REVIEW OF BIOMETHANE FROM MARINE BIOMASS

(DRAFT)

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ABSTRACT

The objective of this report is to review the history, results, and conclusions of research on marine biomass conducted under the sponsorship of the U.S. Navy, gas industry (American Gas Association and Gas Research Institute), and U.S. Department of Energy. The scope of this program was to determine the technical and economic feasibility of production of substitute natural gas (SNG) from marine biomass using anaerobic digestion as a conversion process. This work began in 1968 and continued until about 1990, ending as a result of low energy prices in the U.S. and reduced emphasis in renewable energy. The focus of this report is on growth of seaweeds and conversion to methane via anaerobic digestion. Since this program ended in 1990, interested parties met several times to continue discussing this topic and possibilities for obtaining new support its further development. The results of our dialogue at these meetings are summarized, including alternative ideas for marine energy farms and conversion of methane to methanol.

Research from other concurrent programs sponsored by the gas industry to produce SNG from biomass and wastes is summarized and compared with those presented for marine biomass. These programs addressed herbaceous and woody species, water hyacinth and sludge generated from aquatic plant waste treatment systems, and municipal solid waste.

For each of these feedstock categories, feedstock growth or collection (in the case of wastes), harvesting, conversion by anaerobic digestion, and systems and economic analysis are addressed. Also discussed is the potential impact of this form of renewable energy on mitigation of carbon dioxide emissions from fossil fuels.

In general, marine biomass was the least developed of these systems by this research effort. The greatest uncertainties were related to the technical and economic feasibility of large-scale growth of macroalgae in the open ocean, especially concerning provision of nutrients. The anaerobic conversion aspect of this system was better developed and is not likely to be significantly different than that developed for other similar feedstocks. The gas cost estimates for marine biomass systems were 3-6 times those for U.S. fossil fuel gas. Terrestrial biomass systems were developed to a greater extent by this research because of a better prior knowledge of growth and harvest of the feedstocks emphasized. SNG from this category was about 2-3 times that of U.S fossil fuel gas. The lowest cost was associated with SNG from municipal solid waste, reflecting the tipping fee received for treating this waste. However, these costs are not competitive with landfilling.

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LIST OF ABBREVIATIONS

ac, AC	acre (0.405 ha)
AGA	American Gas Association
A & E	architectural and engineering
BFR	fluidized bed reactor
BMP	biochemical methane potential assay
CFMR	continuously fed and mixed reactor
COD	chemical oxygen demand
CSTR	continuously stirred tank reactor
CWRF	community waste research facility
DAFT	dry ash free metric ton
DT/AC	dry U.S. ton/acre (~ 2.24 dry Mg/hectare)
DOE	Department of Energy
ECSA	energy crop systems analysis
EPRI	Electric Power Research Institute
ERDA	Energy Research and Development Administration
ETU	experimental test unit
g	gram
Gg	gigagram, 10^9 gram (~ 1,102 U.S. tons)
GJ	gigajoule, 10^9 Joules (~ 0.948 MMBtu)
GTCY	gigatons of carbon per year
gL^{-1}	grams per liter (1 gL^{-1} = 0.0624 lb/cu ft)
GRI	Gas Research Institute
hr	hour
ha	hectare (~ 2.47 ac)
HRHS	high rate high solids biogasification process developed at Cornell Univ.
HRT	hydraulic retention time
IFAS	Institute of Food and Agricultural Sciences
IGT	Institute of Gas Technology, Chicago, Illinois
in	inch (~ 2.54 cm)
ISC	Integrated Science Corporation
k, k^1	first order reaction rate coefficient
kg	kilogram (~ 2.20 lbs)
kph	kilometers per hour (1 kph = 0.62 mph)
kW	kilowatt (1 kW = 1.34 hp)
L	liter
LBAFR	leachbed attached film reactor
LBL	Lawrence Berkeley Laboratory
L/hr	liters per hour (1 L/hr = 0.264 gal/hr)
L/kg	liters per kg, milliliters per gram (1 L/kg = 0.01602 cu ft/lb)
m^3	cubic meter (1 m^3 = 35.3 cu ft)
MBP	marine biomass program
MCF	thousand cubic feet, approx. 10^6 Btu or 1 GJ if methane
MED	methane enrichment digestion

Mg	megagram, 10^6 grams, 1 metric ton
Mg/ha	metric ton (megagram)/hectare (~ 0.44 U.S. ton/acre)
mL, ml	milliliter
mL/g, ml/g	milliliter per gram = L/kg
MMBtu	million ($l0^6$) British thermal units (~ 1.055 GJ)
MRF	materials recovery facility
MWh/year	megawatt (10^6 Watt) hours per year
NMVFR	non-mixed vertical flow reactor
NOAA	National Oceanic and Atmospheric Administration
NSF	National Science Foundation
NYSGI	New York Sea Grant Institute
O & M	operation and maintenance
OM	organic matter
OFEF	ocean food and energy farm
OFMSW	organic fraction of municipal solid waste
OSTP	offshore test platform
PFR	plug flow reactor
Pi	petajoule, $l0^{15}$ Joules (~ 0.948 x Io^{12} Btu)
psi	pound per square inch (~ 6.89 kPa)
psu	practical salinity units (1 gm/kg = 1 psu)
PTO	power takeoff, mechanical connection to tractor engine
RefCoM	refuse conversion to methane
RS&H	Reynolds, Smith and Hills, Inc.
SA/V	surface area per unit volume
SCF	standard cubic feet
SCR	solids concentrating reactor
SEBAC	sequential batch anaerobic composting
SNG	substitute (or synthetic) natural gas
SOLCON	solids concentrating digester
SRIC	short rotation intensive culture
SRT	solids retention time
SS	suspended solids
STP	standard temperature and pressure
SUNY	State University of New York
Ton	U.S. customary ton, 2,000 lbs (~ 0.907 Mg)
TS	total solids (dry matter)
UFM	utility financing method
VA(VFA)	volatile fatty acids
VS	volatile solids (ash-free dry weight)
vvd	volumes per unit volume of reactor space per day

REVIEW OF BIOMETHANE FROM MARINE BIOMASS

Chapter 1: INTRODUCTION

1.1. Objective

The objective of this report is to review the history, conclusions, and status of research conducted under the sponsorship of the U.S. Navy, gas industry (American Gas Association and Gas Research Institute), and U.S. Department of Energy to determine the technical and economic feasibility of production of substitute natural gas (SNG) from marine biomass. This work began in 1968, continued until about 1990, and ended as a result of low energy prices in the U.S. and reduced emphasis in the U.S. on renewable energy. The focus of this report is on growth of seaweeds and conversion to methane via anaerobic digestion. Other products (e.g., ethanol), by-products, and process waste streams are not addressed in detail. Since this program ended in 1990, interested parties have met several times to maintain interest in and possibly obtain new support for this project. The results of discussions at these meetings are summarized, including alternative ideas for marine energy farms and conversion of methane to methanol. The renewed interest has been kindled by the threat of global warming and related potential mitigation of carbon dioxide emissions through use of non-fossil energy resources. Since the author is not an economist, the economics are presented as published with no attempt to correct the values for the current economy.

1.2. Background

Humans began using fossil fuels in the middle of the first millennium (AD) and their depletion is expected around 2500 based upon current use projections and reserves data. The world reserves for gas, oil, and coal have been estimated at 70, 45, and 250 years, respectively (Alternate 2002). While these estimates are debatable and depend upon changing estimates of reserves, population, and energy use patterns, fossil fuel supply is finite and its use at current or increasing rates will have large global economic and environmental impacts. Energy conservation and use of sustainable alternative energy resources must therefore be sought and biomass energy is one major renewable resource under consideration. It could not only be a large resource, but also would require a significant increase in plant standing crop, which would serve as a significant carbon dioxide sink.

Commitments to biomass energy needed to significantly replace fossil fuels would require significant crop production areas. For example, one estimate indicates that ~20 exajoules (<25% of U.S. energy needs) per year could be obtained from U.S. cropland currently not used for food or feed production land organic waste residues (Legrand 1993). Also, available terrestrial area is likely to decrease with increased demands associated with population increases and demands for exported food and feed. The ocean, however, is a relatively unexploited resource. Unlike the terrestrial environment, it is not limited by water and temperature; its potential for biomass production is currently limited primarily by availability of nutrients. With nutrient enrichment, high biomass yields are possible resulting in a large supply of feed, food, industrial chemicals, and feedstocks for conversion to energy. Establishment of large ocean farms would also result in large natural fish and seafood populations. It has been estimated that 100% of the U.S. energy supply could be produced from macroalgae grown on farms equivalent to 2.6 million km^2 (Chynoweth et al. 2001). Nutrients needed to obtain the required high growth rates could be supplied by upwelling, artificial fertilization, and nutrient recycling from conversion processes.

Seaweeds from natural populations have been used since the beginning of civilization for food, feed, and fertilizers. This has led to cultivation of this resource and extension of its use for industrial chemicals such as agar, alginate, carrageenans, and fucerellans. As of the early 1980s, the Chinese and Japanese planted, cultivated, and harvested macroalgal crops valued at $1 billion annually from over 60,000 ha of sea surface (Doty 1979, Tseng 1981).

Thermal and biological conversion processes have been considered for conversion of marine biomass to usable energy forms. Thermal conversion processes are not attractive because of high-energy penalties associated with dewatering wet feedstocks; associated water prevents achieving temperatures exceeding its boiling point (~100 °C). Prospects for obtaining bioconversion energy products from marine biomass include hydrogen, ethanol, and methane. Hydrogen produced directly by or from conversion of algae is not well developed and will not be discussed further. Conversion of algae to ethanol is possible and will be discussed briefly, but this process has a poor net energy. The focus of this review will be on biomethane. This technology (better known as anaerobic digestion) is not only well developed but may be a high net energy conversion process. The infrastructure for transmission and utilization of methane is also well established. Methane may be used directly or converted to other energy forms, including hydrogen, electricity, and methanol.

1.3. History of the U.S. Marine Biomass Energy Program

The marine biomass bioenergy concept leading to the basis for development by the U.S. gas industry and other sponsors was conceived by Howard Wilcox in 1968 (Benson & Bird 1987). It consisted of large, open ocean macroalgal farms as alternate sources of food, feed, fertilizer, other chemicals, and energy (Figure 1). In 1972, the U.S. Navy initiated a project on this concept with focus on *Macrocystis pyrifera*, selected because of its high growth rates in natural beds and its potential for repeated harvest of new growth originating from holdfast cells. An oil embargo in the early 1970's led to energy shortages and encouraged many countries to look for indigenous energy supplies, including renewable forms such as biomass. The gas industry (American Gas Association, AGA), the U.S. Energy Research and Development Administration (ERDA), and their subsequent counterparts, the Gas Research Institute (GRI) and the U.S. Department of Energy (via the Solar Energy Research Institute) took over funding management from the U.S. Navy. The General Electric Company was selected as the prime contractor to oversee the technical project management. The original Wilcox multi-product concept was refocused with the goal to provide energy in the form of substitute natural gas (SNG) via anaerobic digestion. The emphasis of this program was on optimization of kelp growth biology, engineering design of an offshore kelp growth facility, evaluation and optimization of conversion by anaerobic digestion, and systems analysis. Up to the late 1970's, conversion of kelp to methane was successfully demonstrated, but several attempts to sustain kelp growth on artificial farms were unsuccessful; i.e., high growth rates observed in natural beds could not be demonstrated on artificial structures. Beginning in the late 1970's, GRI and DOE continued the programs with emphasis on an offshore test platform with nutrient upwelling and conversion design and optimization. Although evidence was obtained in support of high growth rates of kelp using upwelled nutrients, storms dislodged plants and eventually destroyed the test platform. These events led to withdrawal of funding by DOE and refocus of the GRI program to other macroalgal species (including *Laminaria*, *Gracillaria*, and *Sargassum* and nearshore aquaculture approaches with these species and *Macrocyctis*). This work was co-funded by the U.S.DOE, New York State Energy Development Authority (NYSERDA), New York Gas Industry Group (NYGG), and the University of Florida Regional Biomass Program. New elements of seaweed genetics and biotechnology were added to the program as well as emphasis on new bioconversion technologies that would lead to improved conversion yields, kinetics, and process stability.

In the next few years, numerous breakthroughs and successes were obtained including improvement of seaweed yields, development of methods for genetic modification of and maintenance of cultivars, successful artificial growth of plants on a sustained basis, and improvements in bioconversion yields, kinetics and stability. Despite this record, the program was cancelled in 1986 because of a decreased emphasis alternateon gas supply and renewable energy by the U.S. gas industry. Influencing this decision was the high-perceived cost of biomass energy, especially marine biomass.

Tables 1 and 2 show the major funding and research institutions and key persons involved in marine farming programs.

1.4. Other Biomethane Programs

During the period of 1979–90, the Gas Research Institute organized several other biomass energy programs involving co-funding agencies with focus on production of SNG from herbaceous and woody feedstocks (Table 3) and community wastes (Table 4).

The warm-season grass program focused on sorghum, Napier grass, and energy cane. Participants included the University of Florida Institute of Food and Agricultural Sciences and Texas A & M University. Elements of the program included growth, production, harvest, and ensiling of biomass; conversion via anaerobic digestion; and systems analysis. Texas A & M University focused on sorghum production and ensiling. The University of Florida focused on production of other herbaceous species. The University of Florida and Cornell University studied conversion of all herbaceous species. Systems analysis was conducted by the University of Florida, Reynolds, Smith and Hills, and Radian Corporation.

The woody biomass program focused on short rotation hard woods, mainly hybrid poplar and willow. Co-funding institutions along with GRI included NYSERDA and NYGG. Growth of hybrid popular and willow was the emphasis on growth research at Syracuse University and University of Toronto. Anaerobic digestion research was conducted at the Institute of Gas Technology, Chicago, IL and the University of Florida. Systems analysis was conducted at Reynolds, Smith, and Hills, Jacksonville, FL and Radian Corporation, Austin Texas.

GRI was the program organizer and co-funder of three community waste programs (Table 4). One looked at the technical and economic feasibility of using water hyacinth (and to a limited extent, other aquatic macrophytes) for wastewater treatment and production of methane and compost. This project, initially funded by United Gas Technologies, eventually involved the Gas Research Institute and U.S. Department of Energy. The project eventually lead to a demonstration located at Walt Disney World, with technical input from Walt Disney World, the University of Florida, the Institute of Gas Technology, Black and Veatch, Reynolds, Smith and Hills.

A second program evaluated the demonstration of a front-end sorting and anaerobic digestion system (referred to as RefCoM) for conversion of municipal solid waste to methane. This project was co-funded by USERDA (and later USDOE), NSF, and GRI and the major technical participants were the University of Illinois and Waste Management Energy Systems, Inc.

A third program evaluated the extraction of methane from landfills. Research focused on enhancing production and recovery of gas from landfills, increasing the number of landfills from which pipeline quality gas can be economically recovered, and reducing the cost of product gas. Enhancement of landfill gas was examined at three different scales: 36 kg of refuse in laboratory lysimeters under controlled conditions, 900 tons of refuse in each of 9 field test cells, and 4500 tons of refuse in each of six field test cells. Key enhancement parameters tested were: increasing moisture content, addition of supplemental nutrients and bacteria through sewage sludge addition, buffer addition, and leachate recycling. These projects were co-funded by NYSERDA, Pacific Gas and Electric Co. This author was not involved in these programs and will not review the results as part of this report.

Emphasis of GRI projects on high-solids feedstocks (grass, wood, and MSW) led to the development and patent of a novel high-solids anaerobic digestion process by the University of Florida, referred to as sequential batch anaerobic composting (SEBAC). This work was funded in separate projects from the Florida State Energy Office and the Tennessee Valley Authority.

The results of these biomass biomethane projects will be summarized in a later section and compared from a systems viewpoint to the marine biomass systems.

Chapter 2: MARINE BIOMASS BIOMETHANE SYSTEMS

This chapter will introduce several of the major marine biomass systems investigated, which varied depending upon emphasis on off- or nearshore macroalgal species production and proposed by-products in addition to methane.

2.1. Offshore

One offshore concept, was the Ocean Farm conceived by Wilcox in 1975 as described by (Leese 1976) is to grow and harvest seaweeds from submerged supporting lines and buoyancy-control structures covering thousands of hectares and lying 10 – 30 m below the ocean surface. The plants would achieve high growth yields using the unlimited water of the ocean, dissolved carbon dioxide in surface waters, and nutrients either upwelled from nutrient-rich ocean water (from 150 m – 300 m) or recycled from processing effluents. As shown in Figure 1 and 2, a portion of seaweeds and associated animal communities are harvested periodically and converted to methane, fertilizer, food, feed, and other by-products.

After surveying numerous seaweed species, giant brown kelp (*Macrocystis pyrifera*) was selected on the basis of several characteristics, including its anchoring holdfasts, high growth rates, and a large data base of growth and physiology. The holdfasts allow it to be naturally anchored on to rope structures. This plant has a high light absorptive capacity, doubles its weight every six months, and does not appear to exhibit natural aging. Replanting is not expected to be required after harvesting and replacement is necessary only after losses due to disease, animal grazing, and storms. Although *M. pyrifera* is a cold-water plant, its growth may be possible in tropical regions where it is bathed by upwelling of cool nutrient-rich waters.

One of several farm designs shown in Figure 3 depicts 400 ha modules with umbrella-like sections of lines for attachment of plants (3 m apart, about 1000 plants per ha) positioned around a processing plant, including an upwelling pump and distribution system, conversion operations, living navigation quarters, and a helicopter platform. This system is not moored and has the capability of moving its location at low speeds.

The earliest and most significant engineering work on an offshore biomass farm was done by the Naval Ocean Systems Center under the direction of Howard Wilcox (Leese 1976). As indicated by its title, Ocean Food and Energy Farm (OFEF), the Navy concept included production of food and other by-products from the farm.

The Navy did a series of studies on the farm and produced a major document on each farm component. Artificial upwelling using wave pumps was a major component of the Navy's farm. They concluded that a simple modified Isaacs wave pump could provide deep upwelled water adequately to the farm. Also, contrary to General Electric's later analysis (Sullivan et al. 1981), the Navy concluded that a moored farm was too costly. The final OFEF consisted of a floating farm dynamically positioned with marine diesels.

Dr. Wilcox continued to believe that a partially dynamically positioned farm was the only economic choice.

The Navy, in conjunction with other funding agencies, made three attempts with at-sea construction. At San Clemente, a three hectare farm was constructed and partially planted, but one anchor failed after a year and the farm became hopelessly entangled. Two other smaller farms were constructed but they too were lost after one month.

The Gas Research Institute, funding General Electric as the prime contractor, continued the Navy program. With Global Marine as subcontractor, GE built the Offshore Test Platform (OSTP). This system utilized a Navy buoy and consisted of the basic Wilcox inverted-umbrella substrate design. The detailed structural engineering and mooring were well done, but the platform was not suited for the growth of kelp. While the structure held firm, the kelp plants abraded and were lost. Observers reported large vertical motions of the buoy. Apparently, no study had been done to look at the relationship between the kelp plant and the substrate. It was learned, however, that small kelp plants would establish themselves on the substrate and mooring lines.

In an attempt to obtain maximum kelp yield in the open oceans, GE attempted to reconfigure the OSTP and considered over 20 alternatives (Sullivan et al. 1981). The basic problems were that the OSTP dynamics were incompatible with the kelp and that the system was too small to fertilize kelp adequately. Any current quickly carried the upwelled water away from the plants. The most attractive redesign alternatives (according to a review committee of engineers, biologists and administrators) were a closed "Hemidome" (a large floating closed system adjacent to the OSTP) and a "2-D grid" (an artificial substrate tuned to dampen out the motions of the OSTP). The "2-D grid" still had the problem of nutrient wash-out and the “Hemidome” would not survive open ocean conditions. The OSTP was kept under minimal maintenance through 1981 and at the end of that year was lost.

With a goal of achieving maximum yield (no longer open ocean) the test program was moved in 1981 to Catalina Island, CA where the Hemidome was constructed and installed in a nearshore cove ; the kelp received high levels of fertilization to stimulate maximum growth. The Hemidome was a floating ring with a 50ft (15m) diameter by 50ft (15m) deep membrane suspended below it. The membrane kept its shape with slightly higher pressure inside than outside.

In 1978, General Electric Company conducted a Systems Analysis Study (Sullivan et al. 1981) on the marine biomass system. This document was an expansion and continuation of the Navy concept except that the GE farm was moored and it did not take into account food or other by-products. This systems analysis study represents the major engineering effort done to date by GE and GRI on an offshore farm. The engineering work was integrated into a cost analysis computer model of the entire farm. It was an attempt to estimate the capital cost of the system and finally the cost of the gas produced. This work has been a major driving force behind the Marine Biomass Program (MBP) since 1978. This systems analysis study makes four conclusions in the executive summary: kelp genetics, kelp growth rates, offshore engineering, and digestion kinetics should be studied further.

Commencing in spring 1981, GE was directed to consider a nearshore farm together with possible by-products. Previously, nearshore farms were excluded from consideration and the offshore farm had to be justified solelyon energy.

It was concluded from the review of past work on the Marine Biomass Program (MBP) (AquacultureAssociates 1982) that only superficial engineering work has been done on the offshore farm and that this work had been the major support of the cost estimates to date. Several independent, but all preliminary, engineering studies had been done resulting in striking differences in conclusions. The Navy (Budharja 1976) concluded that it must not be moored. GE and the Navy concluded that wave pumps are feasible and economical but Dynatech (Ashare et al. 1978) concluded that they are not feasible. These differences in conclusions strongly point to the preliminary nature of the work thad been done by all parties.

Early research efforts focused primarily on developing basic nutrient delivery and artificial substrate designs. Contract work by the Institute of Gas Technology (IGT) (Chynoweth et al. 1978b) provided a positive indication of the technical feasibility of converting kelp to methane. Out of these early studies emerged an attractive farm concept which embodied: 1) use of wind or wave actuated pumps to deliver necessary plant nutrients; 2) use of an artificial kelp anchoring substrate which would be positioned well offshore; 3) use of shore-based methane conversion facilities and 4) development of co-production and by-production capabilities. Interest in this engineering concept was strong despite the fact that little was understood about either the overall economic feasibility of growing kelp for methane conversion, or the cost effectiveness of alternative farm configurations.

2.2. Nearshore

2.2.1. *Macrocystis* (Bird 1987a)

Based on extensive experience of nearshore seaweed biomass systems in Japan and elsewhere, and their expected improved economics over farshore systems, a systems analysis of a nearshore *Macrocystis* system was conducted by R.M. Parsons (Brehany 1983). A prototype farm design of 2670 hectares was selected near Goleta, California with dimensions of 0.8 km wide by 34 km long and depths between 8 to 18 m. Small juvenile plants would be obtained from nursery stock and fastened to bags of rock aggregate and lowered into the water from barges and tugs on lines designed to space the plants (Figure 4). The plants would grow up to form a canopy in two years. A dock harvesting facility would be located at the farm mid-point. A dedicated harvester would cut the kelp at a rate of 440 tons per hour pumping it into a barge that could be cycled in and out by tugs. The harvested kelp would be pumped into a storage tank and then to digesters. The barges would be filled with nutrient-rich digester effluent to be pumped back into the farm for fertilizer.

2.2.2. *Laminaria-Gracillaria* Multicrop System

The multicrop system developed by the New York Sea Grant Institute (Squires & McKay 1982) involved growth of *Laminaria* in the winter and *Gracillaria* in the summer months with the goal of producing biomass production seasonality. The farm design was based upon Japanese technology (Hanada et al. 1984) involving a hanging rope curtain cultivation system in which two cultivation ropes are joined at the bottom and weighted by a sinker (Figure 5). Preparations for the winter *Laminaria* crop would begin in June, when the culture ropes would be inoculated with *Laminaria* spores; the plants would be ready for planting in September. Culture ropes would be transported by planting/harvesting boats, which would lift two large lines out of the water and attach seeded culture ropes to connection points. Mature plants would be cut harvested twice, in December-February and March-May. In a similar manner, *Gracillaria* would be seeded to culture ropes in December, planted on the farm during the second *Laminaria* harvest and harvested twice during June-August and September-November. The cycle would be repeated by planting *Laminaria* during the second *Gracillaria* harvest. Harvesters would pump biomass into barges, which would be towed to the bioconversion facility for conversion and return of nutrient rich digester effluent.

2.2.3. Tidal Flat Farm

Tidal flats experience one or two water exchanges per day. Macroalgal farming in this environment involves enclosing areas 1.5 m or less using netting enclosures supported by pilings (Figure 6). Seaweed would grow in the enclosure and be harvested daily by boats entering through boom gates. The seaweed may be shredded during harvesting and hauled by barges to bioconversion facilities. One concept (Bird 1987b, a) is a 5344 ha circular farm with a 19 km circumference. The enclosure would be constructed of pilings every 15 m joined at the top by cables. The top of fish net would be secured to the cables and pilings and bottom buried in the sediment. Interior drift seaweed fences prevent concentration of seaweed within the structure.

2.2.4. Floating Cultivation

Some species of macroalgae, e.g., *Sargassum*, float on the ocean surface. This property allows the possibility of enclosed farms of floating algae reducing the high costs of elaborate farm structure and associated planting and harvest. Although this technique was not evaluated technically, a preliminary economic analysis is presented later.

2.2.5. Terrestrial Cultivation

A novel concept for growth of macroalgae on arid lands using seawater spray for irrigation was presented by (Moeller 1982).Very high growth rates of the alga *Ascophyllum* were obtained in small-scale trials of this concept. Large areas of near-ocean arid land are available world wide for this concept. This concept has a number of advantages over in-water systems described above, including 1) ease of plant management; 2) use of plants with or without holdfast structures; 3) ease of nutrient application without dilution; 4) avoidance of open sea problems such as bad weather, disease, and predation; and 5) possibility of farm operations located in close proximity to conversion operations.

Chapter 3: MARINE BIOMASS SPECIES

Marine macroalgae are the basis for a large commercial food, feed, and chemical industry, especially in China and Japan. In the United States, giant brown kelp was harvested from natural beds for extraction of useful chemicals. Of over 100 genera of economic importance and harvested from wild populations, only four, *Eucheuma*, *Porphyra*, *Laminaria*, and *Undaria*, are domesticated as crops with *Gracilaria* nearing that state. Marine biomass is a worldwide resource that is largely untapped. Its growth is limited primarily by light, temperature, and nutrients. Selection of candidates for domesticated mariculture, and conversion to energy, depends on several factors, including high sustainable yields in the climate of interest, holdfast, flotation organelle or other physical properties needed for farming, and compositional properties ideal for conversion and database on propagation.

Seaweed species suitable for biomass energy systems should display high productivity. They should tolerate long exposures to full sunlight, be easily harvested by mechanical techniques, and able to withstand water motion in the high-energy ocean environment. Another desirable property includes the potential for rapid nutrient translocation, which facilitates growth at high densities and a long-lived perennial property, which avoids the need for frequent replacements.

The major initial focus of biomass energy research sponsored by GRI and other institutions was on *Macrocystis pyrifera*. The two primary contractors were California Institute of Technology (Wheeler North and Valrie Gerard) and Neushul Mariculture Inc. (Michael Neushal). Other species were added later in the program, including *Laminaria*, *Gracilara*, and *Sargassum* (Bud Brinkhuis at SUNY, and Dennis Hanisak, Bryan Lapoint, Kimon Bird, and John Ryther at Harbor Branch). Emphasis of this work was on determination of growth yields and factors influencing them, development of methods of artificial propagation and maintenance, and to a limited extent, other physiological characteristics and genetic modification.

3.1. *Macrocystis pyrifera*

M. pyrifera is the only seaweed harvested in the past on a large scale in the U.S. for commercial purposes, including extraction of animal feed, algin and, at one time, fertilizer (potash) (Neushul 1987). It has a number of properties that serve as a basis for initial marine farm evaluation, including 1) rapid growth rates, 2) holdfast cells for anchoring, 3) extended life of five years or more, and 4) extensive data base on natural growth and composition (Neushul & Harger 1987, North 1987). The plants (Figure 7) consist of a root-like holdfast, stem-like stipe, and leaf-like blades. Larger plants may grow as long as 43 meters with blades 30-35 cm long and 8-10 cm wide. The stipe, blades, and floats collectively form a fern-like frond, which is a determinate structure with an average life of about six months. Basal branches give rise to root-like haptera, which grow downward and bunch at their adherent tips to form holdfasts. The holdfasts adhere to rock or other solid surfaces and act as a weight to anchor plants in sand. Reproduction occurs by formation and release of zoospores, which anchor themselves and give rise to male or female gametophyte plants. A spore-produce plant can develop in 12-18 months, completing the life cycle in less than two years (Neushul & Harger 1987).

Of primary importance to energy farming is the biomass yield. This parameter is difficult to determine in the absence of harvests from a known standing crop over a sustained period of a year or more. From a conversion viewpoint, this would be best expressed as grams (ash-free dry weight) per cm^2 per year. Unfortunately, growth data are presented in different ways, often not permitting extrapolation to this desired value. Few well-documented measurements have been made on marine benthic algae. Intensive culture in tanks on land has produced 31 $g(dw)m^{-2}d^{-1}$ for *Gracilaria* (Ryther et al. 1979) and 16 $g(dw)m^{-2}d^{-1}$ for *Chondrus* (Craigie 1985). Yields of 25 $g(dw)m^{-2}d^{-1}$ were reported for natural populations of *Laminaria* off Nova Scotia (Mann 1973).

The normal growth rates of *M. pyrifera* in natural waters are 5 – 9% at seasonal temperatures of 13 – 15°C and drop drastically at temperatures above 18 – 20°C (Wheeler & North 1981). Growth rates of 7 $g(dw)m^{-2}d^{-1}$ were observed in a small test farm at the highest of several planting densities of one plant per 1, 4, and 16 m^2. However, these plants decreased in size as the experiment progressed and exhibited the highest mortality of the three densities.

Marine biomass production varies with density or standing crop. At higher densities, light and/or nutrients may become limiting. (Gerard 1987) showed that the optimum density for *M. pyrifera* was 5-6 $kg(wet)m^{-2}$ with the highest yield of 3 $kg(wet)m^{-2}mo^{-1}$ (Figure 8). In the range of densities studied (0.7 – 6.3 $kg(wet)m^{-2}$), the specific growth rate decreased from 2.5 to 1.1 percent per day.

Yields and growth experiments were conducted at five offshore locations in southern California (North 1987). Experiments at one deep mooring site involved a structure of rope and buoys bearing gametophytes and juvenile sporophytes in artificially upwelled water. Structures at four other sites were designed to hold adult plants. All except one farm were fixed structures. The Laguna test farm was a floating structure held on location by a three-point mooring. A hemidome experiment conducted nearshore involved about 50 plants included in a flexible floating bag approximately 15 m diameter and supplied with a controlled flow of seawater containing added nutrients. These test farms were used to evaluate numerous methods for propagation and maintenance of plants as well as to obtain growth yield data.

Nutrients are significant to plant growth and composition. Ocean waters are generally nutrient limited for plant growth and nutrients influence composition. The most critical element limiting growth in seawater is nitrogen (North 1987), but fertilization regimes should include phosphorus which may be limiting as well (Manley & North 1984). Among micronutrients, copper and zinc may be limiting in surface waters (Gerard 1982a) and manganese and cobalt in deeper waters (Kuwabara 1982, North 1987).

A major challenge in rapid biomass production systems is supplying needed nutrients. They may exist naturally in zones of inorganic pollution or natural upwelling or supplied by direct application or discharge of nutrients recovered from conversion processes. Diffusion of applied nutrients as a function of plant density has been evaluated as well as dipping plants in nutrient-rich digester effluent for pulse application between harvests. The residence time of water in natural kelp beds is a few days (Jackson & Winant 1983) suggesting that large-scale application of nutrients would be effective. (Phlips 1987) discussed the possible application of using nitrogen-fixing plants (e.g., *Sargassum*) for overcoming nitrogen limitations.

The suitability of seaweed for conversion to methane is influenced by its composition, e.g., C:N ratio (lower is better) and mannitol content (higher is better) (Chynoweth et al. 1987). Composition is influenced in turn by growth conditions, e.g., mannitol accumulates (to as high as 30% of the ash-free dry weight) when carbon assimilation is high relative to growth under high light conditions, or when growth is limited by another factor such as nitrogen (Gerard 1982).

Kelp diseases have been attributed to physiological factors or to pathogenic bacteria or fungi (Golf & Glasgow 1980) and have their greatest effect on plants grown under marginal conditions (high temperatures, high densities, and limiting nutrients). Symptoms observed on offshore farms included black rot, brittleness in blade tissues, lesions, and sloughing; the causes were not documented. Plants can also succumb to epiphytes and grazers. (North 1987) described flora and fauna associated with kelp beds. Encrustation was caused by the bryozoan *Membranipora*. Mud tubes caused by the amphipod *Jassa* lead to deterioration of underlying tissues. Effects of harvesting were controversial ranging from no effects (North 1968, Coon 1981) to the thought that canopy cutting would reduce translocation of photosynthate to basal branches (Neushul & Harger 1987). Two herbivorous fishes, the half-moon perch *Medialuna* and opal eye perch *Girella* were common natural harvesters of kelp. A small snail *Mitrella* became a significant grazer on one farm experiment.

3.2. ***Laminaria*** (Brinkhuis et al. 1987)

Laminaria is also a variety of kelp closely related to *Macrocystis* but which inhabits both cold and temperate waters. This genus is one of the major seaweeds used for food and chemical extracts, ranking number one in terms of quantity harvested or cultivated (Tseng 1981). The total worldwide harvests were estimated at two million tons per year where it is used for food, feed, and phycolloid industries. There are no commercial kelp farms currently in North America, nor is it harvested from wild populations. Interest was kindled for use of this kelp as a bioenergy crop that would grow in Atlantic waters (Brinkhuis & Hanisak 1982, Doty 1982).

(Tseng 1962) estimated that over one million tons per year were needed by the Chinese to meet the demand for food products. About 70,000 ha of coastal water were estimated to be available for growth of this alga. At that time, typical farm production approached 16 tons (dw) per year. The Chinese were able to extend the growing season of *Laminaria* by forced early cultivation; this increased production by 30 – 50%. The Chinese method of deployment is to attach individual plants to rope structures by entwining stipes and holdfasts. Nitrogen may be a limiting factor for growth of this kelp. Along the Chinese coast, nitrogen concentrations were limited during the late spring when light and temperature conditions are optimal for rapid growth (Wu 1962). Mariculturalists approached this deficiency by either spraying liquid ammonium nitrate from boats or by seepage from porous ceramic pots located along the farm structure. Juvenile plants could be treated by soaking them in concentrated fertilizer troughs aboard boats. Plants could sustain high growth rates 4 - 6 days after treatment. Plants 1-2 m long required about 6 mg nitrogen for rapid growth.

Although the two major seaweeds cultivated in Japan are *Porphyra* and *Undaria*, *Laminaria* production in 1992 totaled 30,000 dry tons. Seed-string bearing juvenile sporophytes (60 – 300 plants per meter) wee attached to ropes which wee anchored by concrete blocks. The final surviving number was about 60-100 per meter. The maximum yield was 63 wet kg m^{-1} (9 kg m^{-1}dry). This yield decreased to 20 wet kg m^{-1} by July.

The New York Marine Biomass Program (Brinkhuis et al. 1987) focused primarily on a two-species system, including *Laminaria* for cold and *Gracilaria* for warm periods. After numerous tests with these and other species, a Biological Engineering Experimental Farm (BEEF) was designed, constructed, and deployed in collaboration with the Department of Materials Science at the State University of New York and the Engineering Department at Cornell University. The rope buoyed and anchored structure consisted of six 37 m ropes and had dimensions of 15 x 37 m. Two methods of deployment were tested: 1) the Chinese method of manually attaching plants and 2) the Japanese method of inserting segments of seed string bearing juvenile sporophytes. In one deployment, 1382 plants were located at three different densities, i.e, 15, 10, and 5 cm between plants. Growth rates (based on blade elongation) were not significantly different at these densities. Growth and survival of *Laminaria* was sufficient to obtain meaningful data, whereas the growth method and location tested did not seem adequate for a summer plant like *Gracillaria*.

The survival rate for the Japanese planting method was ~100% compared to 62 – 83% for the Chinese method. Survival rates were higher at higher planting densities. Fertilization with nutrients (time released nitrate, ammonium, and phosphate located in cylinders throughout farm) resulted in higher levels in plants but did not result in increased blade elongation rates. Using the Japanese planting method and the highest density, the BEEF resulted in biomass yields of *Laminaria* of 28-46 tons (daf) $ha^{-1}y^{-1}$. These yields are comparable to reported Japanese yields of 40 – 85 tons (daf) $ha^{-1}y^{-1}$ (Brinkhuis et al. 1987).

3.3. ***Gracilaria*** (Hanisak 1987)

One of the most successful seaweed culture programs was conducted at Harbor Branch Oceanographic Institution at Fort Pearce, FL. (Hanisak 1987). The initial goal was to use algae to purify nutrients from sewage and shellfish industrial discharges. Eventually this program addressed energy farming of seaweeds along the vast coastal waters of Florida. The red alga *Gracilaria tikvahiae* was the focus of 10 years of research, including factors influencing growth, yields, and methods of cultivation.

Several factors were found to influence yields of *Gracilaria*. Under intensive culture conditions, the optimum stocking density was found to be 2 kg (wet wt) m^{-2} with a final growth density of 2 – 4 kg m^{-2} (Lapointe and Ryther 1978). These values seem to be related to availability of light and nutrients. Although it is not generally feasible to control physical factors such as light, temperature, and salinity, knowledge of their effects could help understand seasonal yield fluctuations. Under laboratory conditions, light saturation was observed at 100 µE $m^{-2}s^{-1}$, a level typical of natural environments. Growth occurred at a temperature range of 12-36 °C with the optimum of 24-30 °C. The salinity growth range was 6 - 42 psu with an optimum of 24 - 36 psu. These results indicate that this alga could be cultivated in any combination of temperature and salinity conditions in the coastal waters of Florida. Under optimum intensive cultivation, a photosynthetic efficiency was 4% of the active radiation, which is high. (Hanisak 1987)

Large turnover rates of seawater required for optimum growth of *G. tikvahiae* were not related to nutrient availability, but more probably prevention of elevated pH and associated limitations of carbon dioxide and bicarbonate (Blinks 1963, Lapointe & Ryther 1978, Ryther & DeBusk 1982, Blakeslee 1986). Carbon dioxide enrichment significantly increased growth rates in batch cultures with no seawater exchange (DeBusk & Ryther 1984). Water turnover resulted in mixing, which improved yields in at least four ways: 1) maximizes light exposure by minimizing shading; 2) reduces nutrient boundary layers; 3) increases gas exchange; and 4) dislodges and flushes out competing cells.

As with other algae discussed, nutrients were usually limiting. The optimum nutrient application was enough to sustain maximal yields, but without excesses, which contribute to epiphyte problems and unfavorable economics. The best method of monitoring nutrient status was to measure tissue levels. In tank cultures, the critical nitrogen concentration was determined to be about 2% or a C:N ratio exceeding 15 (Figure 9). Pulse nutrient application was demonstrated to be effective *in vitro* with soaking in nutrient enriched water for six hours resulting in non-nutrient limited growth for 7-14 days (Ryther et al. 1981); similar results were observed with *in situ* cultures (Hanisak 1982, Lapointe 1985, Lapointe & Hanisak 1985). Growth of *G. tikvahiae* was identical when either nitrate or ammonia was the nitrogen source (Lapointe & Ryther 1978). Although most studies have focused on nitrogen nutrition of macroalgae, *G. tikvahiae* was more limited by phosphorus than nitrogen in the Florida Keys. Large-scale seaweed farms will undoubtedly require fertilization with a balance of macro- and micronutrients. Recycled digester residues were shown to provide 62-83% (recycling efficiency) of the required nutrients for seaweed cultivation (Hanisak 1981b, Habig & Ryther 1984). Given ambient levels of inorganic nitrogen in Florida coastal waters, a recycling efficiency of only 45% would be required to support *Gracilaria* productivity of 73 dry tons $ha^{-1}yr^{-1}$.

Of several algal species screened in culture chambers (0.23 m^2 each), *Gracilaria tikvahiae* exhibited the highest yields of 34.8 g dw $m^{-2}d^{-1}$ (127 dry tons $ha^{-1}yr^{-1}$) using vigorous aeration and rapid exchange of seawater (20-30 times per day)(Lapointe & Ryther 1978). Growth was maximal (46 g dw $m^{-2}d^{-1}$) at the end of July and minimal (12 g dw $m^{-2}day^{-1}$) in late January. Although these yields were among the highest for any plant, they are probably not achievable on a commercial scale. However, yields of 22-25 g dw $m^{-2}d^{-1}$ were consistently obtained in larger tanks (2.4 - 29 m^2). Cultures in shallow earthen ponds and spray cultures exhibited lower yields of 5 - 8 and 20 g (dw) $m^{-2}d^{-1}$, respectively, but yields were not sustainable in spray cultures due to growth of epiphytes. Finally, cage cultures placed in an estuary exhibited growth yields of 7.8 – 13.9 g dw $m^{-2}d^{-1}$. Growth of epiphytes and other fouling organisms on the cages prevented sustained growth by this technique.

3.4. ***Sargassum* and *Ulva*** (Hanisak 1987)

Studies of *Sargassum* and *Ulva* have been less extensive. *Sargassum* was considered as an energy farm crop because of its floating and nitrogen fixing properties. High short-term yields of 34 g dw $m^{-2}d^{-1}$ were not sustainable (Hanisak 1987). Longer-term yields ranging from 7-12 g dw $m^{-2}d^{-1}$ were observed. In Florida waters, phosphorus rather than nitrogen was limiting. This may be due to precipitation of phosphate by calcium carbonate sediments and supply of nitrogen by nitrogen-fixing epiphytes.

Ulva was considered because of its high potential growth yield and high conversion by anaerobic digestion. Biomass yields of 18.8 and 6.8 g dw $m^{-2}d^{-1}$ were obtained under aerated and non-aerated conditions, respectively (DeBusk et al. 1986). As with *Gracilaria*, this alga could be successfully fertilized by pulse addition of nutrients. The optimum stocking density was reported as 0.8 kg wet m^{-2}, a level lower than that reported for other macroalgae. The favorable composition, rapid digestion, and almost complete lack of epiphytes make this an attractive candidate for further study.

Chapter 4: BIOMETHANE VIA ANAEROBIC DIGESTION (Chynoweth et al. 1987)

Selection of a process for conversion of biomass to usable energy depends upon the desired end-product and the physical and chemical characteristics of the material. Widely used processes for recovering usable energy from biomass include direct combustion, anaerobic digestion, fermentation to alcohol, thermal liquifaction and thermal gasification. Because marine algae contain about 90% moisture, processes particularly suited to this biomass type are those which are compatible with high amounts of moisture. Such processes include anaerobic digestion for production of methane and fermentation for production of alcohols.

A limited number of studies have investigated the conversion of several marine algal species to methane by anaerobic digestion, including: *Macrocystis pyrifera, Tetraselmis, Gracilaria tikvahiae, Hypnea*, and *Ulva* (Bird et al. 1981, Fannin et al. 1983b, Bird & Ryther 1985). In general, these studies have concluded that marine algae are good feedstocks for the anaerobic digestion process as demonstrated by high conversion efficiencies, rapid conversion rates, and good process stability. The residues from marine algal digestion can also be used as nutrient supplements for subsequent algal growth (Hanisak 1981b). It has also been demonstrated that the acid phase of anaerobic digestion may be used to produce acetic acid from the marine alga, *Macrocystis pyrifera*.

For several years GRI and cooperators funded development of processes for converting marine algae to methane via anaerobic digestion. Initially, this research was concerned with the effect of several variables on anaerobic digestion, e.g., separation of juice and non-juice fractions, temperature, inoculum, nutrients, freshwater versus seawater dilution, and non-dilution (Ghosh et al. 1976, Ghosh et al. 1977, Klass & Ghosh 1977, Chynoweth et al. 1978a, Chynoweth et al. 1978b, Chynoweth et al. 1979, Klass et al. 1979). More recently, this work focused on advanced digester designs, process optimization, and kinetics (Fannin et al. 1983a). The purpose of this chapter is to summarize the results of this work and to discuss proposed future directions.

4.1. Overview of Anaerobic Digestion

Methane production by anaerobic digestion is a process occurring widely in nature within environments such as ocean and lake sediments, marshes, and digestive tracts of animals. This process involves the biological conversion of the organic components of biomass into simple products such as acetate, carbon dioxide, and hydrogen by a mixed population of non-methanogenic bacteria. These products are then utilized by a mixed population of methanogenic bacteria to produce methane and carbon dioxide. The non-methanogenic acid producing bacteria are a relatively hearty and fast-growing group of organisms, whereas the methanogens are generally fastidious and slow-growing.

Because at least two very distinct microbial consortia are involved in anaerobic digestion, some investigators have proposed separating these organisms into two phases. Whether methane production is performed with these phases combined or separate, the process is strictly anaerobic and must be performed in the absence of air. Several bacteria have been isolated from methane-producing digesters and ecosystems receiving various biomass and waste feeds. The complexity related to the numerous bacterial species involved, however, has prevented the identification of all of these organisms and a thorough understanding of their complex interactions. Nevertheless, knowledge on overall process performance and microorganism interactions at the population rather than at the species level, has permitted effective use of anaerobic digestion for waste treatment and conversion of a wide variety of organic feeds to methane.

Controlled anaerobic digestion for producing and recovering methane is performed in digesters or reactors designed with the major objective of producing methane at low cost. Low costs require high methane yields (vol CH_4/wt feed) and high methane production rates (vol CH_4/vol-reactor/day). Generally, high methane yields are achieved through long solids retention times (SRTs) while high organic loading rates and resultant short hydraulic retention times (HRTs), along with high methane yields, promote high methane production rates.

4.2. Approach to Biological Gasification Process Development

A protocol was developed to determine the suitability of biomass and waste feedstocks for biological gasification to methane (Figure 10). It was tested on a variety of biomass and waste feedstocks, including marine algae. The entire scheme of testing was employed to develop a process to convert sludge and water hyacinth, which was evaluated in a small pilot-scale conversion facility at Walt Disney World in Florida (Biljetina et al. 1984).

The approach begins with a simple assessment of the biochemical methane potential (BMP; related to anaerobic conversion) and relative conversion kinetics of the test feed under ideal conditions in small serum bottle reactors (Fannin et al. 1983b, Chynoweth et al. 1984a, Chynoweth et al. 1985). Low conversion efficiencies may lead to an evaluation of the effects of various pretreatment techniques or to studies to determine presence of inhibitors in the feed. Poor conversion efficiencies in these screening tests may also lead to the decision to terminate further work on a particular feedstock.

High conversion efficiencies support continuation of research onbench-scale process development stages. Initial process development work involves determination of conditions for optimum microorganism activity with respect to parameters such as nutrients, feed concentration, retention time, temperature, and product inhibition. Using these data, a process is conceptualized, tested, and optimized with respect to conversion yields rates and process stability. The selection process may be narrowed by previous experience with feeds having properties similar to the test feed. At the end of this stage of development, a preliminary process design is formulated and utilized to conduct preliminary systems and economic analysis. Supportive results may lead to the design and operation of a process research development unit of sufficient size for continuous operation and for evaluation of feed preparation, process scale-up, materials handling, and effluent processing. This process provides a basis for a detailed process analysis.

4.3. Physical and Chemical Characteristics

4.3.1. Biomass Variability

Research on marine algal anaerobic digestion was concerned with the brown alga, *Macrocystis pyrifera* and to a limited extent, *Laminaria*. Typical total and volatile solids content of these algae, compared to other biomass feedstocks in Table 5 (Fannin et al. 1983b, Chynoweth et al. 1984a, Chynoweth et al. 1985) indicate that the total solids content in these marine algae was higher than freshwater aquatic biomass feedstocks such as in water hyacinth and considerably lower than with sorghum or hybrid poplar.

