ETHANOL PRODUCTION IN HAWAII

Processes, Feedstocks, and Current Economic Feasibility of Fuel Grade Ethanol Production in Hawaii

Prepared for

State of Hawaii
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Final Report

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About the author

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NOTICE

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Throughout this document, statements are made in the form of suggestions or recommendations that grow out of the analysis. These conclusions represent the views of the consultant and do not necessarily coincide with the position of this Department, other government agencies, or the Administration.

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ACKNOWLEDGMENTS

In responding to the request for proposals for this project, it appeared that completing this work would be a rather straight forward task. In reality, obtaining details on every aspect of the analysis proved to be vastly more difficult than originally anticipated. The completion of this evaluation would not have been possible without extensive assistance from many individuals and organizations, particularly those listed below:

AMFAC/JMB Hawaii, Inc.
George St. John, Vice President of Plant Operations and Planning for AMFAC/JMB, contributed numerous hours assisting in evaluating potential options associated with using the sugar crop for ethanol.

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Joe Masin, Project Engineer with the Alternative Feedstock Development Department of Amoco, provided assistance with cost estimates and development of the economic evaluation procedures. He reviewed process flow diagrams and designs of facilities for processing biomass to ethanol. His assistance was fundamental in refining the capital and operating cost evaluations.

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William Farone provided continuing assistance with many aspects of the technical considerations that are the basis of this report.

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Alan Kennett, Director of Sugar Technology and Engineering for C. Brewer, contributed substantially to providing an understanding of the operating considerations and costs associated with the production and processing of sugarcane in Hawaii.

Cargill, Inc.
Loren Luppes and Tom Geiger of the Ethanol Division have been most helpful in providing general technical information on manufacturing ethanol from sugars.

Electric Power Research Institute (EPRI)
Personnel with EPRI's Biomass Program expressed interest in the possibility that Hawaii might serve as a location for a 3,000- to 5,000-acre biomass to energy demonstration site. Jane Turnbull, Project Manager for the Biomass Program, assembled a technical team to visit Hawaii during May, 1993. The group consisted of Jane Turnbull, Jack Ranney with Oak Ridge National Laboratory, Pam Sydelko with Argonne National Laboratory, and Dave Schlagel with the University of California Agricultural Research Station. Interactions during the visit provided a perspective for the evaluations presented in this report.

Hawaii Natural Energy Institute (HNEI)
HNEI has been extensively involved in evaluating the potential of using crops for energy production. Dr. Charly Kinoshita made substantial contributions to the program and has continually reviewed and evaluated technical data developed. His previous work on biomass crops in Hawaii was exceptionally valuable in this evaluation.

Hawaiian Sugar Planters' Association (HSPA)
HSPA was exceptionally helpful in providing production data on sugarcane and other potential energy crops. Dr. Robert Osgood and Mr. Lee Jakeway contributed substantial time and information to clarify issues on crops and energy, including a detailed summary of all costs associated with the planting, production, maintenance, harvesting, and transporting of sugarcane and alternative biomass crops which appear to have potential for energy conversion in Hawaii. HSPA also provided yield data on potential energy crops based on previous studies conducted in Hawaii.

National Renewable Energy Laboratory (NREL)
NREL has had a long term involvement in the development of technology for producing energy from biomass. Work conducted in the laboratory of Dr. Charles Wyman has been exceptionally useful in developing a format for the

technical evaluations. Dr. Ralph Overend of Dr. Wyman's program has been particularly helpful in providing technical information and referrals to other individuals and laboratories for technical assistance.

Pacific International Center for High Technology Research (PICHTR)
In May, 1993 PICHTR established the Sustainable Biomass Energy Program. The current study provided a substantial amount of information for the PICHTR activity. John Sprague provided significant assistance in accessing information and analyzing technology

State Department of Business, Economic Development & Tourism, Energy Division
Maria Tome, Transportation Energy and Fuels Specialist, served as the project manager. In reality she was also a major contributor to the to the development and completion of this report. Over the course of a year Maria spent weeks assisting in acquisition of technical information, redefinition and refinement of the topics, analysis and evaluation of the data, and assisting with refinement of numerous drafts of this document. Without Ms. Tome's assistance and inputs this report would not be possible.

Tennessee Valley Authority (TVA)
TVA was contracted to evaluate the design and assist in determining the financial performance of alternative technologies for the production of ethanol from biomass. Wayne Barrier and Millicent Bulls assisted in the creation of process flow diagrams, and financial projections on capital and operating costs for the various technologies under review. Dr. Bulls contributed to the development of an economic model that was used in parts of the evaluations.

The author also wishes to acknowledge the assistance of the individuals associated with each of the private sector technology developers who patiently contributed technical information for the report. They include:

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Mark Carver - Arkenol
David Fowler - Bioenergy
John Taylor - Staketech
George Lightsey - Mississippi State University
Roger Hester - University of Southern Mississippi

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SYNOPSIS

The objective of this study is to provide technical information and analysis to assist investors and decision-makers in evaluating the potential for the near-term production of ethanol in Hawaii. This is a "pre-feasibility" study designed to provide guidance as to whether or not a full-scale feasibility study is warranted.

WHY THE INTEREST IN ETHANOL?

There are several reasons for current public and private interest in the production of ethanol in Hawaii, such as:

- Interest in establishing a new industry;
- Interest in development and use of locally-produced, renewable fuels, and reduction of demand for imported petroleum;
- Interest in the use of locally-available agricultural materials, thereby providing additional markets for agricultural products and benefiting local farmers; and
- Interest in diverting organically-based municipal solid waste materials to higher value uses;
- Interest in reducing negative impacts on the environment; and
- Interest in the attraction of private-sector and government investment in biomass energy projects in Hawaii.

TECHNICAL BACKGROUND

A number of private sector companies interested in establishing ethanol production facilities in Hawaii have re-stimulated a local interest in the economic feasibility of ethanol production. Experts in the field have stated that “over the past ten years, efficiencies have improved and costs have decreased to the point that an ethanol plant built today may cost as little as a third as much (in constant dollars) as a comparably sized ethanol plant built ten or fifteen years ago.”[1]

Also leading to increased levels of interest are statements such as, “during the last two to three years there has been more progress in the technology for the conversion of lignocellulosic materials to ethanol than in the previous twenty years.”[2] The technical progress has been accompanied by commensurate economic improvement. Simple extrapolation of the results of earlier studies could not capture the effects of these technological improvements on the economics of ethanol production in Hawaii.

SELECTION OF BIOMASS FEEDSTOCKS

Historically, production of ethanol was limited to using sources of sugar that were available in soluble forms, such as sugar (sucrose), molasses from sugar cane, or fructose from the corn plant. Since these soluble sugars are edible, their relative value tends to be higher than for the rest of the plant (leaves, stalks, etc.) which is inedible and usually has a much lower value. In many cases, the inedible portions of the plants are considered to be waste materials.

