MIT-T1-78-004 C2

The MIT/Marine Industry Collegium
Opportunity Brief #11

The Economics and Engineering of Large-Scale Algae Biomass Energy Systems

M.I.T.
SEA
GRANT
PROGRAM

A Project of
The Sea Grant Program
Massachusetts Institute of Technology
MITSG 78-11

The MIT Marine Industry Collegium

THE ECONOMICS AND ENGINEERING OF LARGE-SCALE ALGAE BIOMASS ENERGY SYSTEMS

Opportunity Brief #11

Revised Edition

May 1, 1978

Marine Industry Advisory Services

MIT Sea Grant Program

Cambridge, Massachusetts 02139

Report No. 78-11

Index No.78-711-Zlg

CONTENTS

PREFACE

This Opportunity Brief and the accompanying Workshop were presented in collaboration with a Collegium member company, Dynatech R/D, under sponsorship of the Department of Energy's Fuels from Biomass Program. This Opportunity Brief is based on the work carried out by Dynatech R/D and their subcontractors and on contributions suggested by attendees of the Workshop, which was held at MIT on January 24 and 25, 1978.

The author remains responsible for the assertions and conclusions presented herein.

Norman Doelling

About the MIT/Marine Industry Collegium

This document was prepared as part of the MIT/Marine Industry Collegium program, which is supported by the NOAA Office of Sea Grant, by MIT and by the more than 90 corporations and government agencies who are members of the Collegium. Through Opportunity Briefs, Workshops, Symposia, and other interactions the Collegium provides a means for technology transfer among [illegible] industry and government for mutual profit. For more

1. A Business Perspective

Algae and other plants are unique energy converters in that conversion and storage of energy are both carried out via the process of photosynthesis. Interest in biomass as a source of fuel is not new. Biomass in the form of wood was the source of energy until the early 1700s. However, interest in microalgae, seaweeds, and other aquatic plants as energy sources is new. Only recently has their potentially high efficiency of energy conversion been appreciated. If one calculates the annual solar energy falling upon a forest and then measures the caloric value of the annual harvest of wood, the efficiency (solar energy input/energy out as heat of combustion) is about 0.1%. On the other hand, the efficiency of aquatic plant systems is frequently near 1% and under special laboratory conditions can be made to be near 10% for short periods of time. Thus a review by economists, engineers, and biologists of the potential of energy systems based on large scale growth of aquatic plants is appropriate at this time.

The Department of Energy is sponsoring a program on fuels from biomass and a subprogram on algae as a source of biomass. The goal of these programs is to investigate sources of energy on a scale that could provide around 5% of national energy needs around 1990. Our goal in this Brief is more modest: we seek to outline the current state of the art and the potential of aquatic plant biomass systems over the next three to five years, and to suggest industrial development and research opportunities.

The primary references we draw on are reports (Ref. 2 and 3) in preparation by Dynatech R/D Company with the cooperation of principal investigators from the Woods Hole Oceanographic Institution, California Institute of Technology, and the University of California at Berkeley. The reader with more than casual interest in large scale aquatic plant husbandry will find in Reference 2 an excellent compendium of the state of the art, identifying where research and development is being carried out, and also providing an extensive bibliography.

Reference 3 includes the engineering and economics of large scale aquatic plant biomass systems including a careful listing of the assumptions used in analysis of the baseline systems and variations of parameters around the baseline assumptions in order to provide a sensitivity analysis.

While the 150 attendees at the Symposium/Workshop differed on many points, the conclusions of the studies as presented can be summarized as follows:

1) Because the state of the art in mass culture of algae and other aquatic plants is extremely primitive, there are large potential errors and uncertainties in attempting extrapolations from today's small-scale systems to 100 square-mile farms.

2) Based on current knowledge of mass aquatic plant culture and extrapolations from current knowledge, designing, building, and operating very large aquatic plant biomass

systems solely for the energy product appears excessively costly and probably not feasible because of institutional constraints such as environmental problems, competing uses for land and water, etc.

3) For very large systems, providing the requisite quantities of nutrients (carbon dioxide, nitrogen, and phosphorus) is the major bioengineering and cost problem. In fact one feels there are distinct diseconomies of scale in the nutrient issue.