4.3.1.1. Total and Volatile Solids Content of Selected Biomass Feeds

Macrocystis has a high ash content and therefore a lower volatile solids content compared to *Laminaria* and to the other biomass feeds. In addition, the organic composition of marine algae is qualitatively and quantitatively different from that of non marine biomass. *Macrocystis,* for example, contains algin and mannitol as principle organic components whereas sorghum and hybrid poplar contain cellulose, hemicellulose, and lignin. *Macrocystis* also differs from other biomass feeds in that its unique rheological properties make it easily pumpable in an undiluted form of up to 12% total solids concentrations.

Composition within a biomass species can vary considerably, depending upon growth and time of harvest conditions. For example, Table 6 shows the chemical composition of several lots of *Macrocystis pyrifera*, which were harvested on different occasions. While the total volatile solids content only varied slightly among the several lots, other characteristics, such as the mannitol content, carbon-to-nitrogen ratio, heating value, and stoichiometric methane yield, showed much greater variation. The algin and mannitol content of several lots of *M. pyrifera* varied considerably and were inversely related (Fannin et al. 1983a). The mannitol concentration ranged from 5.2% to 25%, while the algin concentration ranged from 12.4% to 19.5%. Although the growth conditions causing this variation are not well documented, they have been related to nutrient availability. These parameters can significantly affect the performance of the marine algae species in anaerobic digestion as is discussed below.

4.3.2. Effect of Biomass Variability on Biodegradability

Typical BMP assay data for two kelps, *Macrocystis* and *Laminaria*, are compared to other biomass and waste feeds in Figure 11 (Fannin et al. 1983a, Chynoweth et al. 1984b, Chynoweth et al. 1985). *Macrocystis* exhibited a higher overall conversion efficiency and rate than the other feeds. Although the conversion rate for *Laminaria* was high, it was 30% lower than that of *Macrocystis.* These data suggest that both marine algae would be good candidates for further process development research and *Macrocystis* appears to be one of the most attractive biomass feedstocks tested for anaerobic digestion to methane.

The BMP assay was used to evaluate biodegradability of several different samples of *Laminaria* grown under a variety of conditions. Results of these assays are summarized and compared to *Macrocystis* in Tables 7 and 8 (Chynoweth et al. 1985). Note that high conversion efficiencies and methane yields were observed. Plants grown under high light conditions were more biodegradable, with methane yields of 0.29 SCM/kg (4.7 SCF/lb) VS added, than those grown under low light, which had methane yields-ranging between 0.24 and 0.26 SCM/kg (3.8 and 4.1 SCF/lb) VS added. Fertilization did not seem to have any effect on the biodegradability of plants grown under high light conditions; however, fertilized plants grown under low or ambient light exhibited approximately 10% higher methane yields than unfertilized plants. The anaerobic biogasification potential of *Laminaria* was significantly lower than that of *Macrocystis*, which may be related to growth conditions affecting composition.

The suitability of different *Gracilaria* and two *Sargassum* species for bioconversion to methane was determined through bioassays of methane yield (Bird et al. 1990). *Gracilaria* species were excellent feedstocks for high methane yields, ranging from 0.28 to 0.40 m^3/kg VS added. These yields ranged from 58 to 95% of theoretical stoichiometric yields. Methane yields were highly correlated with acid soluble carbohydrate components of the *Gracilaria*. Both *Sargassum fluitans* and *S. pteropleuron* were poor feedstocks, with methane yields ranging from 0.12 to 0.19 L/g VS added, corresponding to 27 to 46% of theoretical stoichiometric yields, respectively. The various tissue types of these *Sargassum* species were also poor feedstocks for anaerobic digestion to methane. While there is no clear explanation for the low methane yields, the two *Sargassum* species appeared to contain a high proportion of an insoluble, non-extractable component, which may not be available as a substrate for bioconversion to methane.

The standard procedure for conducting the BMP assay is to use an inoculum obtained from a conventional sewage sludge digester. Because marine algae contains organic components, e.g., algin and mannitol, not present in sewage sludge, it was thought that an inoculum adapted to a marine alga may effect greater conversion than the sludge inoculum. To evaluate this, BMP assays were conducted with the standard sludge inoculum and an inoculum developed for several years on *Macrocystis*. Both inocula exhibited similar BMP values of 0.30 SCM/kg (4.8 SCF/lb) VS added, suggesting no advantage for the adapted inoculum (Fannin et al. 1983b).

Obviously, variations in biomass composition require consideration during process development since they can have a significant effect on the degree and rate of biomass conversion to methane during anaerobic digestion. These effects have been well documented with *Macrocystis* for mannitol, algin, and nitrogen content and will be discussed further.

4.4. Organic Composition

Although variable, Figure 12 shows a typical content of mannitol. Kelp has a high ash content and the major organic components are mannitol, algin, and cellulose. Mannitol is a highly biodegradable organic storage component of *Macrocystis pyrifera.* Research demonstrated that the bioconversion of this marine alga during anaerobic digestion is highly related to the mannitol content of the particular lot studied. Anaerobic digestion studies conducted in continuously mixed stirred tank reactors (CSTR) at a loading rate of 1.6 kg VS $m^{-3}d^{-1}$ (0.1 lb VS $ft^{-3}d^{-1}$), 15 to 18-day solids residence time, and 35°C demonstrated that mannitol concentration had a significant effect on the fraction of the theoretical methane yield achieved experimentally. This fraction increased logarithmically with the mannitol content. This relationship, illustrated in Figure 13 (Fannin et al. 1983b), can be described by the following equation:

$$Y_E = Y_T\ (0.055 - 0.19 \ln X_M)$$

Where:

Y_E = experimental methane yield
Y_T = theoretical methane yield
X_M = mannitol concentration, % dry

The relative biodegradability of pure mannitol and algin was evaluated using the BMP assay. The results (Figure 14) indicate that both the rate and degree of degradation were higher for mannitol than for algin, and that ultimate methane yields were 100% of the upper theoretical values based on their empirical formulas. The data indicate that a high degree of conversion of both components should be possible during anaerobic digestion; however, a longer SRT would be required for algin conversion. Therefore, the concentrations of mannitol, algin, or other biodegradable substrates such as agar can have an important impact on the achievable methane yield (Bird et al. 1981).

Compositional variation in different sample lots of the same biomass species can have a dramatic effect on performance and stability of digesters. Table 9 shows methane yield as a function of loading rate for two different lots (50 and 53) of *Macrocystis* (Fannin et al. 1982, Habig & Ryther 1984, Bird et al. 1990). At loading rates of 1.6 to 4.8 kg VS $m^{-3}d^{-1}$ (0.1 to 0.3 lb VS $ft^{-3}d^{-1}$), Lot 53 exhibited higher methane yields and lower volatile acids (VA), indicating greater stability than Lot 50. The digester receiving Lot 50 failed at a loading rate of 4.8 kg VS $m^{-3}d^{-1}$(0.3 lb VS ft^{-3} d^{-1}), whereas the digester receiving Lot 53 did not fail until a loading of 11.2 kg VS $m^{-3}d^{-1}$(0.7 lb VS ft^{-3} d^{-1}). These data illustrate the extreme variability that can exist in lots of the same species with respect to performance as a feedstock for anaerobic digestion. Although the compositional differences responsible for the variation in performance in this case were not documented, differences in mannitol have a significant effect.

The correlation of mannitol and acid soluble carbohydrates with methane yield has been further corroborated (Habig & Ryther 1984, Bird et al. 1990).

4.4.1. Inorganic Nutrients

Literature on nutritional requirements during anaerobic digestion is limited. Speece (1984) reported that the nutrients in decreasing order of importance are nitrogen, sulfur, phosphorus, iron, cobalt, nickel, molybdenum, and selenium. Since nutrients can be reused, given a sufficiently long retention time in the anaerobic digester, they seem to have a greater effect on the conversion rate than on the biodegradability of the feed. Generally, nitrogen is the major nutrient, other than carbon sources, limiting anaerobic digestion. The amount of nitrogen required is affected by factors such as the organic composition of the biomass feed and the rate of cell growth (synthesis) in the digester. For example, nitrogen requirements for carbohydrate degradation are six times those for volatile acid degradation (Speece 1984). Digesters promoting long SRTs (solid retention times) have lower nitrogen requirements than those with short SRTs such as CSTR (continuously stirred tank reactor) digesters (Fannin et al. 1983a).

Digesters can be nutrient limited. A C:N ratio of 15:1 and a C:P ratio of 75:1 were determined to be non-nutrient-limiting for digestion of *Macrocystis* during conventional mesophilic (30-35°C digestion in a CSTR reactor at a loading of 1.6 kg VS $m^{-3}d^{-1}$) and a retention time of 15 to 18 days (Chynoweth et al. 1980). The relationship between C:N ratio and methane production from kelp in CSTR digesters is illustrated in Figure 15. Methane production rapidly decreased as C:N ratios increase. It should be emphasized that the biodegradable values of nitrogen and phosphorus rather than total N and P actually determine limiting conditions. The requirements by the micro-flora are based on biologically available nutrients and not total measured values.

Reactors promoting longer SRTs have lower cell synthesis requirements and, consequently, lower energy and nutrient requirements. Ammonia nitrogen concentrations in effluent from *Macrocystis* fed digesters operated at different SRTs and loading rates, ranging from 0.32 to 9.6 kg VS $m^{-3}d^{-1}$ (0.02 to 0.6 lb VS $ft^{-3}d^{-1}$), are shown in Figure 16. The ammonia concentration in effluent of digesters operated at SRTs of 7, 66 and 200 days were 100 to 220, 750 to 770, and 790 to 810 mgL^{-1}, respectively. These data indicate that ammonia concentrations in these digesters were derived from sources within the feed and support the hypothesis that either the nitrogen requirements for anaerobic digestion can be reduced or additional bound ammonia is made available by increasing the SRT. They suggest further that a lower C:N ratio is required in feeds to digesters that promote longer SRTs and that the ammonia enriched effluent from such reactors will have a higher value as fertilizer.

Gracilaria tikvahiae was successfully fermented to produce methane with gas production and bioconversion efficiencies comparable to those of other biomass substrates (Hanisak 1981b). Experiments were performed which determined the feasibility of recycling nutrients found in both liquid and solid residues of this digestion process. Various amounts of residue were removed from digesters and added to cultures of *G. tikvahiae* over the course of a year (Hanisak 1981a). Cultures grown in digester residue grew as well as, if not better, than cultures grown on inorganic fertilizer (Hanisak 1981b, Habig & Ryther 1984).

Measurements have been made on the ability of *G. tikvahiae* to utilize the nitrogen contained in both liquid and solid digester residues. Calculated as the amount of nitrogen assimilated, divided by the amount of nitrogen present in the residues added, average nitrogen recycling efficiencies ranged from 62-83% (Hanisak 1981a, Habig & Ryther 1984). Levels of nitrogen assimilation and recycling efficiency depended largely upon the ammonium content of the residues added to the cultures. Ammonium comprised 40 to 70% of the total nitrogen content of the residues. This percentage was largely a function of the retention time of the digester (Habig & Ryther 1984).

4.5. Inoculum

Initial work at IGT (Ghosh et al. 1976) concluded that raw kelp caused inhibition of anaerobic digestion, which was attributed to salt toxicity. This observation led to the treatment of raw kelp to remove salts and resulted in removal of the toxicity. (Chynoweth et al. 1978b) discovered that an inoculum derived from sewage sludge digesters could be adapted to overcome the salt toxicity and the result would be elimination of the need for its removal. In fact, raw kelp untreated and undiluted resulted in higher methane yields that the treated kelp. A subsequent study was conducted using batch BMP assays to compare performance of inocula obtained from sewage sludge digester with those obtained from abalone gut and marine sediments (both receiving kelp naturally). No significanct differences were observed in the extent and rates of conversion by the two inocula.

4.6. Bench-Scale Process Development

4.6.1. Continuously Mixed Stirred Tank Reactors

Anaerobic digestion has been widely used in wastewater treatment plants to reduce sludge volumes. For this application, conventional CSTR mesophilic digesters are employed and operated at loadings in the range of 0.8 to 1.6 kg VS $m^{-3}d^{-1}$ (0.05 to 0.1 lb VS $ft^{-3}d^{-1}$). However, these systems are not suitable for energy production because: 1) such low loadings require unacceptably large reactor sizes; and 2) energy requirements of conventional digesters receiving dilute feeds are excessive (Klass & Ghosh 1977).

Although CSTR digester data are useful for obtaining kinetic data on the relationship between SRT and feedstock conversion, operation at loadings required for energy production resulted in a reduction in biomass conversion and digester instability (Fannin et al. 1982). A tripling of loading rates caused a dramatic increase in volatile acids concentrations and a decrease in methane yields. However, as discussed previously (Table 9) a particular lot (Lot 53) of *Macrocystis* resulted in substantially improved performance in a CSTR reactor (Fannin et al. 1982). In fact, loading rates up to 9.6 kg VS $m^{-3}d^{-1}$(0.6 lb VS $ft^{-3}d^{-1}$) were possible before instability and failure occurred. As anticipated, methane yield and digester stability decreased with increased loadings due to washout of microorganisms and unreacted solids. As a result of these observations, a new vertical flow reactor configuration was designed and tested with *Macrocystis* as the feedstock.

4.6.2. Solids Concentrating Vertical Flow Reactors

In order to reduce the limitations of a CSTR digester, a non-mixed vertical flow reactor (NMVFR) was designed and evaluated with the objectives of increasing microorganism and solids retention as a means of increasing the biomass loading potential of the conversion system (Fannin et al. 1983b). When this reactor (Figure 17) was operated as an upflow solids reactor (USR), feed was added from the bottom and effluent was removed from the top of a non-mixed vessel. Solids (including microorganisms and feed solids) are passively concentrated by settling, resulting in a longer solids than liquid retention time.

Data summarized in Figures 18 and 19 indicate that performance in terms of methane yield and methane production rate was consistently better in the NMVFR than in CSTR digesters (Fannin et al. 1983a). This is related to the higher solids retention of SCR as illustrated in Figure 18. High concentrations of volatile acids are a good indicator of digester instability; SCR runs exhibited lower volatile acids concentrations and greater stability than SCRs operated at increased loading rates.

The NMVFR resulted in three to four-fold longer SRTs at different loadings than the CSTR (Table 10). As illustrated in Figure 16, ammonia nitrogen concentrations were also higher in effluents of digesters with longer SRTs, resulting in reduced feed nitrogen requirements and an increased buffering capacity of the digester. Since considerable variability existed from lot to lot, a NMVFR was operated on a different lot (Lot 54) with lower mannitol and nitrogen content and the performance was compared with Lot 53 (Chynoweth et al. 1985). Although performance was stable, methane yields were lower than those observed with Lot 53 (Table 11). However, the methane production efficiency, defined as the ratio of experimental methane yield to the stoichiometric yield, was similar (The stoichiometric yield is calculated from the chemical composition of the feedstock). These observations suggest that bioconversion performance for this reactor was not design limited, rather only by the quality of the feedstock.

4.6.3. Solids-Concentrating Baffle Flow Reactor

A horizontal plug-flow digester was designed with baffles to increase the solids retention time (Fannin et al. 1982). Although the vertical flow reactor discussed above was selected for detailed study, this system showed slightly better performance than the stirred tank reactor with methane yields of 6.0 compared to 5.6 SCF/lb VS added (0.37 compared to 0.35 L/g VS added and methane production rate of 0.6 compared to 5.6 vvd, respectively.

4.6.4. Fluidized Bed Reactor

The fluidized bed reactor is another solids-concentrating digester that was evaluated which concentrates microorganisms in the form of biofilms but does not retain feed particles as does the SCR and BFR reactors discussed above. Studies were conducted in 4L reactors using fine sand as the support medium (Fannin et al. 1982). Experiments were conducted at different temperatures, loading rates, and feed concentrations. In general, feed plugs prevented sustained operation above total solids concentrations of 3.5%. This system could be operated at loading rates as high as 6.08 kg VS

$m^{-3}d^{-1}$ (0.38 lb VS $ft^{-3}d^{-1}$), a HRT of 3 days, without a reduction in methane yield or other measures of performance. This performance exceeded that of all other reactor designs investigated. Control CSTR digesters failed at loading rates of 2.4 kg VS $m^{-3}d^{-1}$ (0.15 lb VS $ft^{-3}d^{-1}$). The methane yields were slightly lower than those observed with SCR runs, probably due to the lower solids retention times.

4.7. Two-Phase Digestion

At very high loading rates, which result in lower hydraulic and solids retention times, both CSTR and NMVFR digesters show production of a high concentration of unconverted volatile acids (indication of instability) (Fannin et al. 1981). Thus, digesters were operated so that marine algal hydrolysis and acidification occurred, but not conversion of VFA to methane. This system was characterized by the predominance of hydrolytic- or acid-phase digestion. A second digester, in which the HRTs and SRTs were longer, was used to develop a reactor which promoted the growth of methanogenic bacteria and which was referred to as a methane phase digester (Fannin et al. 1982). Coupling hydrolytic- or acid-phase digesters to methane-phase digesters, it was possible to develop a two-phase system. Numerous reports suggest major advantages of two-phase over combined-phase digestion (Ghosh & Klass 1977, Fannin et al. 1982, Chynoweth et al. 1985, Ghosh et al. 1985).

For the experimental work, hydrolysis-fermentation phase (acid-phase) of the NMVFR kelp *Macrocystis* fermentation was developed by increasing the loading rate of the reactor to 11.2 kg VS $m^{-3}d^{-1}$ (0.7 lb VS $ft^{-3}d^{-1}$) (Fannin et al. 1983b). The first phase reactor was allowed to achieve steady state and the methane yield potential under these conditions was evaluated. The first phase had a methane yield of 0.09 SCM/kg (1.4 SCF/lb) VS added. The supernatant, fed in a second stage, had 0.20 SCM/kg (3.2 SCF/lb) VS added, for a projected total methane yield in a two-phase system of 0.29 SCM/kg (4.6 SCF/lb) VS added. This is substantially lower than the methane yield of 0.34 to 0.41 SCM/kg (5.5 to 6.5 SCF/lb) VS added observed in the combined-phase NMVFR reactor. This reduced yield was accounted for in the unreacted solids. The lack of conversion of these solids could be attributed to either lack of sufficient retention in the hydrolysis-fermentation phase or inhibition of hydrolysis and fermentation by the accumulation of the fermentation products.

More recent work on two-phase anaerobic digestion of diluted kelp using NMVFR demonstrated substantially improved overall performance in anaerobic digestion. While the methane yield in the acid phase digester remained low, the VFA concentration was high. The effluent from this digester was fed to a second reactor, which was operated as a NMVFR methane phase digester. This digester had very high methane content of greater than 75% and the overall methane yield significantly exceeded that previously observed with undiluted kelp.

4.8. Co-Digestion of Algae and Wastes

The marine algae *Gracilaria confervoides* and *Ulva rigida* were harvested from the Venice Lagoon where they are a menace resulting from nutrient pollution. Two studies showed their successful anaerobic digestion as mixtures with sewage sludge (17 – 38% algae/sludge total solids basis)(Cecchi et al. 1992a) and the organic fraction of municipal solid waste (9:1 algae/ofmsw total solids basis)(Cecchi et al. 1992b). Toxicity was observed at higher concentrations of algae in the feed mixture.

4.9. Conclusions

Marine algae are an abundant, highly biodegradable renewable resource that was demonstrated to be an excellent feedstock for production of methane by anaerobic digestion. Under the proper conditions, which include long SRTs, *Macrocystis pyrifera* can be anaerobically digested to achieve greater than 80% of the theoretically attainable methane yield. Algal growth and environmental conditions can significantly alter algal composition and performance as a feedstock for anaerobic digestion. While several compositional variables may affect marine algae anaerobic digestion, mannitol and nitrogen content of the feed are two key parameters influencing biodegradability and digester stability. With *Macrocystis pyrifera*, for example, there is a correlation between the percent of theoretical methane yield achieved and mannitol content (when digested at 35°C at 15 to 18 day SRTs). Since the theoretical methane yield of algin is substantially lower than that of mannitol, kelp lots that have higher concentrations of algin relative to mannitol can be expected to have lower methane yields.

Although lower C:N ratios can be limiting to anaerobic digestion, evidence indicates that nitrogen limitations are related to the operating conditions of the anaerobic digester. For example, longer SRTs promote higher concentrations of ammonia-nitrogen in the digester effluent. Data suggest that the cell synthesis requirements for digesters decrease and that additional ammonia in the effluent is released at longer SRTs.

Longer SRTs promote higher methane yields, improved process stability, and lower nutrient requirements. Long SRTs in conventional CSTR reactors, however, also require long HRTs. This means that very large reactor sizes would be required to provide the long SRTs needed for good performance. The use of NMVFR reactors, however, promotes longer SRTs than HRTs, improving overall process performance. Consequently, reactor volumes and resultant costs can be reduced significantly.

Two-phase anaerobic digestion of marine algae is another potential way of improving the overall economics of the process. By separating the acid or hydrolytic phases of anaerobic digestion from the methane phase, it is possible to increase the methane concentration of the product gas, thus decreasing gas clean-up costs. In addition, this approach to marine algae digestion can promote process stability by providing a first-phase system that can protect the methane phase system from toxic or other environmental shocks that might be encountered with the feed.

Considerable progress has been made with marine algae toward improving an understanding of anaerobic digestion of biomass. Findings made in research on marine algae are also applicable to other forms of biomass as was the case with water hyacinth/sewage sludge and the design and operation of a small pilot plant located at Walt Disney World. There remain, however, several important areas of research and development needed before development of marine algal biological gasification processes can proceed. Additional research should include large-scale demonstration reactors to enable the evaluation of materials handling, process control, and effluent utilization options. Further work is also needed on the effect of feed composition and inocula development on anaerobic digestion of macroalgae.

Chapter 5: ENVIRONMENTAL CONSIDERATIONS

5.1. Introduction

The Lawrence Berkeley Laboratory (LBL), under the sponsorship of the Gas Research Institute (GRI), conducted a workshop on the topic of "Environmental Impacts of Marine Biomass" (Ritschard et al. 1981). This workshop involved over 40 experts from a wide range of disciplines including biological, chemical, and physical oceanography, ocean engineering, and several related marine areas.

The workshop had three objectives. First, the participants identified the potential environmental issues, both positive and negative, of an open ocean biomass system that employs artificial upwelling. Second, the experts evaluated each issue through an extensive discussion to determine how critical the issue was to the success of the marine biomass program. Finally, the attendees developed a set of recommendations for GRI that suggested research needs regarding the environmental aspects of the kelp farm system.

The format of the workshop provided a flexible structure emphasizing small working groups. The first day of the meeting commenced with a presentation of the marine biomass program by the prime contractor, Re-Entry Systems Division of the General Electric Company. This presentation set the boundary conditions for the subsequent working group sessions. The participants were divided into two working groups (biological and physical/chemical) that identified and evaluated the potential environmental issues in their area of expertise. Interaction between the two groups was encouraged through periodic plenary sessions where each chairman and selected participants presented a summary of the working group activities. These meetings of the entire group provided an opportunity for further elaboration and refinement of the specific issues and subsequent research recommendations produced by each study group.

5.2. Marine Biomass Farm Concept

A marine biomass farm is one of the few biologically-based systems that has the potential to contribute large quantities of synthetic gaseous fuels to the nation's future energy supply. This is especially true because biomass grown in the open ocean would not be limited by space, plant nutrients, or water availability as it is on land. Below, the history of the marine biomass program is briefly outlined and a description of the commercial size-farm, which was used as a hypothetical model during the workshop discussions, is provided.

5.2.1. History of Marine Biomass Program

In 1974, the marine biomass program was initiated by the American Gas Association (AGA) and the Energy Research and Development Administration (ERDA), with the U.S. Naval Undersea Center in San Diego, California, as prime contractor. The overall objective of the program was to develop a system for the production of methane gas on a commercial scale that would contribute in a major way to the nation's gas supply.

In 1976, the prime contract was shifted to the General Electric Company's Re-entry and Environmental Systems Division, because G.E. had the capability and corporate interest to develop and commercialize such a system. A year later, AGA's research program was transferred to the Gas Research Institute (GRI) and the Department of Energy (DOE) assumed the activities of ERDA.

The marine biomass program, which funded over $9 million of directed research since 1974, continued under the joint sponsorship of GRI and DOE. In addition, supporting research projects aimed at a better understanding of marine plants, their cultivation and potential new uses, were funded by several other Federal agencies to a total of about $1 million a year.

The approach utilized the concept of growing macroalgae on an open ocean farm to capture and store solar energy through the photosynthetic process. The macroalgae, after harvesting, would then be converted by anaerobic digestion to pipeline quality substitute gas (methane) and other possible byproducts (fertilizer, animal feed supplement, chemicals, etc).

5.2.2. Overview of Commercial Marine Farm

The basic concept of the marine biomass system is to culture and harvest seaweed plants on artificial structures submerged at the same depth as natural kelp beds. Marine kelp require light, carbon dioxide, water, and nutrients from the surface layers of the ocean. However, many of the areas along the southern California coast that could support marine algae may be nutrient-limited for most of the year because of a lack of upwelling. Therefore, fertilizing operations are clearly necessary to produce high yields of kelp on ocean farms. The selected process considered at this workshop for fertilization was to pump up nutrient-rich waters from depths of several hundred to a thousand feet.

Past and present work on this program has had the primary objective of determining the economic and technical feasibility of a system for the production of methane from California giant kelp, *Macrocystis pyrifera*, grown on man-made structures in the open ocean. *Macrocystis* was selected as the biomass source because of its high growth rate, its size, structure and growth patterns that allow it to be mechanically harvested, and its year-round growth cycle. Table 12 lists some baseline parameters regarding the composition of *Macrocystis.*

A set of basic parameters for a hypothetical 1000-square mile (2600 km^2) commercial size farm was presented to the workshop attendees (see Table 13). This size farm, which could theoretically contribute about 0.3 EJ of substitute natural gas (SNG) to the nation's current natural gas supply of 22 EJ, could represent a commercial scale operation. The specific configuration and other dimensions and properties of the farm should be viewed only as hypothetical values of the baseline system that was used by the participants in their environmental examination. Figure 2 depicts the elements of the hypothetical system. The actual dimensions and parameters are dependent upon cost studies, yield analyses, and other technical research. In the kelp farm discussed at the workshop, the standing crop is harvested by special ships several times a year. The vessels are patterned after the Kelco Company design used for commercial harvesting along the California coast for many years. Some pre-processing, e.g., removal of water and grinding, could be accomplished on the harvesting ships prior to transporting the kelp to onshore processing plants. This pre-processing step was not included in the system used as a prototype. The only harvesting and transportation information available to the attendees was an estimate that a commercial size farm (2,500 km^2) would require an many as fifty 10,000 dwt (dead weight ton) ships making three roundtrips per day to the onshore dock facility and pipeline system.

The SNG processing and conversion plant was hypothetically sited one mile (1.6 km) inland from the dock facility. It was assumed that the raw wet kelp would be shredded and subsequently transported by pipeline to the process site. The digester itself would require a unit capacity (inside volume) of about one million standard cubic feet (28,300 $m^{3)}$, which is about 2.5 times the largest existing digester. The process would also include a carbon dioxide scrubbing unit, which releases pure carbon dioxide, and compressors for delivery of pipeline-quality natural gas.

Several separation steps would be used to segregate the electrolytes, carbohydrates, water, and volatile solids (VS). The kelp (about 60% VS) would be placed into a heated air-tight digester where methane and carbon dioxide are produced. Bacteria would decompose the feedstock over a period of about two weeks in the absence of oxygen. A waste sludge, high in nitrogen, will also result. Table 14 contains the basic parameters of the digestion process.

Since there are no full-scale marine fare systems in operation today, the parameters that were used at the workshop represent a compilation of data from bench-scale experiments, from-conceptual plans, and from the data obtained on a biological test platform placed 5 miles (8.01 km) off the coast in southern California. In order to provide a database on kelp yield, which is one of the key parameters affecting the initial capital requirements and unit gas costs, GRI and DOE designed and constructed near-shore biological test farms. These experimental test facilities were used to conduct kelp yield experiments on adult kelp plants in a controlled fertilization environment.

The identification of important environmental issues and the recommendations of research to address these issues were developed at the workshop using the design parameters described here. No attempt was made to predict what an actual marine biomass farm might look like. Rather, the information was used to provide sample conditions within which a discussion of potential environmental concerns could be conducted.

5.2.3. Conclusions

During the extensive discussions over the three days of the workshop, several issues were identified by the participants that needed to be addressed by the GRI environmental research program. The major research recommendations from both the biological and physical/chemical group are summarized in Table 15 (biological) and Table 16 (physical/chemical). These issues and recommendations cover a wide spectrum of areas including biological, physical, and chemical oceanography as well as ocean engineering. Several issues critical to the development of the marine biomass concept, as a whole, emerged from the Individual working group discussions. These overall concepts seemed to dominate the workshop and served as the main conclusions.

First, questions arose regarding kelp productivity in an open ocean system. Efforts should be made to define more precisely the expected yield in offshore farms. This information would be required for the projection and evaluation of several other potential impacts. It is also needed to determine the feasibility of the ocean farm concept from a biological standpoint. Since a major problem for cultivated kelp beds is to supply the farm with proper nutrients in correct quantities, the dynamics of upwelled water must be understood, especially related to nutrient availability and uptake and kelp growth and stability. Workshop participants were concerned with how much upwelled water is required to maintain desired productivity.

Second, concerns were expressed at the workshop of the stability and survivability of offshore kelp farms. Can kelp plants remain attached to a floating structure in the open ocean? If not, can the amount of drift kelp that reaches the shore be kept to socially acceptable levels? Kelp fragments and other organic particles from the farm are expected to sink and affect oceanic oxygen budgets.

The potential oxygen depletion in the water column and bottom sediments, due to the enhanced sinking flux of organic particles, is one of the most serious problems that was identified. Therefore, a detailed assessment is needed of particulate organic matter flux from the kelp farm to deep water and sediments.

Chapter 6: SYSTEMS ANALYSES

6.1. Introduction

Two major uncertainties of biomass-to-energy research are cost competitiveness and availability of sufficient resources such as area, water, nutrients. Consequently, economic analyses have been used to address these questions. These analyses are generally of two types. The first determines a "state-of-the-art" or baseline energy cost, using biomass yields and conversion performance, which might be currently possible. The second fixes the price of energy to meet some cost goal and then predicts needed biomass yields and conversion performance in order to reach cost effectiveness. These predictions are often considered "performance drivers" as they are perceived as the keys to commercial feasibility and are often used as targets which research and development programs must achieve.

Biomass-to-energy systems must be viewed in total, with all the components integrated. The size of the system in terms of required energy production affects the kind of conversion system used and the performance of this system governs the amount of biomass required. Conversely, limitations on production (such as cultivation area available) can also impact the size, economics, design and cost. Within these constraints, however, it is possible to disaggregate the total system into two components: 1) feedstock production costs, which include cultivation, harvesting and transportation to a conversion facility and 2) conversion costs, which include storage, conversion to energy and recovery or purification of the end-product, such as purification of biogas to produce "pure" methane (industry pipeline standards of ca. 3.7 x 10^7 Joules m^{-3}), alcohol distillation, or electricity generation.

6.2. Resource Base

The resource base for biomass systems was been calculated in various ways. A first approximation was generated by simply calculating the ocean area available, regardless of biological, engineering, environmental, or sociological restrictions. Later, these caveats were considered in more detailed resource studies, which often reduced the original estimates by an order of magnitude.

The resource base for deep water offshore marine biomass production has been estimated with varying degrees of detail. Three analyses of the western U.S. coast, New York through New England, and the Florida peninsula excluded only major shipping lanes and port areas. General Electric estimated that 187,000 km^2 were available between 18-900 m depths (Sullivan et al. 1981). Estimates of the area between 50 m depth out to 320 km offshore included 290,000 km^2 (Snow et al. 1979).

More site-specific selections refined the areas of potential nearshore cultivation. In the area between Pt. Conception and San Diego, California, at least three prime areas and two secondary areas could support nearshore *Macrocystis* farms on the order of 2500-5300 ha (Mariculture 1982, Tompkins 1983). These site selections were based on naturally occurring kelp beds, sediment particulate size, run-off, turbidity, institutional conflicts, etc.

The New York Sea Grant Institute examined areas in the New York Bight suitable for *Laminaria* and *Gracilaria* cultivation on rope farms. After consideration of the biological and institutional restrictions, it determined that approximately 100,000 ha could be used for marine biomass cultivation (Squires & McKay 1982).

In Florida, the area between St. Petersberg and Pensacola was examined for two different marine biomass systems, tidal flat farms and floating seaweed systems. After consideration of shipping lanes, ports, conflicting fisheries, national parks and broad areas devoid of seaweed, 190,000 ha were found available between 0.5-1.5 m depth and 1,900,000 ha between 1.5-18 m depths (Bird 1987b). However, these areas were not scrutinized to the extent that the Southern California or New York Bight areas were, with respct to institutional conflicts or biological and physical limitations.

Other areas of the U.S. were given less attention. Tidal flat farms could be used in areas such as Texas, the Carolinas, and Chesapeake Bay, all of which have extensive shallow water areas. Oil platforms off the Gulf Coast support extensive marine floras, indicating that floating seaweed systems could produce biomass in these areas, even though the adjacent shoreline may be devoid of seaweed.

6.3. Open Ocean Farm

Four economic/systems analyses of open seaweed farms were considered in a program review (AquacultureAssociates 1982). Tables 17 through 22 compare the study approach, assumptions and principal conclusions of these four studies. These will be referred to in the following discussion.

6.3.1. ISC (Integrated Science Corporation) Report

The ISC multi-volume report (ISC 1976) represented the first comprehensive overview of the economics of producing methane gas from a marine biomass farming system. This study is also historically significant because it proposed a model for economic feasibility analysis, which would be used extensively in subsequent feasibility assessments. Notable features of the ISC study approach include: (1) careful attention given to refinement of process and component designs; (2) use of simplistic (and inaccurate) procedures for determining capital costs and annual operating expenses; (3) use of average gas cost estimates (derived from a utility finance model) as the primary indicator of system feasibility, and (4) failure to fully account for systemic risk and uncertainty. Since the last three features were evident in other systems studies, each deserves further elaboration.

The following steps were employed in ISC's capital cost determination procedure:

1. Cost and performance data for all subsystems were collected. Often, cost estimates reflected previously optimized subsystem processes or materials characteristics. Cost estimates were used with no explicit consideration given to scale economies and diseconomies in procurement.

2. Procurement costs of individual subsystems were summed.

3. An installation cost factor was then added to arrive at total plant investment cost. In many instances, the installation cost calculations seem overly optimistic.

4. Fixed percentage contingency contracting and working capital factors were then added. No downstream working capital requirements were included.

5. Construction interest expenses and start-up costs were added to arrive at total system capital costs. Both of these cost factors were based on optimistic lead times in construction and deployment.

Annual operating costs were calculated as the sum of maintenance expenses, labor costs, and other miscellaneous expenses. Except for the harvesting subsystem, maintenance cost estimates were far less than we would expect to keep subsystem components intact and operable throughout the projected life of the farm.

Finally, the calculations for total capital costs, total plant investment, and operating costs were used to determine first year and average SNG costs. This task was accomplished using the "utility financing method" (UFM). As we noted later, serious doubt can be raised about the validity of using either of these cost estimates as a measure of system feasibility.

ISC estimated that if mariculture co-production credits were considered, use of the above costing algorithm resulted in a total capital cost estimate of $60 million and an average unit (MMBtu or GJ) gas cost estimate of $3.65. A slightly higher average gas cost of $4.91 was calculated for a farm system without mariculture co-production. Besides generating previously unavailable capital and unit gas cost estimates, the ISC study group also tested the sensitivity of cost estimates to perturbations in selected cost and physical performance parameters. Their results showed a possible variation in average annual gas costs between $2.28 and $6.86. It is important to mention, however, that this range is based on varying only one parameter at a time by an arbitrary percentage amount. No explicit treatment was given to the real possibility of simultaneous and significant variations in a number of system parameters. Furthermore, no consideration was given to the cost consequences of subsystem component failures or process interruptions.

Based on their findings, the ISC study team concluded that the offshore kelp farm concept “offers a long-term promise for supplying large quantities of energy and food.

The cost and productivity estimates make it roughly competitive with other energy systems."

6.3.2. Dynatech Report

Quite the opposite conclusion was reached in an ensuing study of offshore kelp farming conducted by the Dynatech Corporation (Ashare et al. 1978). This study was directed at determining the economic feasibility of deriving energy from aquatic biomass sources in general, including offshore kelp farms.

Dynatech's investigation of kelp farming economics followed earlier work by ISC fairly closely. In general, however, assumptions used by Dynatech were pessimistic. A farm concept similar to ISC's was used with the notable exceptions that the Dynatech substrate was permanently moored as opposed to dynamically positioned and that the nutrient delivery system was based on fossil fuel powered rather than wave or wind driven pumps. These changes led to relatively higher capital and annual operating costs, along with lower energy conversion efficiencies than those projected by ISC. The basic cost determination procedure used by Dynatech was analogous to that employed by the ISC study team. Certain prominent exceptions were that Dynatech did not consider co-production credits and used a much higher installation cost factor (50% of sub-system component costs). These changes, when combined with higher nutrient delivery cost assumptions, resulted in total investment requirements for a marine biomass farm of $1432 - $2269 million, 300 to 400% higher than those of ISC. Consequently, Dynatech's unit gas cost estimate of over $20 was almost four times ISC's most pessimistic estimates. Rudimentary sensitivity analyses indicated that reasonable variations in individual parameters would not alter these financial projections significantly. The combined effects of multiple and simultaneous parametric variations were not considered.

Although the Dynatech report concluded that "ocean farms have little economic potential" due to excessive nutrient delivery costs, it nevertheless gave support for further consideration of land based biomass production systems, particularly for emerged aquatic angiosperms. In certain cases, unit gas costs as low as $5.00 were calculated.

6.3.3. SRI Study

In 1979, SRI (Jones 1979) reported yet another set of cost estimates associated with producing methane from ocean-grown kelp. Their findings showed that, due to the high projected cost of producing kelp feedstocks, unit gas costs would not be below $20. Essentially, the SRI study supported earlier Dynatech findings, but for different reasons.

6.3.4. GE System Analysis

The most recent marine biomass feasibility study was provided by GE (Sullivan et al. 1981). Following closely the conceptual as well as cost estimation models developed earlier by the ISC study groups, GE estimated total capital requirements for their baseline farm to be $1274 million and average unit gas costs to be $6.15 per GJ. This improved financial outlook compared to Dynatech and SRI projections was primarily due to more optimistic assumptions about key system parameters, which affect kelp feedstock costs and methane conversion efficiency.

6.3.5. Conclusions

The feasibility of producing large quantities of low cost SNG from kelp feedstock has now been scrutinized for almost a decade. To date, no consensus has been reached on this basic question principally because there is a lack of concrete data concerning critical system parameters and because of uncertainty about subsystem costs.

There are, however, important areas of agreement among the four analyses:

1. *Kelp Yield*. All stated or implied that kelp yield strongly affects overall system viability and that obtaining kelp yield data is of high priority.

2. *Kelp Cultivation Costs*. The studies generally agreed that the capital costs associated with manufacturing and deploying an artificial kelp substrate are substantial. Furthermore, cultivation subsystem costs represent a sizable portion of total system capital costs (74%, GE estimate). By implication, it was agreed that production of low cost SNG depends on growing low cost kelp feedstock on low cost kelp farms.

3. *Farm Life Expectancy*. The studies agreed, without clear justification, that components of a kelp farm have a life expectancy of 20 years.

4. *Nutrient Requirements*. The consensus of the studies is that kelp will have to be fed in order to achieve low cost kelp feedstock in large quantities. Furthermore, the studies agreed that use of commercial fertilizers is not a viable alternative for kelp feeding. Instead, use of artificial upwelling is preferred even though pump costs are high.

5. *Processing Costs*. The studies agreed that it is possible to process kelp or other biomass feedstocks into methane fairly inexpensively. Capital outlays for methane conversion facilities would contribute little to final unit gas costs.

6. *Annual Maintenance Expenses*. The studies commonly held that annual expenses to keep a kelp farm operable would be less than 5% of total kelp farm investment.

7. *100% System Efficiency*. Consensus was that kelp farms operate at 100% efficiency 365 days a year. There is no need for planned excess capacity in case of system interruptions or failures. Furthermore, it was generally agreed that it makes economic sense to grow kelp at its maximum growth rate, and to operate all subsystems at maximum physical efficiency.

8. *Utility Finance Method*. All of the studies used the same costing assumptions and economic model. The utility finance method was been used to compare "average gas cost" over 20 years of plant operation with current costs of fuels from other sources. Of the four systems studies, the ISC analysis (with the exceptions noted) appeared to be the most complete. Based on the project documentation reviewed to date, the study assumes relatively reasonable system parameters and project scenarios. The Dynatech, SRI, and GE studies suffered from questionable system parameter selection.

The offshore kelp concept was the first marine biomass system analyzed for baseline methane costs to determine performance drivers needed to achieve cost competitive gas. Numerous studies of the offshore kelp concept approximated methane costs ranging from $32-80 per GJ using a kelp yield range of 2-111 daft $ha^{-1}y^{-1}$ (Ashare et al. 1978); $12-15 per GJ at kelp yields of 33 daft $ha^{-1}y^{-1}$ (Jones 1979); and $5 per GJ (Budharja 1976). None of these analyses were based on any demonstrated kelp yield data, nor incorporated any advanced reactor designs, which would improve bioconversion performance. Kelp yield approximations, for example, have ranged from 3-140 daft $ha^{-1}y^{-1}$ (dry ash free metric tons/hectare/year). General Electric Company (Sullivan et al. 1981) developed a systems model based on the offshore test platform design which estimated that kelp yields would have to be around 140 daft $ha^{-1}y^{-1}$ to compete with estimated costs of substitute natural gas from coal gasification (ca. $6 per GJ).

6.4. Nearshore Farm Concepts (Bird 1987b, a)

Nearshore *Macrocystis* systems from a total systems perspective ane discussed below, including how improvements in one component of the overall process can improve the economics of all the system components. Feedstock production costs of other marine biomass concepts, the economics of different conversion processes and finally, the use of these specific analyses to reach some generalizations about cost effective approaches to marine biomass for energy systems. As much as possible, costs were based on: 1) the detailed engineering estimates of the nearshore kelp study (Brehany 1983) to provide continuity between analyses; 2) from other cost estimates, such as the Japanese marine biomass systems reports; previous studies by qualified architectural and engineering firms; and 3) contractor price quotes. Costs were reported using the Gas Research Institute levelized gas cost model (Decision Focus 1984). Both types of analyses were reported, including estimates of "state-of-the-art" energy costs and needed performance drivers necessary to achieve energy costs competitive with other sources. The Gas Research Institute Baseline Energy Projection estimated methane costs at approximately $6 per GJ ($1982) after the year 2000 and the U.S. Department of Energy projections fall within this range (Energy 1983).

6.4.1. *Macrocystis*

Prior to economic and systems analysis of a nearshore *Macrocystis* system based on the nearshore kelp research, program managers, scientists and engineers developed a list of operating assumptions and specifications to be used in that analysis (Tompkins

1983). Chief among these assumptions were those pertaining to kelp yield and bioconversion. For the baseline analysis, a kelp yield of 34 daft $ha^{-1}y^{-1}$ was assumed, even though it was not possible to sustain these yields without extensive quarterly kelp replanting. While these yields have not been sustainable, it was felt that new planting configurations could improve light penetration since low subsurface light appeared responsible for the higher kelp mortalities at high densities. In terms of bioconversion performance, methane yields in a range of 0.4 - 0.5 L/kg VS added were used at solids retention times of 50 days or more.

The economic and systems analysis was conducted by an architectural and engineering company, R.M. Parsons, experienced in design and construction (Brehany 1983). After analysis of potential farm sites below Pt. Conception, CA, a site was selected near Goleta, CA, for a farm design of 2671 ha, which was 34 km long and 0.8 km wide and between 8 to 18 m water depths. Small juvenile *Macrocystis* plants obtained from nursery stock would be fastened to bags of rock aggregate (Figure 4). These would be lowered into the water from barges and tugs on lines, which also spaced the plants apart from each other. Plants would grow up to form a canopy in two years. The dock-harvesting facility would be located at a midpoint of the farm.

Analysis of the harvesting system indicated that the lowest cost system was a dedicated harvester, operating at 1.6 knots, which would cut the kelp at a rate of 440 t h^{-1} and pump it into a 1433 ton capacity barge which would be cycled in and out by tugs. Harvesting occurred over a 300 d period, with 65 days allowed for inclement weather. Due to the distances to the extreme ends of the farm, each of three barges was accompanied by a dedicated tug. The harvested kelp was pumped to a storage tank, then to three fixed film reactors for conversion to biogas and upgraded to pipeline methane. Digester effluent was pumped back to the barges as ballast and later sprayed on the farm as fertilizer. Chief biological assumptions of this baseline system were that the farm would produce 34 daft $ha^{-1}y^{-1}$ and the reactors would yield 0.43 L methane per kg VS added.

This baseline analysis estimated methane costs at $12 per GJ. Detailed capital and operating costs of the different systems components are in the original report (Brehany, 1983) are summarized in Table 23. The greatest single component of these costs were those associated with harvesting, $4.80 of the $12 per GJ. This high harvesting cost was primarily due to labor costs associated with use of seamen at union wages and restrictions (for example, crews are paid for minimum of full 12 h and time over 12 h for a 24 h period). An advanced system which would deliver methane at $6 per GJ required kelp yields of 101 daft $ha^{-1}y^{-1}$, methane yields of 0.53 L/kg VS added, and a 50% reduction in harvesting labor through automation. The results of this study confirmed that large increases in seaweed yield and bioconversion performance would have to be achieved in order for the system to be economically competitive. This study also examined the energy balance of the baseline system and determined that it produced 90% new energy.

Economics of the kelp system was reevaluated (Bird 1986). Progress in bioconversion research indicated the experimental unmixed vertical flow reactor could still produce the baseline methane yields of 0.43 L/kg VS added at a 27% greater loading rate (Fannin et al. 1983b). In addition, use of this reactor reduced capital and operating costs compared to the packed film reactor used in the Parsons analysis (Note that this reviewer, (Chynoweth, does not think that a packed bed reactor would work with kelp; it would clog). When the effects of doubling total baseline facility size and gas output were evaluated, the improved reactor performance reduced the number of reactors from six to five.

The improved economies of scale in the bioconversion process suggested that similar economies of scale might be found in harvesting. Analysis of the doubled farm size, harvester speeds and harvesting rates indicated that the number of harvesters and barges for the harvested kelp also would have to be doubled in the updated baseline system. However, the tugs which return the kelp laden barges to the processing facility did not have to be increased from 3 to 6, rather 4 tugs could effectively support the two harvesters and six barges. The harvesting schedule would also have to be arranged so that both harvesters would not be located at the extremes of the farm at the same time. Doubling the facility size resulted in an increase in the total capital and operation and maintenance costs of the updated systems (Table 24); however, the gas costs of the baseline system were reduced from $12 to 8 per GJ as a function of increased total biomass output and improved economics of scale. Similar economies of scale were found when the advanced system was updated, but more importantly, the performance drivers of kelp yield were reduced from 101 to 50 daft $ha^{-1}y^{-1}$ and methane yields from 0.53 to 0.50 L /kg VS added in order to achieve a target $6 per GJ gas (Table 24).

Subsequent analysis has suggested further ways to reduce methane costs (Bird 1987a). The prior analyses assumed that tugboats would return to the docks with a single barge. However, tugs have sufficient power to pull two or three fully laden barges. If it is assumed that the barges could be left at moorings or anchored at prearranged sites, the tugboat could depart pulling the barges and leave them on the farm at sites where the harvester would switch full barges for empty ones. The tug would then return and pick up the full barges, towing them back to the dock-pumping station. In this manner, the number of tugs could be reduced to one for each of two harvesters. When this decrease in capital, O & M, and fuel was factored into the updated baseline system, the price of the methane was reduced to $6 per GJ without increases in kelp yield, or improvements in other performance drivers. This tug-barge approach was used by the kelp harvesting industry in its early history.

