feasibility based on current prices of fossil fuels is questionable. Alternative sources of fuels such as crop residues are also under development[9].

Heating of poultry and livestock housing units. Numerous studies - starting with brooder houses to full scale production units - have been completed and other schemes are under development. Numerous tests are also in progress using solar energy for the drying of animal and poultry wastes. Water may be used as the collecting and storage medium. Three years of evaluating a solar collector for a poultry laying house in East Lansing, Michigan, showed fuel and feed savings from higher in-house temperatures capable of paying off the collector in about 5 years[10].

Irrigation pumping. 20% of the total agricultural energy production budget is used for irrigation. It reaches as high as 60% for irrigated agriculture. Energy used for irrigation alone may be twice the total energy inputs for rain fed crop production. While these figures apply to the USA, similar energy inputs exist in other nations. A major research effort should be directed toward the more efficient use of solar energy for crop irrigation. The approach should be most opportunistic, since crop water requirements are usually positively correlated with solar energy intensities.

An extensive project is currently underway in Nebraska using solar power to irrigate a 32-ha corn field. Solar generated electricity powers a center pivot irrigation system's motor and water pump and runs fans which dry the grain once it is harvested[11]. The extra electrical energy is used for the production of nitrogen fertilizer by the electric arc method[12].

Water heating for low temperature food processing. About 6% of the energy budget in the USA is used in food processing and packaging. The milk industry is one of the largest users, requiring much of its energy to create warm water. Currently, natural gas, propane, and electricity constitute the main source for heating of water in food processing plants. It has been demonstrated that solar water heating for food processing plants is now economically feasible in many locations in the USA and could become increasingly so as fossil energy prices escalate. Up to 30-40% of the electric energy demand for warm water in dairy plants may now be provided by solar energy[13].

Biogas generation. The primary raw products are human, animal and vegetable wastes with animal manures predominating. These are subjected to anaerobic bacterial digestion which results in the release of methane. This, in turn, is used for home cooking and electrical power generation. Use thus far has been confined largely to agriculturally developing countries[6]. A chief constraint in India, for example, is that the use of animal manures competes directly with their use as a dried raw product for cooking fuel. Hence in all of India it is estimated there are scarcely 30000 family size biogas generating units. This contrasts with The People's Republic of China where there are an estimated 7 million. China has 2 major biogas research stations, one in Sichuan Province, the other near Shanghi. Solar energy collectors are being utilized in development programs to provide the heat necessary to keep the units operational during the cold winter months. Another approach is to develop microorganisms that can function effectively over a range of temperatures from 5 to 45 °C.

Solar greenhouses, stills, plastic covers and mulches for controlled environment agriculture. Greenhouses - glass, fiberglass or plastic - are natural solar energy collectors. Essential components for further refinements are A-frame constructions with saline solar pond collectors and the provision for insulation to prevent heat loss at night. The possibilities of greenhouse-residences are under review[14].

Solar stills may be a means of providing fresh water for crop production in arid lands. They are semi-cylindrical plastic tunnels or ground mulches positioned over polluted or brackish water or over sandy irrigated soils. They can effect considerable water vapor condensation as well as reduce water losses by evaporation. The opportunity lies in integrated solar still-bubble greenhouse combinations for the production of high value crops[15].

The most extensive use of solar energy collectors for crop production is in the use of plastic covers and soil mulches for promoting early seedling growth and water conservation in temperate zone agriculture. Significant developments are those in China where rice crops from seedlings covered with plastic mature 2-3 weeks earlier. Especially significant results have been obtained with maize in France by mulching with clear plastic. Maturity is advanced by 3-4 weeks and the yields are doubled[16]. Indeed, this is one of the important options for the future enhancement of food production in agriculturally developing as well as for industrialized nations.

In conclusion, a model for future agricultural technology relating to resource inputs would be that which is scale neutral, non-polluting and environmentally benign, which would add to the resources of the earth, result in stable production at high levels, be sparing of capital, management and resources, and which could be alternatively labor intensive or labor saving. Future developments in the use of solar energy for the production and processing of agricultural products should well satisfy the above criteria.

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Sugar crops as a solar energy converter*

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Biomass crops are renewable resources with multiple uses that can benefit mankind[1]. Current attention centers on replacement of petroleum as a principal source of energy for transportation applications. Fuels for electric power generation and household heating and/or cooking also are needed. Rising global demand for chemicals, food, construction materials, and paper products increase resource requirements even further.

Sugar crops are of special interest as solar energy converters because effective use of these renewable resources can make available the multiple products that will be required to ameliorate the crises affecting the availability of materials and fuels. Sugar crops