New technologies allow for the production of ethanol from agricultural by-products such as corn stover, bagasse, yard and wood waste, etc. This is very significant: for example, where one acre of sugarcane produces about ten tons of

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[1] Statement made by an engineer who has been building ethanol plants for over twenty years. He was referring to corn-based ethanol; however, many of the cost reductions and efficiency improvements would be valid for non-corn-based ethanol as well.

[2] Personal communication, Mark Carver, Arkenol.

edible sugar and three tons of molasses, it also produces (in the form of leaves and stalks) an additional twenty to twenty-five tons of non-edible materials. It is also possible to produce ethanol from energy grasses or tree crops.

Starting with a list of twenty crops and sources of biomass in Hawaii, a short list of feedstocks was developed. The most promising crops were sugarcane, leucaena, eucalyptus, napier grass, and sweet sorghum. Waste paper and green waste were also identified as potentially promising feedstocks for ethanol production.

TECHNOLOGY EVALUATION

There are several steps in the process of converting biomass to ethanol, and many options available at each step. (For example, at a pre-treatment step, options may include cutting, grinding, or shredding.) Each of these steps, and potential technologies available at each step, were identified.

PROCESS COMPARISON

A combination of direct inquiry and literature review was used to compare capital and operating costs of a variety of technologies in addition to traditional fermentation for the production of ethanol. The seven different systems evaluated were felt to be representative of the range of technologies. These technologies should not be construed to be specifically representative of any one company or developer. The following seven representative approaches were evaluated:

1) Simultaneous saccharification and fermentation;
2) Concentrated acid hydrolysis, neutralization and fermentation;
3) Ammonia disruption, hydrolysis and fermentation;
4) Steam disruption, hydrolysis and fermentation;
5) Acid disruption and transgenic microorganism fermentation;
6) Concentrated acid hydrolysis, acid recycle and fermentation; and
7) Acidified acetone extraction, hydrolysis and fermentation.

These processes were evaluated for their potential to process the entire biomass feedstock to ethanol. Due to the proprietary nature of many of the approaches evaluated, in many cases it was necessary to rely on estimates made by owners of the technologies.

Due to the nature of this study, it was necessary to rely on claims made by those most familiar with the various technologies. In most cases, these individuals were the developers of the technologies and the owners of the patent rights, and therefore may have been somewhat biased in their claims; it should be expected that some individuals may have been more conservative in their projections, and others may have been more optimistic.

Estimated capital costs for plants producing 25 million gallons of ethanol per year ranged from 30 to 130 million dollars. At this scale, ethanol production costs ranged from less than $1.00 per gallon to almost $3.00 per gallon, depending on the technology and cost assumed for the feedstock.

These analyses were not site-specific, and significant differences would be expected for different sites, feedstocks, financing costs, labor costs, and so forth. Costs discussed in this report should be viewed as first-cut estimates only.

Since the level of uncertainty associated with the analyses may be greater than the apparent differences between the technologies, it is not clear from this analysis what process is the “best.”

All technologies evaluated displayed innovations which, if combined in one integrated system, might out-perform any one individual approach. A detailed analysis of each step indicated that additional technical innovations were possible. Although this study did not evaluate the impact of processing the by-products of the system to the most valuable market forms, several options were identified for possible further development.

SUMMARY OF RESULTS

As shown in the following table, the projected cost of ethanol produced from a variety of feedstocks and processes ranges from $0.94 per gallon to over $3.00 per gallon.

ETHANOL FEEDSTOCK AND PRODUCTION COSTS

BIOMASS MATERIAL	$/gallon for feedstock cost alone (high end of range)	$/gallon for feedstock cost alone (low end of range)	$/gallon processing cost (high end of range)	$/gallon processing cost (low end of range)	Total $ per gallon (high end of range)	Total $ per gallon (low end of range)
Bagasse	$0.84	$0.44	$1.66	$0.94	$2.49	$1.38
Molasses	$0.49	$0.49	$1.02	$0.52	$1.51	$1.01
Prepared cane	$1.11	$0.59	$1.66	$0.94	$2.76	$1.53
Leafy tops and cane trash	$0.52	$0.28	$1.66	$0.94	$2.18	$1.22
Unburned sugarcane	$1.01	$0.54	$1.66	$0.94	$2.67	$1.48
Sugarcane varieties	$0.93	$0.49	$1.66	$0.94	$2.59	$1.44
Napier Grass	$1.45	$0.77	$1.66	$0.94	$3.10	$1.71
Sweet Sorghum	$0.85	$0.45	$1.66	$0.94	$2.50	$1.39
Eucalyptus	$1.38	$0.74	$1.66	$0.94	$3.04	$1.68
Leucaena	$1.99	$1.06	$1.66	$0.94	$3.65	$2.00
Newspaper	$0.14	$0.05	$1.66	$0.94	$1.79	$0.99
Municipal Solid Waste	$0.42	$0.00	$1.66	$0.94	$2.07	$0.94

Assuming 25 million gallon-per-year ethanol production facility

GENERAL CONCLUSIONS

In spite of the previously-described uncertainties, variations in levels of optimism, etc., the analyses resulted in similar cost projections. This similarity lends a degree of confidence that, as the technologies mature, ethanol production costs in Hawaii will fall within this range.

Results indicate that there may be potential to establish an ethanol production industry in Hawaii. The projected ethanol production costs for some cases appeared to be in the general range of expected market prices, although site-, process-, and feedstock- specific analyses would have to be carried out before definitive conclusions could be reached with respect to price.

RECOMMENDATIONS

Hawaii's high biomass yields, near total dependence on imported fuels for energy, state policy encouraging energy self-sufficiency, strong agricultural base, desire for economic diversification and apparent feasibility of a biomass-to-ethanol industry in Hawaii are strong reasons for Hawaii to continue its efforts on behalf of ethanol.

Site- and technology-specific evaluations of the production of ethanol in Hawaii could provide the information necessary to justify investment in ethanol production facilities. Construction of pre-commercial facilities could provide operational data as well as develop local expertise. Working with private sector investors and federal laboratories to demonstrate the commercial-scale conversion of cellulosic materials to ethanol may result in accomplishment of several of the objectives listed above, with a minimum level of risk to the state.

Development of a market for the product would provide the link between the point at which the technical and economic feasibility of the projects have been proven and the plant(s) are built.

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I. INTRODUCTION & BACKGROUND

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A. WHY ETHANOL FOR HAWAII?

There are several reasons for current public and private interest and support for the production of ethanol in Hawaii. For example:

- It might be possible to establish a local industry to substitute for some portion of the approximately 50 million barrels of petroleum that we currently import each year to meet our energy needs.

  For example, the use of ethanol in a 10% blend with gasoline is being done nation-wide (in forty-four other states), and all auto makers approve the use of properly blended ethanol fuels in their vehicles.

  Also, the National Energy Policy Act of 1992 requires the purchase of alternatively-fueled vehicles by Federal, state, and other fleets. Ethanol qualifies as an alternative fuel.

- If the economics were favorable, producing ethanol might provide a basis for establishing alternative uses for agriculture lands that are coming out of production and may generate new sources of employment in the agriculture sector.