Other potential cost reductions could come from examinations of the kelp industry and its history. The early harvesters were reported to work at speeds of 4-5 knots, while the assumption used in these studies was 1.6 knots. If it were possible for a harvester to work at a 5 knots speed in a farm with five times the production of natural beds, a single harvester could take care of the whole farm. While these scenarios have not been subject to rigorous engineering/cost examination, they suggest that large reductions in harvesting costs are possible. In turn, cost reductions lead to reductions in required kelp yield and bioconversion performance. For example, the original Parsons study required kelp yields of 101 daft $ha^{-1}y^{-1}$ and methane yields of 0.53 L methane per kg VS added. Should the barge mooring or anchoring system prove feasible, these kelp yield requirements for $6 per GJ gas would drop to 34 daft $ha^{-1}y^{-1}$ and methane yield to 0.43 L methane per kg VS added using the assumptions of the original baseline analysis.

6.4.2. *Laminaria – Gracilaria* Multicrop System

The Japanese have been developing *Laminaria* cultivation as a marine biomass resource resulting in a first order systems description, which was used as the primary basis of this analysis (Ocean Industries Association 1982, Hanada et al. 1984). They currently achieve *Laminaria* yields on the order of 7-16 daft $ha^{-1}y^{-1}$ however, they set a yield goal of 45 daft $ha^{-1}y^{-1}$as a program objective. Since the recent New York experimental farm yields were around the range of the current Japanese yields, a baseline case of 11 daft $ha^{-1}y^{-1}$ was assumed for a New York system, with the same advanced case scenario of 45 daft $ha^{-1}y^{-1}$as the Japanese. A 5344 ha production system was selected based on the West Coast kelp study of best minimum economy of scale. Two farms for a New York marine biomass project were conceptualized to evaluate the effects of distance from farm to shore facilities, the first at 50 km and the other at 200 km. These distances represented the extremes between potential cultivation areas selected by NYSGI (Squires & McKay 1982) and a shore-based facility where high-energy methane could be connected to a gas pipeline.

The multicrop concept focused on an approach in which *Laminaria* would be grown in winter months and *Gracilaria* in the summer months on a rope farm, a strategy that would circumvent problems of biomass seasonality. The research, conducted by the New York Sea Grant Institute, led to an experimental farm which provided preliminary yield data, seasonal "windows" dictating best planting times and seasonal growth patterns.

The farm design used for this analysis assumed use of the advanced Japanese *Laminaria* energy farm which wwould be engineered to support a biomass crop producing 45 daft $ha^{-1}y^{-1}$in water depths averaging 80 m depths similar to the New York Bight. The Japanese studies analyzed the cost of using current *Laminaria* cultivation technology and concluded that at $54,340 ha^{-1} for capital and construction costs alone, this system would not be feasible. However, the Ishikawajima-Harima Heavy Industries have conceptualized preliminary farm designs, which also facilitate mechanical harvesting and estimated a cost of $11,362 ha^{-1} (Hanada et al. 1984). The system envisioned involves a hanging rope curtain cultivation system, in which two cultivation ropes are joined at the bottom and weighted by a sinker (Figure 5). For this analysis, direct purchase of a Japanese hanging rope curtain farm as a turnkey operation was assumed, plus 20% profit. Should the Japanese be successful in developing this design for this cost, the installed farm costs over the life of the facility alone could be $8 per GJ for the baseline system (11 daft $ha^{-1}y^{-1}$) and $2 per GJ for the advanced system (45 daft
$ha^{-1}y^{-1}$).

Preparations for the winter *Laminaria* crop would begin in late June when the culture ropes would be inoculated with *Laminaria* spores in the nursery. Based on data from the experimental farm, planting would start in mid-September. The culture ropes would be taken out to the farm by harvesting/ planting boats which would lift the long lines out of the water and attach seeded culture ropes to the connection points as two long lines run down the length of the ship. As the nearest farm site was about 50 km and the furthest was 120 km, total boat transit time at 15 knots to and from the farms would be 4hr and 16hr d^{-1}, respectively. As boat crews typically worked 12 hours on, 12 hours off, or a 24 h schedule, a shuttle service of culture lines would be required and the harvesting/ planting boats were better left on station, working 24 h shifts. A total of 240 boat days (4 boats @ 60 days) would be required to plant the whole farm. The NYSGI field data indicate that the October-December time frame was a good period for *Laminaria* growth; hence, the farm must be planted quickly and then harvested after three months. Following the same schedule and speed as for farm planting, 60 days would be required for the harvest cycle; hence, the first cycle would be completed in mid-February. The second harvesting cycle would begin in mid-March and end mid-May, allowing three months between harvests. With this planting-harvesting cycle, *Laminaria* cultivation would commence mid-September and end mid-May, a growth period which follows *Laminaria* field growth patterns in the New York area. *Gracilaria* would be seeded to culture ropes in the nursery beginning mid-December and established on the ropes through mid-March. The culture ropes would be simultaneously planted on the farm as the last *Laminaria* harvest is conducted. Two harvests would be conducted, from mid-June through mid-August and mid-September through mid-November. The newly seeded *Laminaria* culture ropes would be simultaneously planted on the farm during this last harvest.

The model and costs for this projected planting-harvesting vessel came from the Japanese marine biomass program. The major limitations to harvesting rate is the speed (1 knot) at which the two long lines could move down the harvester sides while the biomass was stripped from the culture ropes. Enough of the holdfast and meristematic areas would have to be left on the rope to permit new regrowth. These harvesters pump the biomass into barges towed by the harvesters. When the barge became full, it would be exchanged for an empty barge, which would be dropped off at a designated exchange point (an ocean mooring) by a tug. A tug would return to the bioconversion facility towing all the barges.

Costs of feedstock delivered to the digestion facility ranged from $44 per GJ for the baseline system to $12 per GJ for the advanced case (Table 25). The farther farm location added approximately $1 per GJ to these gas costs. The greatest capital expenditures were for the farm and the harvesting fleet, which were 95% of the capital cost of feedstock production. The installed farm cost alone was greater than the combined capital cost for the nearshore *Macrocystis* farm and its harvesting system. There are a number of features which make the current rope farm concept very costly compared to other macroalgal systems. The strong seasonality of the biomass crop is a major deterrent because planting costs for this kind of crop are so high. In the New York system, the entire farm must have a new crop twice a year and the entire farm must be planted within two months. If the *Laminaria* crop were not seasonal, the number of harvesters could be reduced to three, reducing gas costs by $2-3 per GJ in the advanced systems.

Even greater cost reductions could result if the seaweed formed a canopy as does the west coast kelp. In the N.Y. system, the harvester must run down the length of the long lines, stripping off the biomass as it proceeds and significantly reducing the harvest speed compared to cutting through a canopy. If canopy forming kelp were used in N.Y., the feedstock costs could be reduced to $8 per GJ. Another major deterrent was the distance from the conversion facility to the farm (50-200 km). In most of the biomass systems examined to date, the maximum operating range has been 10-20 km. The greatest limitation to any rope farm technology is not only the high capital costs of the farm structure, but the maintenance associated with biological and physical degradation of the farm structure materials. In this study, farm life was assumed to be 20 years and annual maintenance assumed to be one twentieth of the capital costs. While there is insufficient information regarding the longevity of marine farming materials, it is doubtful that current materials would be suitable to meet this low maintenance cost. Increased farm maintenance and materials replacement leads to a rapid escalation in methane prices. Such escalation probably limits the use of any rope farm design for strictly energy producing systems.

6.5. Tidal Flat Farm

Major capital costs are shown in the Table 26; specific farm descriptions and capital costs are reported elsewhere (Bird 1987a). If a circular farm is not feasible, a long rectangular farm, 1 km wide, would cost 15% more to construct (Figure 6). Annual O & M for the farm consists of two components: farm maintenance and seaweed cultivation. The major cost estimated for farm maintenance is the replacement of all the netting every two years in a year round replacement operation. Replacement would be necessary due to biofouling of the netting and material degradation. Seaweed cultivation costs are primarily labor costs if seaweed does not pile up too heavily in select locations. The farmers would be equipped with small boats to move seaweed around. A nursery/laboratory has been included in the capital costs in the event that several species or clones are used over the course of a year, to maintain important clones and inocula for water chemistry measurements.

The total capital, O & M and fuel costs, as well as delivered feedstock costs are shown in Table 26. Feedstock costs on an energy basis for the 11 daft $ha^{-1}y^{-1}$ yields are $3.60 per GJ and for 23 daft $ha^{-1}y^{-1}$, $2.30 per GJ, assuming methane yields of 0.43 L kg^{-1} VS added. Recent bioassays of Harbor Branch Foundation *Gracilaria* clones have indicated methane yields of 0.43 -0.53 L kg^{-1} VS added. Feedstock costs on a weight basis for this system ranged from $44-28 per dry ash free metric ton. When cost sensitivities for both capital and operating costs were performed at the two different biomass yields, the effect was only significant at low biomass yields of 11daft $ha^{-1}y^{-1}$; in this case, O & M costs increased by a million dollars. The greatest cost unknowns in the system were the final farm configuration (site specific) and extent of drift seaweed fences required in the farm. In the 23 daft $ha^{-1}y^{-1}$ system, if the farm is located more than 6 km from the dock or is rectangular in shape, an additional harvester may be required.

The tidal flat farm concept is an untested approach to seaweed farming and as such, will encounter a number of constraints with regard to potential biomass yields. Key problems will be weed species which foul the biomass crop itself, cutting down substantially on production, and the impact of marine herbivores such as amphipods. Currently, chemical control technologies for these pests are not well developed and it may be necessary to develop selective algacides and herbivore control agents. Current speeds will also affect the choice of the biomass crop. In confined bays and estuaries, with low water movement, *Ulva* sp. may be better suited as it is well adapted to such water movement, while *Gracilaria* would be best suited for areas with stronger currents and greater water exchange.

Perhaps most important, however, will be the seaweeds' interactions with the substrate. As the seaweed tumbles and moves across the bottom, a fine particulate substrate can cover the thalli. With wave and wind action, the seaweed can actually be buried in the sediments, greatly reducing farm productivity. The Taiwanese *Gracilaria* farmers prefer ponds lined with coarse sand (Shang 1976). Coarse material is less likely to be stirred up by wave and wind action, or to cover the thalli.

6.6. Floating Seaweed Cultivation

The greatest costs of off-bottom seaweed culture (offshore *Macrocystis* and *Laminaria* rope farms) are those related to the farm structure, which gives rise to the idea of cultivating a floating seaweed by enclosing it and letting it grow. A number of seaweeds, such as species of *Sargassum*, grow floating on the ocean surface. Costs associated with this approach are difficult to project because such an enclosing structure has never been designed for marine biomass and the only yield data were obtained from small 1-2 m^2 test enclosures. However, enclosed structures compatible with the marine environment are used for fish culture in Norway and Japan, hence the technology is partially developed. Enclosed structures have been designed for aquatic biomass systems such as water hyacinth. Capital costs developed for this system have been combined with the harvesting costs associated with nearshore kelp faming to make feedstock cost comparisons at two different biomass yields, 22 and 45 daft $ha^{-1}y^{-1}$. The feedstock costs for this system range from $6-3 per GJ (Table 27). The greatest, cost component was still that associated with harvesting.

6.7. Marine Biomass Feedstock Cost Comparisons

Baseline predictions of marine biomass feedstock costs have been estimated to range from $44 to 538 per daft (Table 28), the latter costs associated with rope farms. When this concept is excluded, costs range from $44 to 73/daft. Yield improvements can further reduce costs to $28-42/daft (Table 28). Using slightly different biomass yield assumptions, systems sizes, engineering costs and economic parameters, (Feinberg &

Hock 1985) placed feedstock costs in the range of $23-72/daft (Table 28). This study also examined costs associated with land based raceway cultivation of marine biomass, which revealed costs in the range of $115-209/daft. At these feedstock costs, it is apparent that yield improvements will have to come if marine biomass is ever to compete with other sources of substitute natural gas, however, this observation is true of the biomass field as a whole.

Feedstock cost comparisons should not be used to suggest that one approach is more cost effective than another. The unknowns associated with the different systems are presently too great to allow differentiation of comparative benefits. Of all seaweeds, the kelp system has been most carefully analyzed; however, the required productivity has not been sustainable. The yields used for the baseline tidal flat farm have been close to those obtained in commercial scale ponds, but not in the proposed tidal flat system. Most likely, local site and biological criteria will dictate the kind of cultivation system used, rather than a selection based on feedstock costs.

6.8. Conversion Costs (Bird 1987a)

There are several potential processes for conversion of marine biomass to energy: thermochemical conversion, or biological conversion to methane or alcohol. Despite some research on thermochemical conversion of marine biomass, this option cannot be considered a viable process since it produces only a low energy content gas and requires a dry feedstock. It is unrealistic to consider drying large amounts of marine biomass with 80-90 % water content. Anaerobic digestion of marine biomass can produce a medium energy content biogas (50-60% methane with the remainder largely as CO_2) which can be further refined to pipeline quality methane, converted to electricity, or burned for onsite applications. Anaerobic digestion can also be used at a wide range of scales from large industrial gas production to sizes suitable for farms and villages. All analyses reported here considered large-scale production for the gas transmission and distribution industry. Capital costs for these facilities are generally in the range of ten million dollars or more, depending on scale and involve more than a million dollars/year of operating costs.

The conversion costs alone contribute $1.50-3.50 per GJ to the final cost of the gas based on data from bench-scale reactors. In scaling up a vertical flow solids concentrating reactor developed in the marine biomass program from bench-scale to small pilot scale for use in the water hyacinths/sewage sludge digestion research, a significant improvement in digester performance was observed for over 18 months of continual operation. Gas purification to pipeline quality (high energy content) can add another $1-2 per GJ. The conversion costs are particularly sensitive to methane yield, even more so than solids retention time in the reactor. A thorough examination of small-scale systems suitable for island nations or coastal communities needs to be performed and would indicate whether marine biomass could be used for local energy needs. In such situations, energy production integrated into aquaculture or wastewater treatment systems might prove most cost effective. If a medium energy content gas is adequate for local needs, some of the baseline systems described are already at or near cost competitiveness.

Little research has been done on marine biomass conversion to alcohol; however, some costing of such a process has been attempted (Feinberg & Hock 1985). Conversion of marine biomass to alcohol is assumed to require more process energy due to the higher water content of macroalgae compared to grains and high energy requirements of feed hydrolysis and distillation for product recovery. Key compositional characteristics of the feedstock, which affect process economics are the percentage soluble carbohydrates of total carbohydrates, which can range from 20% in *Sargassum* to 70% in *Gracilaria*. The ratio of hexose to pentose sugars is low in macroalgae, a positive feature for alcohol conversion compared to some terrestrial, lignocellulosic biomass feedstock. Ethanol prices range from $0.50-0.75 per liter for the baseline technologies and $0.25-.30 per liter for the advanced cases (Table 29). These estimates base on 1980s figures should be regarded as tentative, as there are limited bench-scale fermentation data to support the product yield assumptions.

Chapter 7: BY-PRODUCTS AND CO-PRODUCTS

7.1. Introduction

The possibility of integrated marine biomass systems which produce energy, chemicals, food, fertilizer, wastewater treatment, etc. would reduce energy prices as other incoming sources of revenue help to defray capital and operating costs. In the original study of nearshore kelp economics, every million dollars of added revenue from by- and co-products reduced the baseline $12 per GJ methane price by $1.30 per GJ (Brehany 1983). Such systems did not receive much attention, however, since funding for energy research came primarily from an energy perspective of developing technologies with large energy supply impacts. If co-production by extraction of valuable algal hydrocolloids such as agar and alginate and then conversion of the rest of the material to energy were considered, saturation of the total hydrocolloid market by this technology would produce only a miniscule amount of the total energy demand.

Nonetheless, by- and co-product approaches make sense for chemical companies or aquaculture concerns, as a number of valuable products can be extracted from marine biomass and anaerobic digestion can subsequently be used to convert residues to usable energy and for waste treatment. For this discussion, co-products and by-products would be derived from the biomass and the residues are converted to gas to generate additional revenue. An example of the former might include a technology that would extract a hydrocolloid, leaving residues that could be effectively digested to biogas, with the biogas separated into methane for energy and into CO_2 for the industrial gas market. A by-product of this process might be any biomass solids left over after digestion, which could be dried and sold as soil conditioner. It should be noted that, with this definition, one company's co-product could be another company's by-product. A company might wish to stress soil conditioner production, an hence develop the technology to improve the characteristics of the recovered biomass solids.

An analysis of the original nearshore kelp system indicated that over 21 possible products besides methane were available (Table 30). It should be noted that a similar number of products should be available from other seaweeds, such as agar or carrageenan from red seaweeds, rather than alginates from the brown seaweeds. The analysis assumed that 15% of the harvested kelp would not be converted to methane, but be used for production of higher value products, primarily alginate based compounds, mannitol and fucoidans, with the rest of the material digested and the by-products (including liquid CO_2) recovered fromeffluent streams. This integrated chemical and energy process would increase gross sales receipts by a factor of two or more, and resultes in methane costs of $5 per GJ (Tompkins, 1982).

There has been some interest in using algae to clean up wastewater (Ryther et al. 1979, Lehnberg & Schram 1984, Schramm & Lehrberg 1984). Analysis of an integrated wastewater treatment by water hyacinths with subsequent bioconversion of sewage sludge/biomass blends produced methane costs of $2.50 per GJ, assuming that the treatment plant would receive the same treatment revenues of current wastewater treatment technologies (Hayes et al. 1985). A number of brackish water algae, especially species of the green algae, that have high growth rates and nutrient assimilation in mixtures of sewage effluents and marine waters warrant investigation (Lehnberg & Schram 1984).

7.2. GE Study (Tompkins 1983)

7.2.1. Background

Several valuable chemicals and products could be economically recovered as by-products and co-products of methane production. Net revenues from the production of these chemicals can be used for partially or totally offsetting the methane production costs as summarized in Table 31. It is strongly recommended that research in the by-product and co-product area be initiated and pursued vigorously. A high priority to this task in the overall Marine Biomass evaluation is recommended due to the large anticipated returns.

a.) Of more than a dozen chemicals that could be recovered as by-products and co-products, only four or five offer the potential for achieving significant reductions in gas cost. These are iodine, L-fraction, algin, mannitol, and possibly carbon dioxide. All except the L-fraction are commercial products at present. Further, the technical evaluations conducted in this study show that these chemicals could be produced as by-products or co-products of methane production. Laboratory samples of L-fraction have been prepared from raw kelp and from digester effluents. Based on preliminary characterizations of these samples and discussions with technical researchers in this area, potential applications of L-fraction are suggested to be as a feedstock or a component for making specialty plastics, and adhesives, and timed-release substances such as pharmaceuticals or pesticides. Such applications suggest the L-fraction to be worth $1-2 per lb ($2.2-4 per kg) and up to $6-7 per lb ($13-15 per kg) depending on the particular usage. For purposes of this analysis, L-fraction was valued at $1 and $3 per lb ($2.2 – $6.6 per kg).

b.) In one scenario analyzed in this study, in which all the kelp from the farm is used for methane production, recovery of iodine and carbon dioxide from the digester effluents could decrease the gas cost of $13.47 per GJ by an estimated 16 percent. Recovery of the L-fraction could further decrease the gas cost. With L-fraction valued at $1per lb ($2.2 per kg), the gas cost reduction due to net revenues from by-products is estimated at 30-35 %. At $3 per lb ($6.6 per kg) of L-fraction, more net revenues could be anticipated from the sale of by-products than needed to completely offset the cost of methane production.

c.) In the second scenario, approximately 15% of the farm output is devoted to the production of selected chemicals such as algin and mannitol, and the remainder could be used for methane production. Net revenues from the production of these chemicals and of iodine and carbon dioxide from digester effluents could reduce the gas cost of $15 per GJ* by an estimated 55-60%. With L-fraction included and valued at $1 per lb

($2.2 per kg), the gas cost reduction is estimated at 65-80 %. At $3 per lb ($6.6 per kg) of L-fraction, as in the first scenario, the by-products and co-products would generate more net revenues than needed to pay totally for the cost of methane production.

A detailed system study and economic assessment of commercial production of methane from kelp was conducted for the Gas Research Institute by The Ralph M. Parsons Company (Brehany 1983). The Parsons analysis was based on a system concept of a nearshore farm off the coast of southern California in which kelp would be grown and harvested, and transported to a land site for the production of methane gas using an anaerobic digestion process. In the system concept studied, the digester effluents from the digestion process would be returned to the kelp farm to supplement the naturally occurring nutrients. The nominal system capacity would be three million SCFD of pipeline quality gas. This study wass adjunct to the Parsons' study and considered the production of by-products* and co-products** within the framework of the system concept analyzed by Parsons.

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*By-product: Chemicals or products recovered in conjunction with the production of methane from the same pound of kelp.

**Co-product: Chemicals or products recovered from a portion of baseline farm kelp used exclusively for chemicals production.

The objective of this investigation was to evaluate the technical and economic feasibility of producing inorganic and organic chemicals as by-products or co-products of methane production. These could be produced from the digester effluents, a fraction of the kelp grown in the farm, or both. The results of the study provide an assessment of the effect of an integrated production system (methane + co-products/by-products) on the cost of gas.

Kelp has been used for the past 60 years to produce a variety of organic and inorganic chemicals such as algin, mannitol, potash, and iodine. In each case, however, only one product was made from a given kelp mass. Some of these chemicals such as potash and iodine could be extracted from either kelp or digester effluents since only the organic constituents of kelp would be consumed in the anaerobic digestion gas production process. The anaerobic digestion process also would yield carbon dioxide, hydrogen sulfide, and bacterial protein as by-products. From the data on historical kelp usage, knowledge of kelp composition, and the data on the various digestion products, one can identify potential products that could conceivably be recovered as by-products or co-products of gas production from kelp. Table 30 lists such potential chemicals and products.

Except for fucoidan and the L-fraction, all of the chemicals and products listed are commercially produced. While kelp continues to be the sole current source for commercial production of algin at, the sources for the production of the rest of the chemicals and products are non-kelp based. Cellulosics and plant protein are currently derived from terrestrial biomass sources. Brines from various lakes and underground water throughout the world are primary sources for the production of iodine, bromine, and magnesium. Potash, sodium compounds, and sulfur are primarily produced from mining sources. Limited production of potash and sodium compounds is also based on brine sources. Sources of commercial carbon dioxide include flue gases resulting from the combustion of carbonaceous fuels, synthetic ammonia and hydrogen plants in which methane or other hydrocarbons are converted to carbon dioxide and hydrogen, fermentation processes, lime kiln operations involving thermal degradation of carbonates, and natural carbon dioxide gas wells.

The residual solids from kelp digestion are rich in protein, and have been estimated to contain over 50% protein matter in samples taken from kelp digesters (Hart 1977, Tompkins 1980). It has also been shown that these protein-rich solids can readily be separated from the total digester effluents using physical separation methods based on sedimentation and centrifugation. The bacterial protein product appears to be an economical source for protein supplement for animal and poultry diets based on its composition analyses (Hart 1977).

Kelp digestion experiments conducted during the GRI Marine Biomass Program showed the presence of algin in the digester effluents (Tompkins 1980). This algin is termed the by-product algin. It is recoverable and that is the basis for including it in Table 30. Fucoidan is not available commercially at present, and is used only as a laboratory chemical for scientific purposes, however, the material is considered to have unusual colloidal characteristics, which may be of considerable interest in various industries such as cosmetics and pharmaceuticals. Table 30 includes a product "phenolic compound" as a potential by-product or a co-product.

The existence of such a fraction in raw kelp and digester liquid effluents has been confirmed during laboratory investigations in the Marine Biomass Program. Small laboratory samples of this material have been isolated and characterized. Based on limited analyses and discussions with experts in the materials evaluation area, it appears that the phenolic compound (L-Fraction) may have applications in areas such as plastics, adhesives, and timed-release dispersants. It has been suggested that the L-fraction in kelp biomass may be analogous to the lignin structure in terrestrial biomass as it contains similar phenolic groupings.

It should be noted that a listing in Table 30 does not necessarily imply technical and/or economic producibility of each chemical, but only that it is present in the feedstock stream. Conceivably, some of those products listed may not be technically producible unless one or more are "sacrificed" during the processing scheme. Indeed, one of the purposes of this study was to determine which ones are technically feasible and are economically most attractive.

A screening of the producibility of by-products and co-products was necessary for several reasons: 1) The number of potential products is too large to permit a reasonable technical and economic investigation of each one; 2) the status of recovery technology in several cases is undefined or non-existent; 3) only those which have the potential for significant economic impact need to be studied. The screening was conducted using available technical and marketing data, and these results were presented in the report (Tompkins 1980). The market data reviewed included current U.S. demand and production, anticipated growth rate of the demand/production, current sources and methods of production, and major applications. Revenue potential was also considered in the screening process.

Detailed process systems designs and cost analyses of the production of selected chemicals from raw kelp and digester effluents are presented in the G.E. report (Tompkins 1983). Also included is a discussion of the economic impact on gas cost. In order to develop cost estimates, inputs were obtained from experts who have had extensive experience in developing and operating algin, mannitol, and iodine production systems. Based on these analyses, several research needs are identified and recommendations are made which are included in this report.

7.2.2. Screening of Potential By-Products and Co-Products

The purpose of the screening process discussed here was to identify the most technically and economically attractive potential co-products and by-products. Presently, available market and technical data were used in the screening process.

7.2.2.1.Technical Screening

The products listed in Table 30 were evaluated technically for their producibility potential (from kelp or the digestion process effluents) and classified into three categories. The first category includes only those products, which at some time or another, have been produced from kelp at commercial scale. It also includes those which have a high technical probability of being produced from digestion process effluents, (e.g., iodine, potash, and bromine). These chemicals have been and are currently being produced from subsurface brines. The digester effluent liquid fraction is considered essentially a brine, and contains a variety of inorganic materials amenable to existing processing steps that are currently used for the production of these chemicals. Equipment for the production of CO_2 and sulfur from a mixture of gases containing CH_4, CO_2, and H_2S is commercially available. The second category of products includes those which have been produced at pilot scale or laboratory scale. This includes mannitol, fucoidan, L-fraction, bacterial protein, and algin residual from the digestion process. The last category includes those products for which there is no experimental evidence that they can be produced from kelp or digestion effluents but which are present in raw kelp. This includes the cellulosics and plant protein fractions, and the sodium and magnesium compounds.

The results of this screening process are presented in Table 32. The cellulosics and the protein products were dropped because there are no technical data presently available to evaluate the producibility. Furthermore, they are likely to be at a disadvantage in the marketplace in terms of competition from established terrestrial biomass sources. Magnesium and sodium compounds were eliminated from further analysis because there are no technical data readily available to support the potential for their recovery from kelp or digester effluents. While one could conceive of processing techniques, for example, based on fractional crystallization and electrolysis for their recovery, these methods are likely to interfere with the recovery of other inorganics such as iodine which is a high value chemical.

Algin as a by-product from digester effluents was also eliminated from further analysis. Samples of residual algin were recovered from laboratory digester effluents. Samples exhibited significantly lower viscosities than those from fresh kelp. Apparently, as the algin molecule passes through the digestion process, its original polymeric structure changes resulting in loss of viscosity. The application of the residual algin (by-product) would be significantly limited compared to algin recovered from raw kelp.

7.2.2.2. Potential Revenues

Revenue potential was used for evaluating the contribution to the reduction of gas cost by each of the candidate co-products and by-products. Total revenues were used in the initial screening because the range of the gross revenues from various chemicals was very wide, such that the ones at the lower end of the revenue range could be justifiably eliminated for purposes of the current study since net revenues cannot exceed total revenues.

For purposes of this study, two of many possible production scenarios were developed. In the first, gas production was maximized; only residual materials from the anaerobic digestion process were treated for by-products recovery. In the second scenario, approximately 15 % of the kelp farm output was used exclusively for the production of chemicals and the rest for the production of gas. The revenue screen was developed on the basis of the second system scenario since it was the more comprehensive of the two analyzed in detail in this report. The scenario is depicted in Figure 20 and includes the recovery of by-products from digester effluents. As the main objective of the system is to produce gas, it is necessary that the bulk of the farm output be used for that purpose. At the same time, the size of the chemicals production facility must approach commercial scale in order to achieve economical viability. Preliminary calculations indicated that using 10 to 20% of the farm output kelp for chemical production achieved both objectives. For purposes of this particular scenario, it was assumed that 500 t d^{-1} of raw kelp are used for the production of chemicals which, for the baseline kelp farm, amounts to approximately 15% of the total output.

Kelp composition data were used as the basis for estimating the annual production of various co-products from kelp which, when multiplied by the respective current market prices, yielded estimates of annual revenues. The bases for these calculations are summarized in Tables 33 and 34. Fucoidan is currently available on the market only as a laboratory chemical at approximately $10 per gram. However, it is considered to have unique colloidal properties which may be of interest in several applications (Saddington

1982). For purposes of this analysis, it is valued the same as mannitol. The L-fraction is valued at $1-3 per lb ($2.2-6.6 per kg) depending on its usage, whether it is in the materials manufacturing area, for example in specialty plastics, or in controlled timed-release dispersants, for example, in pharmaceuticals or pesticides. Algin was valued at $3 per lb ($6.6 per kg) for comparison purposes; it is realized that its exact value will depend on the particular alginate product, purity, and the intended usage.

Approximately 85% of the farm output is devoted to the production of gas and by-products. Potential revenues from gas and by-products production are summarized in Table 35. In making these calculations, experimental data on gas production and digester effluent composition obtained on the Marine Biomass Program were used. The recovery efficiencies of various products shown in Table 33 are discussed in detail in this report. Bacterial protein product was valued at $70/ton based on a preliminary study conducted for the Marine Biomass Program in 1978. Lacking any further development on the subject, the same value is used in the analysis although the value in 1982 dollars may have increased substantially. Total revenues from the production of various by-products and co-products are summarized in Table 36. Methane production was valued at $10 per 1000 SCF only for comparison purposes. Bromine and sulfur showed the lowest potential revenues, being an order of magnitude lower than any of the other contributors, and therefore, were eliminated from further consideration.

7.2.2.3. Market Data

For several products, market data were collected and reviewed in more detail. The data included the U.S. demand, production, market growth-rate, current production methods and major applications. From a review of these data, several significant observations can be made:

a. Other than the phenolic materials and fucoidan, all other products are currently produced commercially and thus have established commercial applications

b. The market is projected to continue to grow for all the products.

c. The U.S. demand for potash, iodine, and algin outstrips production and must be met by imports.

d. U.S. dependence on outside sources for iodine, potash, and algin in the future is likely to continue to increase.

e. The co-products and by-products from a baseline kelp farm would improve the U.S. supply, but would not exert a dramatic influence in the marketplace on pricing or significantly affect competitive sources of supply. Fucoidan, which does not have a bulk industrial market, is an unknown factor and cannot be evaluated based on available data.

From the analysis and observations above, production of selected co-products and by-products should have a solid market. The results of the screening process could be summarized by stating that, of the fifteen chemicals and products identified in Table 30 as potential co-products and by-products, the technical and market data available support eliminating seven of those. Analysis was continued on the remaining eight; these are algin, mannitol, fucoidan, L-fraction, iodine, potash, carbon dioxide, and bacterial protein.

7.3. Effect on Gas Cost

In the integrated gas and chemicals production system, net revenues (pretax profits) could be used to reduce gas cost directly. Table 37 shows the impact on gas cost for Scenarios 1 and 2. Parsons has estimated a gas cost reduction of $5.94 per GJ resulting from 5 million dollars of by-product/co-product revenues (pretax profits) (Brehany 1983).

7.4. Recommendations

a.) Based on the results of this study, there is little doubt that the production of by-products and co-products could effect major reductions in gas cost and dramatically change the overall economics of the gas production system. Research on by-products and co-products therefore should be assigned a high priority and pursued vigorously. Recommended areas of investigation include:

- Preparation of larger samples of L-fraction from raw kelp and digester effluents; detailed characterization and testing for potential applications in specialty plastics, adhesives, and controlled-release materials.

- Acquisition of technical and process data on co-production of mannitol and algin from raw kelp.

- Acquisition of process data on the recovery of iodine from aqueous digester effluents.

Other potential areas of investigation included gathering process data on the recovery and the testing of the bacterial protein product from digester effluent and the co-production of fucoidan (with that of algin and mannitol) from raw kelp. Under the assumptions made, bacterial protein and fucoidan appear to be of marginal value in terms of ability to reduce methane cost. However, that would change if a basis could be developed to assign higher values to them. The tests and the data on these products should be designed to reduce uncertainties in their costs and values and to help determine if their production is economically justifiable.

b.) The economic analysis did not explore the effect of variation of key elements of the financial structure such as debt/equity ratio of the investment to investment tax credits, costs on a life-cycle basis, inflationary effects, and income taxes.

It is recommended that these parameters be factored into future analyses consistent with the financial structure of the gas production portion of the system and that an integrated and complete economic analysis be carried out. A more detailed sensitivity analysis is also recommended.

Chapter 8: POST- MARINE BIOMASS WORKSHOPS

Beginning in 1990, several workshops where held by interested parties to facilitate continued interest in the marine biomass concept and take advantages of potential opportunities for initiation of a new program in this area. These discussions focused largely on the use of marine farms for mitigation of release of atmospheric carbon dioxide and its potential effect on global warming. The initial workshops were initiated by Richard Spencer of the Electric Power Research Institute (EPRI), Mike Neushul (U. California, Santa Barbara) , and Wheeler North (Cal. Institute of Technology). Subsequent workshops were organized largely by Peter Schauffler (consultant) and William Busch of the National Oceanic and Atmospheric Administration (NOAA).

8.1. July 1990 Newport Beach, FL (MarineBiomassWorkshop 1990)

The objective of this workshop was to discuss the potential role of macroalgal farms to mitigate carbon dioxide emissions leading to global warming. A report (EPRI 1990) including a detailed bibliography summarizes this conference which addressed: enhancing natural systems; marine farm structures, algal species, nutrient supplementation; bioconversion, sequestration of carbon, environmental concerns, useful products, and utilization of existing resources.

Calculations presented indicated that a farm totaling an equivalent of 4 x 10^6 km^2 (1.4 x 106 mi^2) would be required to stabilize CO_2 emissions, i.e., 3 GTCY (See calculation in Table 38). Farm areas about half of the size the contiguous U.S. would be required which indicated that they would have to extend beyond coastal waters into the open ocean. This estimate addresses carbon removal by growth of algal and sequestration by sinking algae to the ocean bottom. It does not include replacement of fossil fuel by conversion of a portion of the algae to renewable methane.

One option discussed is enhancement of natural algal populations using principles illustrated in Figure 21. The resulting algae would be caused to sink into the sea bottom. The greatest challenge for this method is to supply limiting nutrients at a reasonable cost. This may be addressed by conversion of algae to useful products, including methane, which replaces fossil fuels with a carbon-neutral fuel and uses by-products to subsidize the farming operation.

Two main farm concepts were discussed: 1) a tensioned grid system (TGS) and OASIS concept and 2) a circular, semi-enclosed structure. The tension grid system involves triangular substrate modules interconnected by corner buoys. These modules would be crisscrossed by three tension-bearing cables, which would subtend 30 smaller lines for anchoring the plants (e.g., *Macrocystis*) (Figure 22). Tension would be maintained by small diesel-powered propulsion units situated beneath the three apices of each triangular module. Modifications of this concept presented by Schauffler are shown in Figure 23. Costs ranged from \$110 million to \$600 million for a 400km^2 farm module.

Using an optimum estimate, a cost of $39/ton of carbon assimilated was calculated. A cost of $100-200/ton of carbon was estimated by Spencer for treatment carbon released from power plants.

The OASIS farm consists of two major components, a circular peripheral breakwater and a circular hub (Figure 24). The strong bicycle wheel structure gives it resistance to battering by waves and other ocean forces. The interior of the OASIS is a captive lagoon including an enclosed floor, which is the algal growing area. A hydraulic system powered by OTEC will upwell nutrient rich water into the lagoon. The statistics for a full-scale unit (1678 acres ~ 680 ha) are presented in Table 39. The estimated cost is $350 million or $50 million per km^2 compared to a range of $0.25 million to $1500 million for the tension grid system farm.

A list of several candidate genera of macroalgae were presented (Table 40). Several criteria for such species were presented:

- Productivity and yield of a candidate alga should be high and determined in an environment similar to the growing conditions existing in an oceanic farm.

- Good growth should occur at a high C:N ratio (to reduce the amount of nutrient needed per unit of carbon assimilated). Nutrient uptake rates should be high at the dilute nitrate and phosphate concentrations anticipated on a grid-design marine farm.

- The tissues of a plant should be strong and durable so as to withstand water motions likely to occur on an exposed grid system.

- The alga should be coppiceable or allow harvest of portions of the thallus without creating a need for replanting the entire crop.

- Flotation mechanisms are desirable in some cases and require species with gas bladders or with tissue densities less than that of seawater.

- Flotation mechanisms should withstand increases in pressure if the farm structure will be lowered to moderate depths during stormy periods or as a result of strong current. Plant biomass should be easy to harvest, preferably by mechanical means.

- The environmental requirements of a species (e.g., temperature, salinity, irradiance, water motion, etc.) should correspond well with actual conditions at the farming site.

- The plant should be able to cope with diseases and grazers occurring at the site. If the plant will be used in polyculturing, it should be nutritious for the animals proposed to be cultivated.

- The natural community associating with a stand of plants may be of value and this feature could be considered. If the bioconversion option is exercised, the plant species should provide good methane (or other fuel) yields at high C:N ratios.

There was lack of agreement on the usefulness and economic feasibility of nutrient upwelling to promote algal growth. The deep-water requirement was estimated at 1.4 $m^3 day^{-1}$. There was complete agreement that the most attractive option for nutrient supplementation was recycling critical compounds back to the farms from biogasification reactors.

Biogasification was discussed. Conversion efficiencies and methane yield ranges for several algal genera were presented (Table 41). An estimate of 16 EJ of energy in the form of methane could be derived from one gigaton of fixed algal carbon. This assumed that 50% of the fixed carbon is lost to storms, disease, and predation.

Two options for sequestration of algal carbon were discussed. One involves sinking of unconverted algae to the ocean bottom. This option precludes nutrient recycling and may result in release in the potent greenhouse gas methane resulting from anaerobic decomposition in sediments. The other option is to sink digester residues and clathrate hydrates (formed from the carbon dioxide component of biogas) into the ocean depths.

Several environmental impacts of ocean farming were addressed, including:

- food chain effects
- balance of atmospheric carbon
- production of dissolved organic carbon
- production of dimethyl sulfides
- production of halogenated compounds
- production of methane
- production of other greenhouse gases
- climatic effects
- regional fogs
- vulnerabilities of monocultures
- effects on navigation
- encouragement of non-indigenous species
- interference with marine fisheries

Although by-products were not emphasized, the following uses and products from marine farms were identified:

- fuel production (e.g.,e.g., methane, alcohols, oils)
- organic compounds (e.g., acetone, organic acids)
- biopolymers (e.g., agar, algin, carageenan)
- protein (invertebrate and fish cultivation)

- pharmaceuticals
- fertilizers and soil conditioners
- metallic chemicals
- fish/invertebrate polyculture
- cloud nucleation

Finally, the following list of research and development needs to assess the potential oceanic farming of macroalgae were discussed:

Enhancing Natural Systems

- How does Sargasso Sea operate biologically?
- Test algal outplants in gyres & major current systems

Farm Structures

- Select promising option(s)
- Develop engineering design studies
- Construct and test prototypes
- Define interactions between structures and experimental crops

Sequestration

- Sinking algal biomass
  - determine settling and decomposition rates
  - determine potential for methane escape to atmosphere
  - assess environmental impacts including bioenhancement

- CO_2 and methane hydrates
  - determine optimal conditions and time required for production and dispersal,
  - avoiding hydrate decomposition during dispersal, efficiency of the process, and examine effects on benthos from dispersal
  - investigate possibilities for formation of methane hydrates

Species to be Utilized

- Select and field-test candidate plants under realistic conditions
- Determine productivity/yield in field
- Assess potential for bioconversion using latest technology
- Examine possibilities for mixed crops or crop rotation

Environmental Impacts

- Assess production rates of methyl halides and DMS vs. species
- Determine net CO_2 and surface fog production from upwelling
- Examine other effects in field tests

Genetics & Breading

- Develop a fast-growing *Sargassum*

- Engineer morphology to enhance bioconversion, durability, etc.
- Investigate possible epiphytes to cultivate with main crop (including epiphytes suitable for *Macrocystis* and other major farm-candidate plants)

Marine Engineering

- "Tune" the structure to enhance water motion during calm periods and reduce flow velocities during storms
- Provide capability for sinking the farm structure at will

Site Selection

- Acquire necessary oceanographic and other environmental data

Scale-Up Problems

- Collect and process data from field tests of farm structures

Uncertainties

- Determine net release of CO_2 when upwelling from below the mixed layer
- Clarify the fate of CO_2 when organisms produce $CaCO_3$

8.2. July 1991 Washington D. C. (MarineBiomassWorkshop 1991)

The objective of this meeting was to further discuss the Delta Ocean Farm concept (Figure 25) and synthesize an R&D plan for development of the farm/conversion system.

8.3. November 1992 Washington D. C. (MarineBiomassWorkshop 1992)

The major objectives of this workshop were to further define an R&D plan for farm development and the beginnings of a proposal. Related to that were a summary of a study conducted by EPRI, details of farm design, and further discussion of anaerobic digestion. A four-year development plan was outlined, including natural farms, structured farms, and impact investigation tasks. A report (Earle&Wright 1992) for EPRI indicated that it is technically feasible to design a 10,000–acre macroalgal (*Macrocystis*) support structure module for deployment in the open ocean. An orbiting towed algal mat support structure is the preferred system. The mats are towed only under calm sea conditions in order to minimize the number of tug “tenders”, i.e., they are not towed continuously. Each 1000-acre (405 ha) farm is provided makeup nutrients with an upwelling pipe delivering 7000 gpm of deep (2000 feet ~610m) water to the farm. This makeup requirement assumes that 95% of the nutrients required for kelp growth are recycled back to the farm as liquors from anaerobic digesters. Dynamic analyses of the structure have been performed with various tether lengths to define optimal tether length for 20 ft (6m) plant spacing. Optimal minimum tether anchorage depth is 70 ft (21m) with a tether length to the holdfast buoy of about 40 ft (12m).

More details were presented on the delta farm concept. Research plans were presented for evaluation anaerobic digestion of macroalgae (Table 42) and of algal decomposition associated with ocean sinking of algae (Table 43). A typical mass balance was presented for anaerobic digestion of *Gracilaria* (Figure 26).

8.4. February 1995, Washington D. C. (MarineBiomassWorkshop 1995)

This workshop began to focus on a different offshore concept to be located on the Pacific equatorial belt (between longitudes 150^o and 90^o West (Figure 27) west of South America. A research plan to study this concept was initiated. This area offers a high favorable opportunity of initial testing of an ocean farm concept because:

- The water temperature is ideal for a very high productivity plant (*Gracilaria tikvahiae*).

- Natural upwelling along this belt can provide the plants with a continuous supply of nutrients.

- Stable surface and subsurface current patters permit net-structured farm panels to remain stationary with a continuous low-velocity flow of nutrient-rich current through the plants.

- The area is relatively free of severe storms.

8.5. October 1996, Vero Beach, Florida (MarineBiomassWorkshop 1996)

This workshop focused on a detailed plan and research proposal to evaluate the Pacific Equatorial farm concept using six benchmark and native species *Gracilaria* and *Kappaphycus.* The plan was to deploy 12 rafts to test open ocean growth of the algae to obtain detailed data on productivity, chemistry, and nutrient uptake over a period of four weeks. The tests were to be conducted 200 miles (322 km) west of the Galapagos Islands in a series of test rafts pulled by a research vessel. Samples would be collected for study of biogasification potential and physical/chemical properties. The budget for this test was estimated at $400,000.

A detailed analysis of malcroalgae and the value of by-products was presented (Figure 28). A presentation on mariculture opportunities was made.

8.6. March 1997, Washington D. C. (MarineBiomassWorkshop 1997a)

A new concept for open ocean seaweed farm suitable for the Pacific Equatorial environment was presented that would serve as a basis for future studies. This workshop focused on conversion of seaweeds to fuels, foods, pharmaceuticals, and chemicals.

A new farm concept was presented (Figures 29 - 34) that would be suitable for growth of macroalgae like *Gracilaria* in the calm waters of the Pacific Equatorial waters. A module has two 300 ft (91m) wide plastic nets with plants attached on one ft. (0.3 m) centers, extending several miles along the equator and serviced by a 350 ft x 500 ft (107m x 152m) semi-submersible platform. The nets are held stationary, and the platform moved along the nets for harvesting by means of vaned drogues in the strong undercurrent that balance the farm drag in the moderate surface current. Processing equipment on a platform include a anaerobic digester sized for daily input of 500 dry tons of plant mass, a two stage methane-to-methanol converter with 200 ton per day output, and appropriate units for protein, pharmaceutical, and chemical extractions. A preliminary estimate of the net and platform combination is $137 million.

Legrand discussed a general equation for estimating CO_2 carbon displacement. The following terms were identified.

P – net productivity of algal biomass production (dry weight)

S – specific energy content of biomass (J/g dry matter)

E1 – convertibility of biomass

E2 – conversion efficiency of biogas to ultimate delivered fuel

He discussed advantages of different energy products, e.g., ethanol, algal lipids, methanol, and liquefied natural gas.

A representative from Kelco discussed the numerous potential products from seaweed.

The option of conversion of methane to methanol as an easily transported fuel was introduced. It was pointed out that a significant amount of energy (~30%) of the product methane is lost in this conversion.

8.7. July 1997, Guayaquil, Equador (MarineBiomassWorkshop 1997b)

The purposes of this workshop were: 1) to discuss the content of a proposal to the World Bank to conduct a short-term open ocean macroalgal growth test 200 miles west of the Galapagos Islands (discussed above) at the October 1996 workshop; 2) to visit the Galapagos Islands and interact with Ecuadorian governmental officials and scientists that would be involved in the test.

A gross carbon balance was presented for the global CO_2-C mitigation concept (Figure 35). A calculation (Figure 36) estimated that the farm size and area required for mitigation would be 7 million sq. miles (~18 million km^2), or ~5% of the total world ocean surface.

This was the last workshop held on this subject that this author is aware of. The proposed test near the Galapagos Islands and other proposed research was not conducted due to lack of funding.

Chapter 9: SUMMARY OF MARINE BIOMASS PROGRAMS

The economic feasibility of marine biomass cultivation for energy production has always been controversial. The difficulties in establishing detailed costs lies in uncertainties of biomass yields at a commercial scale, operations and maintenance costs associated with marine farm operations and lack of pilot or larger scale experience with marine bioconversion to energy. While there are commercial scale seaweed farms in existence, these are managed for production of high value products such as hydrocolloids or food.

Nonetheless, the analysis to date indicate some types of marine biomass systems may be effective, such as nearshore *Macrocystis* farms or tidal flat farms. Off-bottom culture of seaweeds on rope farms does not appear feasible, mainly due to huge capital costs and especially maintenance costs involved with the farm structure. The only way offshore *Macrocystis* farms appeared feasible was with assumptions of higher sustainable yields than have been demonstrated for any biomass system. Examples of macroalgal yields reported are shown in Table 63. None of the off-bottom culture studies for marine or freshwater aquatic plants took into account degradation and replacement of farm material. It should be remembered, however, that the original offshore *Macrocystis* concept was first proposed as a multi-product facility which would produce food, chemicals and energy (Wilcox & Leese 1976). Perhaps this concept will be re-examined and prove to becost effective. The floating seaweed concept is possible, but will also require major biological improvements in biomass yields, cultivation techniques, and plant compositional improvement for bioconvertability. Again, there has been insufficient emphasis given to farm life and maintenance in all these analyses.

By-product studies have indicated that development of co-products such as alginates or other industrial polysaccharides in feeds, chemicals, and CO_2 could greatly reduce the price of methane. However, by-products have been deliberately excluded from most biomass studies, as their markets become quickly saturated compared to the amount of biomass required for the energy market. An energy co-product approach may be the best initial investment in a technology, however, as it would reduce risk associated with just one product. In particular, such an approach could be used to generate cost competitive methane, albeit in smaller amounts. Such large-scale experience and the development of a commercial infrastructure could provide greater impetus for further development. In fact, such a multiple product facility based on *Macrocystis* processing once existed and produced ammonia, potash, acetone and methane as a by-product. These multiple product approaches may be ideally suited for developing countries or island nations with few natural energy resources.