4) The potentials of largescale aquatic plant systems remain high, but basic research in genetic engineering is needed to learn how to get additional valuable end products (e.g., refinery feedstocks, protein, animal feed, and fertilizer) in addition to energy as outputs, in order to economically justify large aquatic plant systems.

5) Small systems (e.g., one square mile) using sewage wastes as nutrients appear to be worthy of further study. The cost "credits" for getting rid of undesirable sewage waste may, in site-specific cases, make energy production commercially viable.

6) Environment/legal issues may prove to be a vexatious problem.

While the short-term prognosis for very large energy outputs from aquatic plant farms appears dim, it is appropriate to close this Business Perspective with a comment made by Dr. Harris Bixler at the close of the conference:

"I want to put in a plea that you systems people don't overwhelm the experimental biologists, scientists, or engineers in this audience. We rely on them for the hard data that let us inch ahead on our cultivation work, for new biological insights, and, perhaps most importantly, for those technical breakthroughs. Just think about the work you have been doing and how it might change if we could hybridize superfast growing seaweeds, if we could genetically manipulate those fast-growers so that we got a better chemical cocktail out of them, or if we could photoenergetically fix nitrogen in some efficient way."

The story would change very dramatically, and that's going to happen; but it's going to take patient, hard, uphill work on the part of biologists, engineers, and chemists.

2. Some Preliminary Observations About Solar Energy and Biomass Energy Systems.

2.1 Solar Power, Conversion Efficiency, and Energy Storage

Directly beneath the sun at local noon, the power intensity of the sunlight falling on the earth's surface is approximately 1 kilowatt per square meter. The average solar power intensity is much lower. The sun's power per unit area decreases toward sunset and remains zero all night. In addition, the sun appears to migrate south in the (northern) winter months and north in the summer months. Furthermore, the earth's distance from the sun varies annually, being nearer the sun during the northern winter.

The average power intensity from the sun, averaged over a 24 hour day, throughout the year, and averaged over the entire continental United States, is about 0.2 kilowatts/m^2.

Since the per capita power consumption in the U.S. is roughly 10 kilowatts*, the power consumed by each citizen could, in theory, be provided by 50 (10kw/0.2kw/m^2) square meters of solar radiation if 100% of it could be captured and stored. Fifty square meters (500 square feet) is about equal to the area of the typical citizen's roof. On the other hand, if the process of conversion, distribution, and release of the

---

* Reference 1, Energy, contains 18 Appendices which are a delightful compendium of energy facts and figures which are a godsend when one must convert from calories/cm^2/day to BTU/acre/year, and other similar computations.

solar energy is only 1% efficient (a very reasonable estimate), about 50,000 square feet, roughly an acre, would be needed for each citizen... or, for the entire U.S. population, a total area comparable to all the arable land under cultivation in the U.S.

Since the sun provides power only during the day, and since the demand for power continues all night, solar power must be stored if a supply of energy is to be available at all times of demand. When energy must be converted from one form to another in order to be stored, the process is generally inefficient and expensive. Thus the land requirements for total dependence on solar energy may actually be several times greater than those already suggested.

In summary, since solar energy intensity is only a few hundred watts/m^2 on the average, and since solar power conversion is inefficient, very large land areas will be required for any solar energy systems that would provide a substantial fraction of the U.S. per capital energy needs.

2.2 Photosynthetic Efficiency and Energy Balance

Growing mass algal cultures or aquatic plants is an art and science still in its infancy. The aforementioned Dynatech R/D report (Ref. 2) provides an excellent overview of the international state of the art along with citations of over 300 relevant papers. Optimum bioengineering processes for capturing photosynthetic energy in carefully controlled laboratory systems are not yet clearly understood. However, photosynthetic efficiency for storing solar energy in biomass in outdoor systems is roughly 1%, based on a biological productivity of 10 grams of ash free organic matter/m^2/day* and an assumed energy value of 5.5 kilocalories/gram).

The bioengineering problem is threefold: first, to select or breed aquatic plants whose photosynthetic efficiency is perhaps ten percent instead of one percent; second, to provide the nutrients and environment to support the growth rate implied by a 10% photosynthetic efficiency; and third, to harvest and process the biomass efficiently.