- If the economics did not support production of ethanol as a single output, ethanol production might be a viable co-product with other agricultural-based products such as sugar, fiberboard, or diversified agriculture.

- It might be possible to use a significant amount of the material in municipal solid waste to produce ethanol, thereby reducing the flow of material to the landfill and providing a low cost source of feedstock for ethanol production.

- Ethanol production from local feedstocks may offer an opportunity to develop new businesses and provide some economic diversification in rural areas.

B. HISTORICAL PERSPECTIVE

There has been a continuing interest in ethanol production in the State of Hawaii since the turn of the century, specifically with regard to the production of ethanol from sugar cane molasses. Numerous studies have been completed on the economic feasibility of producing ethanol in Hawaii; this interest is not new. For example, the following is contained in an abstract of research in Hawaii from 1930-1952:

> "Experiments on the use of anhydrous ethyl alcohol blended with gasoline for motor fuel have corroborated those reported in the literature, viz., that 10 per cent alcohol in gasoline can be used in any modern automobile engine with no appreciable change in power, efficiency and economy, but with a distinct benefit in its prevention of 'knocking.' " – A. R. Lamb, **1936**

> "Studies now in progress on products which can be made from waste molasses indicate that several possibilities are worthy of further explanation. One which fits remarkably well into present conditions is the manufacture of anhydrous alcohol to be used in blending motor fuel." – A. R. Lamb, **1935**

The energy crises of the 1970s stimulated a resurgence of interest in ethanol production. Substantial subsidies and tax benefits for producing the product were available, beginning with the Energy Tax Act of 1978. In 1980, both Pacific Resources, Incorporated (owner of Hawaii Independent Refinery, Inc.) and C. Brewer and Company proposed full-scale feasibility studies on the production of ethanol from molasses. The C. Brewer and Company study was funded and completed but the facility was never constructed.[3] In 1985, an ethanol-from-molasses facility was constructed at Campbell Industrial Park on Oahu. The facility was poorly designed[4] and ran into several major problems before it was finally closed down and the equipment was auctioned off.

The only remaining ethanol production facility in the state is a one-million-gallon-per-year facility at the Hawaiian Commercial and Sugar Company (HC&S) on Maui. This facility, built by Seagram's in the mid-1960s for the production of rum, has not been operational since 1985.[5]

C. RENEWED INTEREST

A number of private sector companies interested in establishing ethanol production facilities in Hawaii have re-stimulated a local interest in the economic feasibility of ethanol production (2, 6, 7, 8, 9, 10, 11). Each of these companies has something new to offer Hawaii by way of experience, process, or technology.

Economic feasibility studies reflect the technologies and feedstocks available at the time they are completed. While the earlier studies mentioned above provide a valuable base of knowledge, they do not necessarily represent a comprehensive comparison of current “state of the art” options.

For example, several experts in the field have stated that “over the past ten years, efficiencies have improved and costs have decreased to the point that an ethanol plant built today may cost as little as a third as much (in constant dollars) as a comparably sized ethanol plant built ten or fifteen years ago.”[6] Also leading to increased levels of interest are statements that “during the last two to three years there has been more progress in the technology for the conversion of lignocellulosic materials to ethanol than in the previous twenty years.”

The technical progress has been accompanied by economic improvement; several specific problems that heretofore were impediments to the profitable production of ethanol and its use as a transportation fuel have been solved; much progress has been made by government, universities, and the private sector in advancing the technology for hydrolyzing biomass to sugars fermentable to ethanol. Therefore, an evaluation of the appropriateness of the commercial processes to the Hawaii situation was felt to be essential to determine the current economic feasibility of ethanol production.

D. SCOPE OF THIS STUDY

This is the final report to the State of Hawaii, Department of Business, Economic Development & Tourism, under a contract for the evaluation of Optimal Processes, Feedstocks and Current Economic Feasibility of Fuel Grade Ethanol Production in Hawaii.

As stated in the request for proposals (RFP), the objective of this study is the:

> “...evaluation of the feasibility of local production of ethanol for use as an alternative transportation fuel. The purpose of this RFP is to select a consultant to provide professional, technical, and research services in support of the State’s efforts to develop local alternative fuel production capabilities.”

The RFP pointed out that:

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[3] According to a C. Brewer press release, "We have put a great deal of time, effort and expense into ethanol ... but we cannot invest $15 million in capital to produce a product we cannot be assured of marketing within the Hawaiian market as we have no gasoline stations of our own."

[4] Personal communication, R. L. Bibb Swain, P.E., president, Delta-T Corporation, March 25, 1992.

[5] Personal communication, Diane Shigeta, Alexander and Baldwin, 1990.

[6] Statement made by an engineer who has been building ethanol plants for over twenty years. He was referring to corn-based ethanol; however, many of the cost reductions and efficiency improvements would be valid for non-corn-based ethanol as well.

> "Hawaii is dependent on petroleum for ninety percent of its energy needs. In the transportation fuels sector this dependence is even greater. Hawaii currently imports 100% of its transportation fuels. The transportation sector is the largest energy-consuming sector in Hawaii, accounting for about three-fifths of total petroleum demand in 1990.
>
> "Hawaii's energy security would be improved by diversifying the fuels used for transportation and reducing dependency on imported fossil fuels. Local production of transportation fuels and feedstocks could also improve Hawaii's economic security and provide jobs for Hawaii's people. Additionally, the use of waste products as feedstocks could divert wastes from landfills and/or reduce the pollution potential of those wastes and maintain scarce and valuable land resources for agriculture, housing and business."

In essence, this is a "pre-feasibility" study. Before investing significant time and resources in detailed site-, feedstock-, or technology-specific analyses, a survey of the possibilities provides justification and direction for further effort.

The objective of this study is to provide a first-cut estimate of the feasibility of producing ethanol in Hawaii, and to identify the most promising feedstocks and technologies for ethanol production.

If it appears that ethanol production in Hawaii may be feasible, more detailed and/or site-specific analysis may be warranted.