At the beginning of the marine biomass program, it was perceived that huge marine biomass yields of 140 daft $ha^{-1}y^{-1}$ or more would be required for commercialization. Much of the previous analyses were conducted from the standpoint of mechanical and chemical engineering. Reviews of these analyses (especially the offshore *Macrocystis* concept) have been primarily in the form of engineering and biological critiques

(Aquaculture Associates 1981). However, new systems concepts, studies of kelp harvesting history, and research improvements now suggest that systems are feasible in biomass yield ranges of 2334 daft $ha^{-1}y^{-1}$. Such changes should improve perceptions of marine biomass economics and demonstrate that research programs have reduced the performance drivers of biomass yield and conversion. Future efforts in marine biomass systems analysis should move away from engineering design analysis and costing, and more into systems optimization. Using both current and historical data, such an approach would optimize harvesting equipment and schedules; incorporate and take advantage of seasonal biomass yield patterns; match energy production to seasonal demands (and prices); and provide an integrated approach to planting, harvesting and bioconversion operations.

Chapter 10: OTHER BIOMASS BIOMETHANE SYSTEMS

10.1. Water Hyacinth (Chynoweth et al. 1989)

10.1.1. Approach

The general approach used by this project was to concentrate research on an integrated experimental test facility at Walt Disney World, near Orlando, Florida, while relying on systems analyses and engineering tradeoffs to direct R&D toward process performance goals that result in cost-competitive methane. The system concept, depicted in Figure 37 mainly consists of water hyacinth channels for secondary or tertiary treatment of wastewater, hyacinth harvesting and processing equipment, and an anaerobic solids concentrating reactor (SCR). As effluent from the primary settler is passed through the water hyacinth channel, the hyacinth roots and bacteria coating the root mass remove organic pollutants (BOD) and nutrients such as nitrogen and phosphorus. Hyacinths growing on the wastewater are periodically harvested, combined with sewage sludge from the primary settler and introduced to the anaerobic digester. As the feed passes through the digester, bacteria convert complex organic matter to biogas, a mixture of methane (60-65%) and carbon dioxide, which can be upgraded to a product gas (97% methane) suitable for introduction into the pipeline.

In developing the biomass wastewater treatment energy conversion scheme, the hyacinth project emphasized the three technical objectives aimed at reducing the cost of methane produced from a blend of hyacinths and sludge: 1) optimize biomass yields; 2) maximize wastewater treatment efficiency; and 3) maximize methane yields from anaerobic digestion from the sludge/hyacinth feed blend. These objectives were addressed by the work of three research organizations participating in the project, including the Institute of Food and Agricultural Sciences (IFAS) of the University of Florida, the Institute of Gas Technology (IGT), and several subsidiary companies of Walt Disney Productions. Much of the cost analysis and systems evaluation support was provided by the architectural and engineering firm, Black and Veatch. The sponsors included the Gas Research Institute (GRI), United Gas Pipeline Company, the U.S. Environmental Protection Agency and the U.S. Department of Energy.

10.1.2. Wastewater Treatment

Hyacinth wastewater treatment studies and hyacinth productivity research were conducted in five 1/10 ha hyacinth test channels, each with dimensions of 8.8 m x 110 m x 0.35 m deep constructed of reinforced concrete blocks and lined with 20-mil PVC sheet. Previous studies on these channels showed that secondary effluent standards could be achieved under low sewage feed rates (BOD loadings) typically applied to aerobic ponds without hyacinths, amounting to about 70-90 kg BOD_5 $ha^{-1}d^{-1}$ (60-80 lb BOD_5 $ac^{-1}d^{-1}$). In 1983 and 1984, four channels were fed with primary sewage (obtained from the Walt Disney World wastewater treatment settling basins) at loadings of 55, 110, 220, and 440 kg BOD_5 $ha^{-1}d^{-1}$ (60, 100, 200 and 400 lb BOD_5 $ac^{-1}d^{-1}$) corresponding to hydraulic retention times of 24, 12, 6, and 3 days, respectively. The technical objective of this study was to measure channel BOD_5 and TSS removal efficiencies under high loadings that would stress the system's treatment capabilities. Wastewater treatment data collected from the channels included influent and effluent BOD_5 suspended solids (SS), pH, temperature, dissolved oxygen and various forms of nitrogen and phosphorous.

Results from this study over a 9-month test period (November 1983 through July 1984) indicated that a single hyacinth channel is capable of removing 72-90% of the BOD_5 (81% average) and 70-90% of the SS (80 % average) in wastewater at loading rates as high as 440 kg BOD_5 $ha^{-1}d^{-1}$ (3 days HRT). Average effluent BOD_5 and SS concentrations from the hyacinth channels were meeting federal standards for secondary treatment at loadings up to 220 kg BOD_5 $ha^{-1}d^{-1}$ during all but two of the coldest months of the test period, during which time secondary effluent standards were met at the 110 kg BOD_5 $ha^{-1}d^{-1}$ loading rate. A statistical analysis of influent and effluent data as well as channel profile measurements taken over the past four years was conducted to allow more accurate correlations between treatment performance and hyacinth channel operating conditions (e.g., loadings, temperature, retention time, hyacinth density, etc.). Preliminary analysis of the performance data for the four channels suggested that treatment efficiencies could be only marginally improved by extending retention time and it could be cost effective to use staging of the unit processes to achieve a high compounded removal efficiency at an equivalent retention time as opposed to increasing the hydraulic retention time of a single-stage channel.

10.1.3. Water Hyacinth Production

Maximum growth yields of water hyacinth are desirable in the sewage channels because rapid growth is associated with efficient wastewater treatment and results in larger quantities of biomass available for conversion to methane. Numerous factors can influence hyacinth yields, the most important of which are temperature, concentration of CO_2 in air, sunlight capture, nutrient availability, and planting density. Of these, the most controllable parameters are nutrient availability and planting density.

Hyacinth productivity experiments were conducted in the hyacinth channels (0.1 ha) and in small field test units (1.7 m^2). Measurement of biomass yield in each channel was performed using 1.0 m^2 Vexar mesh baskets placed about 18.3 m apart. The large channels were used to observe the effects of sewage loading, channel retention time, seasonal temperatures, and sewage treatment efficiency on hyacinth yield. The small field experimental systems were used to optimize hyacinth production with respect to controllable parameters such as nutrient availability, plant density, and aeration.

Hyacinth productivity under unoptimized conditions ranged from 45 – 58 t $ha^{-1}y^{-1}$. The use of a harvesting schedule that provided an optimum planting density of 36 kg per m^2, however, increased hyacinth yields to 60-70 dry t $ha^{-1}y^{-1}$. Preliminary tests in small field units suggested that further yield increases of 30-50% are possible through discretionary use of aeration.

10.1.4. Anaerobic Digestion Process Development

Anaerobic digestion was selected for the processing of mixtures of water hyacinth and primary sludge since it produces methane as the principal product (60-65%) and is compatible with the conversion of feedstock with high water content. The technical objective of this R&D effort was to develop a data base for the design and operation of an optimized system for biogasification of the hyacinth and sludge and to integrate this process with the hyacinth wastewater treatment facility. It is expected that the resulting process design will be applicable to other aquatic species with high water content. The strategy used for this work consisted of evaluating conventional and advanced reactor concepts at the bench scales, designing the selected reactor on the basis of the laboratory data, and the testing of the reactor at an experimental test unit (ETU) scale under actual field conditions.

10.1.4.1. Laboratory Studies

A number of experiments were conducted to evaluate the performance of a continuous stirred tank reactor (CSTR) and a solids concentrating reactor (SCR) designed to promote long solids retention times under high hydraulic loadings. A schematic of the SCR is shown in the diagram of the digester in Figure 17. This reactor employs little or no mixing. Influent was fed at the bottom of the tank and effluent Is removed near the top of the liquid contents. The laboratory SCR and CSTR units were fed with a 3:1 blend of hyacinths and primary sludge (TS basis) at loadings of 1.6 and 6.4 kg VS $m^{-3}d^{-1}$ corresponding to HRTs between 31 and 8 days. Steady state data plotted in Figure 38 shows that the SCR consistently achieved 10-20 % greater methane yields over a wide range of HRTs. The superior performance of the SCR was attributed the reactor's ability to increase the solids and microorganism residence time significantly above the HRT through sedimentation of particulate solids. Thus, the SCR reactor achieved greater methane production with substantially less mixing. These results provided the basis for the selection of the SCR design for testing at the ETU scale.

10.1.4.2. Experimental Test Unit (ETU)

In 1983, a 4.5 m^3 solids concentrating reactor was designed and constructed beside the five existing hyacinth channels at Walt Disney World. The technical objective of the first phase of the ETU study was to evaluate reactor performance, scale-up, and materials handling parameters at several different loadings of hyacinth/sludge blends. The ETU facility was capable of processing up to 910 kg or 1 ton of wet hyacinth/sludge feed blend (5% total solids) each day. The ETU was sized to ensure that the demand for biomass stock did not exceed the availability of hyacinths from the channels during the coldest months of the winter when hyacinth productivity was at its lowest. Major components of the facility included two feed tanks for short-term storage of sludge and chopped hyacinths, a feed blend tank, and solids concentrating reactor (4.5 m^3), an effluent storage tank, and gas compression and storage. The ETU was initially operated in the upflow mode (fed at bottom and effluent removed at top) but eventually was fed at the top followed by recycle of liquid from the bottom and effluent removed from the bottom. The modification was in response to flotation of solids.

The test plan for the ETU included operation of this reactor at several loadings between 1.6 and 6.4 kg VS $m^{-3}d^{-1}$ with 2:1 and 1:1 blends of hyacinth and sludge. These blend ratios bracketed the composition of solids mixtures expected from a secondary hyacinth wastewater treatment plant. Fed with a 2:1 blend at a loading of 3.2 kg $m^{-3}d^{-1}$, the ETU achieved a methane yield of 0.29 m^3kg^{-1} VS added, which is approximately 60% of theoretical, and about 15% higher than the methane yields obtained from a parallel bench-scale CSTR control. This ETU methane yield also compared favorably with the performance observed with a bench-scale SCR unit that produced 0.28 m^3 kg^{-1} VS added receiving the same 2:1 feedstock mix. When feed conditions were shifted from a 2:1 to 1:1 blend of hyacinth and sludge at a constant HRT (16 d) and loading (3.2 kg $m^{-3}d^{-1}$), the methane yield increased from 0.29 to 0.39 m^3kg^{-1} VS added. These results are consistent with previous batch reactor tests which indicated that the ultimate methane yield of hyacinths (0.30 to 0.37 m^3kg^{-1} VS added) were lower than that of sewage sludge (0.40 to 0.45 m^3kg^{-1} VS added). High sludge content in the ETU feedstock mix should therefore result in higher methane yields. Although the month-to-month hyacinth productivity of the channels can greatly affect the carbon feed rate to the reactor, fluctuations in methane output can be dampened by the higher methane yields achieved from the lower hyacinth/sludge ratio.

10.1.5. Engineering Analysis

Systems evaluations of integrated waste conversion concepts were conducted on a continual basis at the community waste research facility (CWRF) in order to assess progress and to identify promising new research directions. The CWRF project relied heavily upon architectural and engineering (A&E) firms to perform such studies, a practice that added practical experience to the evaluation of conceptual designs and accuracy to system costing. The ultimate goal of these studies was to translate research results into economics that relate to potential investment opportunities in the utilization of community wastes. The systems studies associated with the project included:

- Resource surveys
- Preliminary feasibility analyses
- Computer modeling of integrated waste systems
- Technology assessment workbooks
- Engineering evaluation of new concepts
- Economic analyses

In 1982, a preliminary A&E economic feasibility analysis was conducted on a conceptual secondary treatment water hyacinth system employing conventional anaerobic digestion and gas upgrading to pipeline quality. A schematic of the integrated water hyacinth concept is shown in Figure 37. Results of this study indicated that a significant amount of methane could be generated with the water hyacinth concept at a cost of $2.50-4.50 per GJ at treatment plant sizes of 10 to 50 MGD, which correspond to city populations of 100,000 to 500,000. These costs were based on some key assumptions of system performance, which became the goals of the project. The A&E assumptions included:

- Water hyacinth yields of 20 dry t $ha^{-1}y^{-1}$ in wastewater treatment channels.

- Water hyacinth pond sizes of about 2.8 ha per MGD of sewage flow (188 lb BOD_5 $ac^{-1}d^{-1}$ or 34kg $ha^{-1}d^{-1}$).

- Methane yields from the conversion of the water hyacinth/ sludge blend of 4.7 scf/lb (0.29 m^3kg^{-1}) of organics (VS) added.

- Anaerobic digestion hydraulic retention time of 28 days.

The performance of the integrated experimental test unit at the CWRF met or exceeded virtually all of these goals, largely due to the unique, vertical flow solids concentrating design of the SCR reactor (Table 44). Performance comparisons related to the flow scheme of Figure 37 are shown in Table 45. In comparison to the A&E projections, the mass flow analysis shows that:

- Research at the ETU reduced the required reactor retention time by more than 61% while increasing the methane yield by almost 60% (from 4.7 to over 7.5 scf/ lb VS added) (0.29 to 0.463 m^3/kg VS added).

- Although water hyacinth output from the ponds was 40% lower than the original estimate, the high methane yield from the digestion of the 1:1 hyacinth/sludge blend was more than enough to make up for loss in feedstock, resulting in an increase in the net methane output of the system by 25%.

- The amount of effluent solids requiring disposal was reduced by 65%.

This level of performance observed from the ETU led to a 15% reduction in capital cost and a 20% decrease in O&M compared to the original A&E projections. Capital and operating costs (in 1985 dollars) based on ETU results are broken out for each of the major system components in Table 46. The results of the economic analysis performed on the total system (sized for a 500,000 population) are summarized in Table 47. A similar analysis was conducted for water hyacinth/ anaerobic digestion system sized for 10,000 and 100,000 populations. The levelized costs of all three sizes of systems are presented in Table 48. Reflected in these costs are revenues for wastewater treatment that are 15% less than that assumed by the original A&E study. The levelized cost (in constant 1985 dollars) indicate that if the performance of the ETU can be duplicated at a community scale, methane can be produced from the water hyacinth/ anaerobic digestion concept for less than $2.00 per GJ for populations of over 100,000, and for approximately $3.00 per GJ for populations of 10,000.

Results to date indicate that the water hyacinth anaerobic digestion system has the potential of providing communities with cost-effective wastewater treatment as well as a local, low-cost supply of methane. Because water hyacinth has been used as an example feedstock for the initial development of the ETU digester, the same reactor design may also be effective in the conversion of other buoyant, cellulosic community wastes such as MSW and certain types of industrial wastes, as well as terrestrial energy crops.

10.2. Solid Waste/RefCoM (Wilke & Edwards 1985, Isaacson & Pfeffer 1987)

The organic fraction of solid wastes represents a large potential resource for conversion to methane and compost. This conversion may be conducted in normal or enhanced landfills or in anaerobic digesters. Work by Pfeffer in the early 70's (Pfeffer 1974a and 1974b) showed that good conversion efficiencies and kinetics could be obtained under thermophilic conditions in anaerobic digesters. This work led to systems analyses by Dynatec (Kispert et al. 1975) and MITRE Corp. (1979) indicating that the MSW processing to separate organics and conversion by anaerobic digestion was technically and economically feasible. ERDA (now USDOE) funded Waste Management to design, construct, and operate/ demonstrate the separations and conversion technology at a 50 -100 tpd scale. Starting in 1978, over six months were devoted to testing various options to for development of an effective materials recovery facility (MRF). Other funding agencies, including National Science Foundation and the Gas Research Institute, became co-funders of the project. The system, including the MRF was built and placed into operation in Pompano Beach, Florida. Numerous operation problems with the MRF and digester were experienced over a period of 2.5 years.

These were finally overcome leading to the design shown in Figure 39. The primary shredded refuse passed through several steps before being fed to the digesters. A trommel screen was used to remove most of the fine inorganic material such as shattered glass, sand, ash, etc. A second-stage shredder reduced the size of the particles so they could pass through 3 in (7.6 cm) grate openings and a horizontal shaft shredder with a screen was used to ensure a relatively uniform particle size of 3 in (7.6 cm) or less. From the shredder, the refuse was conveyed to an air classifier. This system produced a "light" fraction consisting of low-density organic material and a high-density inorganic material, which was landfilled.

The "light" fraction was passed through a cyclone for recovery of the solids from the air stream. This air was then filtered to reduce particulate load in the exhaust air from the air separation unit. The quality of this dust was unknown. If it had been primarily organic, a system would have been installed to incorporate this material into the digester feed system.

The separated organic material was conveyed via a weigh-feeder to the premix tank where the digester feed slurry was prepared. Appropriate quantities of make-up water, recycle liquor, sewage sludge and chemicals were added to prepare the desired feed slurry. Steam was also injected at this point to heat the feed slurry to a temperature greater than the desired fermentation temperature. The excess temperature provided heat to make up for the digester loss. Direct steam injection was selected because of the very poor heat exchange properties exhibited by a slurry that may contain in excess of 10% shredded refuse.

Two 50 ft (15 m) diameter digesters, each approximately 45,000 ft^3 (1,300 m^3) were constructed. Fixed-cover tanks were selected to permit the use of mechanical mixing. Variable-speed mixers with impeller diameters of 14 ft (4.3 m) were selected to keep the digester contents from stratifying. Little was known about the mixing properties of the concentrated refuse slurry; however, it was expected that a speed of 25 rpm would provide satisfactory mixing.

The digesters were operated in parallel, each at the conditions specified by the experimental program. A gravity-fed overflow box received overflow from the tanks and the slurry flowed by gravity to the vacuum filter. For initial cost consideration, a vacuum filter system was installed for dewatering the digested slurry and filtrate from the vacuum filter was used as makeup water to slurry the incoming dry refuse. This recycle also eliminated the need for disposal of a significant quantity of contaminated water which would require treatment at significant cost prior to discharge.

Data were acquired from experimental runs of up to 70 consecutive days for various feed rates and concentrations at thermophilic conditions. Gas production rates reached up to 125,000 ft^3d^{-1} (3,600 m^3) (55% methane) and feed rates to the digester of up to18 t d^{-1} (equivalent to 35-40 t d^{-1}raw refuse received) were achieved. The most significant result was that an average of 7.5 ft^3 (0.212 m^3) of total gas per pound of volatile solids fed to the digester was attained in the thermophilic mode. This not only confirmed, but also exceeded the original expectations of the system as developed from bench tests.

The RefCoM technology to convert MSW and SS to methane was demonstrated technically. An effective system was designed to process the MSW, removing the non-biodegradable components prior to digestion and recovering these components for sale along with methane and carbon dioxide.

An economic evaluation of the RefCoM process for a 400 tpd facility in operation in 1990 shows that with 25% equity and 75% industrial development bonds a tipping fee of $53 per ton would be realized (base case). This would provide the equity investor with 25% return on investment, 25% average pre-tax profit and 10% first year pre-tax profit. With more efficient use of the residual material being employed for internal energy generation and some sales of electricity, the base case tipping fee could be reduced to $44.50 per ton.

With a 100% publicly owned facility a tipping fee of $48.90 per ton would be charged for the base case, and with internal energy generation would reduce the tipping fee further to $40.00 per ton. Methane prices would impact the tipping fee as will other revenue streams. Increasing the methane price per $1.00 per GJ would decrease the tipping fee to $36.50 per ton.

The capital cost of the 400 tpd RefCoM facility would vary from $73,000 to $107,000 per tpd, depending upon the type of financing and the operation of the plant. This range competes well with mass burn facilities that average about $110,000 per tpd.

There are over 1,500 communities in the U.S. where this technology can compete. Many of these communities have or will have MSW and sludge disposal problems. The RefCoM technology provides an economical and environmentally sound method of handling these problems.

10.3. High Solids Biomass and Wastes

High solids anaerobic digestion development research led to a novel process for conversion of the organic fraction of municipal solid wastes and other high solids biomass to methane and compost. This process currently under development and commercialization (Chynoweth et al. 1992, O'Keefe et al. 1993) was been patented and has the trademark SEBAC® (sequential batch anaerobic composting) (Chynoweth & Legrand 1993). The process proceeds through three different stages (Figure 40), and at any time, there is at least one reactor functioning at each stage. In Stage 1, coarsely shredded MSW (organic fraction only) is packed into a cell. The cell is started up by recycling liquid (leachate) between this new stage and Stage 3 cell, which has undergone decomposition. This starts Stage 1 by adding liquid, nutrients, and active microorganisms from Stage 3. Organic acids, which would inhibit startup in Stage 1, are conveyed via leachate to Stage 3 and converted to methane. Once started (requiring 5-7 days), Stage 1 becomes Stage 2, the period when most decomposition and methane production occurs. The process moves into Stage 3 after most of the decomposition is complete. The entire process takes 15-40 days depending on the feedstock and operating temperature. Woody components of yard wastes, for example, require longer than paper, food wastes, and other fractions of MSW.

Initial trial runs of a variety of waste feedstocks have been conducted at a pilot-scale SEBAC® facility at the University of Florida. Test runs have been conducted with separated organic fraction of MSW, yard wastes, brewery wood chips, blends of organic MSW and waste-activated sludge, horse manure, and different biomass energy crops. In all cases, the wastes were stabilized and generated methane and compost. Methane yields ranged from 0.14 to 0.3 m^3/kg VS of organic feedstock with conversion efficiencies up to 85%. The typical methane yield was 0.2 m^3kg^{-1}, corresponding to a 50% conversion of organic matter to methane and carbon dioxide. The product biogas is typically 55% methane and 45% carbon dioxide. In runs with activated sludge, destruction of indicator organisms indicated that the process effectively reduces pathogenic microorganisms. The captured biogas generated by SEBAC® can be used directly as a renewable energy source for heating or electric power generation or upgraded for pipeline gas or vehicular use. Recent modifications of the process for microgravity environments associated with space travel have been made which include no-headspace flooded operation with external gas collection and densification of the initial feed leachbed (Chynoweth et al. 2002). This mode of operation has significantly improved kinetics. Anaerobic biochemical methane potential assays were run on several waste feedstocks expected during space missions, including wheat, tomato, peanut, sweet potato, potato, and rice. Extent and rates of conversion of these feedstocks and various paper types were presented. The methane yields ranged from 0.23 to 0.30 L g^{-1}VS added. Of the crop residues, the highest yields and rates were observed for peanut and rice.

A systems analysis of the SEBAC® process was conducted (Chynoweth et al. 1990). The assumptions are shown in Table 49 and summary of results in Figure 41. The costs expressed in $/ton of MSW processed are displayed in the left half of the bar diagram, broken down by each operation. These are levelized costs, i.e., they include debt service and all operating costs. The total cost is $47 per ton of processed MSW in 1990 dollars or $1,422 per day for this 35 tpd facility. Note that in the preprocessing operation, shredding accounts for $4 per ton. Biogasification accounts for approximately 50% of the cost while MSW preprocess and residue processing comprise about 20 and 30%, respectively. Note that if there were no biogasification., i.e., if this were a conventional recycling facility, there would be more solid residue to landfill and the cost of residue disposal would increase substantially. The revenues used to pay these costs are shown in the right half of Figure 41. The tipping fee is $33 per ton MSW processed and covers 70% of the costs. Gas sales provide the remaining revenue. It was conservatively assumed that no net income was derived from the sale of recyclables or compost. The analysis conducts sensitivity analyses of the influence of facility size, feed biodegradability, conversion kinetics, leachate recycle rate, compost value, and methane value. Mass and energy balances are also presented for the system.

SEBAC® is near commercial and prototype reactors have been constructed. A demonstration plant is scheduled to be placed into operation within the next few months.

10.4. Terrestrial Biomass

10.4.1. Crop Production (Legrand 1991b)

10.4.1.1. Napiergrass

Napiergrass and energy cane production was the subject of a major research biomass-to-biomethane effort at the Institute of Food and Agricultural Sciences of the University of Florida (Smith 1986, Smith et al. 1987, Frank & Smith 1993a, b). Napiergrass was grown for up to seven consecutive seasons in different locations in Florida and the Southeastern U.S. It can be grown as a perennial in subtropical to warm temperate climates and as an annual at higher latitudes. Napiergrass should not be harvested more than once a year as this will make it more susceptible to winter kill and jeopardize long-term survival of the stand. Yields of 30 to 40 dry Mg $ha^{-1}yr^{-1}$ have commonly been obtained; sorghum tested yielded at best 50 percent of this. Yields achieved with a typical high yielding variety can be found in Table 50.

10.4.1.2. Sorghum

Extensive data were gathered at Texas A&M (Hiler 1986, Hiler 1987, Hiler 1988, 1989). A brief summary of production results can be found in Tables 51 and 52. The results indicate that triple cropping schemes minimize dry matter yield and maximize moisture content and are therefore undesirable. Single cropping at 150 or 180 days maximizes dryness and may maximize yield. Lodging of the biomass is more likely, and single cropping compresses the harvesting window, requiring more harvesting equipment, which is used less intensively. This has a negative impact on economics. Double cropping appears optimal since it maximizes yield and extends the harvesting window. The only concern is excessive moisture in the biomass, which can be addressed by pre-wilting. This is not an established technique for large-stalk biomass and would need to be developed.

10.4.1.3. Wood Grass Production (White et al. 1990)

Wood grass refers to high density (40,000 to 440,000 trees ha^{-1}) plantations of cropping trees harvested on a one- to two year cycle. The distinction with Short Rotation Intensive Culture (SRIC) is becoming blurred as longer harvesting cycles are considered, to maximize biomass production. Some of the most successful international projects use willow (*Salix* sp.). As can be seen from Table 53, yields of 30 to 48 dry Mg $ha^{-1}yr^{-1}$ have been observed, rivaling the best yields of subtropical grasses. One difference with herbaceous biomass is that annual yield increases from year to year in the first years of the plantation. At Syracuse University, for example, a five-fold increase from year 1 to 2 and a three-fold increase from year 2 to 3 were observed. Constant production is often not observed until five or six years have passed. Spacing (planting density) has little impact on dry matter production as long as the same leaf area index can be achieved. The plantation is healthier at large spacing and a multi-year (three of four years) rotation. If the rotation interval is four years, for example, only a quarter of the plantation would be harvested every year. Reduced planting density would reduce planting cost. Customized forage harvesters have been used to harvest one- and two-year growths. Older trees will require forestry equipment for harvesting.

Research at the University of Florida (Rockwood et al. 1993) focused on varieties of eucalyptus and pine. This work is not discussed further here as the feedstocks resulted in minimal conversion via anaerobic digestion (Chynoweth et al. 1993).

10.4.2. Conversion

10.4.2.1. Herbaceous Biomass

Research on conversion of biomass to biogas (methane fermentation, anaerobic digestion) was carried out at Cornell University, Texas A&M University, University of Florida, and the Institute of Gas Technology. Anaerobic digestion of sorghum was investigated at Texas A & M University; a two-stage silo plus anaerobic filter system was used and methane yields of 0.25-0.28 L/kgVS were achieved (Hiler 1986). Convertibility of biomass sources was investigated using biochemical methane potential (BMP) assays at the University of Florida. BMP methane yields of 0.28 to 0.40 L/gVS were found for various sorghum cultivars (Jerger et al. 1987), 0.20 to 0.33 L per g VS was measured for Napiergrass (Smith 1989). Numerous bench scale reactor experiments were also carried out.

Reactor design work, bench and pilot-scale tests, convertibility measurements, and some crop production were done at Cornell University (Jewell et al. 1993). Methane yields ranged from 0.25 – 0.32 L per g VS in a variety of reactor types at loadings from 1.6 - 14 g VS $L^{-1}d^{-1}$. First, a leach bed concept was explored, whereby biomass is piled up in a reactor and liquid is percolated through. This liquid can be circulated through a better-established leachbed and returned to start up the new batch. During the bench scale phase of this work, the same leachate was used for seven consecutive sorghum batches at 55 °C, without any nutrient or other additions. Compaction to 311 g TS L^{-1} depressed reaction rates by 33%; from 158 - 244 g TS L^{-1}. Hydraulic conductivity was reduced from 660 to 7.2 cm h^{-1}. This work was subsequently expanded to pilot scale; a total of over 780 dry kg of sorghum (approximately 2,600 wet kg) were processed. Note that this system was never operated to maximize rates and much of the reactor volume remained unused. It was verified that CMSTR kinetics apply also to this solid-state system. Smaller reactor volumes (higher dry matter densities) were achieved with a plug flow process with leachate circulation. Long SRTs resulted in plugging problems above 135 g TS L^{-1}; a first-order reaction rate of 0.1 d^{-1} was measured. Finally, a high solids semi-continuously fed and mixed reactor was operated resulting in extremely high densities and rates. The feedstock was a mixture of dried sorghum and cellulose; the mix had to be fine-tuned to avoid nitrogen deficiency. Pure sorghum results in ammonia toxicity at the high conversion rates, low moisture contents, and high pH (7.8) prevailing in these reactors. Addition of trace nutrients was important; first-order reaction rates of 1.5 to 2.5 d^{-1} were calculated.

Pilot biogasification tests were also run on ensiled sorghum with the 4 m^3 Experimental Test Unit (ETU) located at Walt Disney World in Florida by the Institute of Gas Technology (IGT) (Srivastava et al. 1987). The ETU is a vertical flow solids concentrating reactor (SCR) operated at a low solids concentration and was discussed above under the water hyacinth/sludge section. High methane yields of 0.33 and 0.28 L/g VS were obtained loading rates of 4.3 and 7.3 g VS $L^{-1}d^{-1}$, respectively.

Harvesting and storage of herbaceous feedstocks were addressed by Texas A&M University (Egg et al. 1993). The fact that losses of dry matter of 17- 70% may be experienced by conventional harvest and storage practices lead to ensiling research which demonstrated that losses may be reduced to 7% by this process. Energy potential losses are even lower since much of the dry weight lost is in the form of carbon dioxide and reducing potential becomes conserved in fermentation products. Ensiling not only allows a method to store feed, but also results in some pretreatment for anaerobic digestion.

10.4.2.2. Woody Biomass

The anaerobic convertibility of woody biomass was investigated by D.P. Chynoweth at IGT and the University of Florida, starting in the early 1980s. In 1985, BMPs were conducted on "woodgrass" and older poplar and on stems and leaves. A CSTR achieved 58% of the BMP methane yield. A two-stage leachbed attached film reactor achieved a yield of 0.31 L CH_4/g VS in 80 days (Fannin et al. 1986). Poplar and willow were further evaluated in 1986 and ultimate methane yields of 0.250 L CH_4/g VS were measured for both (Turick et al. 1991). Differences between poplar cultivars and bark-containing or bark-free feed were measured. The impact of pH on biogasification of wood was investigated; complete degradation of cellulose in four days was observed at pH 7. Methane yields over 0.25 L CH_4/g VS were measured with three willow clones in 1988, and a bi-phasic pattern of conversion over time was observed. Bark was shown to contain a methanogen inhibitor. Finally, 33 samples of wood (chiefly poplar and willow) were assayed using the BMP test. Methane yields in excess of 0.25 L CH_4 g^{-1} VS were recorded for 19 samples, with three clones in excess of 0.31 L/g VS. Willow, which was earlier thought to be poorly degradable, yielded up to 0.31 L CH_4 /g VS. Conversion rates of willow, however, were generally very low (0.01 to 0.03 d^{-1}) with some exceptions up to 0.2 or 0.3 d. The adaptation of methanogenic cultures to a bark inhibitor was demonstrated. A mesophilic CSTR operated for 30 months with poplar exhibited a methane yield of 0.16 L CH_4/g VS.

10.4.2.3. Methane Enrichment Digestion (MED)

Methane enrichment digestion (MED) is a process patented by GRI to increase headspace methane concentration in a digester from 50 - 60 % to >90%. The original concept called for a two-phase conversion process (e.g., a leach bed followed by an anaerobic fixed film reactor to methanize the leachate). Through judicious management of pH and pressure in both stages, it can be shown that a high methane stream can be produced from the second stage and a high CO_2 stream from the first stage (Hayes et al. 1990)Hayes and Isaacson, 1986). Later work focused on a single stage process whereby digester liquid is circulated through a CO_2 stripper. MED was investigated at the University of Illinois through bench-scale work and modeling. More applied work was carried out at Cornell University and at Walt Disney World.

In 1987, single stage MED with side stream CO_2 stripping was investigated at bench scale at Cornell University (Jewell et al. 1993). Using a reactor fed at a rate of 1.5 g VS kg^{-1} reactor contents/day, a methane content of 91 percent methane was obtained by recycling three volumes of leachate per reactor volume per day (v/v/d).

The methane yield was 20% lower than for the control reactor, probably due to volatile acids oxidation in the stripper. In 1988, the study was expanded into a detailed parametric analysis covering alkalinity, recycle rate and temperature. Using a sorghum leach bed reactor, 22 conditions at two temperatures were studied. Methane content averaged 91% with three to six v/v/d leachate circulations. Methane yield again was only 70 to 80% of control values probably due to COD oxidation in the stripper.

Plugging problems were encountered with the leach bed due to transfer of fines. At leachate recycle rates of 1.0, 1.5, and 2.5 L $kg^{-1}d^{-1}$, alkalinities of 8, 4, and 2 g $CaCO_3$ L^{-1}, respectively, were required to achieve >90% methane. It should be noted that only void space is available for leachate circulation so that a recycle rate of 1 L $kg^{-1}d^{-1}$ really corresponds to a liquid turnover rate of approximately three times per day. Overcoming short-circuiting and plugging and ensuring even distribution of liquid represent significant design challenges. Finally, it was emphasized that high solids digestion is accompanied by high alkalinity, which can result in inhibitory high pH values under conditions of CO_2 removal.

Pilot scale MED research was carried out at the Experimental Test Unit (ETU) at Walt Disney World. The reactor was fed refuse-derived fuel diluted with sewage sludge to five to six percent TS. Digester liquid was led to a stripping tower of the shower deck or baffle plate type. Liquid accumulated at the bottom and was sparged with air. It proved difficult to find a solids free leachate stream and both loading rate and solids inventory in the digester had to be reduced to address this problem. Repeated achievement of methane concentrations in excess of 90% with this pilot scale system were achieved. CO_2 removal rates of 500+ mg CO_2 L^{-1} per pass through the stripper were observed.

An overriding design concern with this process was the management of solids carryover and vigorous biological slime growth due to high leachate CODs combined with potentially high dissolved oxygen concentrations. Such growth would rapidly plug any small openings so an open configuration is required. This would exclude packed towers, conventional sieve trays, turbogrids, valve trays, etc. An intriguing alternative is vacuum stripping, where the leachate is sprayed into a vacuum vessel and CO_2 is removed. This should eliminate biooxidation and increase the driving force to remove CO_2. This option sized for one bioreactor of the demonstration facility described below is sketched out in Figure 42.

MED relies on the transfer of CO_2 from the digester to a stripper to the atmosphere using a liquid as the carrier. At a given gas solubility, the more biogas (and CO_2) is produced per unit reactor volume, the more liquid has to be percolated per unit volume per unit time. High rate reactors could thus be limited by the rate at which liquid can percolate. In conclusion, it appears that the main physical limitations to MED are: 1) the ability to withdraw a carrier liquid from the digester at a sufficient rate, and 2) the need for high hydraulic permeability at high gas production rates.

10.4.3. Systems Analysis (Legrand 1991b, a, Legrand 1993)

10.4.3.1. Introduction

The overall goal of the GRI-EFAS advanced biomass program was the establishment of a technology base to enable the production of methane from biomass as a supplementary long term competitive supply of fuel gas. A gas cost goal of U.S. $3 per GJ was set. In 1987, GRI contracted with Reynolds, Smith and Hills, Inc. (RS&H) to develop a mathematical model of a terrestrial biomass biogasification system to be used by GRI management in achieving the $3 per GJ goal.

The spreadsheet model which resulted is known as the Energy Crop Systems Analysis (ECSA) model. This model was used effectively by both GRI management and researchers. As a management tool, GRI used the levelized cost output of the model to determine research priorities and analyze cost sensitivities. Researchers can quantify the impact of their research results and potential breakthroughs on the entire biomass conversion system.

The ESCA model simulates operation of a biomass biogasification system, including interconnected modules for harvesting, biomass transportation, biogasification, and gas processing subsystems. The model calculates a mass balance, an energy balance, and levelized cost of synthetic natural gas (SNG) for the system chosen

10.4.3.2. Harvesting and Biomass Transportation

The harvesting of a terrestrial energy crop and its transportation to a central conversion facility were simulated. The crop is harvested and transported a short distance to silos in the field; these operations are described by the harvesting module. The growth of the crop is not modeled by ECSA; the output of the BIOMET research model developed by the Institute of Food and Agricultural Sciences (IFAS) at the University of Florida, can be used as an input to the ECSA harvesting module in the form of dry Mg of biomass per hectare per year. The energy crop is grown on plots in a circular area around the central conversion plant; not all of this area is necessarily planted in energy crop.

In a generalized case, harvesting is a seasonal operation while conversion to gas is continuous, therefore, the biomass feedstock has to be stored. Ensilage was selected as the storage technology because it is characterized by the smallest solids losses of all systems considered (Hiler 1987).

The maximum straight-line radius around each silo is determined based on loading throughput, truck speed, etc.; it will be called *"r"*. The total mixed crop area (energy crops and other crops) surrounding the conversion facility can be calculated from the area planted in energy crop, divided by the percent energy crop coverage. The straight-line radius of this entire mixed crop area will be called *"R".*

In order to optimally represent the geographical distribution of silos around the processing plant, it was decided to impose a pattern to this distribution. First, any biomass grown within the harvesting truck range r (R = r) around the plant is stored at the plant. Should energy crop plots exist outside this radius r (R > r), a ring with eight segments is constructed immediately outside the inner circle; each segment is served by a silo located in its middle; the distance from this silo to the farthest corner of its segment does not exceed r. The ratio of the radii of the different circles involved is always constant. This ensures that (1) the areas served by each silo are approximately equal and (2) that each segment retains a reasonably square shape for efficient transportation to its silo.

As the radius of the entire energy area *R* increases relative to the driving radius r around each silo, more concentric rings are added, divided into more and more segments. The aim is always to obtain segments that have similar area and squarish conformation.

The result of the whole exercise is that for every ratio R:r, we can now (a) define the number of silos, (b) divide them into categories according to their distance to the processing plant and (c) calculate the weighed average road distance from silo to processing plant, which is important for the transportation calculations.

Year-round, ensiled biomass is withdrawn from the silos and transported to the processing plant. This operation is described in the transportation module. Front-end loaders at the silos dump biomass into trucks. The trucks drive to the plant where they are unloaded on hydraulic ramps. A dedicated fleet oftransportation trucks is assumed in the model, distinct from the trucks used for harvesting. A mixed fleet of trucks for harvesting and transportation was first considered, since it would result in a smaller total number of trucks. This possibility was rejected for the following reasons:

- Diverting transportation trucks to harvesting operations would require building substantial feed storage buffer capacity at the plant to allow continuous feeding of the digestion system. The cost of such buffer capacity could rapidly negate the economic advantage associated with the smaller number of trucks. Additionallly it was thought that manipulation of ensiled feed and duration of exposure to aerobic conditions between silo and conversion plant should be minimized to limit dry matter loss due to biodegradationand minimize odors.

- The number of trucks required for transportation seems to be generally much smaller than the number required for harvesting so that a mixed fleet would only be marginally smaller than the sum of two dedicated fleets.

10.4.3.3. Conversion

Various types of reactors can constitute the heart of a biomass anaerobic digestion system. The bioconversion reactors described by the model include:

- The continuously stirred tank reactor (CSTR), also referred to as completely mixed flow reactor (CMPR) or continuously fed and mixed reactor (CFMR). In this type of reactor, feeding of substrate, mixing of the reactor contents and removal of effluent all occur continuously. The contents of the digester are homogeneous and identical in composition to the effluent.

- The non-mixed vertical flow reactor (NMVFR), also referred to as solids concentrating (SOLCON) Digester (Srivastava et al. 1987). This low solids digester is unmixed; feeding and wasting are semi-continuous. The reactor is designed and operated in such a way that solids are slowed down relative to the liquid, resulting in a solids retention time that is higher than the hydraulic retention time, short-circuiting is minimized.

- The Plug Flow Reactor (PFR): Plugs of substrate enter sequentially at one end of an elongated reactor and travel linearly through it while subjected to conversion reactions.

- The Batch Reactor: This reactor is filled with substrate and some microbial seed at the beginning of a batch cycle. No mixing, feeding or wasting occurs, although liquids may be run through the mass of solid substrate.

A choice of three possible conversion systems is available:

1. CSTR or NMVFR mowed by PFR. This is an entirely continuous process.

2. Batch reactors followed by plug flow reactors.

3. Batch reactors followed by batch reactors.

All are two-stage systems, whereby the feed is converted in two reactors in series. The main purpose of this arrangement is to have separate reactors optimized to handle (a) the initial rapid conversion and (b) the slower "tail end" of the conversion process. No attempt is made to physically separate the biochemical reactions in an acidogenic and a methanogenic phase. In the model, it is possible to switch off one of the stages to mimic a single stage process, and so a suitable variety of possibilities can be simulated.

The effluent leaving a first stage reactor is elutriated, screened, and dewatered to provide higher solids densities in the second stage in order to minimize reactor size. The intermediate elutriation dewatering step can be switched off if so desired. The material enters the second stage in its dewatered form. Effluent from Stage 2 reactors is also elutriated and dewatered yielding liquid filtrate and solid cake for land application.

10.4.3.3.1. Continuous system

The first stage of the continuous system is a CSTR or NMVFR. Experience at the Community Waste Research Facility at Walt Disney World indicated that feed concentrations should be below 6% TS. In completely mixed reactors (CMR), the solids concentrations are usually kept well below 10%TS to keep mechanical stresses and mixing energy requirements at a reasonable level. However, ensiled biomass feed to the digesters is typically supplied at solids contents well above 20% TS, so that some form of liquid conservation and management is necessary. It is achieved by dewatering digested effluent in a press and recycling part or all of the resulting filtrate to conserve heat, alkalinity, nutrients and inoculum. In this manner, the dry matter content of the feed is decoupled from the solids concentration in the digester; any desired reactor solids concentration can be achieved by manipulating the flow of recycled liquid. In fact, in ECSA, the effluent solids concentration is an input. The filter cake resulting from the dewatering operation constitutes the feed to the second stage. Energy crop biomass is sufficiently moist and biodegradable that excess moisture is produced and removed. The dewatering-liquid recycle system is essential to achieving a favorable energy balance, since otherwise large amounts of water would have to be heated to digester temperature.

10.4.3.3.2. Batch-plug flow system

Under this option, the biomass is first fed to batch reactors, then transferred to plug-flow reactors. Each batch reactor is operated as follows: it is filled with biomass and stored leachate, or leachate from another digester is added to provide sufficient moisture as well as inoculum, nutrients and alkalinity; the batch digester is then closed and the conversion can start. Careful leachate management is essential; leachate from a reactor in the end part of its batch cycle must be recycled to another reactor that is just being started up to recycle nutrients, alkalinity, and active microbiota. Conversely, leachate from a reactor in its early phase, characterized by high organics content and low pH, can be processed in a more established, mature reactor. When a sufficient extent of conversion has been achieved, the reactor is emptied and can be refilled with fresh biomass (Jewell et al. 1993). The entire sequence of events from filling to emptying is called a batch cycle. Gas production during a cycle will fluctuate considerably; starting at zero, it will rapidly increase to a peak value, then gradually decrease. To provide a reasonably constant gas flow, it is necessary to operate several batch reactors on a staggered schedule. For example, if the cycle length is 35 days and 5 reactors are used, one reactor would be emptied and refilled every week so that the peaks and valleys in their gas production overlap. Five batch reactors is suggested as a minimum number to even out these fluctuations.

10.4.3.3.3. Batch-batch system

In this system, biomass is fed to batch reactors in staggered operation in the first stage. At regular intervals, a plug of spent biomass is produced from the first stage and transferred to the second stage, which also consists of batch reactors.

10.4.3.3.4. Gas production

Every unit mass of substrate converted results in the formation of a constant volume of biogas. The amount of methane resulting from the conversion of a unit mass of biomass is dependent on the composition of this feed. Approximately 350 mL of methane at Standard Temperature and Pressure (STP = 0^{o}C and 1atm) are formed when one gram of Chemical Oxygen Demand (COD) is converted to biogas (5.61 scf/lb COD converted) (0.35 m^3kg^{-1}). Depending on the feed considered, a gram of biomass can be equivalent to different amounts of COD; the COD:VS mass ratio of the biomass then determines the amount of methane generated from the conversion of one gram of biomass. For example, if the COD:VS ratio is 1.2, then 350 mL x 1.2 = 420 mL methane will result from the conversion of one dry gram of organics (5.61 x 1.2 = 6.73 scf CH_4 dry/lb organics converted) (0.415 m^3kg^{-1}).

10.4.3.3.5. Residue recycle

The biomass conversion facility produces a liquid residue (excess filtrate) and a solid residue (dewatered filter cake). The latter is transported back to the field using the biomass transportation trucks, which normally leave the plant empty. The liquid residue is pumped to a lagoon for storage during the winter months (four months storage capacity provided). From there, it is applied to land. Maximal recycle of nutrients and organic matter is the objective; the focus is on nitrogen as the key nutrient, assuming that phosphorus and potassium would be recycled similarly. Ammonia volatilization is taken into account.

10.4.3.3.6. Gas processing

The biogas produced from a digester typically contains 50-70% methane. This concentration must be increased to 95% methane for marketing of the gas as synthetic natural gas (SNG). This is done using a membrane process relying on the different diffusion speeds of CO_2 and CH_4 through the membrane. The process requires pressurization to 2,500 KPa (350-400 psi) and results in a methane-enriched pressurized product and a CO_2-enriched waste permeate gas stream at near-ambient pressure. By repressurizing and recycling this permeate stream, a higher recovery of methane can be achieved. However, with typical biogas concentrations, methane recoveries above 90% become prohibitively expensive (90% methane recovery means that 10% of the methane produced is lost with the waste gas). The waste gas is usually too dilute to sustain stable combustion, so catalytic incineration is assumed.

It is possible to remove most CO_2 from a digester as it is produced by absorbing it in the digester liquor, then stripping off CO_2 and H_2S separately from the digester and recycling the desorbed liquor (Hayes et al. 1990). This concept was demonstrated at pilot scale and resulted in headspace methane concentrations in excess of 90%. In ESCA, a vacuum stripping tower is assumed with catalytic incineration of the waste gas.

10.4.3.3.7. Energy balance

The energy balance for the entire biomass biogasification system is calculated by the model and includes plant electricity and fuel requirements, in kWh per day and MJ per day, respectively. A thermal balance is calculated at the annual average and the design (minimum) temperature. First, a sensible heat balance is performed;the sensible heat of all materials entering and leaving the conversion system are quantified, referenced to 0^oC. They include feed, dilution water (entering streams), and wet biogas, filter cake, and excess filtrate (departing streams). It is assumed that dilution water is at ambient temperature or at 5^oC, whichever is highest. Heat gain from mixing digesters and elutriation tanks, and from metabolic heat production companying bioconversion are added. Heat loss resulting from evaporating moisture in the reactor such that the biogas is saturated at reactor temperature, is subtracted. Conductive heat losses associated with recycling filtrate are also subtracted. The conductive heat losses through the walls, roof and bottom of all tanks (digesters and other tanks) are calculated, taking into account temperature difference and thickness of insulation. Air boundary layer resistance is included.

10.4.3.3.8. Levelized Cost model

The cost analysis of the entire system from crop production through residue disposal and gas cleanup is based on a levelized cost-of-service price methodology provided by GRI. The cost-of-service price is a price per unit of methane ($ per 10^6 Btu ~ mmBtu ~ GJ) sufficient to generate revenues to meet the following requirements:

- Amortize debt;
- Cover operating and maintenance costs and fuel expenditures; and
- Provide a return on both common and preferred equity.