The energy cost of providing nutrients and of harvesting must be low, or the net energy production may be

---

* Appendix One contains some helpful conversion units for getting from biological and engineering units to MKS units. Mean daily total incident solar radiation is usually given in cal/cm^2/day - called Langleys. Biological productivity is variously measured in grams/m^2/day, metric ton (1000 kg)/hectare/year, and tons (2,000 pounds)/acre/year. Finally, stored energy of combustion is usually taken to be 5.5 kilocalories/gram of ash free, dry weight of crop. Since data are expressed in varied units, extreme care should be taken in comparing data from various sources.

negative. For example, the energy required to stir a medium, to bubble CO_2 through a medium, or to move water to and from ponds of various types may consume a very substantial portion of the gross energy output. The engineering studies by Dynatech provide preliminary evaluations of these factors (Ref. 3).

Separation of microalgae - or their concentration for digestion - could also be nontrivial from an energy viewpoint. Equipment to contain, grow, move, separate, concentrate and digest aquatic plants represents a potential energy investment to create (as well as to operate) a biomass system and the "energy payback" period must be considered in determining true net operating efficiency of the algal system.

It must be observed that from both an energy viewpoint and from an economic viewpoint, net energy output from a massive aquatic plant system may not be the best way to account for the energetic contributions that a plant system can make to the net of national energy balance.

For example, the net energy output of protein from a plant system should not be measured only by energy (caloric) content of the protein product. At present, at least two calories of energy are expended to catch one calorie of edible fish meat. Other meats and other protein sources are even more expensive in terms of energy cost (Ref. 8). Thus the caloric value of algal protein which replaces fish or other meat may "save" several times the amount of energy represented by its caloric content.

The "savings" of the energy product of an aquatic plant system must also be considered when determining the net effect on the national energy balance. Important contributions to the net national energy balance may be overlooked if energy accounting does not extend beyond the boundaries of the plant system.

The example given also applies to financial balances, or cost considerations. Obviously, the dollar value of algae grown for protein or for refinery feedstock is going to be orders of magnitude more valuable than just the heat value of the protein. In addition, if an algal energy farm "consumes" sewage waste which otherwise would be expensive to dispose of, a credit should be applied to the energy cost and net output.

2.3 Mass Balance

The photosynthetic process involves combining water, carbon, nitrogen, phosphorus and various trace metals in appropriate quantities to form plant materials which are a form of stored energy. The process for aquatic plant mass culturing is depicted in a general way in Fig. 1 (after Ref. 2).

Two aspects of mass balance are important. Obviously all the materials going into the algal growth process on the left must either be disposed of by one or more of the means suggested on the right of Figure 1 or they must be recycled back to the left by some process.

A completely (100%) recycled system cannot be achieved, unless the energy is taken out on the right as heat or electricity. For example, if one is going to remove methane (CH_4) at the end of the process, there must be provisions for a massive source of carbon and hydrogen at the input. Put in the opposite way, if a system is to be designed to achieve very close to 100% recycling of <u>all</u> materials, the energy output must be heat or electricity. If the output is a <u>material</u> form of stored energy, then a source of nutrients such as domestic waste water or diluted solid wastes must be provided as an input to the system to balance the material carried away at the output.

In summary, mass balance considerations demand that truly closed cycle aquatic plant systems for energy production must have as an output only heat or electricity. If the