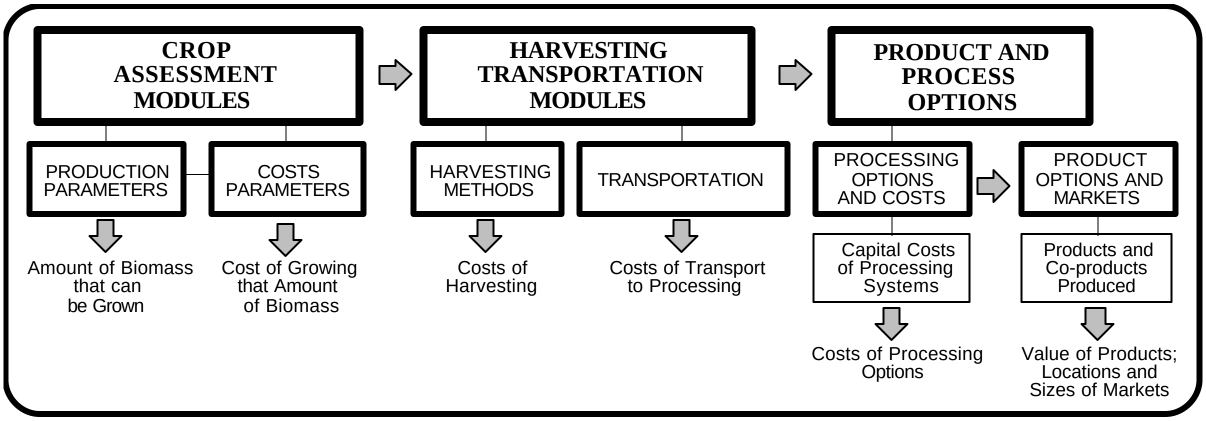
E. APPROACH

The approach used is as follows:

- Discussion of the differences between biomass feedstocks and their chemical composition (Chapter II);
- Identification of types of biomass (agricultural and other materials) available or potentially available in Hawaii for conversion to ethanol (Chapter III);
- Estimation of crop yields and amounts of other biomass available in Hawaii (Chapter III);
- Crop composition and fermentable sugars potentially available for conversion to ethanol (Chapter III);
- Estimation of delivered cost per ton of biomass (Chapter III);
- Identification of technologies for the conversion of biomass to ethanol (Chapter IV);
- Estimation of capital, operating costs and ethanol yields from each technology (Chapter IV);
- Identification of by-products and potential markets (Chapter V);
- Estimates of the overall economics of ethanol production in Hawaii using these feedstocks and processing technologies (Chapter V);
- Summary, conclusions, and recommendations as to the most promising feedstocks, technologies, and suggested next steps (Chapter VI).

A diagram of the overall ethanol production system is presented in Figure I-1 below:

Figure I-1
BIOMASS TO ETHANOL ASSESSMENT PROCESS



Biomass cost elements may be partitioned as follows:

(1) Crop Production Costs;
(2) Harvesting and Delivery Costs;
(3) Processing Costs; and
(4) By-Product Definition and Value.

This report does not assess items (1) and (2) above; values for crop production, harvesting, and delivery costs used in this report are from work done by others. This study focuses on items (3) and (4).

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II. BIOMASS DESCRIBED

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The warm climate and high levels of solar incidence offer unique potential to grow biomass as an alternative method of meeting our energy needs. Before discussing conversion of biomass to ethanol, however, a brief description of biomass itself is in order.

A. THE IMPORTANCE OF CHOICE OF MATERIALS ("FEEDSTOCKS")

The costs of ethanol production are highly sensitive to the cost of the feedstock delivered to the processing site and the volume and composition of the material. The success of any plan to grow crops for ethanol production will be dependent on the selection of appropriate crops, production methods and locations. A system that is established around the lowest cost starting material and is fully integrated to “squeeze out” the greatest economic outputs by utilizing all of the by-products in the system will present the best opportunity for economic success.

B. “LIGNOCELLULOSIC BIOMASS” AND SYSTEM ECONOMICS

Historically, production of ethanol was limited to using sources of sugar that were available in soluble forms, such as sugar (sucrose), molasses from sugar cane, or fructose from the corn plant. Since these soluble sugars are edible[7], their relative value tends to be higher than for the rest of the plant (leaves, stalks, etc.) which is inedible and usually has a much lower value. In many cases, the inedible portions of the plants are considered to be waste materials.

However, new technologies have been developed which now allow for the production of ethanol from “lignocellulosic biomass.” Lignocellulosic biomass is the leafy or woody part of plants: corn stover, bagasse, yard and wood waste, paper pulp, etc. This is very significant: for example, where one acre of sugarcane produces about ten tons of edible sugar and three tons of molasses, it also produces (in the form of leaves and stalks) an additional twenty to twenty-five tons of non-edible materials. Lignocellulosic biomass also refers to energy grasses or tree crops.

Starting with a list of twenty crops and sources of biomass in Hawaii, a short list of feedstocks was developed. The most promising crops were sugarcane, leucaena, eucalyptus, napier grass, and sweet sorghum. Waste paper and organic waste were also identified as potentially promising feedstocks for ethanol production.

C. CHEMISTRY – THE SUGAR CONTENT OF MATERIALS

Figure II-1 below provides a very generalized view of plant cell wall composition. The molecules that give plants their structure can be processed to produce sugars that can, in turn, be fermented to ethanol.[8]

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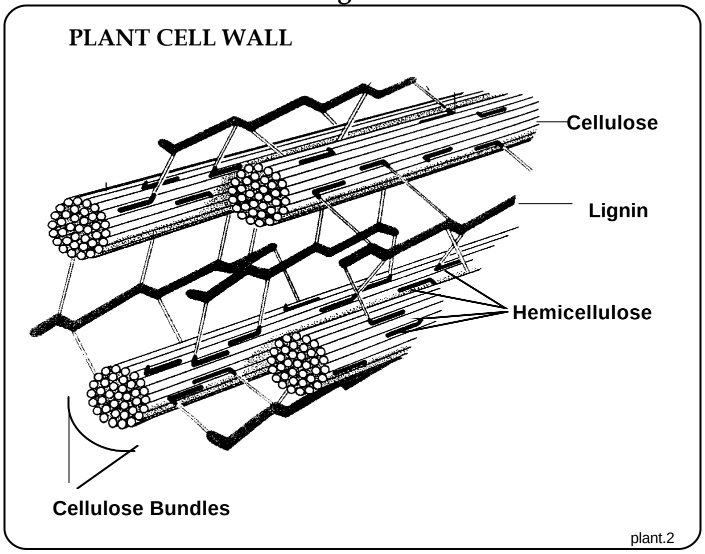
[7] “Edible” as used here means for human consumption.

[8] Modified, from Biological Science. (1986) W.W. Norton & Company, Publisher.

Figure II-1



The primary components of most plant material are commonly described as lignocellulosic biomass. The biomass is principally composed of the compounds **cellulose, hemicellulose, and lignin. Cellulose**, a primary component of most plant cell walls, is made up of long chains of the **6-carbon sugar, glucose** arranged in bundles. (Often described as crystalline bundles). Cellulose is a primary component of paper. In the plant cell wall, the cellulose molecules are interlinked by another molecule, **hemicellulose.** The **hemicellulose** is primarily composed of the **5-carbon sugar, xylose**. Another molecule called **lignin** is also present in significant amounts and gives the plant its structural strength. Improvements in technology have recently provided a variety of methods of extracting and dissolving the cellulose and hemicellulose to produce the component sugars in a form that can be converted to ethanol. Appropriate pre-treatment can free the cellulose and hemicellulose from the plant material. Further treatment using chemicals, enzymes or microorganisms can be used to liberate simple sugars from the cellulose and hemicellulose making them available to microorganisms for fermentation to ethanol.[9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19]

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[9] Bioenergy International, 1901 N.W. 67th Place, Suite E, Gainesville, FL 32606. Personal Communication, August 3, 1992.