The levelized cost-of-service price represents a constant dollar per unit price, which if charged for each unit of output over the life of the plant, would yield the same revenue value as would the actual cost-of-service price, discounted to its present value. Thus, the current dollar cost-of-service price is discounted to its present value and levelized over the life of the plant using a constant dollar annuity factor (Clark et al. 1982).

10.4.4. Results and Interpretation of Model Output

10.4.4.1. Base Case Description and Results

A variety of energy crops were considered in the GRI/FAS program. The leading herbaceous contenders were determined to be sorghum and Napier grass. Base cases were compiled for both and are summarized in Tables 54 and 55. An attempt was made to account for the differences observed between the two species and each base case was optimized for its species. As can be seen, both crops can be converted to substitute natural gas at a cost approximately $6 per GJ (1991 dollars). Sale of co-products could cut that price in half. The cost distribution is displayed in Figure 43; the main cost items are harvesting and conversion.

In Figure 44, a thermal balance is illustrated for a full size thermophilic biomass reactor exposed to an outside temperature of 17^{o}C, a typical annual average for the central USA. The thermal balance is calculated as follows:

+ feed enthalpy	+ 1.4% of raw biogas energy content
+ metabolic heat	+ 3.4%
- wet biogas enthalpy	- 0.6%
- evaporation	- 1.2%
- space heating	- 0.1%
- conductive losses	- 0.5%
- effluent enthalpy	- 1.5%

The total process heat needs of the facility are thus estimated at 1.5% of the energy content of the biogas produced. Note that enthalpies were calculated with 0^{o}C as the reference point. It is interesting to calculate how compatible this process is with cold climates where the ambient temperature was set at –20^{o}C. The total heat requirement is 5.1% of total biogas production. This is not very different from the more temperate climate since 94.9% of the gas production is available vs. 98.5%

10.4.4.2. Crop Productivity

In Figure 45, the economic impact of increasing crop productivity is illustrated using sorghum as the model crop. As can be seen, significant cost reductions are observed up to about 40 Mg ha^{-1}y^{-1}. Beyond that, productivity increases have little economic impact.

10.4.4.3. Potential of technology

Further research can undoubtedly lower the cost of producing methane from biomass, but by how much? This question is addressed in Figure 46, where a selection of Napier grass research breakthroughs is displayed along with their potential cumulative economic impact. These advances are listed in increasing order of difficulty. The first one is not really an advance but merely the result of building experience with biomass-to-methane systems. It is assumed that costs can be calculated without process development allowance and that the downtime is halved from 8% to 4%. That alone lowers the levelized cost of gas from $6.4 per GJ to $5.6 per GJ. Next the implementation of MED is considered; it can further lower cost to $5.3 per GJ. Halving the cost of silos brings a further improvement to $4.9 per GJ. Modifying the crop to increase its biodegradable fraction from 77% to 90% cuts cost to $4.2 per GJ. Increasing first order reaction rate coefficient from 0.085 d^{-1} to 0.2 d^{-1} results in $3.7 per GJ. Increasing the crop productivity by 50% to 60 Mg $ha^{-1}yr^{-1}$ lowers the levelized cost of gas to $3.5 per GJ. Finally, modifying the biomass to raise its COD:VS ratio from 1.1 to 1.5 on top of all previous improvements would reduce the cost of gas to $2.7 per GJ. Sensitivity analyses were carried out earlier with an earlier version of ECSA. Although the model has been refined since then, the main conclusions remain valid:

I . Economies of scale exist up to about four PJ yr^{-1} (4 x 10^{12} Btu yr^{-1}).

2. Facilities that are sufficiently small in area do not require decentralized silos and therefore, do not need a dedicated transportation fleet immediately above a critical size, a transportation fleet becomes necessary for efficient operation. Operation in the size range immediately above this critical level may be uneconomical.

3. At least one quarter of the area surrounding a biomass conversion facility should be planted in energy crops, however, only limited economic advantage is derived from planting more than 30% of this area in such crops.

4. Continuing significant returns will be derived from increasing the energy content of the crop.

5. The hydraulic retention time can be over-designed by 50% without incurring more than $0.10 per mmBtu (GJ) penalty. Such a safety factor greatly increases the reliability of anaerobic digestion.

6. Close attention should be paid to the dryness of the biomass at harvest; significant transportation savings occur between 20 and 35% TS ($1 per mm Btu or per GJ). Further field drying is not advantageous because of increasing losses.

7. State-of-the-art first order reaction coefficients were around 0.09 - 0.1 d^{-1} in 1988. A doubling of these rates would be economically significant, but no further cost improvement is observed above 0.25 d^{-1}. The 1991 state of the art is closer to 1.5 d^{-1}.

10.4.4.4. Woody Biomass

A summary of the costs of producing methane from woody biomass (willow) (Figure 47) shows that the final gas costs were slightly higher than those of grasses and that the costs do not improve significantly above biomass productivity of 20 dry tons/acre/yr. These differences (~about $1 per mmBtu or GJ) are probably within the error of the calculation.

Chapter 11: IMPACT OF BIOMETHANE ON GLOBAL WARMING

Renewable energy is attracting new interest because of a convergence of environmental and energy related factors. Although the magnitude of the problem is still far from defined, increasing concern exists about climate changes brought about by the accumulation in the atmosphere of infrared absorbing gases resulting from human activities. This concern could translate into regulations and international agreements restricting carbon emissions. Renewable energy either is not associated with CO_2 production (e.g., with photovoltaics), or is CO_2-neutral over the long term (biomass). Concern over present and future deterioration of the environment lies at the root of the new discipline of industrial ecology. An ideal industrial ecological system would produce no waste and would be fueled with energy from sunlight. On the road to that lofty ideal, industrial ecologists focus on modifications to our economy that would protect our health, the health of natural ecosystems, and that of future generations. Biomass energy figures prominently among industrial ecology proposals for a sounder economy, especially if advanced technologies like combined cycle gas turbines or fuel cells are used (Hileman 1992). In addition to these new environmental concerns, the U.S. dependence on imported petroleum products is increasing rapidly, and new electric generating capacity will be needed in the near future. By the year 2000, 20% of U.S. fossil fuel generating plants will have to be replaced; another 30% will have to be replaced in the following decade.

A module has been added to the ECSA model in an effort to quantify the potential impact of biomass energy on global climate change (the "greenhouse effect"). It calculates the reduction in carbon dioxide (CO_2) released to the atmosphere when using biomass energy to displace fossil fuel energy sources. The CO_2 output of the three processes for converting biomass to energy are compared with four fossil fuel energy sources.

Biomass energy applied on a large scale would have an impact on global warming for two main reasons:

- A certain amount of atmospheric CO_2 would be immobilized (sequestered) in standing biomass and remain there rather than in the atmosphere, as long as the biomass is maintained at a steady state. There would be a net gain over the amount of carbon immobilized through the previous use of the land since energy crops are projected to have yields an order of magnitude higher than most other vegetation. Such net CO_2 removal from the atmosphere, however, would occur only during initial growth of the crop.

- To the extent that biomass is used for energy production, it can be considered to be displacing other forms of energy (fossil energy) that result in CO_2 production. In first approximation, biomass energy is CO_2-neutral, that is, every ton of CO_2 produced is offset by a ton of CO_2 immobilized in the next generation of biomass through photosynthesis. By displacing fossil fuel, biomass energy prevents the net release of CO_2. This is equivalent to saying that a net removal of CO_2 from the atmosphere has occurred compared to a baseline considering only fossil fuels.

In this study. three forms of biomass energy are considered:

- Production of SNG
- Production of SNG and combustion of the solid residue
- Direct combustion of all biomass

They are compared to four fossil fuel baselines:

- Coal
- Natural gas
- Liquid fuel
- The 1988 U.S. mix of coal, gas, and liquid fuel

The assumptions for this analysis are outlined in Table 56. Twelve possible comparisons between biomass energy and fossil fuel result.

Some methane leakage is likely to occur under the SNG production options; gram per gram, methane is approximately 30 times more powerful a greenhouse gas than CO_2. Metabolization of fertilizer nitrogen can result in N_2O leakage; on a mass basis, N_2O is 300 times more powerful a greenhouse gas than CO_2 (Marland & Rotty 1985, Rodhe 1990). Because of the process energy needs and gas releases, biomass energy is not entirely CO_2-neutral. These contributions to the greenhouse effect have to be subtracted from the gross CO_2 displaced.

For example, consider a SRIC tree farm with average annual yield of 39.2 dry Mg ha^{-1} yr^{-1} on land that previously yielded 4.5 dry Mg $ha^{-1}yr^{-1}$. The tree stands are harvested every four years; the biomass is biologically gasified, the solid residue is dewatered and used as solid fuel. This source of energy is assumed to displace the average 1988 U.S. fuel mix.

If it is further assumed that 0.5% of the CH_4 produced is lost in leaks, and that 0.1% of the fertilizer nitrogen is evolved as N_2O, on average, and 122 Mg of CO_2 per ha is immobilized in the standing biomass. However, 30 Mg CO_2 ha^{-1} are removed from the atmosphere annually by substituting SNG and combustion of dewatered residue for the use of the U.S. fuel mix, compared to a fossil fuel base case.

Figures 48 and 49 graphically depict the results of a base case analysis performed for herbaceous biomass. The CO_2 reduction effects of the three biomass energy farms when used to displace the average U.S. fuel mix are shown in Figure 48. The curves diverge showing direct combustion of biomass as the most effective method of CO_2 reduction. Synthetic natural gas production with residue combustion is next, followed by SNG production only. The difference between these biomass conversion options is primarily due to the amount of energy that can be produced by each method for a given amount of biomass. It must also be emphasized that biogasification produces a versatile and clean fuel, which can be stored, transported, and used as a chemical feedstock. This could tip the balance in its favor despite its lower potential for reducing net CO_2 emissions. By contrast, biomass combustion only generates heat and therefore is limited to power generation, or steam production for immediately neighboring industries.

Depending on which fossil fuel is displaced, the estimate of net CO_2 reduction due to biomass energy will change. This is illustrated in Figure 49. SNG production with combustion of the solid residue is used to displace the combustion of coal, natural gas and the average U.S. fuel mix. Combustion of coal produces the highest output of CO_2 per joule of fuel used and natural gas produces the least. The curves of Figure 49 follow this hierarchy and show that when biomass is used as an energy source to displace coal, the reduction in CO_2 output will be the highest. When biomass is used to displace natural gas, the net reduction in CO_2 output is lower than when any other fossil fuel is displaced. This highlights the fact that natural gas is already a low-CO_2 fuel.

In 1988, approximately 5.8 billion Mg (5.8×10^{15}g) of CO_2 were released by the combustion of fossil fuels in the U.S. Figure 50 depicts the amounts of CO_2 produced by each type of fossil fuel. According to the 1987 Statistical Abstract of the United States, there are 170 million hectares of cropland in this country. Displayed on the same Figure 50 is the percentage of U.S. cropland that would have to be used for biomass energy production in order to displace each respective fossil fuel. This comparison is based on a woody biomass scenario; it is assumed that biomass is converted to gas and the solid residue is burned. Steady state is assumed, in other words, the effect of initial carbon sequestration is ignored.

Note that if a fossil fuel were displaced, CO_2 production associated with the use of this fuel would disappear. However, biomass energy is still accompanied by some CO_2 production, as discussed previously. If all petroleum were replaced by biomass under our assumptions, CO_2 would decline from 2.5×10^{15}g to 0.30×10^{15}g. Similar numbers for natural gas are from 1.1×10^{15}g to 0.18×10^{15}g, and for coal; from 2.2×10^{15}g to 0.16×10^{15}g. Finally, note that there are 159 million hectares of non-federal forest land, some of which may be available for energy crops (SRIC trees, for example).

Chapter 12: CONCLUSION

Several research programs investigated energy crops (aquatic and marine plants, grasses, and woods) and wastes (MSW) coupled with anaerobic digestion for generation of renewable substitute natural gas. These programs integrated research on crop production and harvesting, conversion to methane by anaerobic digestion, and systems analysis. Resource potential estimates for these feedstocks (Table 57) have been reported at 7 EJ (one exajoule = 1 quad = 10^{15} Btu) for wastes and 22 EJ for terrestrial biomass (grasses and woods). These estimates indicate that the potential from land-based biomass is about 22 EJ. As shown in Table 58, energy demands of the U.S. could be met using 103% of existing U.S. cropland. The potential for marine biomass is huge at greater than 100 EJ per year. All of the U.S. energy needs could be supplied by marine macroalgae grown on about 260 million hectares (one million square miles) of ocean. However, this optimistic estimate has many uncertainties related primarily to design of offshore farms. Table 59 shows that the cost of methane from these renewable energy systems was significantly higher (2-10 times) than fossil-derived energy and interest in their continued funding dwindled with continuation of energy gluts and depressed prices in the 1980's.

Tables 60 and 61 summarize the assumptions and economics for a typical biomass energy plant processing about 1000 dry tons per day of Napiergrass and generating a net energy of 10^{13} Joules per day. The system would require about 7,600 hectares of land and thirty 8500 m^3 digesters. The cost of methane from this system is about $6.70 (1986) GJ. Costs can be reduced by increase in feed biodegradability, increase in feed energy content, and use of the biogas without cleanup.

Because biomethanogenesis decomposes organic matter with production of a useful energy product, anaerobic digestion of organic wastes is receiving increased attention. With increased levels of waste production, limited area for land filling or application, and increased awareness of environmental impact, alternative methods for treatment of solid and agricultural wastes are being sought. Currently these wastes release undesired methane into the atmosphere due to anaerobic conversion in landfills, lagoons, or stockpiles. Treatment and recovery of this gas in reactors would reduce this source of atmospheric methane. An attractive option for treatment of the organic fraction of these wastes is to separately treat the organic fraction by composting and applying the stabilized residues on land as a soil amendment. The residues would reduce water needs and prevent erosion. The compost from treatment of wastes from a population of 100,000 could be applied on a sustained basis on less than 2,000 acres of land. This scheme, however, requires effective separation of undesired components such as metals, glass, plastics, and toxic compounds which affect the quality of residues more than the conversion process. In European countries, which lead in this field, the most effective method of separation is source separation, resulting in compost with sufficiently low levels of contaminants for land disposal. Although aerobic composting continues to be a more popular process for stabilization of these wastes, anaerobic digestion has the advantages of methane production and lack of need for aeration or mixing. Several full-scale anaerobic composting plants are in operation in France, Belgium, and Denmark.

In the U.S. biomethane has lost favor to bioethanol as a desired product from renewable biomass. This is mainly related to the ease of use of ethanol as a transportation fuel. Use of biomethane should be reconsidered since the use of methane-powered vehicles is increasing in the U.S., and methane can be put into the pipeline distribution system or used directly by power plants or industries. A comparison of the yields of methane and ethanol from biomass (Table 62) shows that the net energy returns for methane are higher due to the substrate limitations for conversion to ethanol (hexose and pentose sugars only) and high energy consumption of ethanol conversion and recovery processes. Theoretically, 1 kg of glucose can yield either 511 g of ethanol or 267 g of methane, both exhibiting an equivalent energy content of 15,950 kJ. On a carbon basis, 67% of the glucose carbon is converted into ethanol in fermentation while only 50% of glucose carbon is converted to methane in anaerobic digestion. Yet, methane has a higher energy of combustion so comparison of the processes on a carbon basis is misleading. Since anaerobic digestion can also convert proteins and lipids in addition to carbohydrates to methane, overall conversion of biomass to methane should always produce more energy than conversion to ethanol.

In addition, conversion efficiencies of ethanol yields are often reported as a percentage of theoretical yield which is based on fermentable sugars and often exceeds 90%. However if conversion efficiencies were based on the organic content (volatile solids) of the feedstock as are those reported in anaerobic digestion, they would be comparable to or lower than anaerobic digestion conversion efficiencies. Data shown in Table 62 illustrate that processes for production of biomethane have higher feed energy recovery, lower system energy requirements, and lower costs than bioethanol production processes. Furthermore, methane yields and kinetics would be improved significantly if the same drastic depolymerization pretreatment steps employed for conversion to bioethanol were used in conjunction with anaerobic digestion.

Marine biomass offers the highest potential technically for biomass energy farms. The available ocean area and coastline area provide under utilized resources for marine farming. Growth rates of marine macroalgae exceed by far those of terrestrial based plants, mainly because of the lack of water limitations. A summary of reported rates is shown in Table 63. The major factor limiting natural macroalgal growth is nutrients. Overcoming this limitation constitutes the major challenge and cost of ocean farming. Studies presented here suggest that upwelling is too costly and that the most attractive option is recycle of nutrients from conversion processes. Growth is the major cost component of macroalgal farms and can be reduced by nearshore growth versus open ocean. The major technical challenge remaining is to successfully grow macroalgae in the open ocean. Numerous attempts to do so have been unsuccessful.

The suitability of biomass and waste feedstocks for anaerobic digestion depends significantly on the biogasification potential. BMP data for several feedstocks analyzed are shown in Tables 64 and 65. In general, most macroalgal species examined gave good yields and rates of conversion.

Anaerobic digestion of marine macroalgae has been demonstrated with both high conversion rates and yields. These parameters vary among different species and with the same species depending upon growth conditions. Macroalgae have a high salt content and require adaptation of a halophilic inoculum which may be obtained from a conventional digester or halophilic anaerobic environments. The performance of inocula from both sources is similar. The digester of choice is one of several that have longer solids than hydraulic retention times. Promising results were obtained with vertical and horizontal solids concentrating reactors. Good kinetics and conversion were also obtained with fluidized bed and two-phase digester designs.

The overall costs of producing substitute natural gas from marine macroalgae are higher than those of grass, wood, and waste systems and substantially higher than fossil fuels in the U.S. This high cost is related to the elevated cost of farming in the ocean, which may be reduced substantially by recovery of by-products and stimulation of mariculture. The economics of waste systems are the best because of tipping fees associated with treatment. It should be recognized that the current low cost of fossil fuels is dependent upon real subsidies and those hidden such as their environmental impact.

The major incentive for reconsideration of energy crops for conversion to methane is the environmental impact of fossil fuel use. The severity of this impact has led to international discussions of imposing a carbon tax in the range of 50-100 dollars per ton of carbon released as carbon dioxide. The impact of such a tax is illustrated in Figure 51. Considering this tax and the cost of its removal during combustion, biomass will readily become a viable option. Furthermore, the long-term depletion of fossil fuel resources and reduced dependency on foreign imports provide strong additional incentives for rapid development of renewable energy resources.

As population increases and technology development begin to result in significant resource depletion and environmental deterioration, we must take a global view on the ground rules for sustaining our species in a manner that is compatible with preservation of the biosphere. This will require production of feed, food, and energy by technologies that are indefinitely sustainable and which have minimal environmental impacts. This will involve a major shift to renewable resources for energy; sustainable agricultural practices for production of food, feed, and energy; recycle of all non-renewable resources, e.g., minerals, metals, etc.; and elimination of discharge of anthropogenic materials and compounds into the environment, e.g., plastics and toxic chemicals. Derivation of methane from energy crops and organic wastes could play a major role toward this objective.

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Tables

Table 1. Major biomass program sponsors and contractors (marine biomass: *Macrocystis pyrifera*)

Research Focus	Sponsor	Key Persons	Contractor	Key Persons
	American Gas Association/Gas Research Institute	Ab Flowers Peter Benson Kimon Bird Jim Frank Tom Hayes Mike Wilke		
	US DOE/ ERDA/SERI	Leon Loehr Barbara Goodman Rosco Ward		
	U.S. Navy	Howard Wilcox Tom Leese		
	EPRI	Spencer		
Growth			California Institute of Technology	Wheeler North Valrie Gerard
			Neushul Mariculture	Mike Neushul B. Harger
Processing			USDA Lab., Albany, CA	Mark Hart
Biogasification			Institute of Gas Technology	Don Klass Sam Ghosh David Chynoweth Kerby Fannin Vipul Srivastava
			General Electric	John Forro
System Design and Analysis			General Electric	Alan Tompkins Armond Bryce Joe Leone Robert Sullivan K. Jain
			Parsons	Parsons
			Dynatech	Ed Ashare
			US Office of Technology Assessment	
			US DOE, ERDA, SERI	D. Feinberg R. Hoffman V. Budhraja
			US Navy (Naval Weapons Center)	H. Wilcox Tom Leese
			SRT International	J. Jones
			Argonne Nat. Lab	R. Ritschard
			EPRI	I. Snow

Table 2. Major biomass program sponsors and contractors (marine biomass: *Laminaria, Gracilaria, Sargassum, and Ulva*)

Research Focus	Sponsor	Key Persons	Contractor	Key Persons
	Gas Research Institute	Ab Flowers Peter Benson Kimon Bird Jim Frank Tom Hayes		
	New York State Energy Authority			
	New York Gas Industry Group			
Growth			Harbor Branch	John Ryther Dennis Hanisak Bryan Lapoint Kimon Bird
			State University of New York	D. Squires Bud Brinkhuis Valrie Harper H. Levine G. Sclenk S. Tobin
			University of South Florida	Cllinton Dawes
Biogasification			Institute of Gas Technology	David Chynoweth Kerby Fannin Vipul Srivastava
			University of Florida	David Chynoweth Doug Jerger
			Harbor Branch	John Ryther Denis Hanisak
System Design and Analysis			State University of New York	D. Squires
			GRI	Kimon Bird

Table 3. Major biomass program sponsors and contractors (land-based biomass)

Research Focus	Sponsor	Key Persons	Contractor	Key Persons
	Gas Research Institute	Ab Flowers Peter Benson Kimon Bird Jim Frank Tom Hayes		
Growth Grasses			University of Florida	Gordon Prine Stan Schenk Paul Mislevy George S\nyder
Growth Sorgum			Texas A&M	Fred Millar
Growth Wood			Syracuse University	Ed White
			University of Florida	Don Rockwood
			University of Toronto	Louis Zuffa
Biogasification			Institute of Gas Technology	David Chynoweth Kerby Fannin Vipul Srivastava
			University of Florida	David Chynoweth Paul Smith
			Cornell University	William Jewell
			Texas A&M University	Charles Coble
System Design and Analysis			University of Florida	Wayne Mishoe Clide Kiker
			Reynold Smith and Hills/Radian Corp.	Robert Legrand
			Gas Research Institute	Kimon Bird Ann Ashby

Table 4. Major biomass program sponsors and contractors (community wastes)

Research Focus	Sponsor	Key Persons	Contractor	Key Persons
	Gas Research Institute	Ab Flowers Peter Benson Kimon Bird Jim Frank Tom Hayes		
Water Hyacinth				
Growth (water hyacinth)			University of Florida	Ramesh Reddy
Growth Walt Disney World			Reddy Creek Utilities	Tom DeBusk Ben Schwegler
Growth Wood			Syracuse University	Ed White
Harvesting and Feed Preparation			University of Florida	Larry Bagnall
Biogasification			Institute of Gas Technology	David Chynoweth Vipul Srivastava
			University of Florida	David Chynoweth
System Design and Analysis			Reynold Smith and Hills/Radian Corp.	Robert Legrand
Solid Waste				
Feed Sorting			Solid Waste Management	
Biogasification			Solid Waste Management	
			Institute of Gas Technology	Rich Biljetina Vipul Srivastava
			University of Florida	David Chynoweth John Earle
Landfill Gas				
Systems Analysis			Black and Vetch	
			Reynold Smith and Hills/Radian Corp.	Robert Legrand

Table 5. Total and volatile solids content of select biomass feeds. (Chynoweth et al. 1987)

	TS wt%	VS TS wt%	Stoichiometric Methane Yield, SCM/kg (SCF/lb)
Macrocystis sp.	12	60	0.52 (8.4)
Laminaria sp.	10.4	89	0.49 (7.9)
Water Hyancinth	42	82	0.54 (8.6)
Sorghum	84	87	0.47 (7.5)
Hybrid Poplar	87	99	0.53 (8.5)

Table 6. Proximate and ultimate analysis of *Macrocystis*. (Chynoweth et al. 1987)

Kelp Lot No.	48	50	53	56	59
TS, %	11.1	11.7	12.6	11.8	12.9
Moisture, %	88.9	88.3	87.4	88.2	87.1
VS, % of TS	53.8	56.3	60.2	57.9	63.9
Ash, % of TS	46.2	43.7	39.8	42.1	36.1
Elements, % of TS					
Carbon	25.2	26.5	29.8	25.7	29.7
Hydrogen	3.4	3.5	4.0	3.3	4.2
Nitrogen	1.9	1.8	2.0	2.2	1.7
Phosphorus	---a	0.3	0.3	0.3	0.2
Sulphur	1.0	1.1	0.9	1.2	0.2
C/N	13.4	14.7	14.9	11.7	17.5
C/P	---a	88.3	99.3	85.7	14.8
Mannitol, % of TS	9.1	8.3	21.4	15.4	18.7
Heating Value, kJ/kg dry wt	9470	9960	11,300	10,090	11,420
(Btu/lb dry wt)	(4070)	(4280)	(4860)	(4340)	(4910)
Stoichiometric Methane Yield, SCM/kg VS added	0.51	0.50	0.52	0.44	0.48
(SCF/lb VS added)	(8.1)	(8.0)	(8.4)	(7.1)	(7.7)

[a]Not determined

Table 7. Solids composition and biodegradability of *Laminaria saccharina* and *Macrocystis pyrifera.* (Chynoweth et al. 1987)

Lot No.	Growth Conditions Light	Fertilizer	TS (%wet wt)	VS (% TS)	Methane Yield, SCM/kg (SCF/lb) VS added	VS Reduction (%)
			Laminaria saccharina			
D-12	Ambient	Yes	16.6	78.6	0.26 (4.2)	63
SC3-1	High	No	23.5	82.5	0.29 (4.7)	65
SC3-5	High	Yes	24.6	83.0	0.29 (4.7)	77
SC3-2	Low	No	18.9	75.6	0.24 (3.8)	65
SC3-4	Low	Yes	20.6	76.2	0.26 (4.1)	53
KC1	Ambient	Yes	10.4	61.8	0.26 (4.4)	56
KC2	Ambient	No	9.9	60.4	0.30 (4.8)	58
			Macrocystis pyrifera			
53	Ambient	No	12.6	60.2	0.43 (6.9)	82

a-60 day SRT

Table 8. Range of methane yields and conversions efficiencies for different macroalgae (based on biochemical methane potential assays). (Marine Biomass Workshop 1990)

Genus	Decomposition % VS* redn.	L (g VS)$^{-1}$	Methane Yield Mg-C (Mg VS)$^{-1}$
Gracillaria	50 - 85	0.28 - 0.40	0.15 - 0.21
Laminaria	46 - 60	0.23 - 0.30	0.12 - 0.16
Sargassum	12 - 30	0.06 - 0.19	0.03 - 0.10
Macrocystis	34 - 80	0.14 - 0.40	0.08 - 0.21
Ulva	62	0.31	0.17

*VS = ash-free dry wt. (550°C)

Table 9. Performance of CSTR on two different *M. pyrifera* lots at different loading rates. (Chynoweth et al. 1987)

Loading Rates

Loading Rate, kg VS/m^3-day (lb VS/ft^3-day)	Lot 50 Methane Yield, SCM/kg VS (SCF/lb VS) added	Lot 50 VA, mg/L	Lot 53 Methane Yield, SCM/kg VS (SCF/lb VS) added	Lot 53 VA, mg/L
1.6 (0.1)	0.25 (4.0)	3500	0.35 (5.60)	100
3.2 (0.2)	0.24 (3.8)	3000	0.33 (5.30)	--a
4.8 (0.3)	0.03 (0.5)	22,000	0.32 (5.2)	210
6.4 (0.4)	--a	--a	0.31 (4.96)	100
8.0 (0.5)	--a	--a	0.31 (4.89)	2100
9.6 (0.6)	--a	--a	0.28 (4.50)	4300
11.2 (0.7)	--a	--a	0.07 (1.15)	23,300

[a]Data not available

Table 10. Solids and hydraulic retention times in CSTR as NMVFR receiving *Macrocystis pyrifera* Lot 53 at several loading rates. (Chynoweth et al. 1987)

Loading Rate kg VS/m^3-day (lb VS/ft^3-day)	Hydraulic Retention Time, Days NMVFR and CSTR	Solids Retention Time, Days NMVFR	Solids Retention Time, Days CSTR
1.6 (0.10)	50	---a	50
3.2 (0.20)	25	---a	25
4.8 (0.30)	17	66	17
6.4 (0.40)	12	45	12
9.6 (0.60)	10	28	10
11.2 (0.70)	8.5	23	8.5

[a]Not measured.

Table 11. Comparison of solids concentrating reactor on different lots of *M. pyrifera.* (Chynoweth et al. 1987)

Lot No.	53		54	
Loading Rate, kg VS/m3-day (lb VS/ft3-day)	8.0 (0.50)	9.6 (0.60)	8.0 (0.50)	9.6 (0.60)
Methane Yield, SCM/kg VS added (SCF/lb VS added	0.35 (5.6)	0.34 (5.5)	0.31 (4.9)	0.29 (4.6)
Methane Production Rate, vol CH_4/vol culture-day	2.8	3.3	2.5	2.8
Methane Yield Efficiency, [a]%	67	65	69	65
Stoichiometric Methane Yield, SCM/kg VS added (SCF/lb VS added	0.52 (8.4)		0.44 (7.1)	

[a]Defined as the ratio of experimental methane yield to the stoichiometric methane yield.

Table 12. *Macrocystis pyrifera* composition. (Ritschard et al. 1981)

KELP COMPOSITION	Water 87%
	Total Solids 13%
	Volatile Solids 7.6%
CHEMICAL CONTENT	Carbon 302
(of volatile solids)	Nitrogen 1.6%
	Phosphorus 0.3%
ENERGY CONTENT	8000 Btu/lb. dry ash-free (DAF)

Table 13. Basic parameters--commercial kelp farm. (Ritschard et al. 1981)

SITE LOCATION	California coastal waters
	(about 20 miles offshore)
BIOMASS SOURCE	*Macrocystis pyrifera*
BIOMASS REQUIREM ENT	279 million kelp plants
PLANT SURVIVAL	20% plant lose per year due to
	environment and harvesting
YIELD POTENTIAL	50 DAY tons/acre-year
	(Range: 25-75 DAF tons/acre-year)
NUTRIENT REQUIREMENT	3 microgram atoms Nitrogen/liter
STATION KEEPING METHOD	Bottom moored
UPWELLING SYSTEM	Direct Displacement Wave Pump
UPWELLING REQUIREMENT	2100 gallons/minute/acre
UPWELLING DEPTH	300-1500 feet
CONSTRUCTION MATERIAL REQUIRED	6690 kilotons concrete
	760 kilotons steel
	3970 kilotons synthetic

Table 14. Basic parameters—anaerobic digestion process. (Ritschard et al. 1981)

METHANE YIELD	5.5 Standard Cubic Feet (SCF)/lb. volatile solid (VS) added
RETENTION TIME	10-18 days
LOADING RATE	0.2 lb VS/SCF
TEMPERATURE	350 C
DIGESTER GAS COKPOSITION	Methane-CO_2 (by volume) Carbon Dioxide-4O% (by volume)
PRODUCT GAS OUTPUT	3.48 x 10^{11} SCF methane/year 2.32 x 1011 SCF carbon dioxide/year
DIGESTER RESIDUE	200 million tons/year

Table 15. Biological research recommendations. (Ritschard et al. 1981)

Debris	Ranking
Define more precisely the kelp yield expected from offshore farming In order to evaluate potential environmental Impacts of the lose and decomposition of kelp from a farm.	High
Assess the, particulate organic matter (PON) flux from the kelp (due to kelp, wrack, kelp fragments, fermentation residues disposal on the farm, fouling organisms) to the deepwater column and sediments to determine Impact on oceanic oxygen budgets.	High
Develop scenarios for disposal options or utilization of fermentation residues, Including post-treatment processes, animal feed, fertilizer, ocean farm disposal, and by-product utilization.	High
Assess the consequences of farm failure on the sea-floor and/or coastline.	Medium
Organisms	
Assess potential for entrainment of small organisms (small fish, crustaceans, and plankton) into a kelp farm's upwelling system.	Low
Assess potential of a kelp farm to restrict migratory patterns of larger marine organisms (such an whales and sharks).	Low
Communities	
Determine the relationship, positive or negative, of a large kelp farm to recreational and/or commercial fisheries.	Medium
Obtain a better understanding of the biological communities, both benthic and pelagic, expected to be associated with large offshore farms.	Medium
Biochemical/Biophysical	
Determine possible impacts of chemical treatments on the farm to control pests such as weed species, animal grazers, and fouling organisms.	Medium
Address possible changes, both positive and negative, to planktonic systems and detrital food wells downstream of the plume of upwelled water.	Medium
Investigate displacement of planktonic communities as a result of changes in light, nutrients, temperature, etc.	Medium
Consider ways to which polyculture (i.e. the intentional culture of organisms with kelp) could mitigate or modify Issues such as particulate organic matter disposal, non-natural chemical and waste	Low

additions, and organic exudates.

Table 16. Physical/chemical research recommendations. (Ritschard et al. 1981)

Oceanographic	**Ranking**
Develop a model to determine the fate and notion of upwelled water within the form as a prerequisite to determining design issues such an pumping rates and sitting criteria.	High
Analyze data on variable and sodium scale currents to enable detailed farm structural design to be carried out.	Medium
Collect and analyze data on mixed layer depth distribution from the southern California Bright waters on a seasonal and locational basis. These upper waters make up the thermocline and this knowledge to crucial in estimating the amount of water to be pumped.	Medium
Determine the effects of a dampened wave field due to a large kelp farm, on local wave climate, shoreline formation and ultimately on Inshore habitats. Obtain a better understanding of local climatic effects as a result of large scale upwelling.	Medium
Determine residence time of upwelled water.	Medium
Obtain a better understanding of the deep ocean circulation patterns which provide oxygen and nutrients to the kelp farm.	Low
Obtain a better understanding of local climatic effects as a result of large scale upwelling.	Low
Design	
Determine hydrodynamic loading on the kelp farm Installations (kelp plants, mooring system, kelp attachment structure, and deep-water pipe and pumps) as a result of forces generated by ocean currents and large, long-period waves.	Medium
Assess survivability of the farm structure Including fatigue, synthetics and flex joints.	Low
Study deepwater pumping In light of the efficiency and survivability of wave-powered pumps, and other pumping alternatives.	Low
Investigate various farm configurations as methods to minimize current loads and maximize the utilization of wave energy.	Low

Operational

Develop and apply practical site selection criteria that consider site features, farm characteristics, and site usage.	High
Examine the characteristics of the waste generated and develop disposal strategies or utilization options.	High
Investigate the environmental Impact (air, water, land) of a continuous construction and maintenance period on the kelp farm.	Medium
Study legal Issues associated with open ocean farms (international and U.S. policy).	Medium
Determine the biotic and abiotic releases from the kelp farm.	Medium
Determine what other substances (games, trace metals) may be released In upwelling the deep water.	Medium
Evaluate the legal Issues surrounding kelp farms in International waters.	Low

Table 17. Energy from marine biomass studies - an overview. (Aquaculture Associates 1982)

	Dynatech (1978)	SRI Int'l. (1979)	GE (1978)	Integrated Sciences Corp. (1976)	Remarks
1. STUDY APPROACH	Cost analysis of aquatic biomass systems to determine engineering cost information for planning R&D programs of aquatic biomass energy resources. Considered both ocean and land based alternatives.	Analysis of other studies to allow calculations of expected costs of producing methane from marine biomass.	Utilizes an analysis of four subsystems (cultivation, harvesting, processing, support) to determine the economic potential of producing methane from marine biomass.	Examines the concept of ocean food and energy farms (OFEF) by study of five subsystems (cultivation, harvesting, processing, support, mariculture).	Direct comparisons must consider specific study approaches and relevant assumptions.
2. CONCLUSIONS	Open-ocean energy potential does not merit further study based on production yields, nutrient supply costs, environment and legal constraints.	1) Methane from kelp not economic in the near term 2) Kelp costs too high 3) Production of high-value co-products could improve economics and should be investigated.	1) Synthetic natural gas (SNG) production from marine biomass can result in a significant energy product at a competitive price. 2) There is a strong energy cost interaction between kelp yield, kelp volatile solids content, and gas yield. 3) Kelp genetic studies should be conducted to optimize kelp methane production capacity.	1) OFEF offers a means of significantly increasing world food and energy supplies over the long term. 2) It is an environmentally clean, renewable resource technology. 3) Initial cost and productivity estimates appear competitive with future energy sources. 4) Technology advances, optimized designs, and economies of scale are likely to increase future cost competitiveness.	Conclusions reflect specific assumptions and values used in the various studies.

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Table 18. Comparison of general baseline assumptions. (Aquaculture Associates 1982)

	Dynatech	SRI	GE	ISC	Remarks
Feedstock	Macrocystis pyrifera	Macrocystic pyrifera	Macrocystis pyrifera	Macrocystis pyrifera	Choice of feedstock establishes physical and biological requirements. Dynatech also reviews land-based aquatic biomass feedstocks
Gas Conversion Rates	NA	3.75 SCF/lb. VS*	5.5 SCF/lb. VS	4.6 SCF/lb. VS	Directly related to gas productivity and inversely related to gas cost.
Farm Size	64,000 acres (100 mi^2)	19,200 to 22,400 acres (30-35 mi^2)	64,000 acres (100 mi^2)	100,000 acres (appr. 156 mi^2)	Cost of production is directly related to size.
Kelp Yield	1-50 DAFT/acre-yr.**	15 DAFT/acre-yr.	62.5 DAFT/acre-yr.	23.8 DAFT/acre-yr.	Impacts farm size requirement. GE value is gross productivity.
Harvest Loss	NA	NA	16-20%	NA	Direct relation to production costs.
Gas Production Level	NA	5 x 10^6 SCF/day	100 x 10^6 SCF/day	6.7 x 10^6 SCF/day	Affects capital costs of processing plant.
Projected Investment	Ranges \$386 x 10^6 to \$534 x 10^6 for yields of 1 DAFT/acre-yr \$1181 x 10^6 to \$1908 x 10^6 for yields of 50 DAFT/acre-yr.	\$72.5 x 10^6 (Processing Plant Only)	\$1274 x 10^6 (Capital cost all four subsystems) \$117 x 10^6 (Processing subsystem)	\$569.6 x 10^6 (Not including \$156.9 x 10^6 (Processing subsystem)	A wide range of projected costs based on specific study assumptions
Gas Cost	Algae cost range \$170/ton (\$32 mm Btu) to \$330/ton (\$80 mm Btu)	\$12 to \$15/mm Btu	\$6.15/mm Btu	\$4.91/thousand ft^3 \$3.60/thousand ft^3 with mariculture	One thousand ft^3 of methane is approximately equal to a million Btu.

* Standard cubic feet/lb. volatile solid ** Dry ash free tons/acre per year

Table 19. Comparison of baseline design assumptions - cultivation systems. (Aquaculture Associates 1982)

	Dynatech	SRI	GE	ISC	Remarks
1. Ocean Depth	2500 ft.	150 meters (492 ft.)	1200-2500 ft. Range from 600-3600 ft.	Dynamic positioned	Affects capital costs of farm. Dynamic positioning requires direct energy input.
2. Substrate Depth	60 ft.	12 to 24 meters	70 ft.	100 ft.	Impacts substrate design and cost.
3. Farm Site Location	limit of continental shelf	NA	25 miles from California coast	100 miles off S. California coast	Affects transportation costs. Establishes nutrient supplement requirements.
4. Nutrient Uptake Efficiency	30-60%	NA	60%	70%	Inverse relation to nutrient upwelling requirement hence nutrient supply system costs.
5. Nutrient Supply System	Wave pumps, 1 per 50 acres, supplemented by fuel or electric power	NA	Wave pumps, 1 per 10 acres	Wave pumps, 1 per 20 acres	Available environmental energy offsets need for direct conventional energy inputs and costs of nutrient supply system.
6. Current Flow Velocity and Direction	1 knot per hour	NA	2.0 knots per hour maximum, 0.5 knot avg. constant flow velocity and direction	1.0 knot per hour head-on current, 0.3 knot avg.	Affect cost and complexity of farm design, construction, and operation.

Table 20. Comparison of baseline design assumptions - harvesting subsystem. (Aquaculture Associates 1982)

	Dynatech	SRI	GE	ISC	Remarks
1. Wet Kelp Tonnage	13 to 666 wet tons/acre-yr.	200 wet tons/acre-yr.	328 to 1315 wet tons/acre-yr.	340 wet tons/acre-yr.	Tonnage of shipment influences the size and number hence cost of ships.
2. Delivery Distance	100 miles	NA	20 to 100 miles	100 miles	Distance to shore will influence energy and cost.
3 Energy Consumption in Harvest Subsystem	Computed on Yield Basis (T/A-yr) x 10^{12} Btu/yr 1: (0.2-1.6) 80-270 % 5: (0.4-1.9) 44-114 % utilized 10: (0.6-2.1) 41-91 % 30: (1.5-3.1) 38-75 % utilized 50: (2.3-3.9) 36-71 % utilized	NA	NA	3.2 x 10^{12} Btu	Impacts net energy production potential. Not considered in GE study except as indirect energy consumed in construction materials.
4. Harvesting Speed	Used ISC data	NA	1.5 to 4.5 knots/hr	3 knots/hr	Vessel speed and width define harvest capability, number of ships and hence energy and cost. Also impacts kelp growth and survival rates.
5. Harvest Frequency	2 to 14 times/yr	NA	Every 42 days, appr. 8 times/yr	6 times/yr	Impacts energy costs. Determined by farm yield assumptions.

Table 21. Comparison of baseline assumptions - processing subsystem. (Aquaculture Associates 1982)

	Dynatech	SRI	GE	ISC	Remarks
1. Energy Conversion Process	NA	Anaerobic digestion at ambient temperature, appr. 22°C	Anaerobic digestion at ambient temperature, appr. 22°C	Anaerobic digestion at 60°C	Establishes process costs and energy requirements.
2. Processing Location	NA	1,000 ft from dock	1 mile from shore 50 ft rise in elevation	25 miles from shore in California desert	Energy and costs affected by transport distance, elevation.
3. Kelp Pretreatment	NA	Chopped kelp slurried into digester	Grind to size required, slurried into digestor	Temperature raised to 60°C, pressed separation of carbohydrates from salts, filtration to remove soluble carbohydrates	Influences cost and energy required to process kelp for digestor.
4. Digestor Parameters	NA	Loading rate 0.1 lb. VS/ ft^3 digestor-day, 15-day retention	Loading rate .49 lb. VS/ ft^3 digestor-day, 6-day retention	Loading rate .06 lb. VS/ft^3 digestor-day, 6-day retention	Direct influence on digestor volume requirement and cost of processing plant.
5. Kelp to Methane Conversion Efficiency	NA	Conversion at 59% Gas products: 50% CH_4, 50% CO_2	Conversion at 70% Gas products: 60% CH_4, 40% CO_2 by volume	Conversion at least 49%: 40% CH_4, 60% CO_2 by mass	Directly affects kelp mass requirements and digestor volume.
6. Gas Processing	NA	Scrubbed, CO_2 removed, compressed to 1000 PSIG*	Scrubbed, CO_2 removed, compressed to 600 PSIG	Scrubbed, CO_2 removed, compressed to 1000 PSIG	Influences gas costs and storage requirements.

Table 22. Comparison of subsystems costs in millions of dollars. (Aquaculture Associates 1982)

Subsystem	Dynatech	SRI	GE	ISC	Remarks
Cultivation	See Table 6A	NA	Total Plant Investment 718 Working Capital 14 Construction Interest 48 Start-up Costs 284 Subtotal 1066 Annual Operating Costs 18	Total Plant Investment 260.9 Average Ann. Op. Cost 11.0	ISC assumes a larger farm size, dynamic positioning; yet estimates lower investment cost. GE system has been based on significantly higher yields requiring larger investments in substrate, nutrient supply system and mooring.
Harvest		NA	Total Plant Investment 71 Working Capital 1 Construction Interest 0 Start-up Costs 3 Subtotal 75 Annual Operating Costs 14	Total Plant Investment 133.8 Average Ann. Op. Costs 17.4	Harvesting techniques basically the same (scale up conventional kelp harvest methods) ISC estimate probably reflects impact of greater farm size.
Process		Total Plant Investment 58.9 Working Cap. 1.4 Construction Interest 9.2 Start-up Costs 3.0 Subtotal 72.5 Ann. Operating Costs 27.16	Total Plant Investment 99 Working Capital 2 Construction Interest 13 Start-up Costs 2 Subtotal 117 Annual Operating Costs 11	Total Plant Investment 156.9 Average Ann. Op. Costs 24.1	SRI plant is 1/20 size of GE. ISC plant is 2/3 size of GE. Plant size determined by assumptions of farm size, net kelp yields, and efficiency of kelp conversion to gas.
Support		NA	Total Plant Investment 12 Working Capital 1 Construction Interest 0 Start-up Cost 4 Subtotal 16 Annual Operating Costs (NA)	Total Plant Investment 18.0 Average Ann. Op. Costs 8.9	Appear to be in close agreement. Larger farm size may explain ISC's higher cost estimate.
Mariculture		NA	NA	Total Plant Investment 40.1 Average Ann. Op. Costs 74.0	Only consider by ISC in substantial degree. System adds 120% to operating costs. Lowers gas cost by 26%. Does not impact gas output.
Total			Total Plant Investment 900 Working Capital 18 Construction Interest 62 Start-up Cost 294 Total 1274 Annual Operating Costs 44	Total Plant Investment 609.7 Working Capital 9.2 Start-up Cost 177.2 Total 796.1 Annual Operating Costs 135.4	Total project cost of GE system is greater but gas output is 1/3 more than ISC. Most cost difference contributed by cultivation subsystem of GE which is more intensive for high yields.

Table 23. Summation of kelp to methane system and economic study by R. M. Parsons. (Bird 1987)

Summation of Kelp to Methane System and Economic Study by R. M. Parsons.

	Production	Systems Description: Harvesting	Systems Description: Conversion	Methane Yield (L/kg VS added)	Size (J/Y)
BASELINE	34 DAFMT/HA/Y	1 harvester 3 barge-tugs	3 fixed film reactors	.43	1×10^{15}
ADVANCED	101 DAFMT/HA/Y	2 harvesters 6 barge-tugs 50% less labor	7 fixed film reactors	.53	3.5×10^{15}

	Production	Capital Costs (millions of $): Harvesting	Conversion	Gas Clean-up	Total
BASELINE	21	11	3	11	46
ADVANCED	30	24	8	23	157

	Production	O & M/Fuel (Millions of $): Harvesting	Conversion	Gas Clean-up	Total
BASELINE		2.6/0.7	1.0/.03	.1/.06	3.7/ .79
ADVANCED		2.8/1.4	1.4/.03	.2/.06	4.4/1.49

	Production	Levelized Gas Cost (1982$): Harvesting	Conversion	Gas Clean-up	Total
BASELINE	1.46	4.80	3.47	2.03	11.75*
ADVANCED	0.60	1.99	2.09	1.03	5.72

*Original report shows $13/G joule. Error found in O & M associated with bioconversion and gas clean-up.