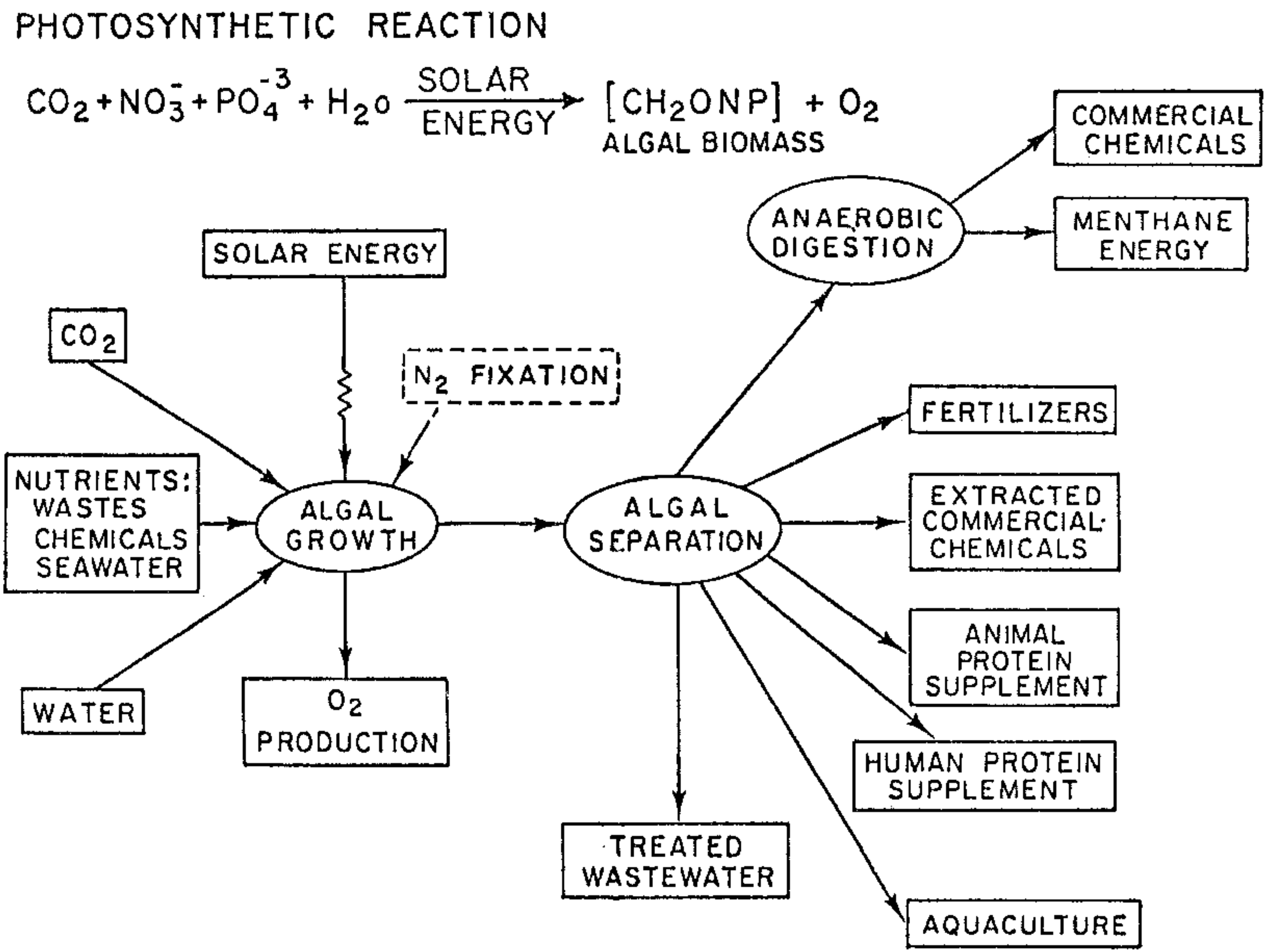

Figure 1

Possible Applications of Algal Mass Culturing methane or other hydrocarbons or protein is taken out as stored energy, the nutrient supply must be provided and the amount of energy will ultimately be limited by the availability of nutrients.

2.4 Standing Biomass

Clearly, rapid growth is a desirable parameter of a biomass system for storing and converting energy. The faster the biomass grows, the more there is to convert into energy. Also, faster growth implies the advantage of less area devoted to biomass culture.

Fast growth is also important for another, less obvious reason: the more frequently biomass can be harvested, the less carbon, nitrogen, and phosphorus will be tied up or stored within the system. In other words, frequent harvesting means more rapid recycling and, hence, greater utilization of essential nutrients. This point assumes considerable significance when one calculates the enormous nutrient requirements for sustaining biomass growth in quantities that make large-scale energy conversion attractive.

The productivity, p, in grams/m^2/day (the mass unit area per unit time) can be expressed as

$$p = M \times g$$

in which

M = the total standing biomass/m^2

g = fractional growth in percent per day.