[10] ARKENOL Inc., Mark Carver, 23293 S. Pointe Dr., Laguna Hills, CA 92653. Personal Communication, May 13, 1993.

[11] Paszner Technologies, Inc., Dr. Lazlo Paszner, 2683 Parkway Drive, Surrey, B.C., V4P 1C2 Canada. Description of the ACOS Process. Personal communication. November 20, 1993.

[12] Tigney Technology Inc. “A Technical Analysis of Partitioning and Transformations of Sugarcane Bagasse and Leaves by the Tigney Refinery System.” Prepared for the Hawaiian Sugar Planters Association, Aiea, Hawaii, January 28, 1991.

[13] Clausen, E.C. and J. L. Gaddy, (1987) “The Production of Chemicals and Fuels from Municipal Solid Waste,” in *Global Bioconversions*, Vol. II, Donald L. Wise, Ed. CRC Press, Inc. Boca Raton, Fla. 62:73.

[14] Grethlein, H.W. and T. B. Nelson. (1992) “Projected Process Economics for Ethanol Production from Corn.” Final Report under Agreement No. 58-1935-2-020, July 17, 1992 to the United States Department of Agriculture, Agricultural Research Service, North Atlantic Area, Eastern Regional Research Center, Philadelphia, Pennsylvania.

[15] Goldstein, I. S. and J. M. Easter. “An Improved Process for Converting Cellulose to Ethanol.” *Technical Association of Pulp and Paper Industry Journal*, August, 1992, 135-140.

[16] Dale, B. and M. Holtzapple. “Technical Summary of Ammonia Freeze Explosion.” Report, Dept. of Chem. Engineering, Texas A&M University, March 1989.

[17] Stuart, Dorsey, President Neugenesis, 2800 Woodlawn Drive, Honolulu, Hawaii 96822, personal communication.

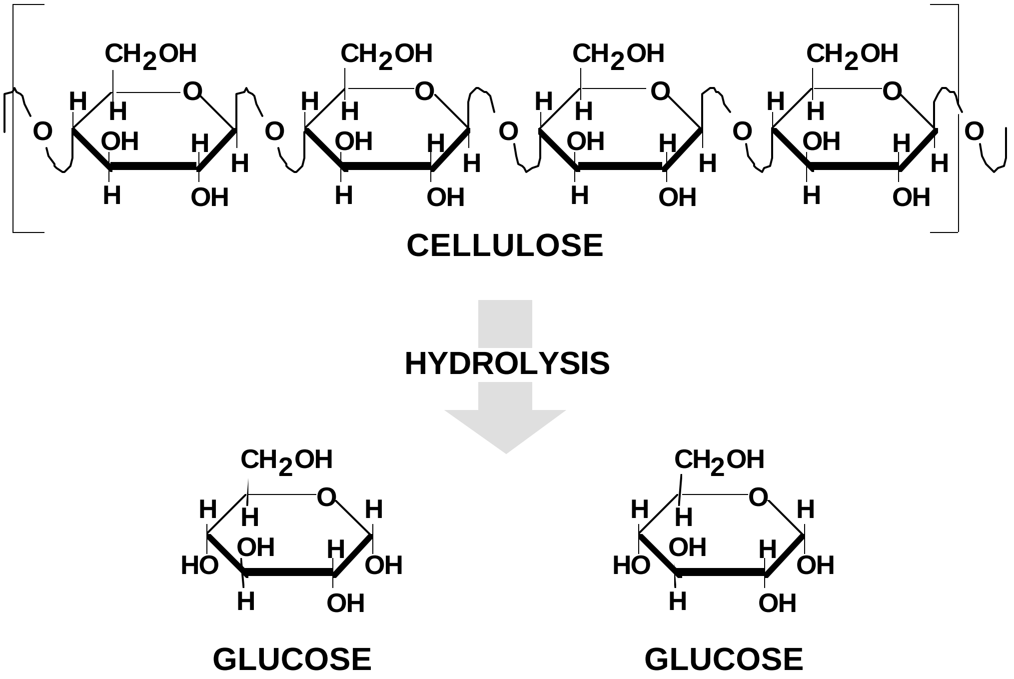
[18] Holtzapple, M. (1988) “Conversion of Grass to Highly-Digestible Animal Feed, Protein Concentrate, and Ethanol.” Report, Dept. of Chem. Engineering, Texas A&M University, June, 1988.

[19] Prasner, L. et al, (1986) “High-Yield Organosolv Process for Conversion of Cellulosic Biomass to Ethanol" in *Energy from Biomass and Wastes* (D. L. Klass, ed.), Institute of Gas Technology, Chicago, 1279: 1318.

D. CHEMISTRY – CONVERSION OF SUGARS TO ETHANOL

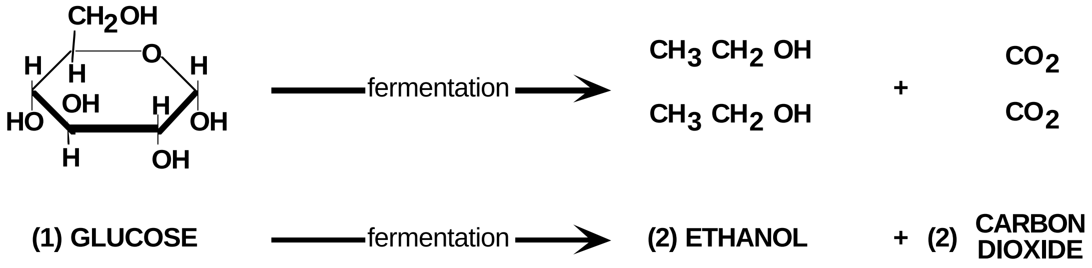
The figures below illustrate the conversion of cellulose to ethanol. The first step involves hydrolysis: splitting the bonds in the cellulose to produce the sugar glucose (Figure II-2).

Figure II-2
CELLULOSE HYDROLYSIS



Once the large molecules are extracted they can be broken down into their component sugars using enzymes or acids. The sugars then can be converted to ethanol using appropriately selected microorganisms in a process called fermentation. The formation of ethanol from 6 carbon sugars is illustrated in Figure II-3.

Figure II-3
GLUCOSE FERMENTATION



One molecule of glucose produces 2 molecules of ethanol and 2 molecules of carbon dioxide.

An examination of the molecular weights of the molecules reveals that the weight of ethanol produced is equal to about half the weight of the starting material (glucose).