Table 24. Updated economics and assumptions for nearshore kelp to methane systems. (Bird 1987)

	Systems Description				
	Production	Harvesting	Conversion	Methane Yield (L/kg V.S. Add)	Size (J/Y)
BASELINE	34 DAFMT/HA/Y	2 harvesters 6 barges 4 tugs	5 upflow	0.43 reactors	1.9×10^{15}
ADVANCED	50 DAFMT/HA/Y	2 harvesters 6 barges 5 tugs	7 upflow reactors	0.50	3.4×10^{15}

	Capital Costs (Millions of $)				
	Production	Harvesting	Conversion	Gas Clean-up	Total
BASELINE	39	15	18	15	87
ADVANCED	45	23	40	23	131

	O & M/Fuel (Millions of $)				
	Production	Harvesting	Conversion	Gas Clean-up	Total
BASELINE		2.7/1.2	1.0/.06	0.1/.08	3.8/1.34
ADVANCED		2.9/1.4	1.4/.06	0.2/.08	4.5/1.54

	Levelized Gas Cost				
	Production	Harvesting	Conversion	Gas Clean-up	Total
BASELINE	2.22	3.42	1.43	0.96	7.83
ADVANCED	1.30	2.32	1.49	0.78	5.89

Table 25. Systems components and capital costs of the New York marine biomass baseline and advanced systems located in the nearest and furthermost distances from the conversion facility. (Bird 1987)

	In Thousands of Dollars			
	BASELINE		ADVANCED	
	NEAR	FAR	NEAR	FAR
FARM				
Hectares	5,342	5,342	5,342	5,342
Capital	73,864	73,864	73,864	73,864
NURSERY				
Capital	1,071	1,071	1,071	1,071
O & M	600	600	600	600
Fuel	100	100	100	100
HARVESTING				
# Harvesters	4	4	4	4
# Tugs	1	1	2	3
# Barges	8	8	12	12
CAPITAL	62,800	67,800	72,400	73,800
O & M				
Labor	4,050	4,250	4,800	5,288
Maintenance	250	250	300	312
Total O & M	4,300	4,500	5,100	5,600
Fuel	2,600	2,750	3,000	3,100
FARM MAINTENANCE				
O & M	3,756	3,863	3,863	3,863
Fuel	20	40	40	40
SHORE FACILITY				
Capital	3,592	7,592	6,514	6,835
O & M	700	700	2,000	2,000
TOTAL				
Capital	146,327	146,327	153,849	155,570
O & M	9,293	9,600	11,500	12,000
Fuel	2,720	2,890	3,140	3,240
Cap+15% cont.	$\$168 \times 10^6$	$\$168 \times 10^6$	$\$177 \times 10^6$	$\$179 \times 10^6$
FEEDSTOCK COSTS AT 0.43 1/kg V.S. added				
$/G joule	44	45	12	13

Table 26. Summary of tidal flat farm feedstock costs by biomass yield. (Bird 1987)

DAFMT/HA/Y	11	23
Capital	$7,288,000	$11,538,000
O & M	1,176,000	1,342,000
Fuel	274,000	314,000
Joule/year*	6.17×10^{14}	1.23×10^{15}
$/G joule	3.60	2.30
Sensitivities ($/G joule)		
+$1MM Capital	4.10	2.46
+$100K O & M	4.14	2.48
+$1MM O & M	5.63	3.22

*based on 85% net methane production from the conversion facility.

Table 27. Feedstock costs of floating seaweed. (Bird 1987)

Yield (DAFMT/HA/Y)	22	45
Capital		
Containment System	$10,850,000	$10,850,000
Harvesting System	$15,000,000	$23,000,000
Operations & Maintenance	2,700,000	2,900,000
Fuel	1,200,000	1,400,000
$/G joule	6	3

(Assumes 0.43 l methane/kg V.S. added, 85% net plant production)

Table 28. Comparison of feedstock costs from marine biomass systems. (Bird 1987)

System	Yield DAFMT/HA/Y	Feedstock $/DAFMT	Cost $/G joule	Feedstock Cost (SERI) $/DAFMT
Nearshore	34	67	5.50	72
Macrocystis	50	42	3.50	41
Rope Farm	11	538	44.00	--
Gracilaria,				
Laminaria	45	147	12.00	--
Tidal Flat Farm	11	44	3.60	48
Gracilaria-Ulva	23	28	2.30	23
Floating	22	73	6.00	71
Seaweed,				
Sargassum	45	37	3.00	36

Table 29. Ethanol production costs from macroalgae. (Bird 1987)

System	$/liter Baseline	$/liter Advanced
Nearshore		
Macrocystis	.45	.30
Tidal Flat Farm		
Gracilaria	.40	.25
Ulva	.45	.30
Floating Seaweed		
Sargassum	.50	.40

*Feinberg and Hock 1985. Feedstock costs based on SERI costs, Table 6. Costs rounded to nearest tenth.

Table 30. Potential co- and by-products from a *Macrocystis* biomass system. (Tompkins 1983)

	By-Products	Co-Products
Organic	Bacterial Protein Product Phenolic Compounds	Algin Mannitol Fucoidan Plant Protein Phenolic Compounds
Inorganic	Iodine Potash Magnesium Compounds Bromine Sodium Compounds Sulfer Carbon Dioxide	Iodine Potash Magnesium Compounds Bromine Sodium Compounds Carbon Dioxide

*From Tompkins, 1982.

Table 31. Summary of by-products/ co-products impact on gas cost. (Tompkins 1983)

SCENARIO 1

- 100% of farm output used for methane production and by-products recovered from digester effluents.
- Baseline Gas Cost = $13.47/MMBTU

By-Products	Est. Gas Cost Reduction
1. Iodine + CO_2	16%
2. Iodine + CO_2 + L-fraction	
(a) L-fraction valued at $1/lb	30-35%
(b) 50% increase in L-fraction recovery costs	10-15%
(c) L-fraction valued at $3/lb at nominal or 50% higher recovery costs	***

SCENARIO 2

- Approximately 85% of the farm output used for methane production and the rest for co-products such as algin and mannitol. By-products recovered from digester effluents.
- Estimated Gas Cost = $15/MMBTU

By-Products and Co-Products	Est. Gas Cost Reduction
1. Algin + Mannitol + Iodine + CO_2	55%
2. Algin + Mannitol + Iodine + CO_2 + L-fraction	
(a) L-fraction valued at $1/lb	65-80%
(b) 50% increase in L-fraction recovery costs	50-65%
(c) L-fraction valued at $3/lb at nominal or 50% higher recovery costs	***

*** NET REVENUES FROM BY-PRODUCTS/CO-PRODUCTS MORE THAN MEET TOTAL COST OF GAS

Table 32. Technical screening of co-products and by-products. (Tompkins 1983)

Technical Producibility	Product
1. Commercially produced from kelp,	Algin Potash Iodine Mannitol
or	
High Probability of producibility from digestion effluents/kelp	Iodine (b)* Potash (b) CO_2 (b) Sulfur (b) Bromine (b, c)* Bacterial Protein Product (b)
2. Laboratory/Pilot Plant Data	Mannitol (c) Fucoidan (c) Phenolic Compound (c, b) Algin Residual (b)
3. No data on producibility from kelp or digester effluents	Cellulosics (c) Plant Protein (c) Magnesium Compounds (c, b) Sodium Compounds (c, b)

*(b) - Denotes recovery as a by-product
(c) - Denotes recovery as a co-product

Table 33. Potential for co-products from raw kelp. (Tompkins 1983)

Basis

- 500 Wet Tons/Day
- 365 Days/Yr.
  = 182,500 Tons/Yr. of Raw Kelp (RK)
- Raw Kelp Composition

Water	87.5%	1750 lbs/Ton RK
Organics	7.5%	150
Inorganics	5.0%	100

Organics		Composition	Recovery Efficiency*	Annual Production
Algin, % of Total Solids (TS)	17%	42.5 lbs/Ton RK	0.72	2792 Tons/Yr
Mannitol	15%	37.5	0.7	2395
L-Fraction	5%	12.5	0.65	740
Fucoidan	1.5%	3.8	0.60	208
Inorganics				
KCl, % of Total Solids (TS)	26%	65	0.60	3558
Iodine	0.3%	0.7	0.65	42
Bromine	0.1%	0.25	0.65	15

*Discussed in Section III

Table 34. Potential of and gross revenues from various co-products. (Tompkins 1983)

BASIS: 500 TONS/DAY OF RK

Product	Market Price, $/Ton	Annual Production, Tons/Yrs.	Potential Revenue $/Yr., Millions
Algin	$ 6000/Ton	2792	16.8
Mannitol	$ 6000	2395	14.37
L-Fraction	$ 2000-6000	740	1.5-4.4
Fucoidan	$ 6000*	208	1.25
Iodine	$14500	42	0.6
Potash	$ 60	3558	0.21
Bromine	$ 1200	15	0.02

*Assumed to be the same value as mannitol

Table 35. Potential gross revenues from gas and by-products. (Tompkins 1983)

BASIS: 1.15×10^6 Tons of Raw Kelp, Wet Basis

	Recovery Efficiency	Tons/Yr.	\$/Ton	\$/Yr.
Methane		20139	473 (\$10/1000 SCF)	9.5 Millions
Carbon Dioxide	90%	4039	35	1.4
Sulfur	90%	322	120	0.04
L-Fraction	65%	4603	2000-6000	9.2-27.6
Bacterial Protein	80%	11220	70	0.8
Potash	60%	22441	60	1.35
Iodine	65%	288	14500	4.2
Bromine	65%	115	1200	0.1

Table 36. Potential gross revenues from various by-products and co-products. (Tompkins 1983)

Methane Gas	$ 9.5	Millions/Yr.
Algin	16.8	
Mannitol	14.37	
Fucoidan	1.25	
L-Fraction	10.7-32.0	
Bacterial Protein	0.8	
Carbon Dioxide	1.4	
Potash	1.56	
Iodine	4.8	
Bromine	0.12	
Sulfur	0.04	

Table 37. Effect by-products and co-products on gas cost. (Tompkins 1983)

	Scenario 1	Scenario 2
Pretax Profits (excluding kelp cost), MM $	3.60	9.75
Annual Kelp Cost, MM $	0	1.2
Pretax Profits (including kelp cost), MM$	3.60	8.55
Estimated Gas Cost Reduction, $/MMBTU	4.27	10.15
Baseline System Gas Cost (No revenues from by-products co-products) $/MMBTU	13.47 (3 MMSCFD)	15.0 (2.6 MMSCFD)
Net Gas Cost, $/MMBTU	9.20	4.85
- Includes revenues from by-products/co-products		
% Reduction in gas cost due to by-products/co-products	31.7	67.7

Table 38. Kelp area required to stabilize atmospheric CO_2; assumes use of upwelled water as a nutrient source (Marine Biomass Workshop 1990)

Anthropogenic CO_2 production = $5X10^9$ tons C/yr (Booth, 1988)

Environmental uptake of anthro. CO_2 = $2X10^9$ tons/yr

Anthro. CO_2 remaining in atm. = $3X10^9$ tons/yr

$$\frac{3X10^9 \text{ T/yr X 2000 lbs/T X 1000 g/kg}}{2.2\text{lbs/kg}} = 2.73 \text{ X } 10^{15} \text{ g C/yr}$$

$$\frac{2.73 \text{ X } 10^{15} \text{ g C/yr}}{365 \text{ d/yr}} = 0.75 \text{ X } 10^{13} \text{ g C/day as anthro. } CO_2 \text{ output}$$

Assume kelp productivity = 3 g $C/m^2/d$, of which 2 g $C/m^2/d$ represents CO_2 removal from the atmosphere *

$$\text{Kelp area required} = K_a = \frac{0.75 \text{ X } 10^{13} \text{ g C/d}}{2gC/m^2/d} = 3.8 \text{ X } 10^{12} \text{ m}^2$$

or $K_a = 4 \text{ X } 10^6 \text{ km}^2$

or $K_a = 1.4 \text{ X } 10^6 \text{ mi}^2$

or K_a is a square 1,169 miles on a side

Table 39. Statistics for a full-scale open ocean OASIS algal farm. (Marine Biomass Workshop 1990)

OVERALL DIAMETER---------------------- 3 KM (1.9 MILES) (9840 FEET)

RIM CIRCUMFERENCE-------------------- 9.425 KM (5.855 MILES) (30,913 FEET)

TOTAL AREA----------------------------- 1,748 ACRES

DIAMETER OF HUB---------------------- 600 METERS (1,968 FEET)

AREA OF HUB--------------------------- 70 ACRES (3,041,873 FT²)

AREA OF CAPTIVE LAGOON-------------- 1,678 ACRES

VOLUME OF CAPTIVE LAGOON----------- 109,070 ACRE FEET (135,717,120 CU. M)

UPWELLING CIRCULATION RATE---------- 1,500 CUBIC FEET/MINUTE

OTEC IHP POWER CAPACITY-------------- 10 MEGA WATTS

MAXIMUM SUSTAINED PROPULSION CAPACITY- 25,000,000 HORSEPOWER

ESTIMATED COST $350 MILLION

500 FOOT DIAMETER TEST ISLANDS
(12-40 METER (131 FT) SEGMENTS)

SCALE---------------------------------- 1/20

DIAMETER OF HUB---------------------- STRUCTURAL 100 FT. MARICULTURE 32 FT.

TOTAL AREA----------------------------- 4.5 ACRES

CAPTIVE LAGOON AREA------------------ STRUCTURAL 4.33 ACRES MARICULTURE 4.48

APPROXIMATE COST $5.5 MILLION EACH

COMBINED TEST ISLAND
(48-40 METER SEGMENTS 120 METER DIAMETER HUB 1/5TH OF FULL SCALE)

OVERALL DIAMETER---------------------- 600 METERS (1968 FEET)

TOTAL AREA----------------------------- 70 ACRES

Table 40. List of suitable genera of marine macroalgae for marine farms. (Marine Biomass Workshop 1990)

Crop Genera	Remarks
Alaria	A. fistulosa is float-bearing, arctic
Corallina	calcareous, widely distributed, small, might be cultured with other large species
Cystoseira	temperate, has float-bearing repro. struct.
Ecklonia	subtropic & temperate, one float-bearing sp.
Egregia	temperate, float-bearing, very durable
Eucheuma	tropic, cultivated, mod. size
Gracilaria	widely distrib., cultivated, high product.
Laminaria	intensely cultivated, temperate
Macrocystis	semi-cultivated, harvested, temperate
Pterygophora	temperate, very durable
Sargassum	widely distrib. incl. Sargasso Sea, many spp, float-bearing, temperate & tropic

Table 41. Variability in anaerobic biodegradability of marine macroalgae. (Marine Biomass Workshop 1990)

Variability in anaerobic biodegradability of marine macroalgae. VS= volatile solids as ash-free dry wt (550° C).

Genus	% VS decomposing	Methane yield, L/g VS
Gracilaria	50-62	0.25-0.31
Laminaria	46-60	0.23-0.30
Macrocystis	34-80	0.14-0.40
Sargassum	12-30	0.06-0.19
Ulva	62	0.31

Table 42. Research plan for anaerobic digestion of macroalgae. (Marine Biomass Workshop 1996)

I. <u>Feed Characterization</u> (different species, growth conditions; samples from Bird, North, and Ryther)

- A. Proximate and Ultimate (Bird)
- B. Organic Component (Bird)
- C. Biochemical Methane Potential (Chynoweth)

II. <u>Bench-Scale Anaerobic Digestion</u> (Chynoweth)

- A. Solids Concentrating Reactor
  - 1. vertical
  - 2. horizontal
- B. Two-Phase (improved stability)
- C. Methane Enrichment Digestion (>90% methane)
- D. Automated Process Control
- E. Residue Use Options

III. <u>Pilot-Scale Anaerobic Digestion</u> (Chynoweth)

- A. Feed Processing
- B. Scaleup of Design Factors
- c. Residue Use Options

IV. Systems Analysis

Table 43. Research plan for study of algal decomposition in sediments. (Marine Biomass Workshop 1996)

1. Extent of decomposition prior to and during sedimentation

2. Dependency of growth farm on conversion for nutrient generation

3. Extent and rate of biochemical methane production during sedimentation and on the ocean floor

4. Fate of methane produced by decomposition of sedimented algae

- diffusive migration
- microbial oxidation
- ebullition

Table 44. Summary of project accomplishments relative to A & E goals. (Chynoweth et al. 1989)

	A&E Projections (Goals)	ETU system performance
Water hyacinth production (dry tons/acre-year)	50	30
Pond area required for secondary treatment (acres/MGD)	7	7
Methane yield (SCF/lb VS added)	4.7	7.5
Hydraulic retention time required (days)	28	11

Table 45. Comparison of system performance with systems goals. (Chynoweth et al. 1989)

Location on Fig. 1 schematic	Description	Units	A&E estimation	ETU performance
A	Sewage flow	MGD	50	50
B	Hyacinth pond area	acres/MGD	7	7
C	Harvested hyacinths	dry TPD*	46	27
D	Primary sludge	dry TPD	25	25
E	Digester feed blend of hyacinths and sludge	dry TPD	71	52
F	Digester effluent to disposal	dry TPD	44	19
G	Net methane produced	MSCFD	400	530
H	Reactor volume	1 MG	9.5	3.0

*Tons/day.

Table 46. Capital O&M costs for the major components of an integrated water hyacinth/ anaerobic digestion facility sized for a 500,000 population. (Chynoweth et al. 1989)

System component	Costs (1985 $$10^6$) Capital	Annual O&M
Wastewater	11.9	1.0
Water hyacinth harvesting	4.1	0.9
Anaerobic digestion	2.8	0.2
Sludge disposal	3.9	0.3
Gas cleanup	1.3	0.3
Total	24.0	2.7

Table 47. Summary of economics for the integrated water hyacinth/ anaerobic digestion facility sized for a 500,000 population. (Chynoweth et al. 1989)

Assumptions			
Return to debt	9.2%	Construction period	1 yr
Return to equity	13.7%	Book life	
Fraction by debt	0.65	Concrete structure	50 yrs
Working capital fraction	0.10	All other	20 yrs
Inflation	6.0%	Tax life	10 yrs
Unit charge for wastewater treatment	$200/MG	Net methane output	530 MSCFD
Costs (1985 $)			
Total capital		$24 million	
Total annual O&M		$2.7 million/yr	
Annual wastewater treatment revenue		$3.7 million/yr	
Levelized gas costs		$1.80/mmBtu	

Table 48. Methane costs from the integrated hyacinth/ anaerobic digestion system. (Chynoweth et al. 1989)

Population of community	Revenue for wastewater treatment*	Costs based on ETU results**
500,000	200	$1.80
100,000	280	$1.90
10,000	760	$3.00

*$/MG; wastewater treatment revenues are 15% less than assumed in the initial A&E projection.

**All costs are in 1985 dollars.

Table 49. SEBAC analysis base case parameters. (Chynoweth et al. 1990)

Mass Balance:	Capacity = 35.3 tpd MSW (7 days/week; = 49.4 tpd, 5 days/week) 15% by mass removed in preprocessing and recycled 30 tpd MSW-derived feed 7 tpd dilution liquid added 8 (dry) tpd converted to gas 27 tpd of filtercake @ 50% TS
Feed:	76.4% TS (see Appendix A) 79.7% VS (of TS) (see Appendix A) 50.0% BVS (of VS) 18.0 lb TS/cu ft 1.2 lb COD/lb VS
Conversion:	Slurry volume = 81,500 cu ft 5 reactors, 25 ft diameter, 38 ft high (incl 10% freeboard) Temperature = 55°C/131°F k = 0.08 day^{-1} (see Section 5.5) VS conversion efficiency = 46.1% Methane Yield = 3.11 scf CH_4/lb VS_a v/v/d Methane = 1.39 v/v/d Biogas = 2.53 VS Loading Rate = 0.45 lb VS/cu ft/day SRT = 32 days (plus 3-day turnover)
Byproducts:	Gas: 206,000 scf Biogas/day at 55% Methane Sold as medium Btu gas at $3/MMBtu Solid residue screened to product compost 7 tpd of rejects landfilled 20 tpd of compost sold at $0/ton (given away)
Economic Inputs:	Landfill tipping fee = $40/ton Electricity purchase = $0.06/kWh Electricity sale = $0.04/kWh Cost escalator = 6%/year Service factor = 90% (10% downtime or 5 weeks/year) Current dollar return to debt (= interest rate) = 8.1%

Table 50. Napier yields achieved. A typical high yielding variety. (Smith 1989; Woodard and Prine 1993)

Location	Years	Avg. Dry Mg/ha
Jay (NW Florida)	1983-85	40.5
	86-87	36.8
	88-89	16.3
Quincy (N Florida)	83-85	31.2
	86-87	34.9
	88-89	18.4
Gainesville (N Central Florida)	83-85	35.8
	86-87	26.5
Ona (S Central Florida)	84-85	
no fertilizer		27.5
max. fertilizer		63.1
	88-89	43.0

Table 51. Sorghum yields. (Hiler 1986; Miller and McBee 1993)

	Dry Mg ha^{-1}	% TS
High Energy Test, College Station		
Sweet Sorghum, mean	20.8	30.4
max. (Mn 1500)	29.3	28.4
Grain x Sweet Hybrids, mean	19.5	35.5
Preliminary Hybrid Trail, Thrall		
Sweet Sorghum, mean	17.2	34.4
max. (AAtlas x Mn 1500)	31.8	38.4
Grain x Sweet Hybrids, mean	16.8	36.6
Harvest Sequence Study, College Station		
60-45-45 days, mean	12.8	14.8
max (AT x 623 x Greenleaf)	17.7	17.8
150 days, mean	16.8	34.9
max (Mn 1500)	27.3	35.2
120-60 days, mean	25.3	33.1
max (Mn 1500)	34.9	33.2
60-60-60 days, mean	15.5	17.5
max (AT x 623 x Greenleaf)	22.0	23.4

Table 52. Sorghum yields. (Hiler 1986; Miller and McBee 1993)

	Dry Mg ha^{-1}	% TS
90-90 days, mean	22.2	26.5
max (AT x 623* Hegari)	25.4	28.6
120-60 days, mean	23.2	26.3
max (AT x 631* EBA3)	31.8	25.8
180 days, mean	22.5	37.7
max (AT x 631* EBA3)	40.7	35.5

Table 53. Experimental willow yields. (White et al. 1990)

Location	Highest Experimental Yield Dry Mg ha^{-1} yr^{-1}
Finland	30
Sweden	40
United Kingdom	30
Univ. of Toronto	48
SUNY Syracuse, clonal screening trial, 10 best	20-34
2 best	27, 34

Table 54. Sorghum base case. (Legrand 1993)

Inputs	
Crop Productivity	30 dry Mg ha $^{-1}$ yr $^{-1}$
Length of Harvesting Period	17 weeks
Dry Matter Content of Biomass	35% TS
Dry Matter Losses in Storage	7%
Biomass Biodegradability	90% of VS
Conversion Process	Batch Reactor (1 stage)
First Order Reaction Rate Coefficient (k)	0.10 day $^{-1}$
Retention Time	32 days
Outputs	
Theoretical * Reactor Loading Rate	4.6 g VS L $^{-1}$ day $^{-1}$
Gross Methane Production Rate	1.4 v/v/d
Gross Methane Yield	0.33 L/g VS added
Unit Cost (assuming 3.00 x 10E15 J/yr)	$6.2/GJ

Table 55. Napier grass base case. (Legrand 1993)

Inputs	
Crop Productivity	40 dry Mg ha $^{-1}$ yr $^{-1}$
Planting Cycle	15 yrs
Length of Harvesting Period	6 months
Dry Matter Content of Biomass	35% TS
Dry Matter Losses in Storage	7%
Biomass Biodegradability	76%
Conversion Process	Batch Reactor (1 stage)
First Order Reaction Rate Coefficient (k)	0.085 day $^{-1}$
Retention Time	31 days
Outputs	
Theoretical * Reactor Loading Rate	4.7 g VS L $^{-1}$ day $^{-1}$
Gross Methane Production Rate	1.2 v/v/d
Gross Methane Yield	0.27 L/g VS added
Unit Cost (assuming 3.00 x 10E15 J/yr)	$6.4/GJ

Table 56. Sample calculation of global warming impact of biomass energy; SNG from a high-yielding wood grass farm is assumed to be displacing natural gas. (Legrand 1991)

	Item		Unit
1.	Previous Biomass Yield of the Land	4.5	dry Mg ha^{-1} yr^{-1}
2.	Previous Average Standing Biomass*	2.25	dry Mg ha^{-1}
3.	Gross Energy Crop Yield	39.20	dry Mg ha^{-1} yr^{-1}
4.	Average Energy Crop Standing Biomass*	78.40	dry Mg ha^{-1}
5.	CO_2 Sequestration in Energy Crop	125.44	Mg CO_2 ha^{-1}
6.	Net Biomass Energy Production (SNG)	312.5	GJ ha^{-1} yr^{-1}
7.	Fossil Energy (NG) Displaced	312.5	GJ ha^{-1} yr^{-1}
8.	Gross CO_2 Release Displaced	17.19	Mg CO_2 ha^{-1} yr^{-1}
	Greenhouse Gas Releases (Equivalent CO_2 Mass):		
9.	Planting, Harvesting, Storage	2.20	Mg CO_2 ha^{-1} yr^{-1}
10.	Conversion, Gas Cleanup	0.40	Mg CO_2 ha^{-1} yr^{-1}
11.	Methane Leaks	0.11-1.10	Mg CO_2 ha^{-1} yr^{-1}
12.	N_2O Release	0.01-5.20	Mg CO_2 ha^{-1} yr^{-1}
13.	Total	2.72-8.90	Mg CO_2 ha^{-1} yr^{-1}
14.	Net CO_2 Release Displaced [(8)-(13)]	**8.3-14.5**	**Mg CO_2 ha^{-1} yr^{-1}**
15.	CO_2 Sequestration in Energy Crop (5)	125.44	Mg CO_2 ha^{-1}
16.	CO_2 Sequestration Increase [(15)-(2)]	**122**	**Mg CO_2 ha^{-1}**

*See Figure 4 for explanation of calculations.

Assumptions:

- Previous vegetation: herbaceous
- Energy crop rotation: 4 years
- CO_2/biomass mass ratio: 1.6 g CO_2/dry g biomass
- Chemical fertilizer application: 275 kg N ha^{-1} yr^{-1}
- 0.01 - 4.00% of fertilizer N evolved as N_2O (Conrad et. al., 1983)
- 10% dry matter loss in storage
- Biomass energy scenario: SNG production
- Fossil fuel used for comparison: natural gas
- Methane yield: 282 L CH_4/kg VS_a
- 10% methane loss in cleanup from biogas to SNG
- Overall methane leakage: 0.1-1% of SNG production

Source: Reynolds, Smith and Hills, Inc., 1990.

Table 57. Energy potential of biomass and wastes in the united states.* (Chynoweth et al. 2001)

Resource	EJ/yr
Municipal Solid Waste	1.5
Sewage Sludge and Sludge-Grown Biomass	0.8
Biodegradable Industrial Wastes	0.4
Crop Residues	4.1
Logging Residues	0.3
Animal Wastes	0.4
Energy crops l	
a. land-based	22.
- payment-in-kind land (32 million hectares)	
- 32 million additional hectares	
b. marine	>100.
Total (excluding marine)	29.5

*Sources: Legrand and Warren (1987); Chynoweth et al. (1987)

Table 58. U.S. cropland needed to displace fossil fuel energy supplies. (Chynoweth et al. 2001)

Fossil Fuel	Weight of CO_2 -C Produced in 1988 10^{15} g	% 1987 Cropland Needed to Displace Fuel
Petroleum	2.5	49
Natural Gas	1.1	28
Coal	2.2	26
Total	5.8	103

Ref: Legrand (1993)

Table 59. Cost estimates for production of biomethane from energy crops. (Chynoweth et al. 2001)

Energy Crop	Methane Cost U.S. $ per GJ[a]
Grass (sorghum)[b]	6-8
Wood (poplar)[c]	3-7
Seaweed (kelp)[d]	6-14

[a]1990 gas cost ~ $2.50 per GJ
[b]Legrand (1993)
[c]Legrand (1993)
[d]Bird and Benson (1987)

Table 60. Base case for production of methane from grasses: assumptions. (Legrand 1993)

Feedstock

- Napier grass: 54 dry tons ha per yr
- Growth Area: 7,600 ha
- Storage: ensiled, in 49 silos

Conversion

- 1,000 dry tons per day
- thirty 8,500 m^3 digesters, 55^oC, HRT 35 days
- Organic conversion: 75%

Energy Production

- 10^{13} Btu/day
- 3 x 10^{15} Btu/year

Table 61. Base case for production of methane from grasses: economics. (Legrand 1993)

Operation	$/MMBtu	% of Total Cost
Crop Production	1.74	26.1
Harvest and Storage	1.29	19.4
Transportation	0.48	7.3
Conversion	2.10	31.5
Residue Recycle	0.11	1.6
Gas Cleanup	0.94	14.1
Total	6.66	100

Table 62. Costs and energy yields for bioethanol and biomethane. (Chynoweth et al. 2001)

Bioenergy System	Energy Yield, Product/Feed, %	System Energy Requirement, % of Product Energy	Costs, $/GJ
Ethanol From Sugar Cane	38[a]	17.3[a]	$12.9[b]
Ethanol With Bagasse Hydrolysis	63[c]	ND	ND
Methane From Sorghum[d]	69.8	7.9	$6.17

[a]From Van Haandel and Catunda (1994)
[b]Based on $1.20 per gal. Ethanol
[c]Estimated from (1)
[d]R. Legrand, Personal Communication

Table 63. Growth rates or yields for macroalgae.

Alga	Growth yield	Comments	Reference
Chondrus	16 g(daf)$m^{-2}d^{-1}$	in lab tanks	Ryther 1979
Gracilaria	6 g(dw) $m^{-2}d^{-1}$	in lab tanks	Ryther 1979
Gracilaria tikvahiae	5-35 g(dw) $m^{-2}d^{-1}$	in lab tanks	Lapoint and Ryther 1978
Laminaria	25f g(dw) $m^{-2}d^{-1}$	natural	Mann 1973
Macrocystis pyrifera	7 g(daf)$m^{-2}d^{-1}$	small test farm	Wheeler and North 1991
M. pyrifera	100 g (wet) $m^{-2}d^{-1}$		Gerard 1976
Sargassum	7-12 g(dw) $m^{-2}d^{-1}$		Hanisak 1987
Ulva	7-19 g(dw) $m^{-2}d^{-1}$		DeBusk et al., 1986

Table 64. Range of biochemical methane potential data for various biomass and waste samples. (Chynoweth et al. 1993)

Sample	B_o L g^{-1} VS	k d^{-1}
Kelp (Macrocystis)	0.39 - 0.41	-
Sorghum	0.26 - 0.39	-
Sargassum	0.26 - 0.38	-
Napiergrass	0.19 - 0.34	0.05 - 0.16
Poplar	0.23 - 0.32	-
Water hyacinth	0.19 - 0.32	0.09 - 0.11
Sugarcane	0.23 - 0.30	0.05 - 0.16
Willow	0.13 - 0.30	0.01 - 0.04
Laminaria	0.26 - 0.28	-
MSW	0.20 - 0.22	0.13 - 0.16
Avicel Cellulose	0.37	0.14

Table 65. Summary of biochemical methane potential ranges for several biomass and waste samples. (Chynoweth et al. 1993)

Sample	$L\ g^{-1}$ VS
All samples	0.014 - 0.94
All seaweeds	0.26 - 0.40
All grasses	0.16 - 0.39
All woods	0.014 - 0.32
Samples with high values	
Vegetable oil	0.94
Primary sludge	0.59
Food waste	0.54
Samples with low values	
Eucalyptus	0.014
Pine	0.059
Bambo	0.016
Avicel cellulose	0.37

Figures

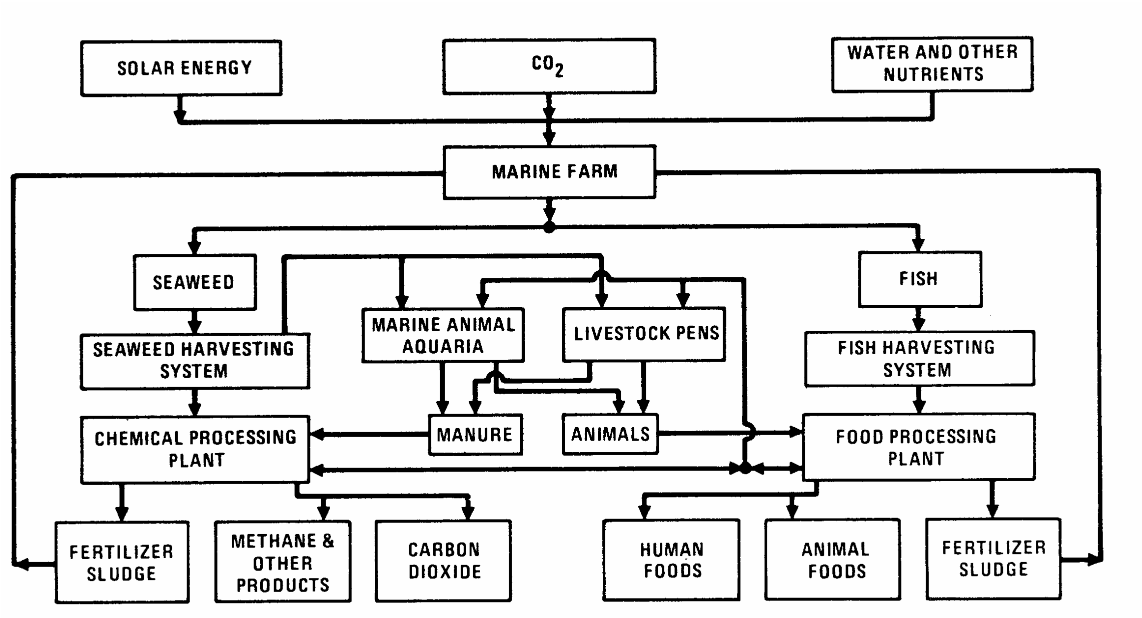


Figure 1. Marine farm system. (Leese 1976)

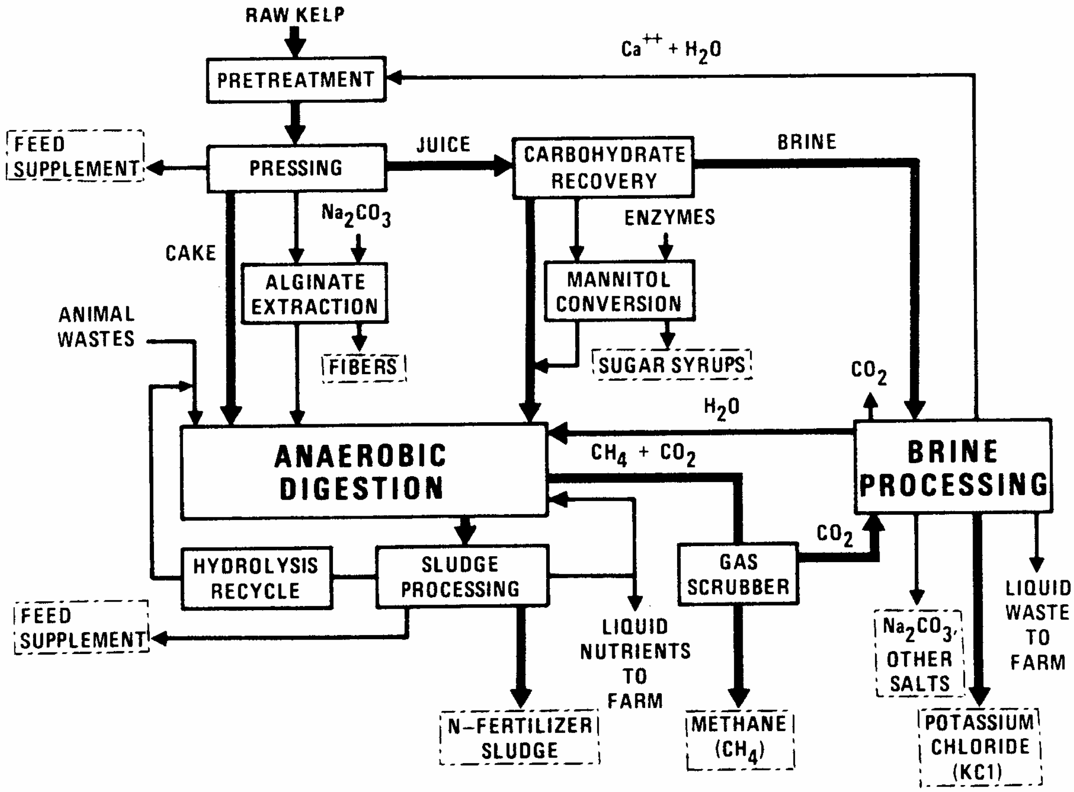


Figure 2. Kelp conversion process. (Leese 1976)

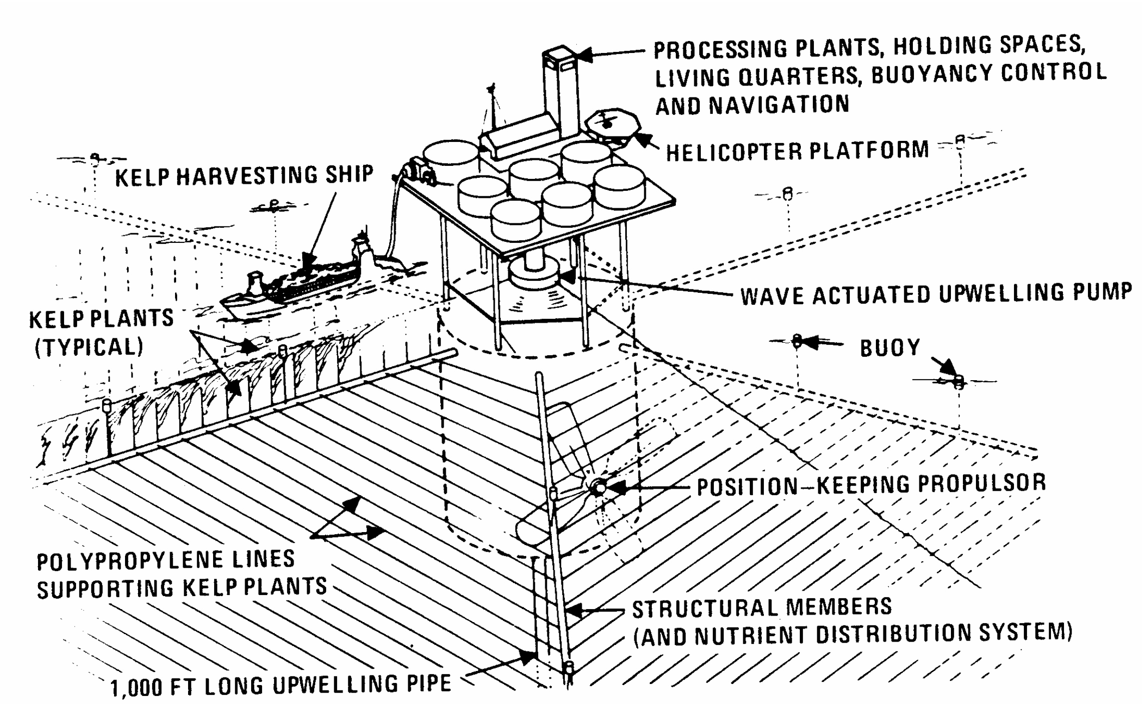


Figure 3. Conceptual design of 405 ha (1,000 acre) ocean food and energy farm unit. (Leese 1976)

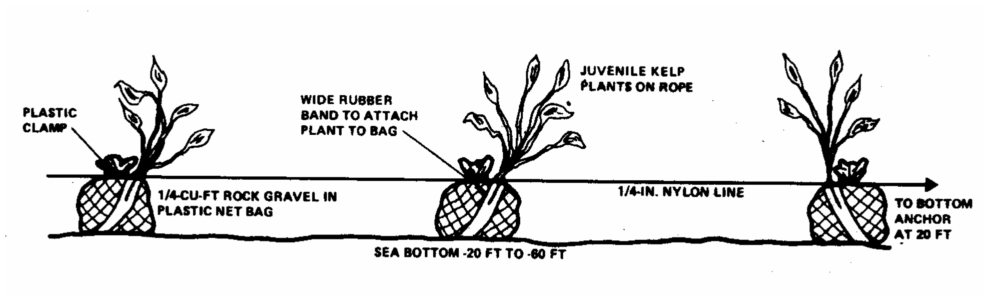


Figure 4. Nearshore *Macrocystis* planting system. (Bird 1987)

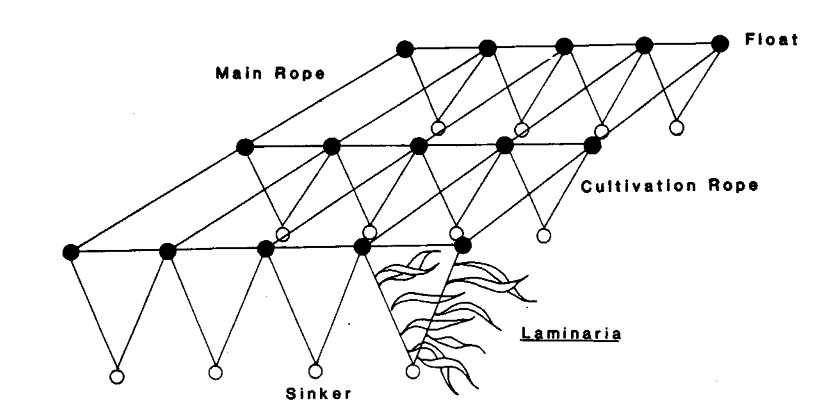


Figure 5. Hanging rope curtain *Laminaria* cultivation system. (Bird 1987)

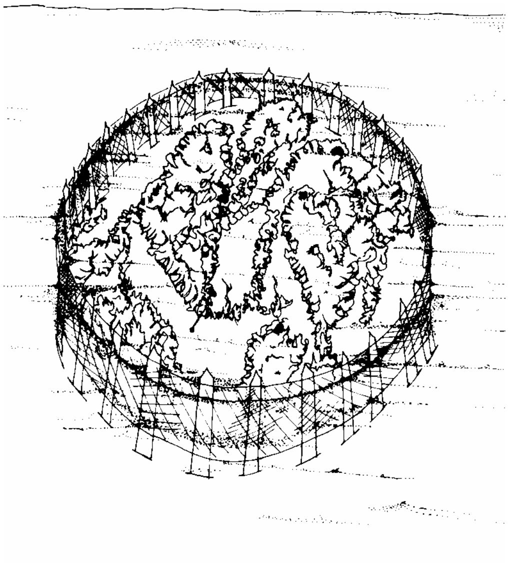


Figure 6. Tidal flat farm. (Bird 1987)

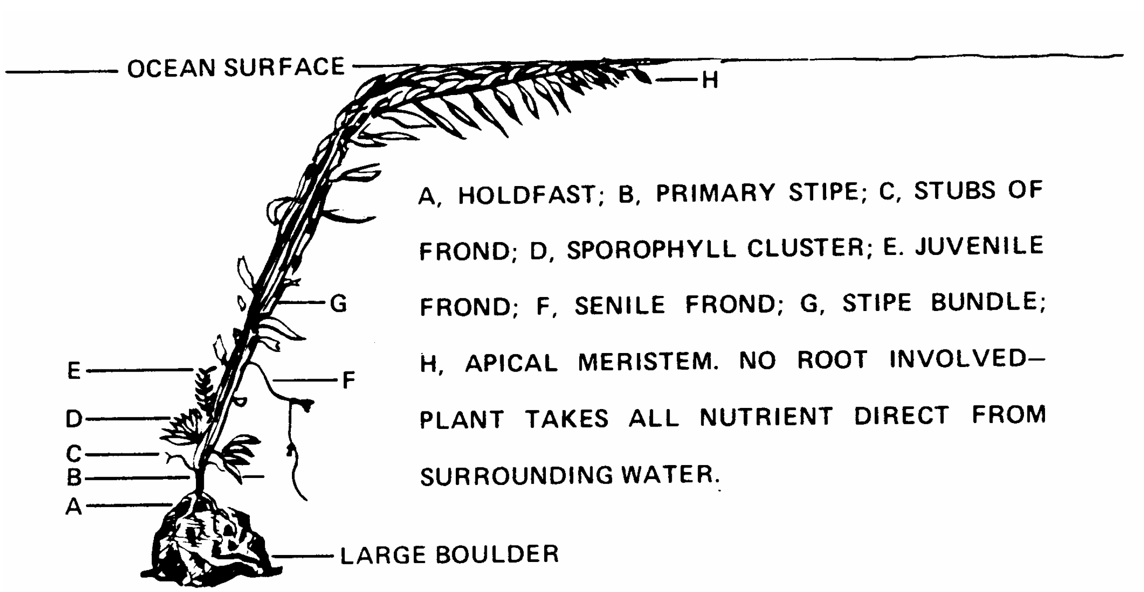


Figure 7. Diagram of young *Macrocystis* plant. (Leese 1976)

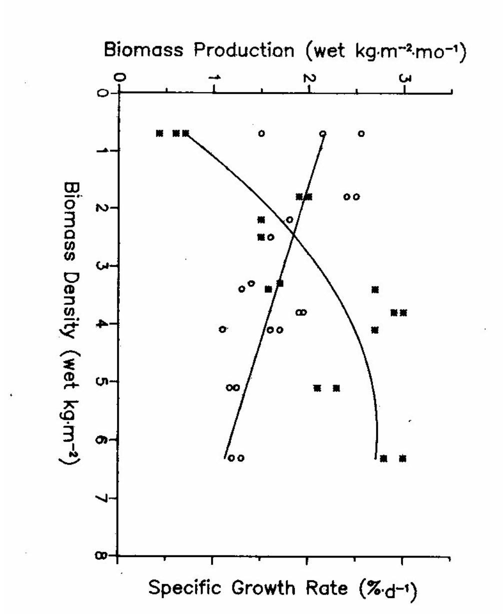


Figure 8. Biomass production and specific growth rate as a function of plant density. (Gerard 1987)

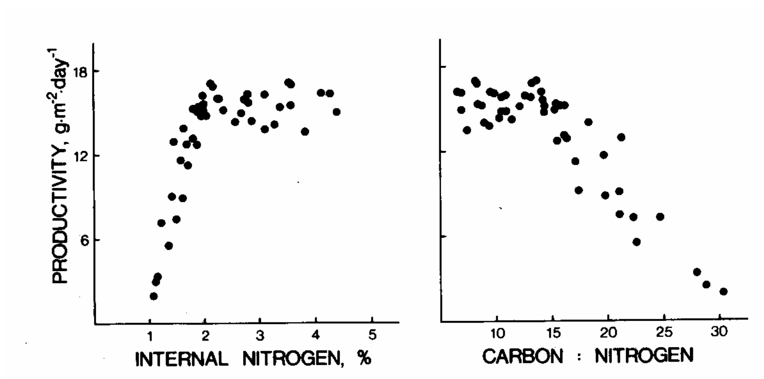


Figure 9. Productivity of *Gracillaria tikvahiae* as a function of internal nitrogen levels and carbon: nitrogen ratios. (Hanisak 1987)

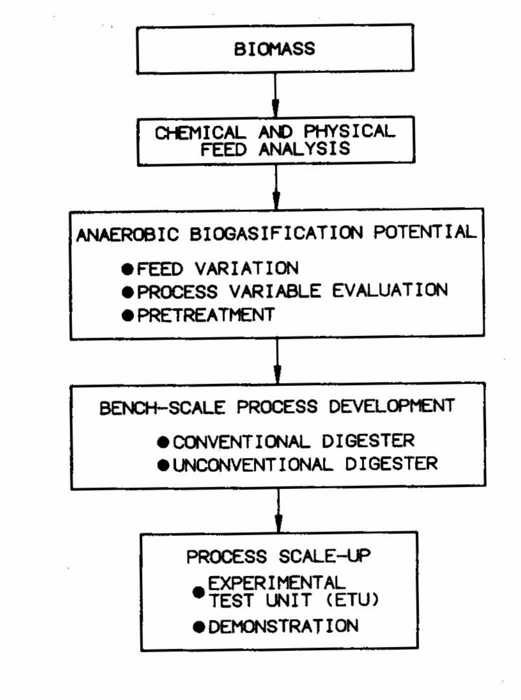


Figure 10. Approach for development of a process for anaerobic digestion of biomass. (Chynoweth et al. 1987)

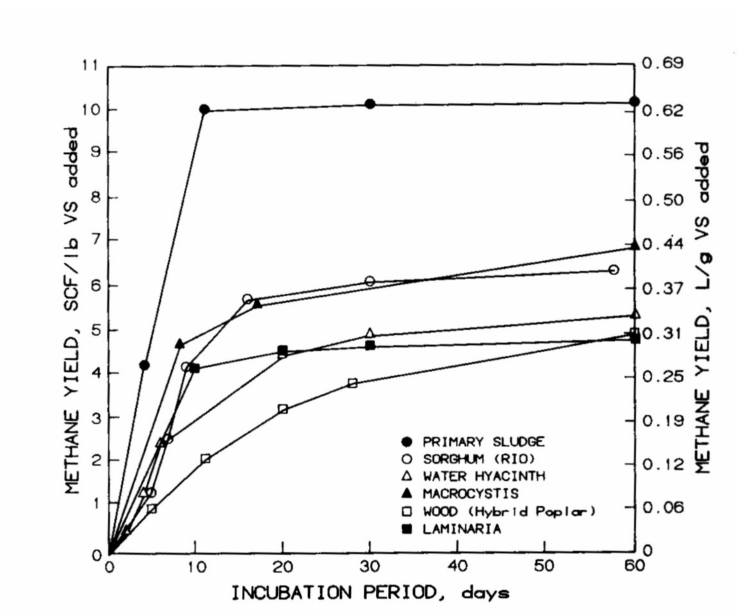


Figure 11. Biogasification of selected biomass feedstocks at 36 °C. (Chynoweth et al. 1987)