One could obtain, for example, 1 gram/m^2/day in many ways. One could have M = 100 grams/m^2 and g be 1% (0.01) per unit/day - or M could equal 10 grams/m^2 and the growth could be 10% (0.1) per day. A forest of trees has a very large M and a small g.

Put in another way, if a crop of size p could be harvested daily (as may be the case with marine algae), only 1/365 as much standing biomass (M) would be needed as if the same crop were harvested yearly.

For microalgal systems, optimum productivity ($gm/m^2/day$) for present systems seems to correspond to harvesting rates of about once per day. In laboratory systems, doublings of biomass 4 to 8 times per day have been achieved, suggesting an important direction for improving efficiency of biomass systems.

Note also that a high percentage growth rate (g) does not by itself assure a high yield (p). The product of growth rate (g) and standing mass (M) must be large.

The above assumes that the harvested part (yield) is equal to the incremental growth. In the case of *Macrocystis* only a fraction of the growth (the canopy) is harvested.

In summary, rapid growth rates are important for two reasons:

1) They can minimize area required for growth.
2) They can minimize the standing biomass which must be managed to start and operate the system.

3. Two Current Approaches to Aquatic Plant Energy Farms

3.1 Open Ocean Systems

Giant kelp (Macrocystis) is capable of prodigious absolute growth rates (but low percentage growth rates) and has long been recognized as a choice source of biomass for energy. A group led by Professor Wheeler North of the California Institute of Technology has worked on the husbandry of kelp beds off the California coast for many years (Ref. 4). Thus, at least compared with most seaweeds, much is known about its nutrient requirements, its ecology, its predators, etc. Kelp is a principal food for snails, sea urchins, some fish, and some small crustaceans, so predator control will be important in ocean farming.

A few species of seaweeds have considerable commercial value for their contained hydrocolloids such as alginic sugar, agar, and carrageenan, which are extracted from the dried plant material and used as emulsifiers and stabilizers in the food, drug, and cosmetic industries. Recovery of such by-products may be crucial to the economics of an open ocean energy system.

Location

One of the advantages of siting a very large energy farm in the ocean is that vast areas of little used empty space are available. If farms on the scale of 10 miles by 10 miles are considered, the potential for conflicting uses (shipping traffic, pleasure boating, commercial fishing, etc.)

will be small, provided the farm is located a long way offshore... at least 25 miles and perhaps 100 miles.

Productivity

Compared to microalgae, the productivity of kelp beds in the natural state is low, being reported as about one ton ash-free dry weight/acre per year, which equals about 0.6 grams/m^2/day or an energy conversion efficiency of less than 0.1%. Thus, although in an absolute sense kelp grows rapidly, the percentage growth per day is not large, and the efficiency is low. Of course, this productivity does not reflect what might be achieved in a more controlled environment with fewer predators, better nutrients, more careful spacing of the plants so they don't shade one another, appropriate hybridization, etc.

Mass Balance

While the sea provides all the carbon necessary for growth in the form of dissolved CO_2 and various carbonate ions, the sea surface far offshore is a relative desert as far as nitrogen and phosphorus concentrations are concerned. Thus one must find a continuous source of nitrogen and phosphorus and/or recycle the nitrogen or phosphorus in some energy efficient manner. One possible source of nutrients is seawater 500 to 2000 feet below the surface, which is much richer in nitrogen and phosphorus than surface water. Thus, the nutrient problem is easily solved in principle, although pumping subsurface water may create an energy balance problem as suggested below.

There is also a mass balance problem in starting up or stocking a kelp farm. Rough calculations show the standing biomass in a kelp farm is on the order of 10 tons per acre. Stocking will take tons of materials and years to accomplish, which may be a very important economic consideration.

Energy Balance

Operation of a kelp farm at sea will be energetically expensive if power must be expended continuously to pump nutrient laden sea water from 500 to 2000 feet below the kelp beds.