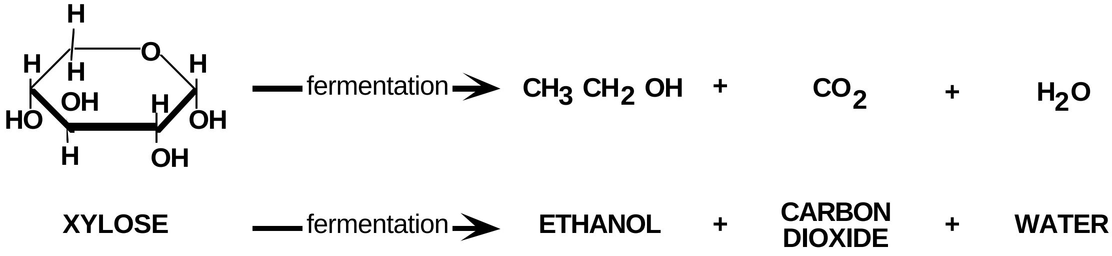
Glucose	$C_6H_{12}O_6$	Molecular Weight	=	180			
Ethanol	C_2H_5OH	Molecular Weight	=	46	x 2	=	92
Carbon Dioxide	CO_2	Molecular Weight	=	44	x 2	=	88

The maximum weight % ethanol from the process would be 92/180 = 51%.

Almost half the weight of the glucose 88/180 (49%) is converted to carbon dioxide.

Hemicellulose is made up of the 5 carbon sugar xylose arranged in chains with other minor 5 carbon sugars interspersed as side chains. Just as with cellulose, the hemicellulose can be extracted from the plant material and treated to release xylose which, in turn, can be fermented to produce ethanol. As reviewed by Roberts and Hilton,[20] xylose fermentation is not straight forward. Depending on the microorganism and conditions, a number of fermentations are possible. The array of products can include ethanol, carbon dioxide, and water.

Figure II-4
XYLOSE FERMENTATION



Actually, three conversions have been documented with yields of ethanol ranging from 30 to 50 percent of the weight of the starting material (weight ethanol/weight xylose).

(3) XYLOSE —fermentation→ (5) ETHANOL + (5) CARBON DIOXIDE
(3) XYLOSE —fermentation→ (4) ETHANOL + (7) CARBON DIOXIDE
(1) XYLOSE —fermentation→ (2) ETHANOL + (1) CARBON DIOXIDE + (1) WATER

However, laboratory results have indicated a wide range of variation. In the discussion of potential yields of ethanol from various materials, a range of hemicellulose-to-xylose conversion efficiencies and a range of xylose-to-ethanol conversion efficiencies have been combined to provide an assumed overall conversion efficiency of hemicellulose to ethanol of about 50 percent. For more information on assumed conversion efficiencies, see tables in the Appendix.

Just as with glucose fermentation, the conversion of carbon dioxide to products of value would vastly improve the economics of ethanol production. This will be discussed in detail later in the report.

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[20] Roberts, R.R. and H.W. Hilton. (1988) "Sugarcane Bagasse as a Potential Source of Ethanol and Methanol Biofuels," Final Report of the Feasibility and Production of Alcohol Fuels from Sugarcane Bagasse Project, Prepared for the Department of Business and Economic Development, State of Hawaii, 1:53.

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III. AVAILABILITY AND COSTS OF BIOMASS MATERIALS

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A. SELECTION OF FEEDSTOCKS FOR FURTHER ANALYSIS

The first challenge is to determine what can be grown or what may be available that produces the greatest amount of fermentable sugars at the least cost. Crop potential is very location specific. Environmental conditions (sunlight, water, and soil) must be consistent with the needs of the crop. Economic factors such as production, harvesting, and transportation costs must be considered. Economy of scale – to provide contiguous land areas of sufficient size within a reasonable distance of the processing plant – must be available. Processing technologies appropriate to the source of biomass must be available.

The technical feasibility, costs associated with the use of various feedstocks, and the potential of any feedstock to be used for ethanol production depends on:

- The yield of biomass per harvest of the crop;
- The number of years required to produce a harvestable crop;
- The content of sugars and sugar containing molecules in the harvested biomass;
- The delivery cost of the biomass to the plant; and
- The cost of the technology required to process the biomass material to ethanol.

The ethanol production process may be partitioned as follows:

1	2	3	4	5
BIOMASS SUPPLY OR PRODUCTION	BIOMASS HARVESTING	BIOMASS TRANSPORT	BIOMASS PROCESSING	BIOMASS CONVERSION TO ETHANOL

For example, a quoted cost of “$50 per delivered ton, dry matter basis” would include steps 1, 2, and 3 above. Note that this quoted cost refers to the calculated dry weight content of the material, although the material may not actually be "dry" at the time of delivery. The actual weight of material delivered to the plant might be 2-4 times the dry weight.

The nature of the feedstock puts certain constraints on the technology required for the manufacture of ethanol. For example, molasses or sugar solutions can be fermented directly by yeast, using traditional and well-established technology. However, lignocellulosic feedstocks such as wood or bagasse must be hydrolyzed into component molecules and sugars before fermentation by one or more specifically selected microorganisms. Though currently requiring increased capital investment, technologies for conversion of lignocellulosic materials are near-term and have the potential for dramatic improvements of ethanol yields.

If the cost of a feedstock is sufficiently low, more expensive conversion technology may be justified.

1. Feedstock Selection: Criteria

Materials selected for evaluation were those for which:

- Production or availability in Hawaii had been demonstrated;
- Production requirements and yields were known;
- Material composition (see Table III-1) was consistent with objectives; and
- Yields and production costs appeared to be consistent with objectives.

Data on crops and material composition were obtained from technical publications and direct discussions with researchers who had unpublished information. This provided the basis for development of a short list of promising feedstock materials that are available or could be produced in Hawaii.

2. Feedstock Selection: Results

The short list of materials, and corresponding contents of sugars, cellulose, hemicellulose, and lignin (based on dry weight), is shown below. As can be seen in Table III-1, some non-crop materials also show promise. Municipal solid waste (MSW) and newspaper are exceptionally fine sources of cellulose and hemicellulose.

Table III-1
COMPOSITION OF BIOMASS
(% BY WEIGHT, DRY BASIS)

Biomass Source	Sugars	Cellulose	Hemicellulose	Lignin	Other
Bagasse	3	38	27	20	12
Molasses	61	--	--	--	39
Sugarcane ("prepared" cane)	43	22	15	11	9
Sugarcane leaves	--	36	21	16	27
Sugarcane (whole plant)	33	25	17	12	13
Napier grass	--	32	20	9	39
Sugarcane hybrids	28	37	14	15	6
Sweet sorghum	34	36	16	10	3
Eucalyptus grandis	--	38	13	37	12
Eucalyptus saligna	--	45	12	25	18
Leucaena leucocephala	--	43	14	25	18
Municipal Solid Waste	--	33	9	17	41
Newspaper	--	62	16	21	1

For information on sources and references, see tables in Appendix.