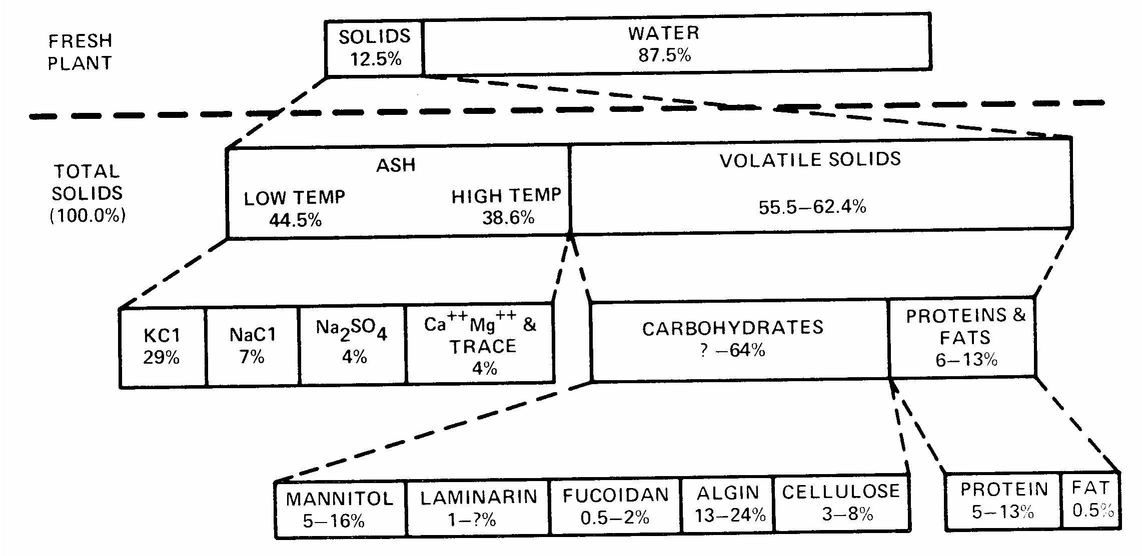


Figure 12. *Macrocystis* composition. (Leese 1976)

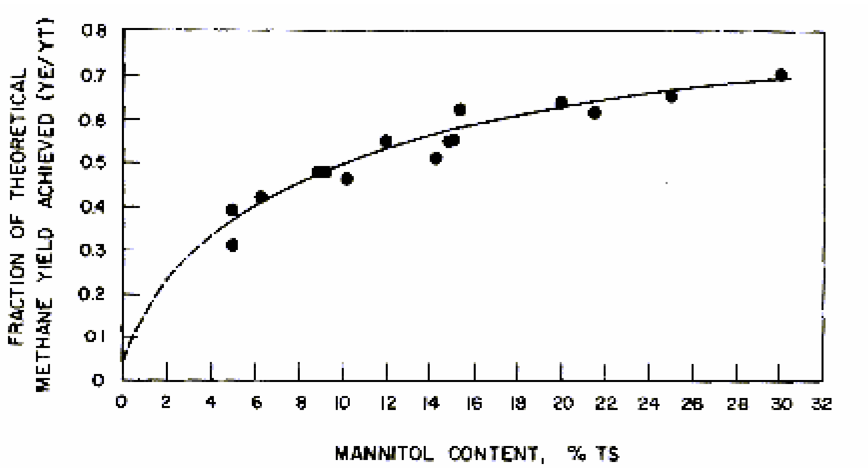


Figure 13. Fraction of theoretical methane yield achieved experimentally with different *M. pyrifera* lots. (Chynoweth et al. 1987)

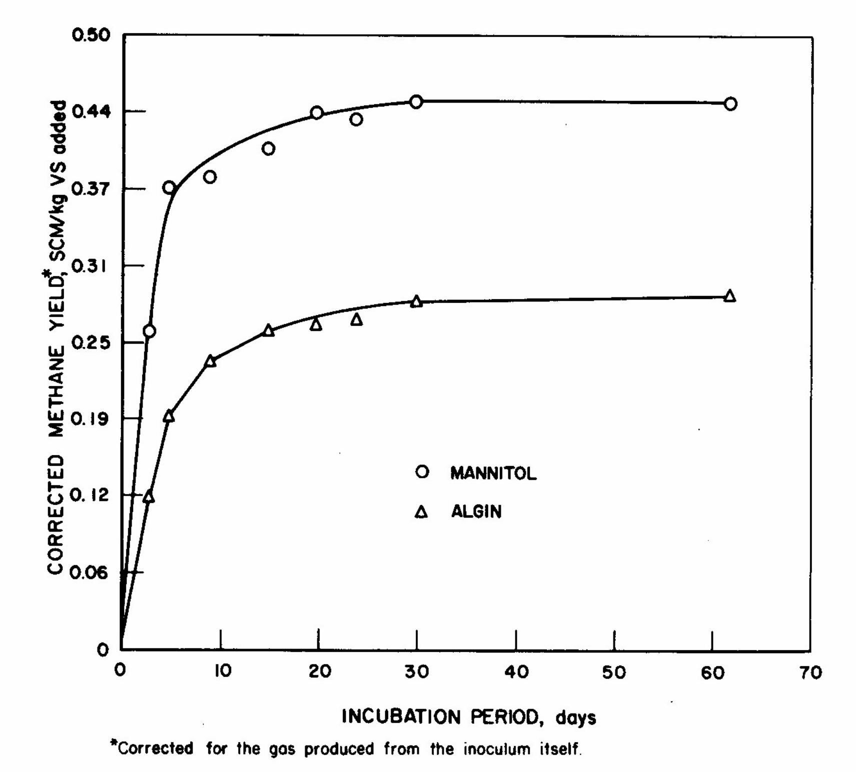


Figure 14. Biodegradability of manitol and algin. (Chynoweth et al. 1987)

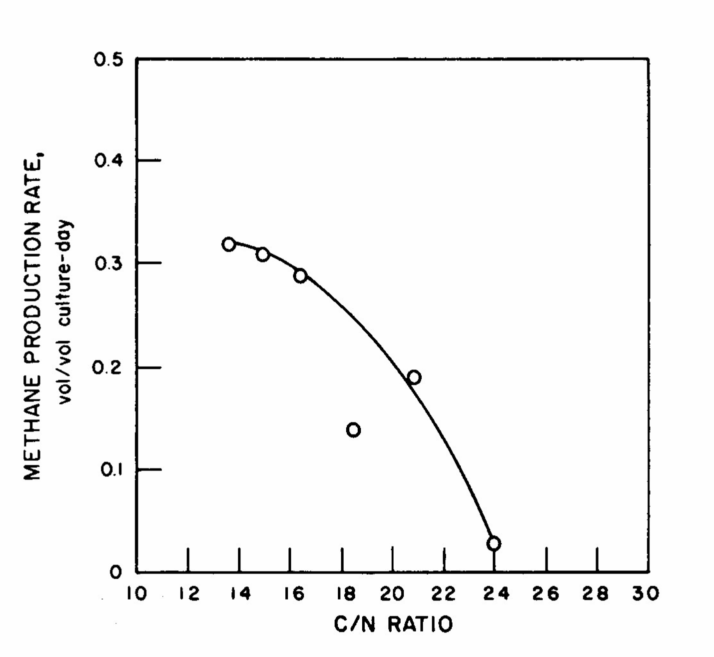


Figure 15. The effect of carbon-to-nitrogen ratio on the biological gasification of *M. pyrifera*. (Chynoweth et al. 1987)

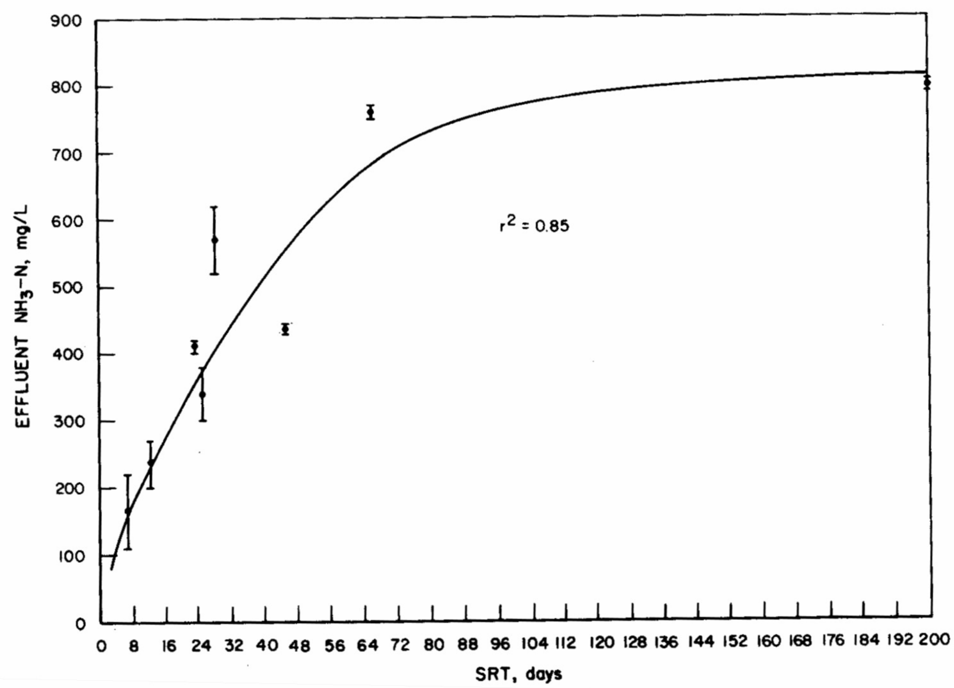


Figure 16. Relationship between solids retention time and ammonia nitrogen in *M. pyrifera* digester effluent. (Chynoweth et al. 1987)

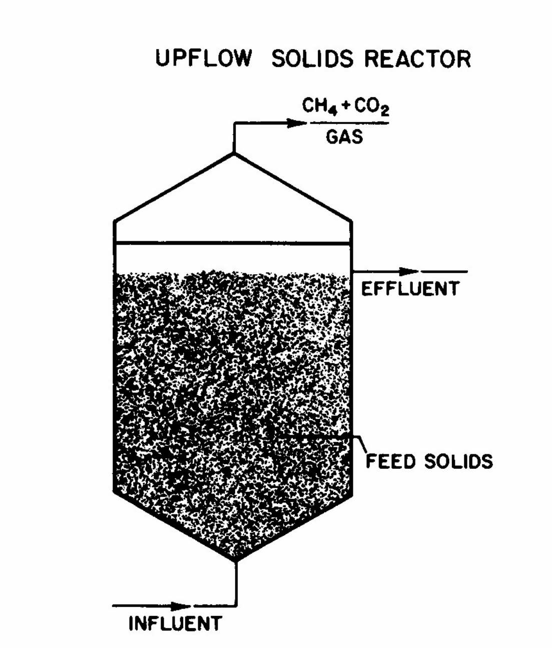


Figure 17. Solids concentrating reactor. (Chynoweth et al. 1987)

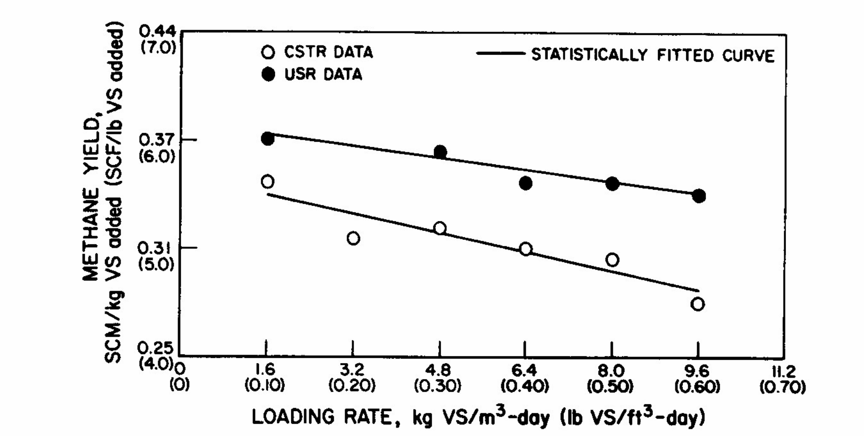


Figure 18. Methane yield in CSTR and SCR digesters receiving *M. pyrifera* Lot 53 at different loading rates. (Chynoweth et al. 1987)

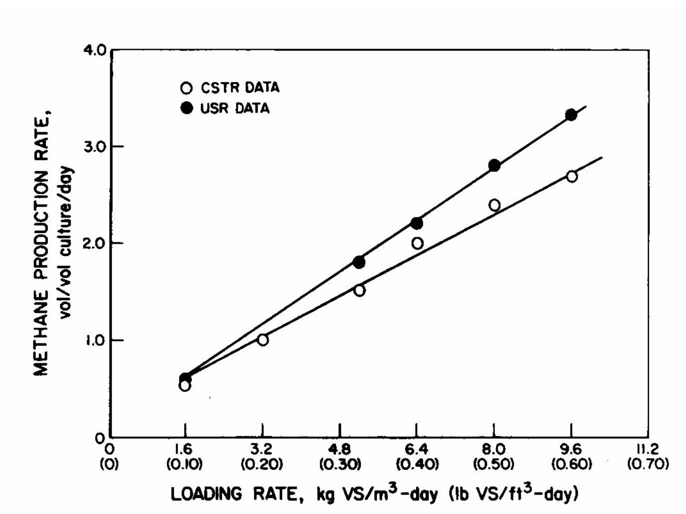


Figure 19. Methane production rate in CSTR and USR receiving *M. pyrifera* Lot 53 at several loading rates. (Chynoweth et al. 1987)

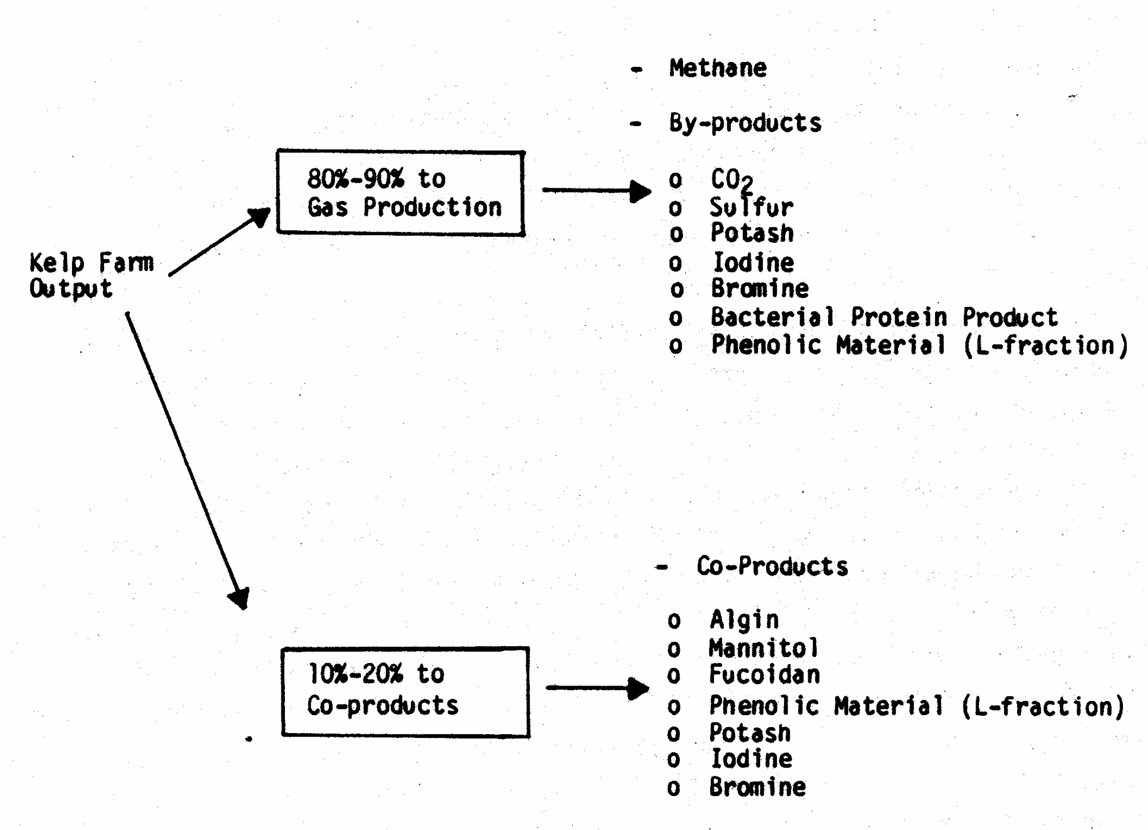


Figure 20. Scenario for relative comparison of kelp products. (Tompkins 1983)

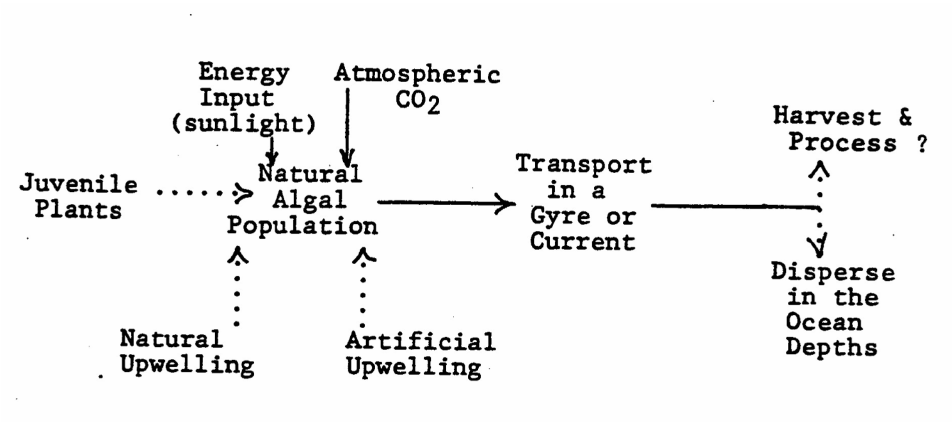


Figure 21. Materials and energy flow in an enhanced natural population of drifting macroalgae. (Marine Biomass Workshop 1990)

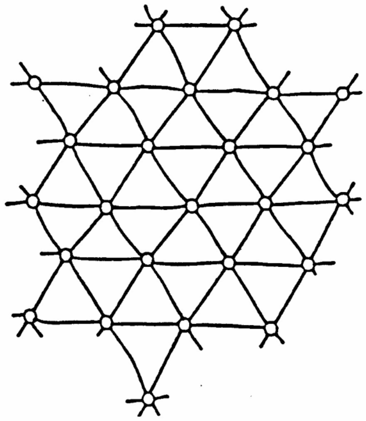


Diagram showing a section of the tensioned grid system on an oceanic farm. The structure consists of triangular substrate modules interconnected by corner buoys.

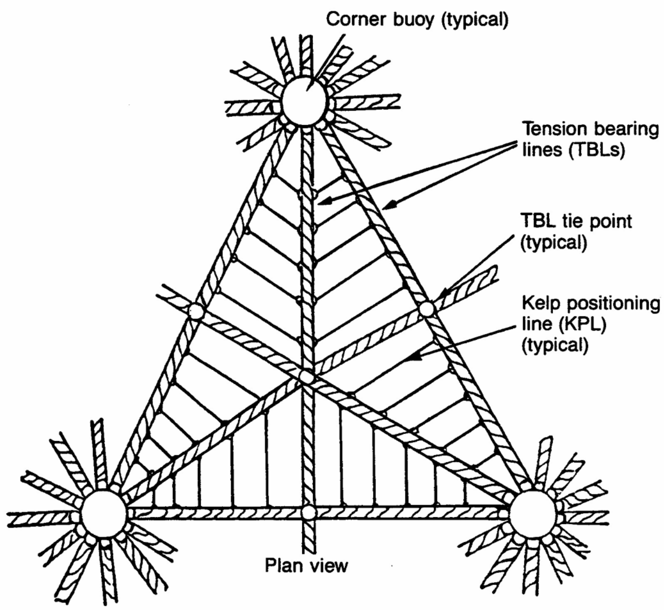


Diagram of an individual triangular substrate module showing detailed arrangements of the functional lines.

Figure 22. Tension grid system for marine seaweed farm. (Marine Biomass Workshop 1990)

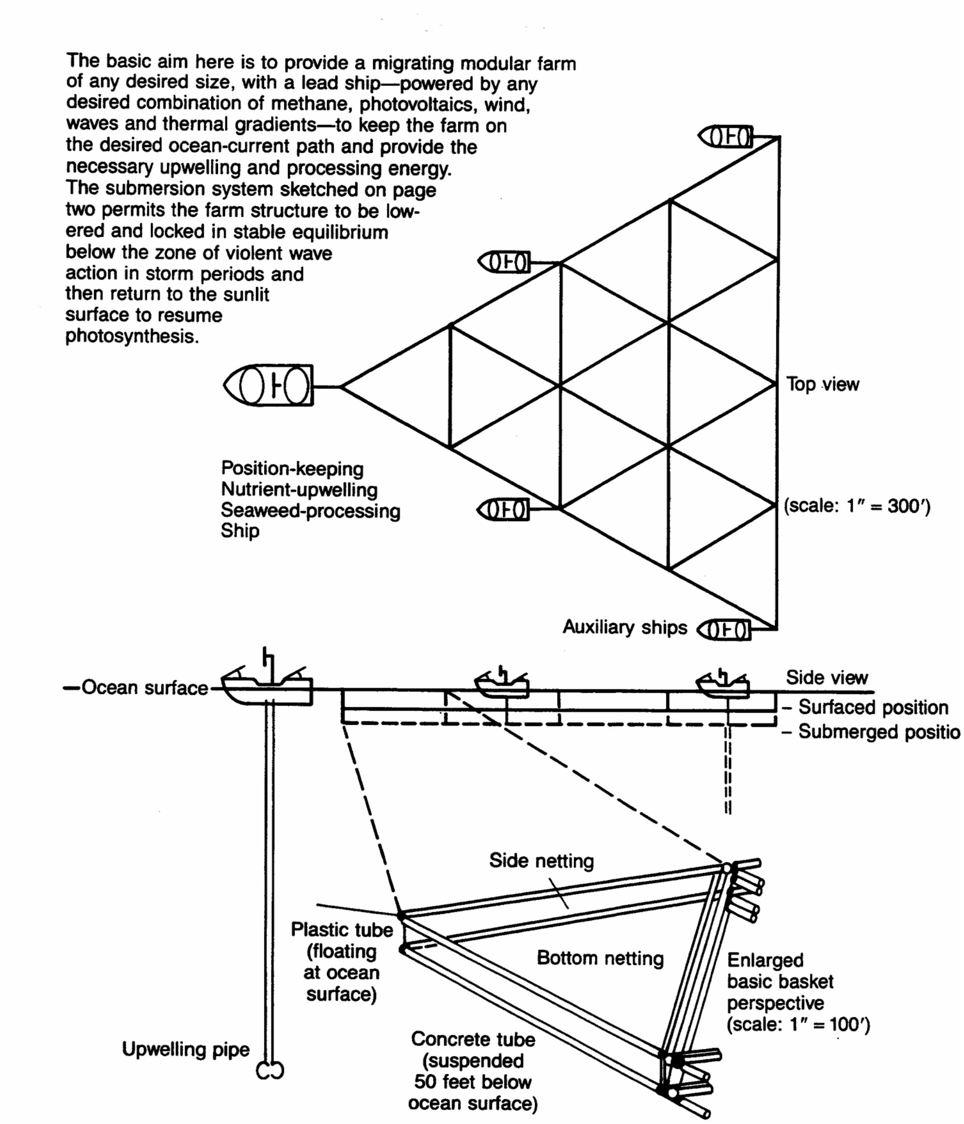
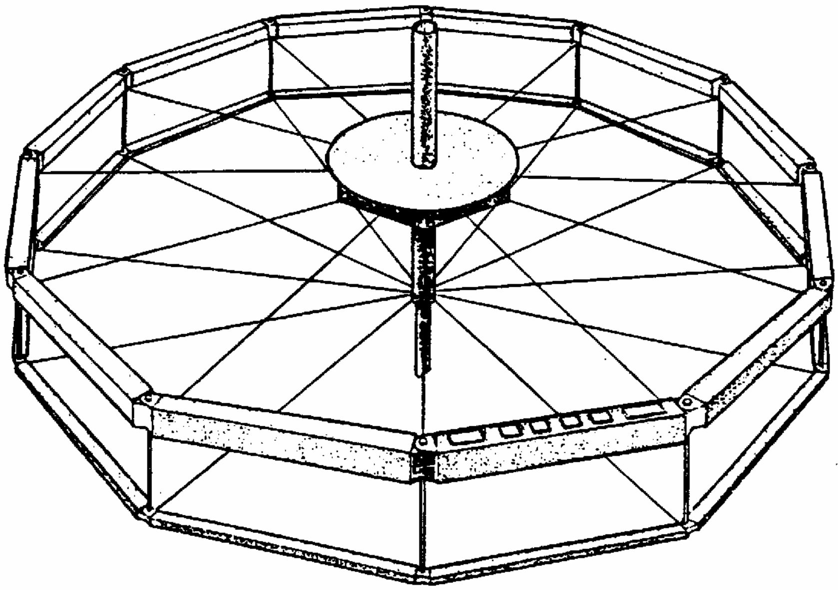
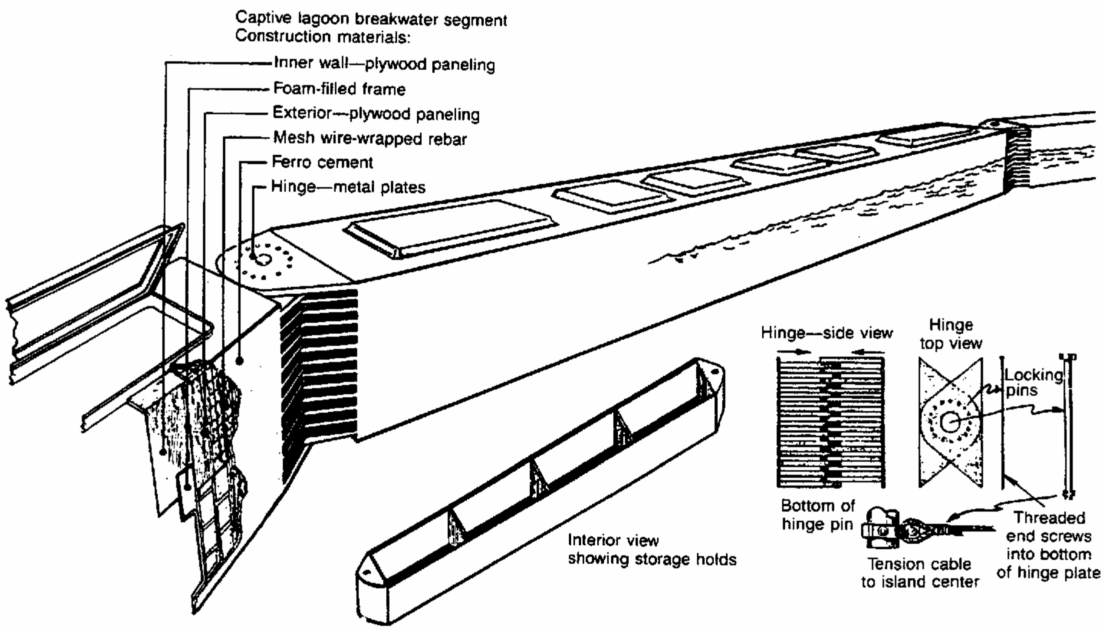


Figure 23. Modified grid-based structure. (Marine Biomass Workshop 1990)



.: Artificial island and captive lagoon, OASIS concept.



. Detail of breakwater segment.

Figure 24. OASIS marine algal farm concept. (Marine Biomass Workshop 1990)

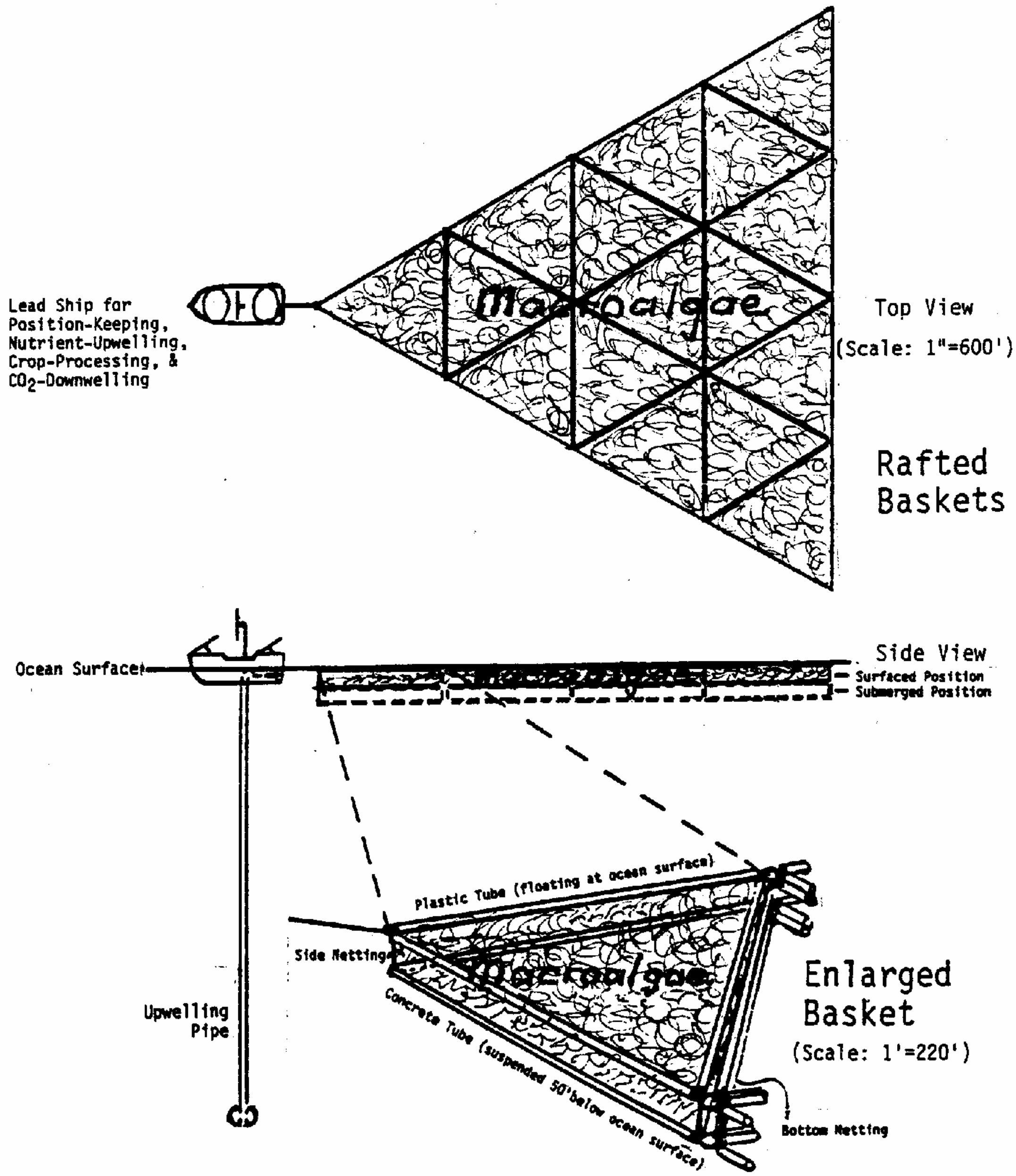


Figure 25. Illustration of delta marine farm test unit. (Marine Biomass Workshop 1991)

Assumptions:

Ash: 35% of dry weight
Carbon: 30% of dry weight
Biochemical Methane Potential: 0.4 L $(g\ VS)^{-1}$
Seaweed → 60 mol% CH_4 + 40 mol% CO_2 + Residue

Dry Weight (total solids)

1 Mg seaweed-TS → 0.19 Mg CH_4 + 0.34 Mg CO_2 + 0.47 Mg Residue-TS

Ash-Free Dry Weight (volatile solids)

1 Mg seaweed-VS → 0.29 Mg CH_4 + 0.53 Mg CO_2 + 0.18 Mg Residue-VS

Carbon

1 Mg seaweed-C → 0.47 Mg CH_4-C + 0.31 Mg CO_2-C + 0.22 Mg Residue-C

Figure 26. Mass and carbon balance calculation for anaerobic digestion of *Gracilaria.* (Marine Biomass Workshop 1995)

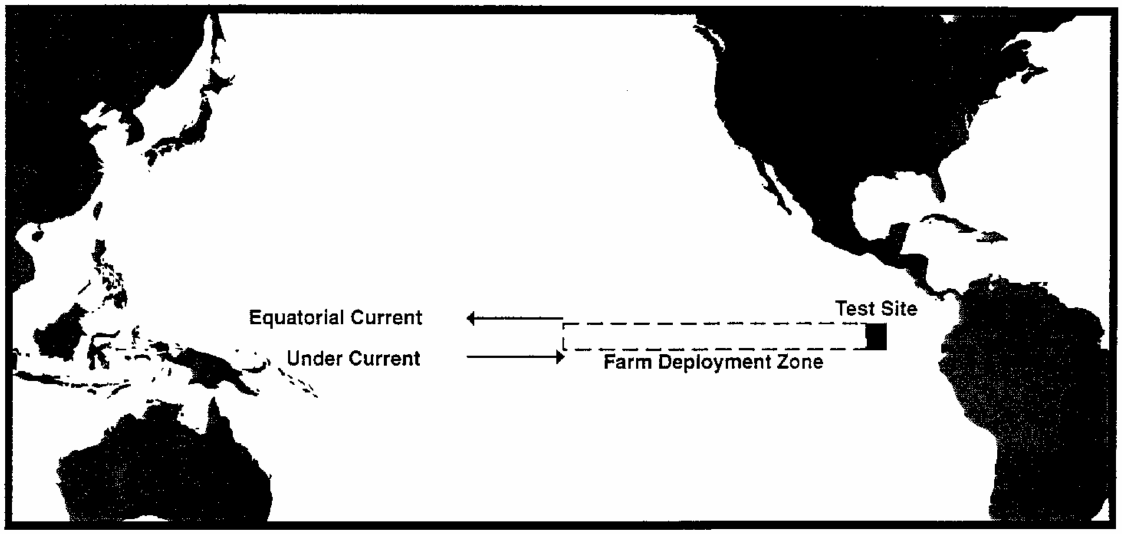


Figure 27. Proposed site for Pacific equatorial belt farm. (Marine Biomass Workshop 1995)

30-50% Ash (trace metals, usually in chelated form)
70-50% organic material
- 3-10% as N (proteins, amino acids)
- 25-85% polysaccharides
- 1-10% lipids and fatty acids
- ? 'cellulose' - lignin free
  - ß- 1.4 glucans (cellulose I and II)
  - ß- 1.4 xylans
  - ß- 1.4 mannans
  - galactans
- 1-10% 'secondary' chemicals - pharmaceutical, agrochemical
  - phenolics
  - vitamins
  - steroids & other terpenoids
  - unusual amino acids, peptides, aminosulfonic acids
  - polysulfides and polysulfates

PRESENT CONSUMPTION OF MACROALGAL PRODUCTS

	VALUE	PRODUCTS TONS/Y	RAW MATERIAL TONS/Y
FOOD CONSUMPTION:			
Nori *(Porphyra)*	> $ 1.8 billion	40,000	400,000
Wakame *(Undaria)*	≈ $ 600 million	20,000	300,000
Kombu *(Laminaria)*	> $ 600 million	300,000	1,300,000
INDUSTRIAL CONSUMPTION:			
Alginate	≈ $230 million	27,000	500,000
Agar	≈ $160 million	11,000	180,000
Carrageenan	≈ $100 million	15,500	250,000
Seaweed meal	≈ $ 5 million	10,000	50,000
Fertilizers	≈ $ 5 million	1,000	10,000
Soil Additives	≈ $ 10 million	510,000	550,000

PRESENT AND POTENTIAL PRODUCT SOURCES

CURRENT:
- Agars, Bacteriological- Difco, Gibco/BRL, Sigma
- Agars and Agaroses, Biotechnological- FMC, Pharmacia
- Agars, Food- FMC, TIC Gums, Meer
- Carrageenans- FMC, Shemberg Marketing U.S. A., TIC Gums
- Alginates- Kelco, Grinsted Products, FMC
- Omega 3 Fatty Acids- Martek, Omega Tech
- ß Carotene- Nutrilite Products, (Owned by Amway)
- Protein (Spirulina)- Unisyn, Cyanotech, Earthrise
- Fertilizers, Soil Conditioners- Aquatend, R&D Plant/Soil
- Pigments- Several Companies
- Lectins- Several Companies
- Fine Chemicals- Martek

EMERGING:
- Methane and Methanol
- Artificial Fish Meals
- CO_2 Scrubbers/Sinks
- Heavy Metal Adsorbants, Chelators- Specific and Wide Capacity Systems
- Feed Supplements- Aquaculture, Animal Feeds
- Food Supplements- Formulaid® by Martek
- Algal Polysaccharides and Fiber Sources from Algae
- Pharmaceutical
  - Anti-ovarian cancer terpene- Portieria (red alga) Stage li trials
  - Anti-viral Sulfolipids (Screening and Isolation)
  - Anti-virals - Algal proteins and secondary products (Screening)
- Bioremediation Applications (Nutrients and heavy metals)

Figure 28. Macroalgal composition and potential product. (Marine Biomass Workshop 1996)

A discussion at PMEL on April 29 indicated that there are two conditions on the Eastern Pacific equator in which vaned drogues may be unable to shape and operate a large-scale open-ocean seaweed farm.

The first condition exists for about three months each spring as the undercurrent comes to the surface, temporarily removing the sheer between the surface current and undercurrent that makes the vaned-drogue operation possibl

The second condition occurs in major El Niño events (perhaps every 10 yea or so) when the strong easterly undercurrent weakens and may even go westerly for a short period, again removing the crucial intercurrent sheer.

To assure the preservation and at least partial operation of the farm in these conditions, consideration should be given to the comparative costs and benefits of a possible moored-farm arrangement. One such scheme, simply for illustration, combines eight of the farm-net modules into a raft about a mile wide (north/south) as shown in Fig. 1. In this arrangment, the platform would continue to be positioned and moved through its mowing cycle by vaned drogues extending from its bottom corners into the undercurrent.

To compare the benefits and costs of the moored vs. drogued farms, the combined guidance of the PMEL and DTMB people will be needed on points such as these:

- the depth profile along the equator from 95°W to 170°W;
- the bottom characteristics along this belt;
- the optimum spacing of mooring bridles along the nets;
- the forms, materials and approximate unit costs (in place) of the bridle anchors;
- the bridle materials -- again including unit costs;
- the required ratio of bridle scope to ocean depth;
- the depth to which marine fouling problems will extend along the bridles (a point on which we will also attempt to get Dr. Venn's judgment); and
- the dimensions, materials and approximate unit costs of the buoy structures (exclusive of data-gathering/transmitting gear) and the possible desirability of adding finned frameline buoys between the bridle-connection points -- to assist in maintaining the lateral net tension.

Figure 29. Pacific equatorial macroalgal farm: general description. (Marine Biomass Workshop 1997a)

Net: 12"-mesh plastic netting extending 300' north-south and 36 nmi east-west -- with a plant fastened at each intersection, with roller-tipped spreaders every 100' east-west, and with removable buoys on short tethers to weights in between to maintain the desired plant insolation depth (Fig. 1).

Farm: Two adjacent net lanes -- with boundary framework lines supported by large buoys every 500', hooked to the nets with ties and kept stationary by drogues and paravanes/depressors powered by water turbines (Figs. 2-3).

Platform: A 500'X350'X175' semisubmersible steel and ferro-concrete structure with:

- a large controllable drogue and paravane/drepressor at each bottom corner, permitting the platform to move at ½ knot along each lane -- with the net being guided in at the forward face for mowing and a 12-hour nutrient pulse and then pulled out at the after face to resume insolation, and with the platform turning and shifting lanes at the end of each three-day run, assisted by thrusters at each corner;
- cranes at the forward and after faces to disconnect and reconnect the net/frame-line ties as the platform advances along each lane and to initiate the net-handling operation;
- 300' rods and net-guiding pulleys at the forward and after faces and a mower at the forward face to remove half the mass of each plant;
- a 500'X300'X60' nutrient tank in which the mowed net can be hung in curtains by means of side rails for the spreader rollers -- to be pulled out at the after face when each plant has received a 12-hour nutrient pulse;
- a wet-harvest tank to hold the mowed plant mass awaiting delivery to processors;
- protein and pharmaceutical extraction and processing equipment;
- an anaerobic digester sized for a daily input of 550 dryweight tons of plant mass;
- a two-stage (reforming/methanation) methane-to-methanol converter with a capacity of 200 tons/day;
- methanol storage and ballast tanks;
- a small plant culture facility;
- deck space for workboats;
- a farm control center; and
- crew quarters (Fig. 4).

Figure 30. Pacific equatorial macroalgal farm: specific description. (Marine Biomass Workshop 1997a)

Site: Equator at 100° W.

Current: ½ kt. westward at surface, 2½ kts. eastward at 100 m. depth.

Plant Growth Rate: 6 days from half mass (after mowing) to full mass.

Plant productivity: 40 $g/m^2/d$ dryweight (DW) with 33% ash and 28% C.
= 26.7 $g/m^2/d$ volatile solids (VS) and 11.2 $g/m^2/d$ C.

C Distribution: 22% in digester sludge (sequestered on ocean floor),
47% in methane off-gas (recycled), and
31% in CO_2 off-gas (with 33% recycled as methanol*).

Methane Yield: 0.34 liters/g VS = 5.46 cu.ft./# VS.

Heat Content: 1000 BTU/cu.ft. for methane and 9500 BTU/# for methanol.

Conversion Efficiency: 70% for methane to methanol

CALCULATIONS

Farm Growing Area: 300'(91.44m) X 2 X 36 X 6076'(1852m) = 12 X 10^6 m^2.

Daily VS Yield: $$\frac{26.7 \times 12 \times 10^6}{4.536 \times 10^2\ (g/\#)} = 7.07 \times 10^5\ \#\ VS.$$
$$= \frac{7.07 \times 10^5 \times 1.5\ (DW/VS)}{2 \times 10^3\ (\#/ton)} = 530 \text{ tons DW}$$

Daily Methane Yield: $5.46 \times 7.07 \times 10^5 = 3.86 \times 10^6$ cu.ft.

Daily Methanol Yield: $$\frac{3.86 \times 10^5 \times 10^3 \times 70\% \times 1.33^*}{9.5 \times 10^3 \times 2 \times 10^3} = 189 \text{ tons}$$

Daily-Methanol-Yield Storage Requirement: $$\frac{191 \times 2000}{78\ (\#/cu.ft.)} = 4897 \text{ cu.ft.}$$

Atmospheric C Sequestered/Recycled:

$$\frac{(22\% + 47\% + 33\% \times 31\%^*) \times 11.2\ (unit) \times 12 \times 10^6\ (area) \times 365}{4.536 \times 10^2 (g/\#) \times 2000\ (\#/ton)}$$

= 43,000 tons/yr.