The issue of nutrient provision is a nontrivial engineering and physics problem. The energy cost of pumping the nutrient laden deep water to the top is a relatively straightforward engineering problem. However, estimating how long the relatively cold nutrient laden water remains near the surface (residence time) where it can be absorbed and utilized by the kelp is very difficult. Until further experiments are carried out, the amount of nutrients used by the kelp and hence the total amount of water which must be pumped remain extremely uncertain. Since the energy balance of the farm depends strongly on the amount of deep water which must be pumped, we can only obtain a very rough estimate of a lower bound on cost, i.e., one which corresponds to a very long residence time. If residence times are very short, the amount of water which must be pumped is huge, and the energy input to the farm will exceed the energy output.

Harvesting and transporting the kelp to shore must be done by ship. Since petrochemical plants, pulp plants, and nuclear reactors are now being designed to operate aboard floating platforms, it may also be worthwhile, economically and energetically, to consider digesters and liquification plants located permanently at sea. Thus only methane would have to be transported to land, rather than hauling the whole kelp ashore and hauling the nutrients back to the kelp farm.

Special Considerations

There are enormous problems of ocean engineering and bioengineering involved in providing a substrate for growing kelp at sea. General Electric, sponsored by the American Gas Association, is investigating the design and construction of a 1/4 acre module which is a central, vertical module with six radial arms supporting webbing between the arms. The module looks roughly like a hexagonal inverted umbrella frame. This module is to be used in helping to estimate the wave and current forces transmitted to the supporting structure via the kelp, and to understand many of the bioengineering problems.

Since the structure will span more than a wavelength of many ocean waves, the net forces on the mooring may turn out to be surprisingly low, even though the forces on individual elements are relatively large. In any event, ocean engineering technology developed by the offshore oil industry in designing tethered drilling rigs, supertankers and single point moorings for loading and off-loading supertankers can be applied. The costs of applying such technology may be prohibitive.

In the engineering of ships and offshore platforms, engineers acknowledge that almost anything man builds can be destroyed by a large enough storm. Ocean structures are typically designed to survive a storm of such magnitude that it occurs only once every twenty years on the average. Of course, a "20-year storm" may arrive next year, or the year after, or not until 60 years from now, so there's no assurance to the designer or owner that just because he designs a structure to withstand a 20 year storm that it will last 20 years. Natural kelp beds are frequently destroyed by storms, as North's reports testify. Thus even if the structure survives a storm, the kelp beds may require replanting. In building structures in the ocean, there is a risk element that has no land-based counterpart. That risk must be offset by higher return on capital and higher cost.

Cost

Under some optimistic assumptions about residence time, yield, capital costs, interest rates, etc., Reference 3 shows a representative cost of energy (in the form of methane) of about $40 per million BTU or roughly twenty times the current ($1.75) price set by Congress. As suggested earlier, there are many unknowns involved as well as many explicit and implicit assumptions. The cost models permit variations in assumptions and allow alternative optimizations to be carried out; but a price of $40 per million BTU severely limits the potential of large-scale kelp farming as an energy source.

Recapitulation

Kelp farming is in its infancy. Percentage growth is low, the standing biomass is large compared to that of micro-algae. Enough is known about kelp to estimate its nutrient requirements reasonably accurately and to begin engineering considerations of how a kelp-based energy farm might be designed. Preliminary engineering studies (Ref. 3) indicate that both the dollar costs and the energy costs of providing nutrients (particularly nitrogen and phosphorus) will be prohibitively high. Pumping deeper sea water uses very large amounts of energy and requires expensive distribution systems. Recycling nutrients sounds appealing, but the issues of residence time and the fraction of nutrients lost to the kelp noted above are just as important (and as poorly understood) as in the pumping case. Thus, we believe open-sea kelp farming for energy will require locating farms in areas of natural upwelling. (In these areas, deep ocean currents are forced towards the surface carrying with them nutrient laden deep ocean water.) The location, extent, and nutrient content of these upwellings have not been investigated in detail, so it remains speculation as to whether a kelp farm in an area of natural upwelling will be a viable source of biomass for fuel. It appears quite certain that without natural upwellings, kelp farms are not viable sources of fuel from biomass if pumping nutrients is required. Finally, ocean structures are expensive and involve a great element of risk or uncertainty. The availability of space and carbon offered only by the ocean systems does not appear to be worth the costs that must be incurred to provide nutrients (nitrogen and phosphorus), to harvest, and to recycle.