B. AGRICULTURAL CROPS

1. Sugarcane (traditional varieties)

a. Sugarcane terminology

The following are definitions of common terms:

Field cane	Cane as it comes from field after burning; usually collected by push-raking; contains mud and rocks. This is the cane that actually arrives at the mill.
Prepared Cane	Cane after washing off mud and rocks; still has some leaves and water. This is processed to sucrose (sugar), molasses and bagasse.
Net Cane	A calculated value, representing the cane stalk without leaves.

b. Sugarcane yields

Sugarcane production in Hawaii has fluctuated with changes in weather and other factors. Sugarcane production in the most recent twelve-year period is shown in Figure III-1.[21]

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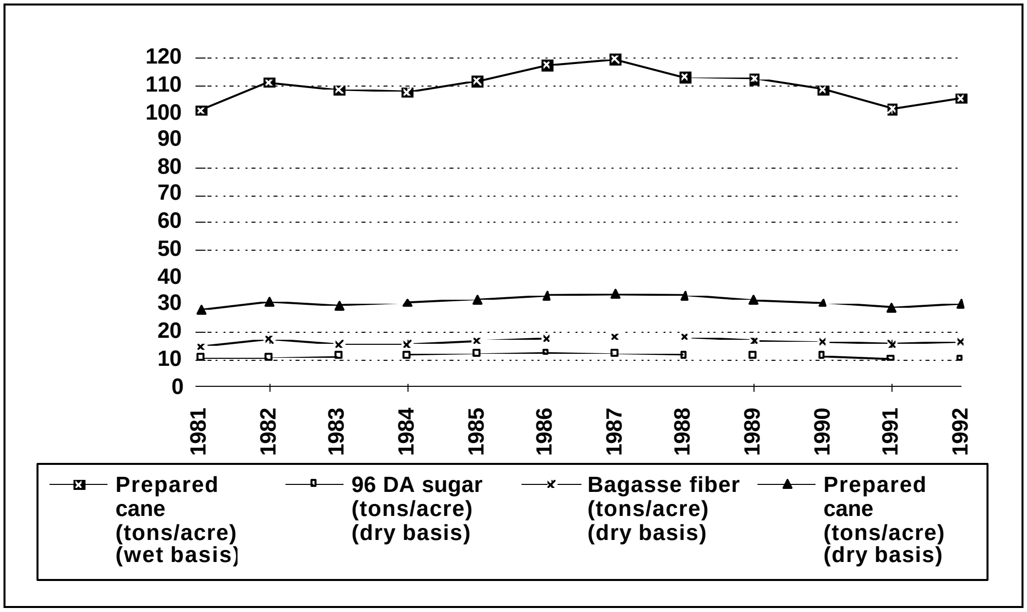
[21] Unpublished Hawaiian Sugar Planters' Association data, 1980-1992 *Energy Reports.*

Figure III-1

SUGARCANE PRODUCTION IN THE STATE OF HAWAII, 1981-1992



c. Sugarcane components and products

1) Stalks

"Prepared cane" is primarily the stalk of the sugarcane plant, with some leaves and some water remaining from the washing process. Sugar (sucrose), the primary commercial product of the sugar industry, is contained in the stalk. The sugarcane stalks are processed to sugar, bagasse, and molasses. Most of the raw sugar is sent to California to be refined; most of the bagasse is burned in boilers to produce process steam and electricity; and most of the molasses is shipped to California and sold as cattle feed.

2) Leafy trash

Prior to harvesting the sugarcane, the fields are usually burned (weather and other conditions permitting) to reduce the harvesting, transporting, and processing costs associated with hauling in excess material (primarily leafy trash). Most reported amounts of "field cane" and "prepared cane" do not include the total amount of biomass that was available before the fields were burned.

Twenty-one plots of unburned cane, on eleven plantations, were hand-cut prior to field burning to determine total biomass available in unburned cane. Results indicated that approximately thirty-five per cent of the total fiber is consumed in open field burning.[22] In other words, the reported bagasse (dry basis) represents only sixty-five per cent of the original fiber. Therefore, the amount of fiber in unburned cane may be calculated by multiplying bagasse produced (dry basis) by 1.54 (the reciprocal of 0.65). Figure III-2 shows reported and projected yields for burned and unburned sugarcane.

For more information on calculations, assumptions, and sources of information, see tables in the Appendix.

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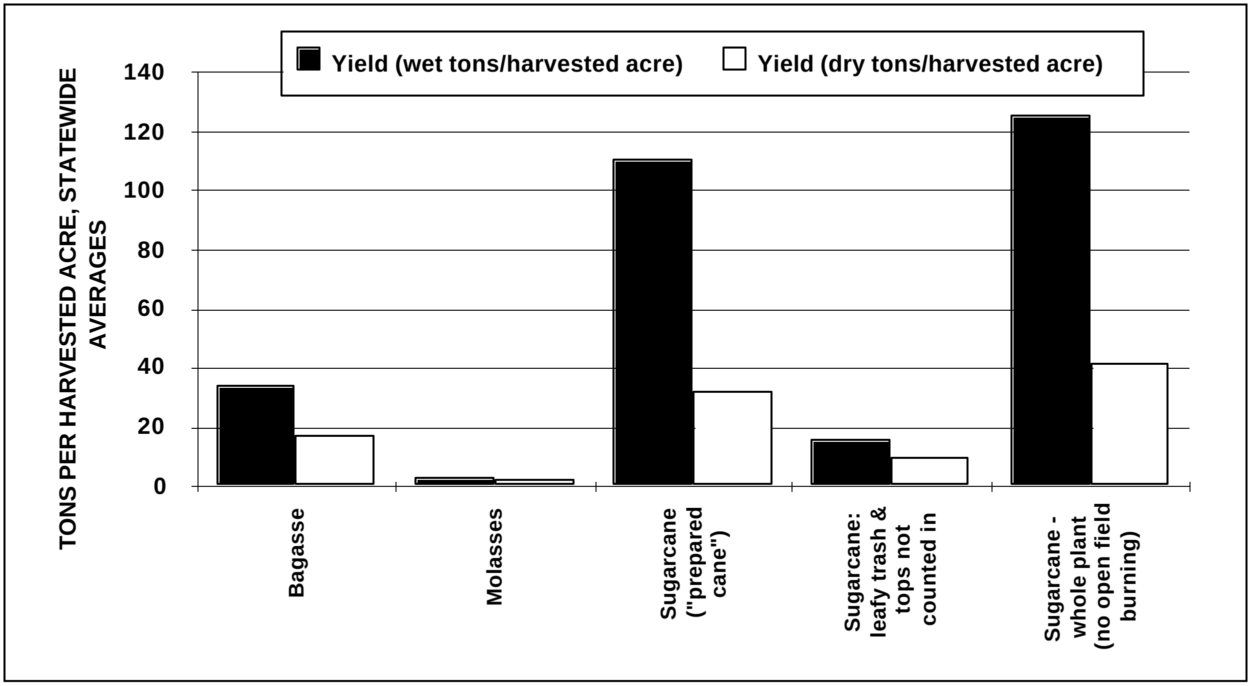
[22] Kinoshita, C. K. 1988. "Composition and processing of burned and unburned cane in Hawaii." *International Sugar Journal*. Volume 90, Number 1070.