Figure 31. Pacific equatorial macroalgal farm: assumptions. (Marine Biomass Workshop 1997a)

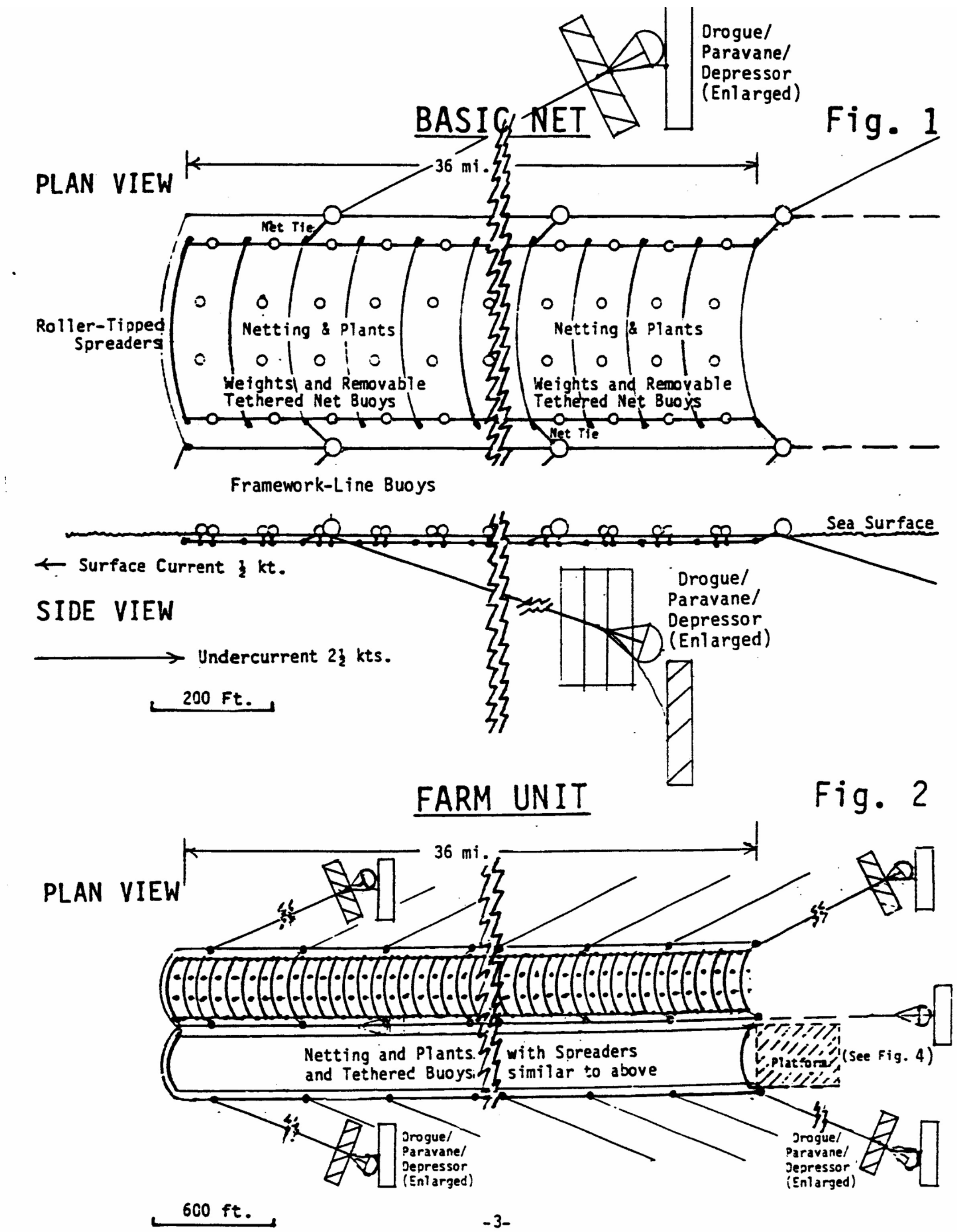


Figure 32. Pacific equatorial macroalgal farm: net structures. (Marine Biomass Workshop 1997a)

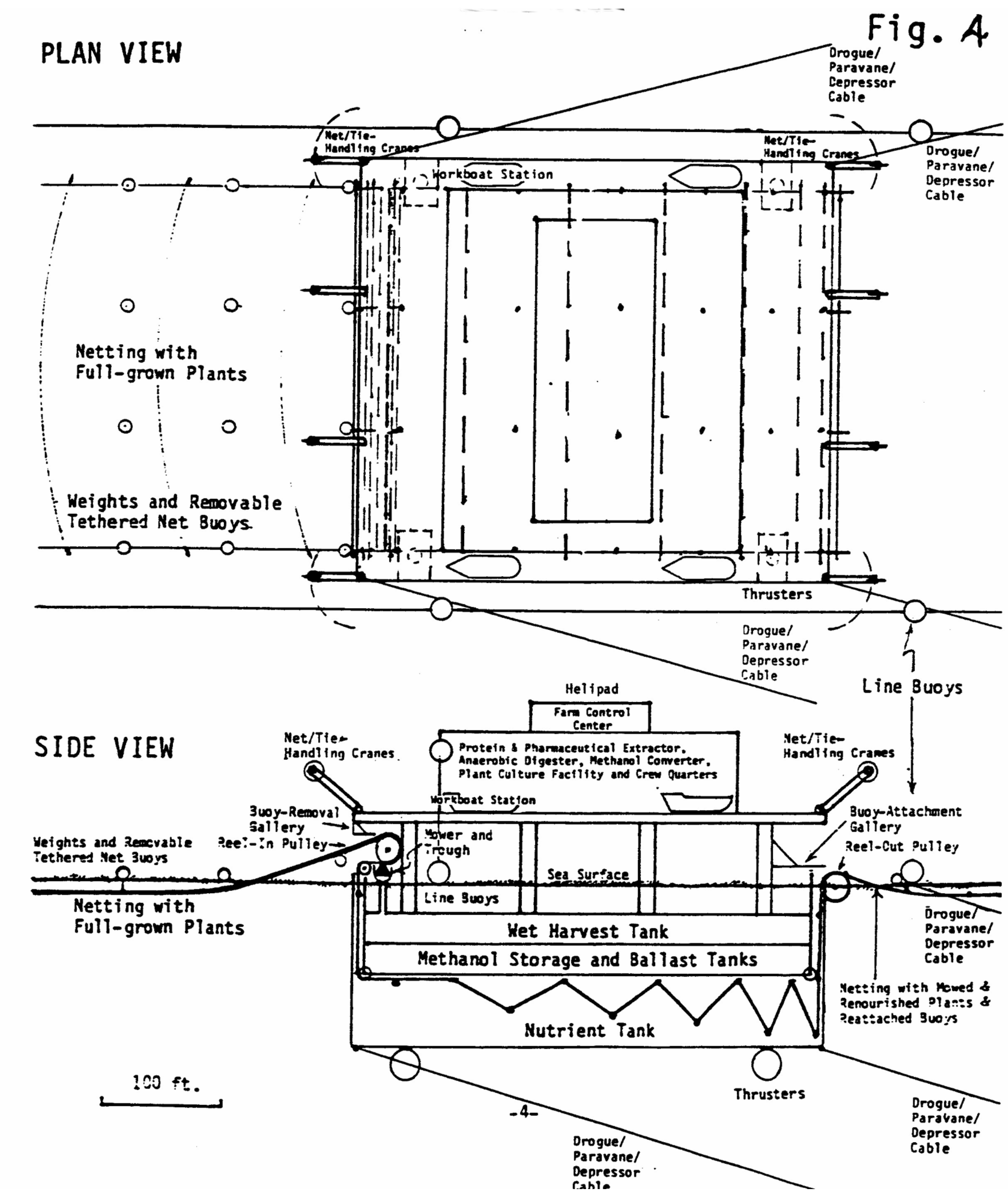
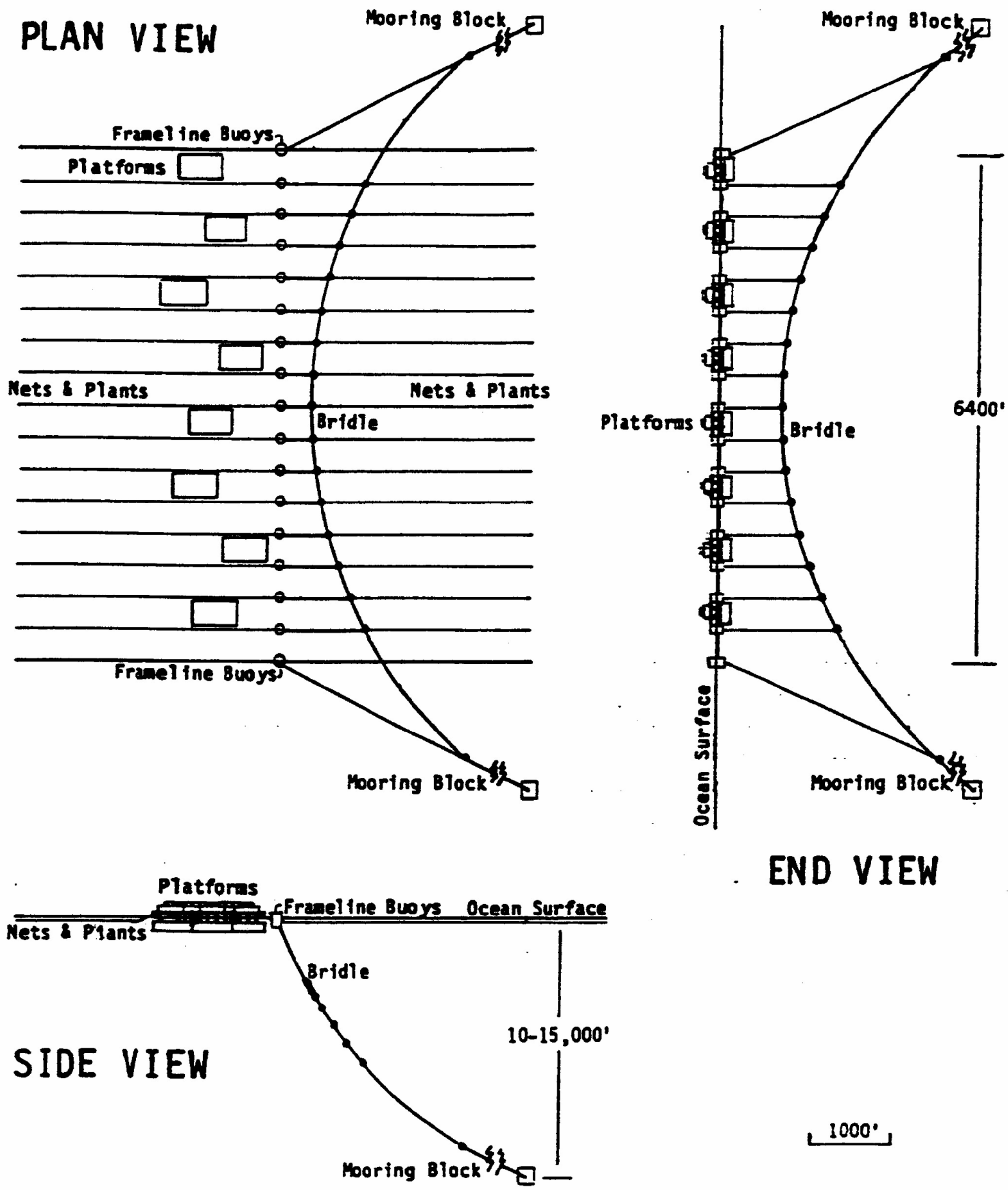


Figure 33. Pacific equatorial macroalgal farm: platform and conversion system. (Marine Biomass Workshop 1997a)



During the spring months when the surface current is easterly, the platforms' westerly mowing movements (taking about 12½% of the total annual mowing time) can hopefully be accomplished by corner thrusters, winch cables hooked successively along the framelines, and perhaps large spinnakers set in the trade winds. If the desired half-knot mowing rate cannot be achieved with such a combination, the mowing cycle will need to be extended during this period.

To assist in maintaining the lateral net tension during the transition in surface-current direction, it may be helpful to offset the buoys a few feet from the framelines and add transverse fins on their lower surfaces and perhaps sheeted sails on their upper surfaces. Alternatively or additionally, light plastic trusses might be placed between the net weights.

Figure 34. Pacific equatorial macroalgal farm: overview diagram. (Marine Biomass Workshop 1997a)

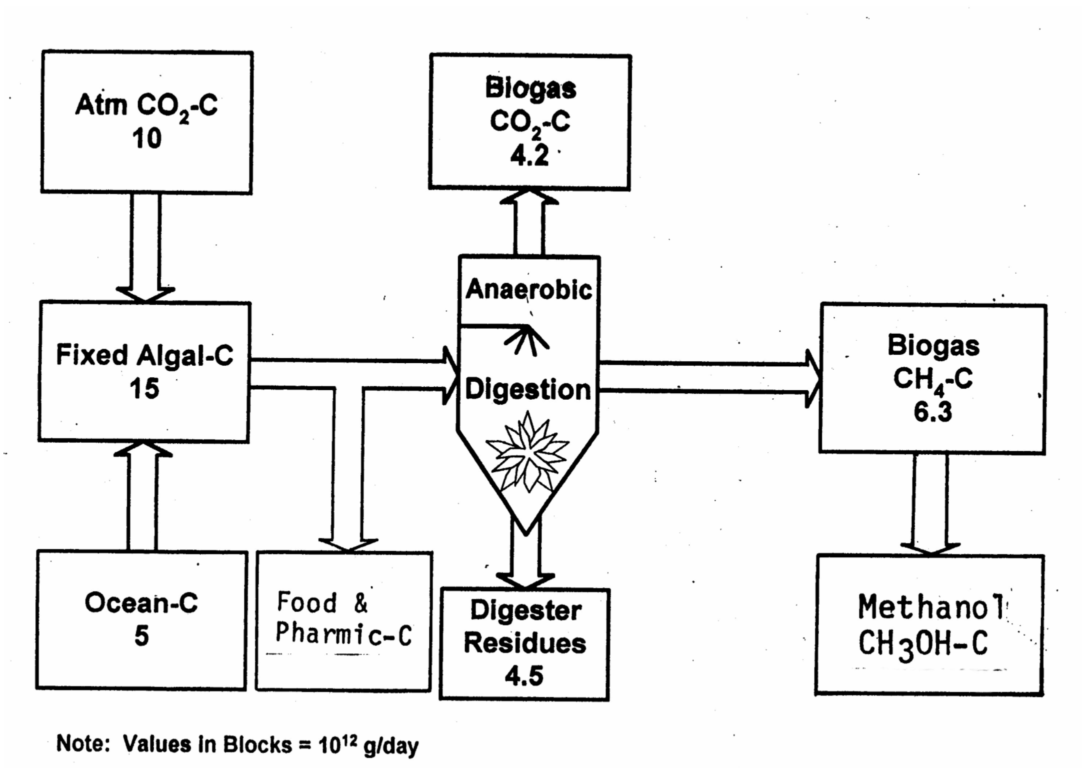
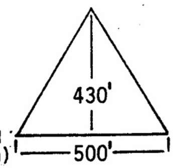


Figure 35. Carbon balance for macroalgal mitigation of CO_2 emissions. (Marine Biomass Workshop 1997b)

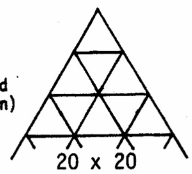
Units | Areas

Basket (see attached illustration)



430' x 500'/2 = 107,500 sq. ft./43,560 = 2½ acres.

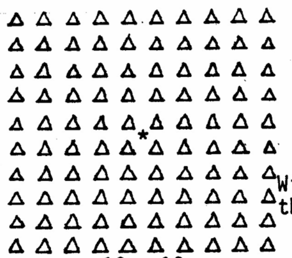
Raft (see attached illustration)



20 x 20 Baskets

20 x 20 x 2½ = 1000 acres/640 = 1.56 sq. mi.

Farm



10 x 10 Rafts

10 x 10 x 1.56 = 156 sq. mi.

With 1 raft space between rafts, the maximum travel to the plant ship (*) will be $\frac{1.414 \times 95{,}000'}{5{,}280'} = 25$ mi.

Total number of farms to provide 1 MM sq. mi. of growing area -- sufficient for 2 GTY of atmospheric carbon absorption (EPRI Report OCBD 7303, p. 7):

$$\frac{1{,}000{,}000}{156} = 6{,}410$$

Total number of rafts = 6,410 x 100 = 641,000

Total number of baskets = 400 x 641,000 = 256,400,000

(approximately one basket for each 20 people in the present world population)

In addition to taking 2 GTY of carbon out of the atmosphere, and assuming that all of the processing power comes from other-solar sources, this farm program as a whole could generate 120 quads of methane a year -- over a third of the world's current total energy consumption.

Ocean area required for each farm: $\frac{190{,}000' \times 161{,}000'}{5280^2} = 1097$ sq. mi.

Total ocean area thus required for 1 MM sq. mi. of growing area = 6,410 x 1,097
= 7 MM sq. mi.

Portion of total world ocean surface required for this farming program:

$$\frac{7{,}000{,}000}{140{,}000{,}000} = 5\%$$

Figure 36. Ocean farm area calculation. (Marine Biomass Workshop 1997b)

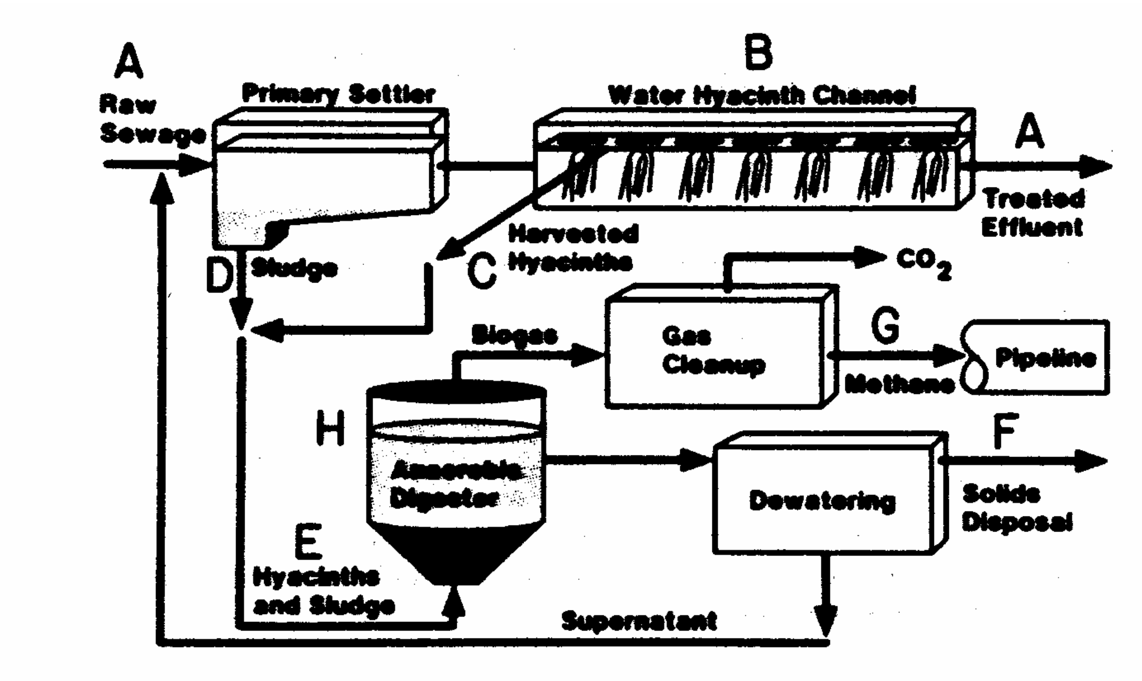


Figure 37. Schematic of integrated water hyacinth wastewater treatment system. (Chynoweth et al. 1989)

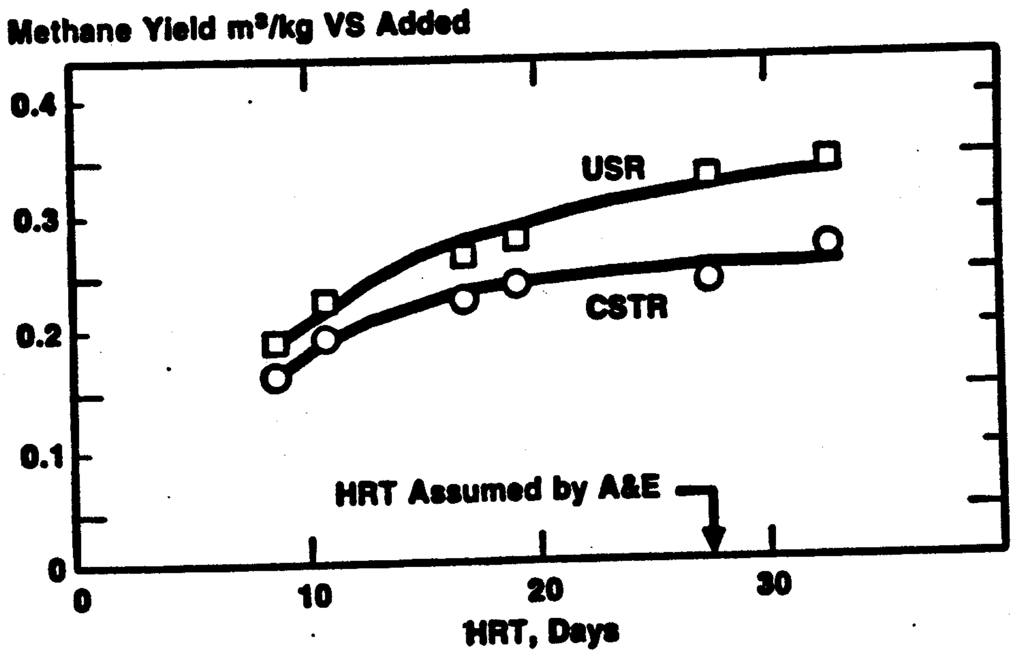


Figure 38. Methane yield versus hydraulic retention time for bench-scale SCR and CSTR reactors operated on a 3:1 feed blend (dw basis). (Chynoweth et al. 1989)

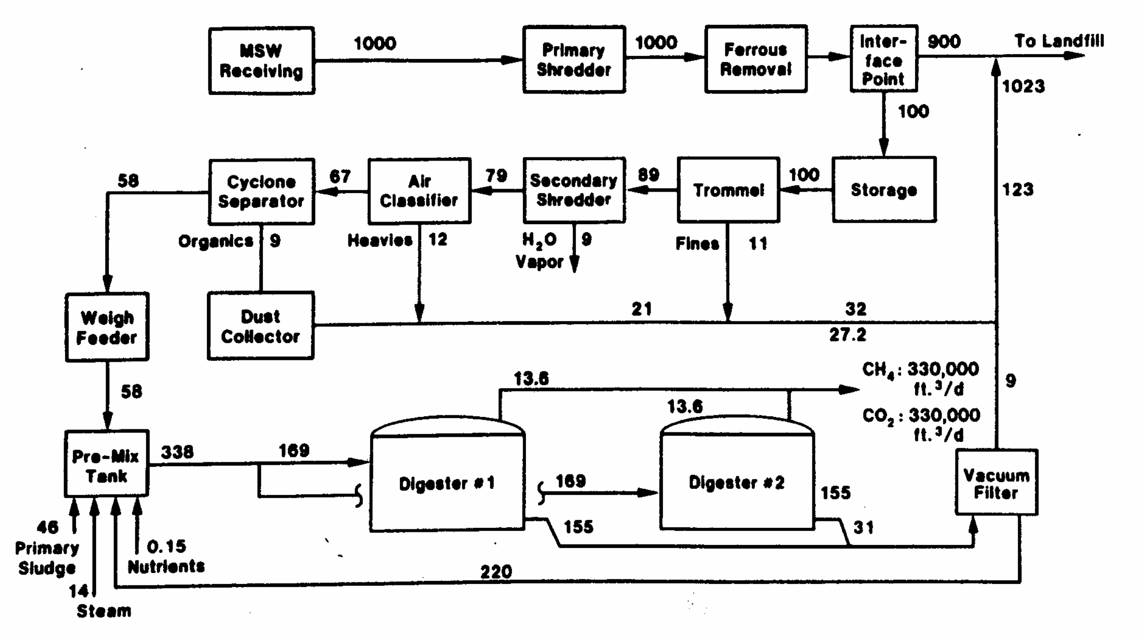


Figure 39. RefCoM MRF and anaerobic digestion system as built. (Isaacson and Pfeffer 1987)

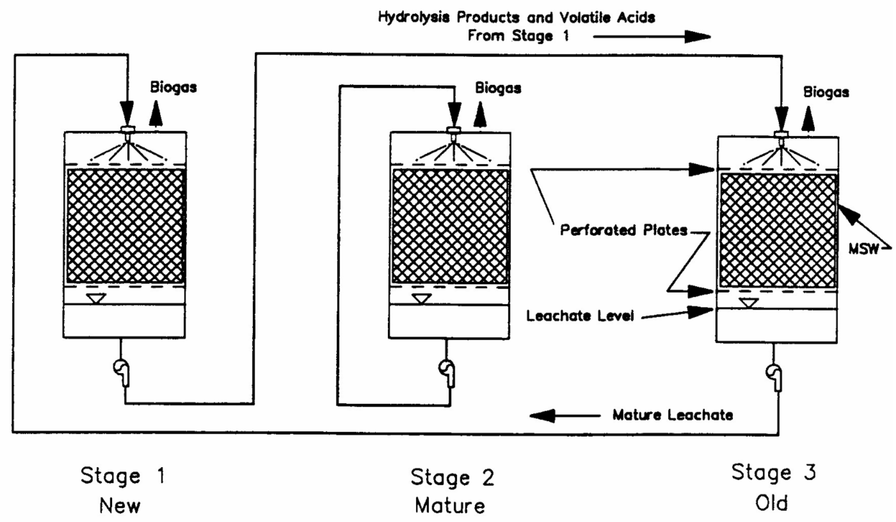


Figure 40. Schematic of SEBAC. (Chynoweth et al. 1992)

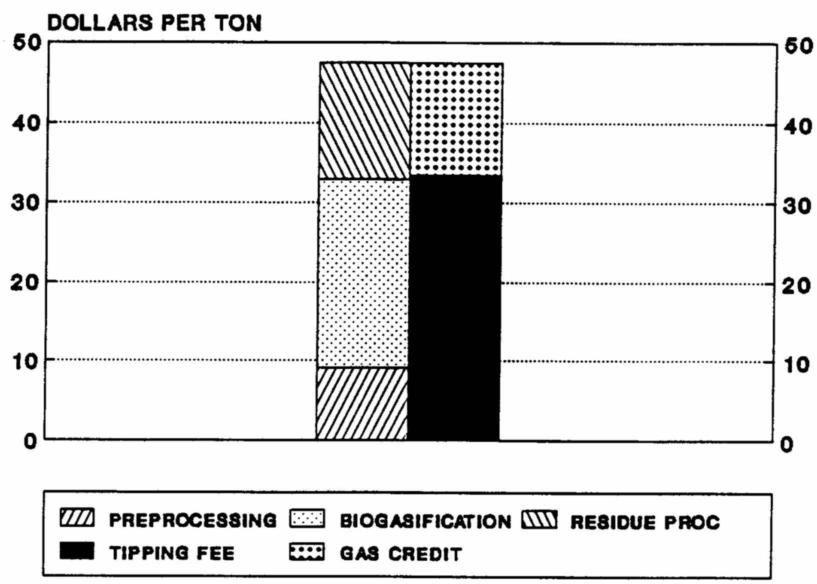


Figure 41. Summary of SEBAC economics. (Chynoweth et al. 1992)

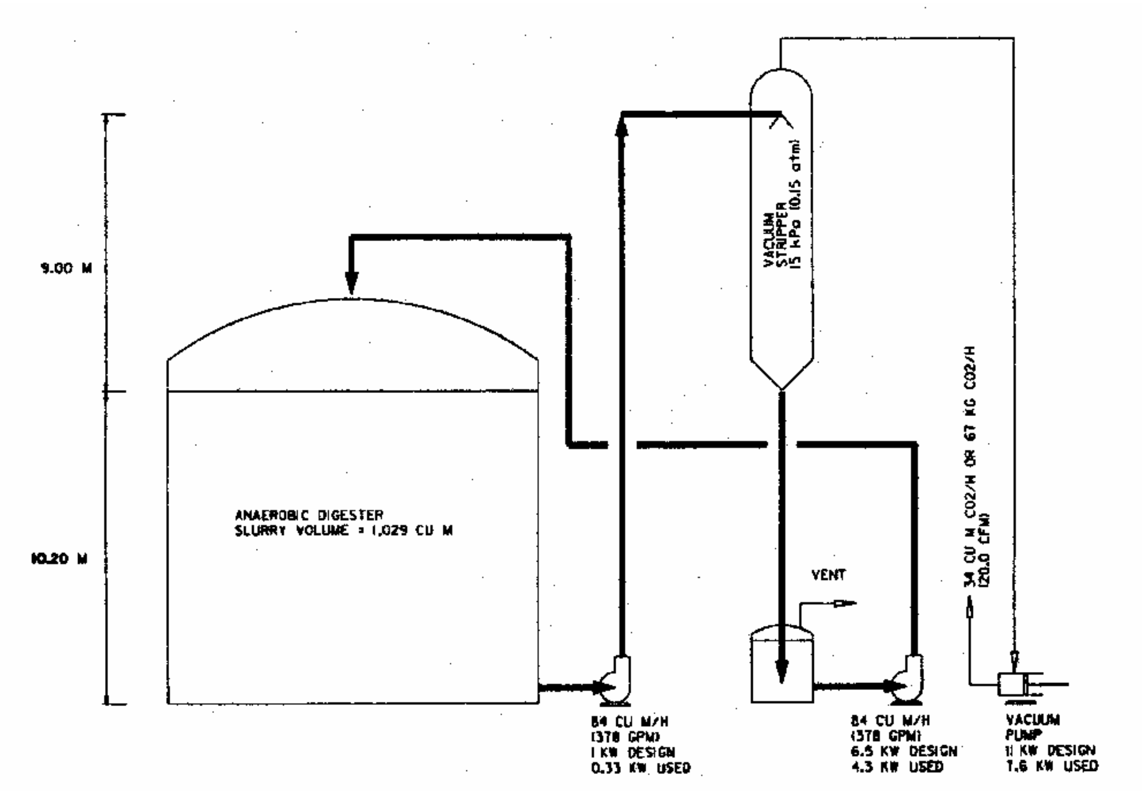


Figure 42. Conceptual process diagram, vacuum stripping of CO_2 for MED. (Legrand 1991)

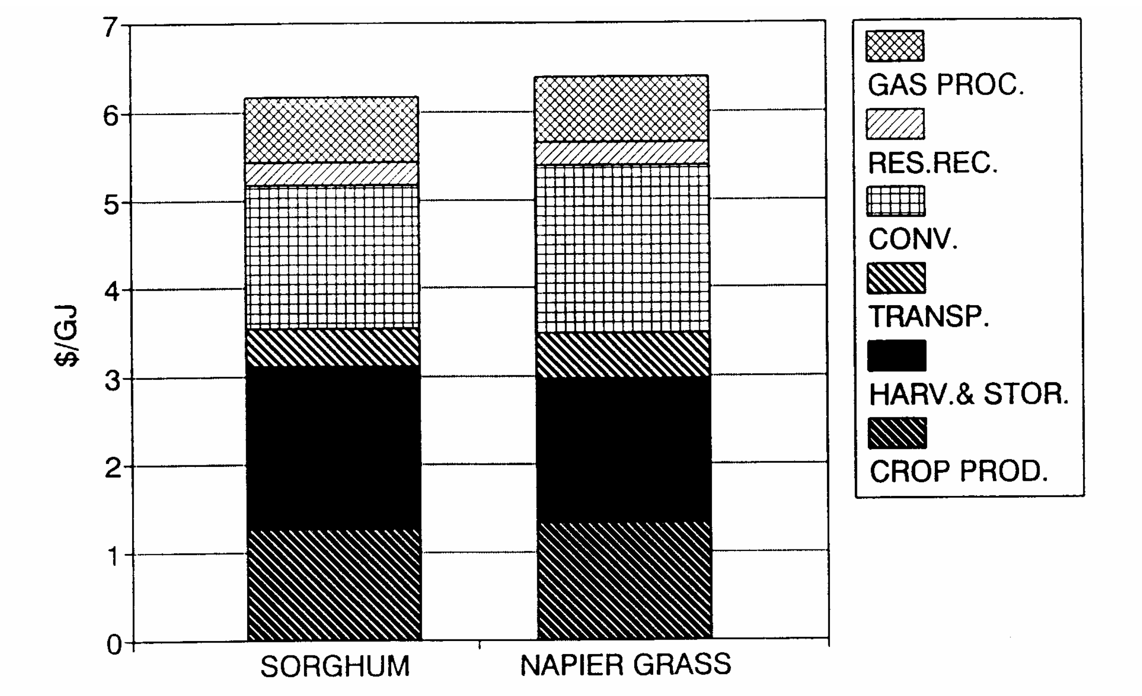


Figure 43. Sorghum and Napier grass base cases cost distribution. (Legrand 1993)

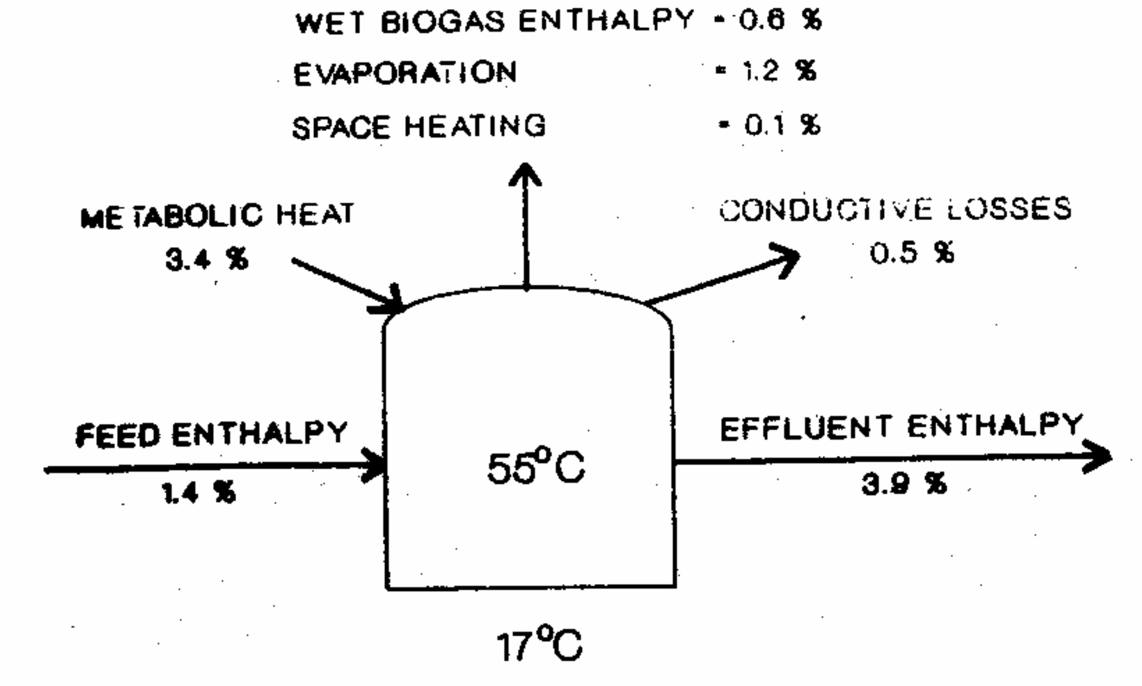


Figure 44. Thermal balance for full size thermophilic biomass reactor in 17°C air, heat deficit = 1.5% of biogas produced. (Legrand 1993)

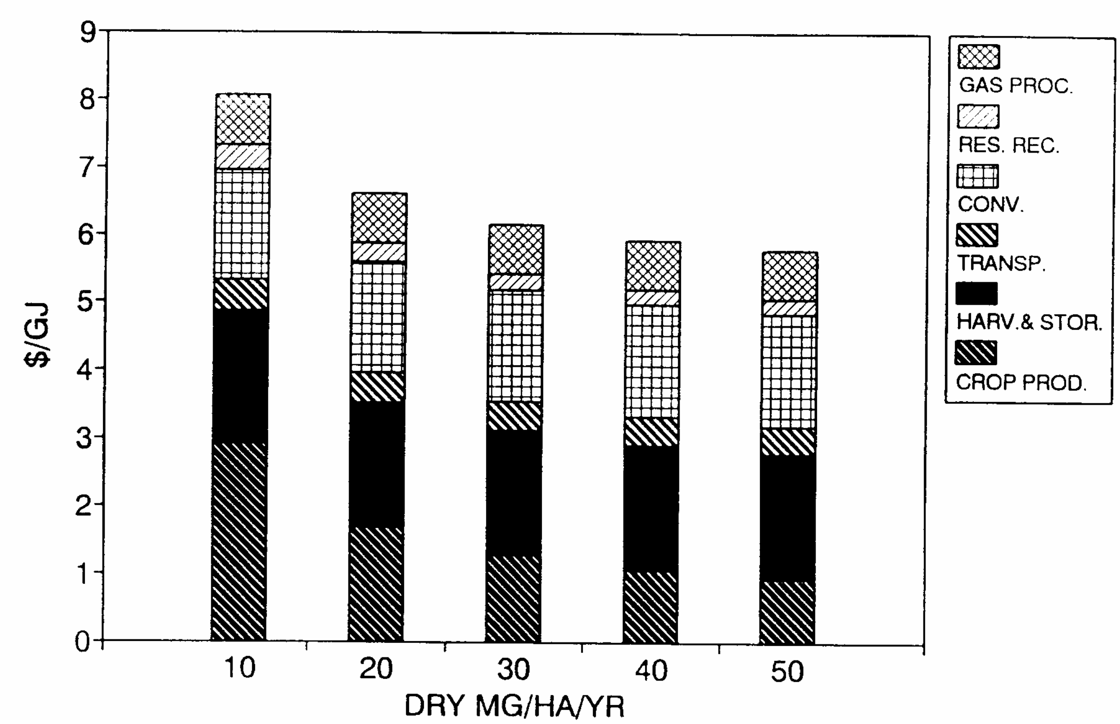


Figure 45. Cost impact of increasing crop productivity (sorghum). (Legrand 1993)

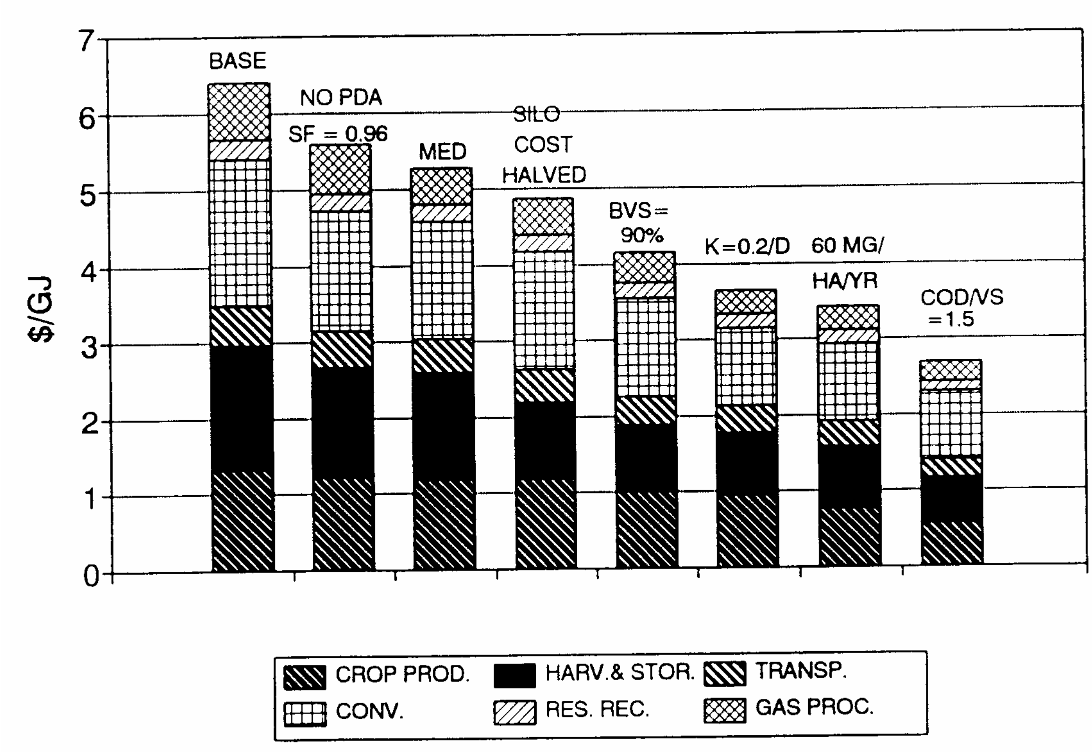


Figure 46. Cumulative cost impact of successive technological breakthroughs (Napier grass). (Legrand 1993)

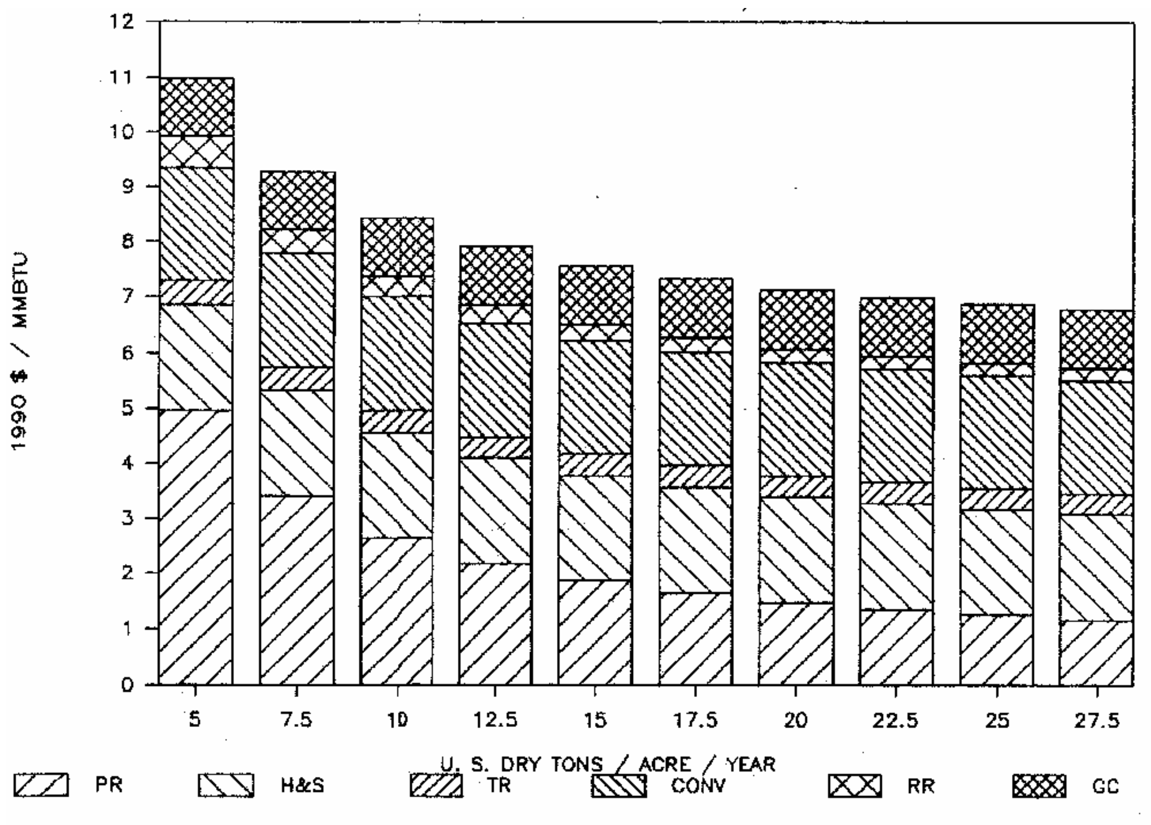


Figure 47. Economics of biomethane costs from wood (willow) as a function of biomass yield. (Legrand 1991)

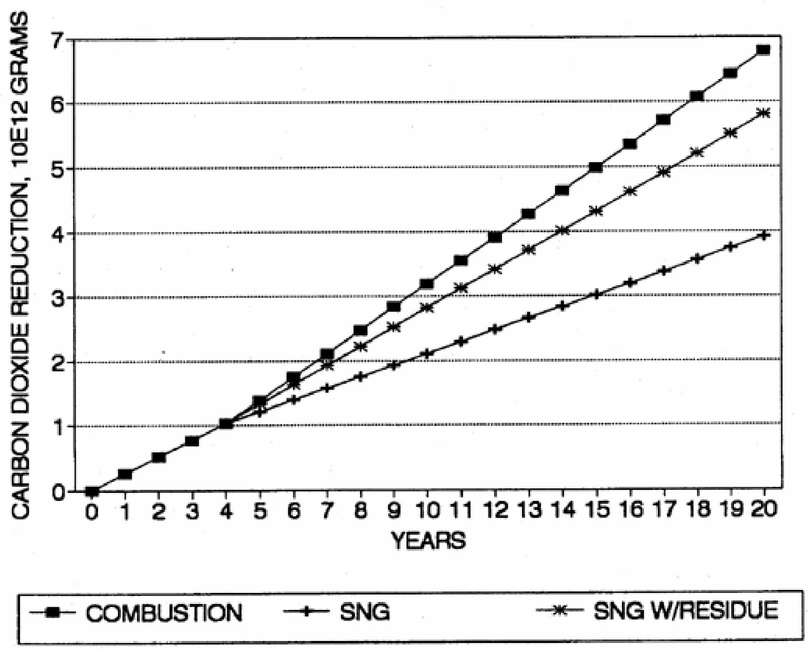


Figure 48. CO_2 abatement resulting from a 3 PJ/yr energy crop farm; 3 forms of biomass energy are considered; the 1988 U.S. fossil fuel mix is displaced. (Legrand 1993)

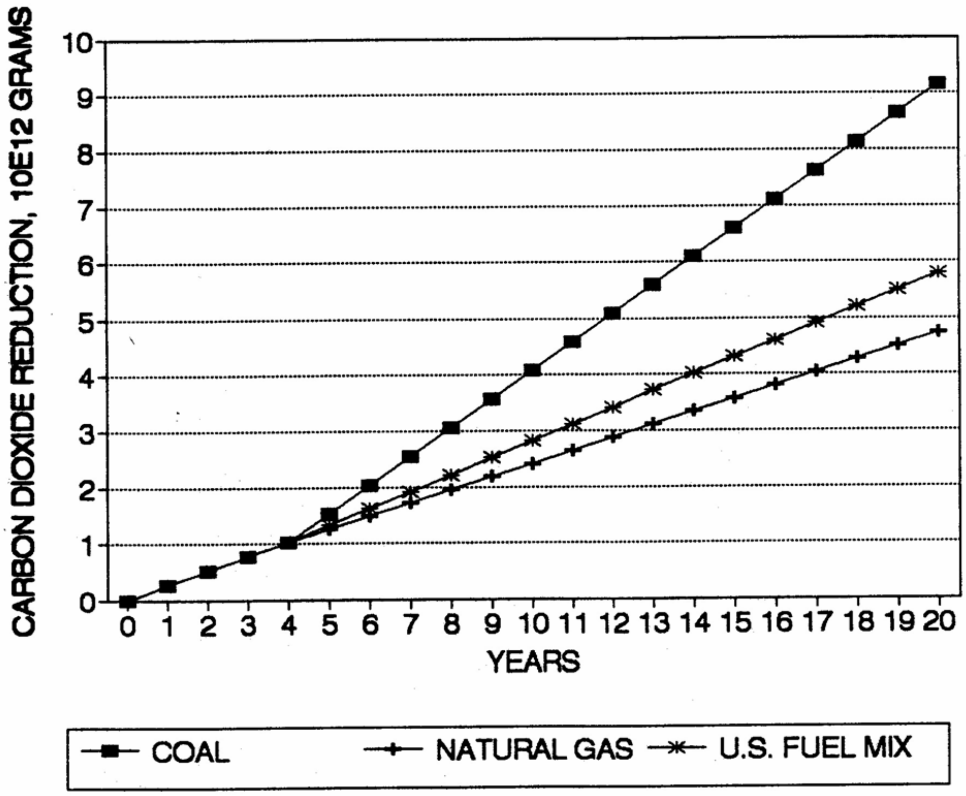


Figure 49. CO_2 abatement resulting from a 3 PJ/yr energy crop farm; biomass is biogasified and residue burned with power generation; various fossil fuels are displaced. (Legrand 1993)

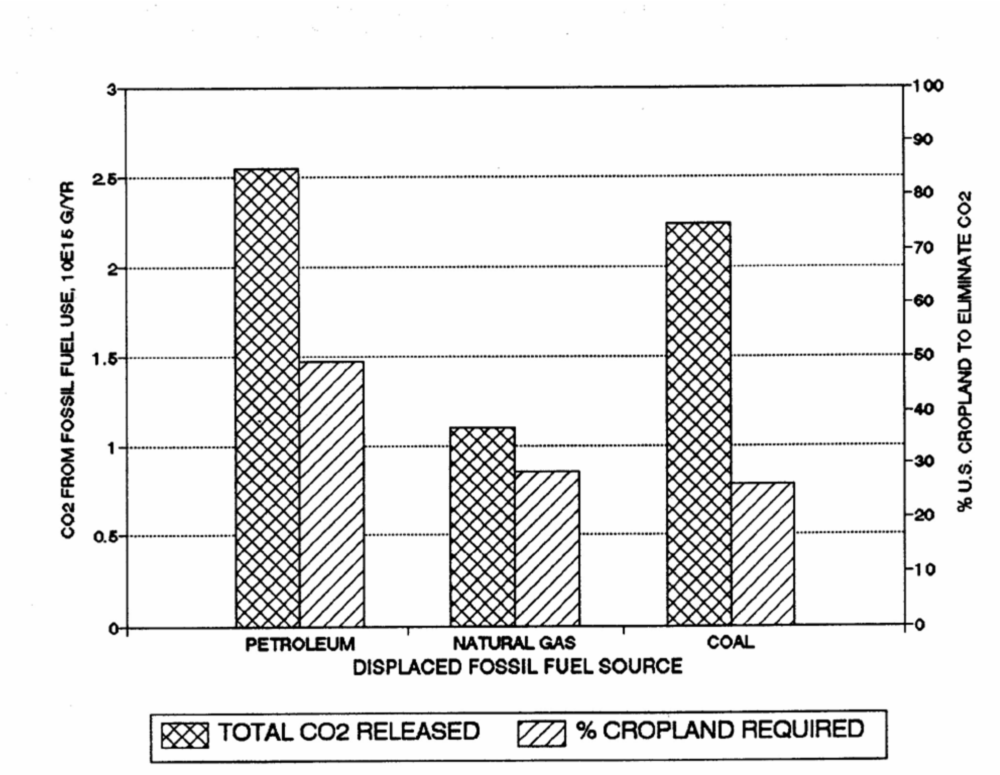


Figure 50. CO_2 production from fossil fuels in the U.S. area requirements for herbaceous energy. (Legrand 1991)

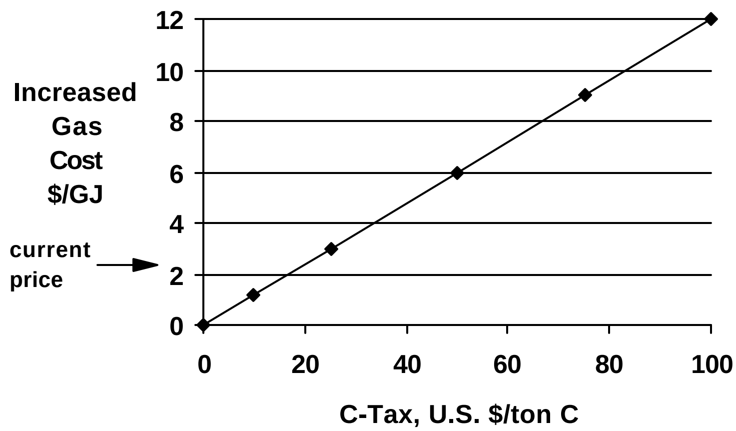


Figure 51. Effect of Carbon Tax on U.S. Gas Prices. (Chynoweth et al. 2001)