3.2 Land-Based Systems

Wastewater, laden with nitrogen and phosphorus, is a logical source of nutrients for land-based algal systems. The costs of getting the nutrients into solution and of bringing large volumes of water to a single point are already borne by wastewater disposal systems of an industrial society. Over the past decade a number of investigators have focused on the growth of algae using wastewater in land-based ponds as a means of converting nitrogen and phosphorus into more valuable forms for fertilizers or as the basis of an aquaculture system. Professor W. J. Oswald of the University of California has been a pioneer in algal/wastewater systems (Ref. 6) and Dr. John Ryther of Woods Hole Oceanographic Institution has investigated wastewater/algal/oyster/seaweed systems (Ref. 5). Two of our earlier Opportunity Briefs dealt with related topics (Ref. 7 and 8).

Location

A major criterion for energy production is that the site for land-based algal wastewater treatment systems be near the source of nutrients; otherwise the capital (and energy) costs of moving wastewater become enormous. At the same time, if the energy farm is too near an urban area, land costs become prohibitive.

Other criteria are similar to those for ordinary farms. The land must be relatively flat, in fact, about as flat as a rice field, since algal ponds must be shallow (less than one meter) to take full advantage of available sunlight. Rainfall and evaporation must be in near balance, so arid desert areas cannot be used. Thus algal farms may come into competition with traditional farms. As noted earlier, the land required is inversely proportional to the productivity (grams/m^2/day), so it is difficult to estimate area requirements until productivity is well known. However, the amount of land needed has been estimated to be a substantial fraction of the arable land in the U.S. Land cost and land availability are the two most formidable problems in considering land-based algal systems.

Productivity

The good current technology for outdoor microalgal systems permits a sustained year-round average productivity of about 10 grams dry ash-free weight/m^2/day, which corresponds to about a 1% efficiency for storing solar energy. In controlled laboratory experiments, productivities ten times higher have been achieved on a short term basis. Thus prospects for achieving a 4% conversion efficiency over longer periods may be possible.

Harvesting and Energy Conversion

The major unsolved problem in algal farms is harvesting the algae in a way that does not consume more energy than it produces. Centrifuging and drying require so much energy as to be prohibitive. Filtering is more likely to be possible, but again, the energy and dollar cost may be prohibitive. Ryther and others have proposed harvesting by filter feeders such as clams, oysters, or milkfish. Such methods of harvesting have a great deal to recommend them on an economic basis and on a "quality" of energy basis. However, as a means of storing energy, these techniques cannot be considered.

The most probable technique to be used in harvesting and in energy conversion is some form of filtering and concentration of the algae, by means of induced settling, floatation, or filtering, followed by anaerobic digestion of the algae medium to produce methane. Experiments have been done that show the digestion process to be about 50% to 75% efficient. The residues of the process can be recycled as nutrients for the algae or used as a fertilizer for land crops.

<u>Mass Balance</u>

Wastewater can satisfy nitrogen and phosphorus requirements but not carbon requirements. Since almost any output product of the farm - methane, other hydrocarbons, protein, etc. - will contain carbon, a source of carbon is essential. The carbon mass balance may be the most difficult portion of the mass balance to satisfy.

Some have proposed using scrubbed flue gases from power plants as a source of CO_2. This may be economically possible, but it is an energy intensive process and raises serious problems concerning energy balance (Ref. 3).

Dynatech (Ref. 3) proposed using water hyacinths as a source of biomass since they take carbon dioxide from the air and not through their roots. As a source of biomass, water hyacinths seem quite appealing, but little is known about their efficiency of conversion to methane by anaerobic digestion.

If the product of the energy farm is methane, surplus quantities of nitrogen and phosphorus will be available. Major questions arise about how to use the nitrogen and phosphorus that is not recycled. Eventually a steady state is reached where the nitrogen and phosphorus coming in must be balanced by nitrogen and phosphorus leaving the system. Perhaps they can be used as fertilizers, but the problem has not been adequately addressed.

Costs

The detailed cost analysis is presented in Reference 3. Representative results show the cost of methane derived from biomass to be \$12 to \$15 per million BTU. Thus costs of energy from land based systems appear to be a factor of three or four lower than the marine based systems. The difference is probably significant but a factor of three or four is also about the degree of uncertainty of the estimates.

Nonetheless, land based costs do appear to be within an order of magnitude of today's prices (\$1.75/million BTU), and depending on how one "credits" the value of solving sewage disposal problems, land based energy farms may become economical.

4.0 Problems and Opportunities

Based on the results of the detailed engineering and economic studies done by Dynatech and on discussions at the Symposium/Workshop, we can identify several key problem areas on which the commercial future of large scale aquatic plant energy systems depend.

Productivity and Yield

First and foremost, almost all cost parameters are directly proportional to the size of the farm per unit energy output - or per unit of any other output. Thus the productivity, p, in grams/m^2/day, and yield are the key economic and engineering variables. Proprietary processes to improve productivity will be extremely valuable. If the specific productivity, g, in percent growth per day (e.g., doublings/day) can be improved so that the standing mass, M (grams/m^2), can be minimized, other system simplifications and cost reductions can occur. It should be obvious therefore that investment in basic aquatic plant research and in "aquatic plant engineering" for productivity and yield ought to have a high priority.

Energy Conversion

Recycling of nutrients represents in some sense an inefficiency in the photosynthetic energy conversion process. The materials recycled can be viewed as aquatic plants that were grown, concentrated, and harvested, but which were not converted to energy. Thus species engineering or selection to maximize energy output while minimizing recycled materials will also have a substantial impact on cost.

Methane is a useful form of stored energy output. It can be transported cheaply and safely. Also, anaerobic digestion processes for obtaining methane are well understood. In short, methane is a useful and valuable output of an algae energy farm.

However, research on optimizing such a farm for other outputs should be considered. Since photosynthesis is simply a way of fixing carbon, nitrogen, and phosphorus in organic matter, more profitable business opportunities might be sought through research on aquatic plants and processes to yield higher level outputs, such as petro feedstocks, protein carbohydrates, and animal feeds. For example, some research is being carried out at MIT with algae that contains about 80% lipids by weight. These algae, if harvested and processed appropriately, might yield more complex, more valuable, and more profitable hydrocarbons.

REFERENCES

1. Romer, R.H. Energy. W.H. Freeman & Co. San Francisco, 1976.

2. Wilson, E.H. et al. Sources and Systems for Aquatic Biomass as an Energy Resource. Will be available through NTIS.

3. Ashare, E. et al. Cost Analysis of Algal Biomass Systems. Spring, 1978. Will be available through NTIS.

4* North, Wheeler. Kelp habitat improvement project - Annual Reports W. McKeck Lab of Environmental Health Engineering. California Institute of Technology, 1969 and following.

5* Ryther, J.h., J.A. DeBoer and B.E. Lapointe. Cultivation of seaweeds for hydrocolloids, waste treatment and biomass for energy conversion. Proc. IX Int'l Seaweed Symposium, Santa Barbara, California, August, 1977. (in press)

6* Oswald, W.J. Determinants of feasibility in bioconversion of solar energy. Int'l Congress Photobiology, Rome, Italy, August 29 - September 3, 1976.

7. ______. Electron Irradiation Sewage Sludge and Aquaculture. Opportunity Brief #6, MIT Sea Grant Report #77-14, Cambridge.

8. ______. Closed Cycle Aquaculture. Opportunity Brief #7, MIT Sea Grant Report #77-15, Cambridge, MA, 1977.

9. Rawitscher, M. and J. Mayer. Nutritional Outputs and Energy Inputs in Seafoods. Science, Volume 198 No. 4314, 21 October 1977.

* More extensive references to the works of Ryther, North, and Oswald are given in Reference 2.

Appendix

Some Useful Data

1 acre = 43,560 ft^2 = 4,047 M^2 = .4047 hectare

1 square mile = 640 acres = 259 hectares

1 kilocalorie (kcal or Cal) = 4184 Joules = 3.968 BTU
= $1.16^2 \times 10^{-3}$ kw/hr

1 BTU = 1.054 Joules = .252 kcal = 2.929×10^{-4} kw hours

1 gm/m^2/day = 3.65 metric tons/hectare/year
= 1.34 (short) tons/acres/year

1000 cubic feet of natural gas has an energy content of about 10^6 BTU.