Figure III-2
SUGARCANE YIELDS, BURNED AND UNBURNED CANE



2. Sugarcane (other varieties)

One possible approach in the development of sugarcane as a feedstock for energy and fuels is the development and improvement of varieties of sugarcane optimized for the production of all components of the biomass – including sucrose, cellulose, hemicellulose, and lignin – rather than optimized for the production of sucrose alone. Several varieties of sugarcane, including varieties for energy production, have been grown and evaluated in Hawaii.[23]

a. Energy Cane Theory

A researcher and author on the subject, A. G. Alexander, has written extensively over the past thirty years on various aspects of sugarcane growth and production. In the 1970s, sponsored by the United States Department of Energy, growth trials on hybrids of sugarcane and energy grasses were conducted.[24] Alexander's 1985 book entitled *The Energy Cane Alternative*[25] discusses a variety of sugar cane which he calls "Energy Cane."

"Energy cane" is managed as a total crop. In contrast to current practices in Hawaii, this crop is grown for only one year and harvested as the total plant for its sucrose, cellulose, hemicellulose and lignin content.[26] As described by Alexander,

> "...Conceptually, the 'energy cane' approach to the management of sugarcane and allied tropical grasses is based on simple but solid premises.

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[23] Osgood, R. V. and Dudley, N. S. 1987. "Comparative Yield Trials with Tree and Grass Energy Crops in Hawaii: a Preliminary Report on Current Research" report 88-04 of *Cane Energy Utilization Symposium Proceedings*.

[24] Alexander, A.G. (1982) *Production of Sugarcane and Tropical Grasses as a Renewable Energy Source.* Final Report to the U.S. Department of Energy. DOE/ET/20071--T5.

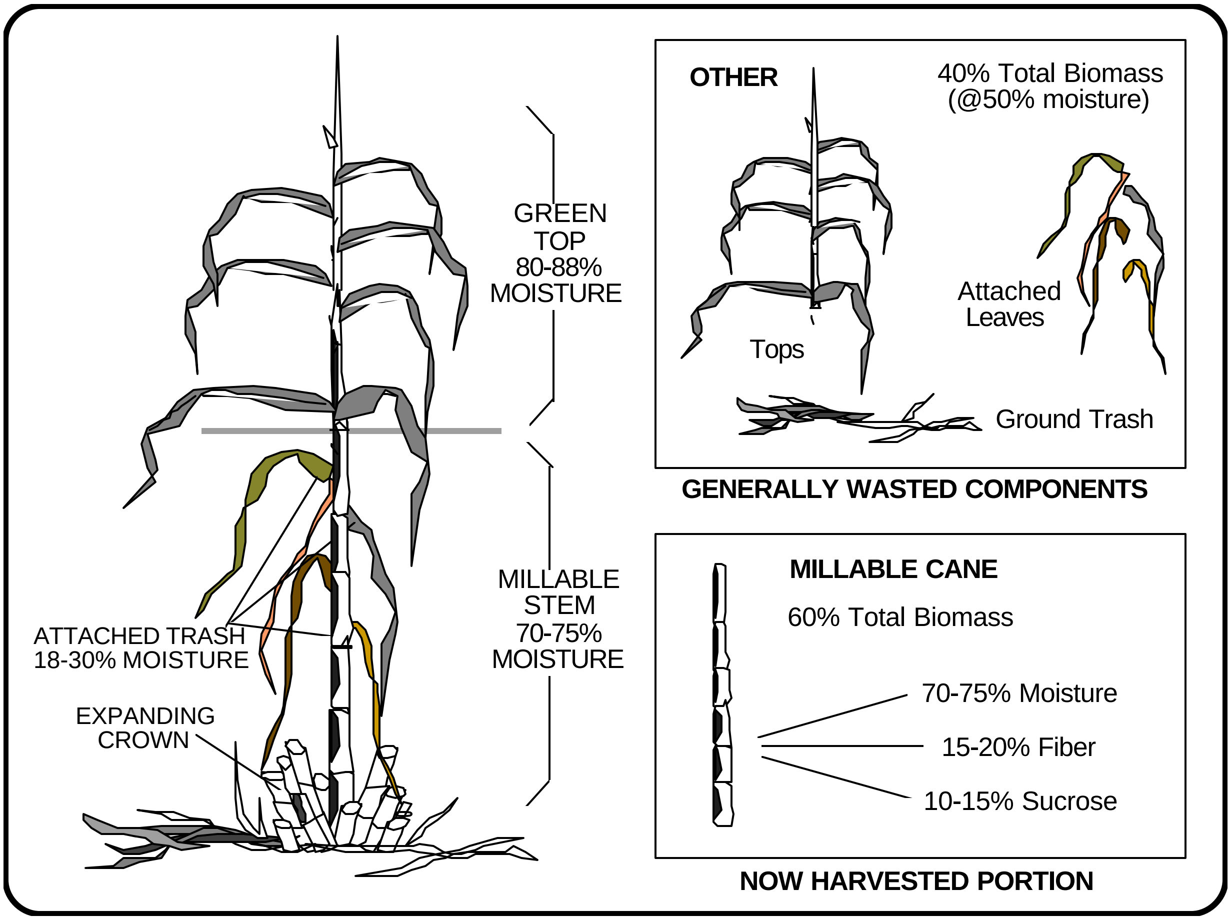
[25] Alexander, A.G. (1985) "The Energy Cane Alternative." Sugar Series #6. Elsevier Science Publishing Co., Inc. New York, New York. pp. 1- 479.

[26] This is only possible in locations where the land is relatively flat and rainfall is limited. Much of Hamakua, for example, would not be an appropriate location for this type of harvesting system.

> First, sugarcane is botanically more effective as a producer of biomass (lignocellulose) than of fermentable solids (sugars). Second, the biomass producing attributes are underutilized when the cane plant is managed strictly as a sugar commodity. Putting this another way, the cane plant falls short in its "quantitative" potentials when its agriculture is directed toward its "qualitative" potentials, i.e., toward sucrose accumulation. Third, sugar cane grown as a sugar crop is a "monolithic" commodity, for which the bagasse is a residue of much less importance. Fourth, cane managed as a total biomass crop is a "multiple-products" commodity, for which sucrose (although a by-product) remains one of a family of important products.
>
> A fifth premise is the decline of quality (sugar content) of the energy cane on a per-plant basis, while sugar yield increases on a per-acre basis. In brief, sugar retains a significant impact in energy cane agriculture by virtue of vastly-higher tonnages of cane harvested per acre. Sixth, the upscaled importance of lignocellulose, both qualitatively and quantitatively, opens the field of cane planting to new industrial technologies and their attendant supporters never before associated with the cane sugar industry.
>
> In addition to a field management oriented to higher numbers of larger plants per acre, energy cane conceptually encompasses the whole cane plant, that is, the harvest of the entire above ground fraction. This is often a point of concern for sugar mill engineers. As illustrated in Figure III-1, four discrete components of energy cane are harvested (**green top, attached trash, detached trash, and millable stem**), whereas only the millable stem figured prominently in the traditional harvests of sugarcane. By this means the annual dry matter yield is increased materially quite aside from growth management considerations. Moreover, the concern over the milling of added tonnages of fiber is not really valid when the engineer understands that the energy cane mill is a dewatering plant for lignocellulose, rather than a sugar-recovery facility as he had known in the past.”

Figure III-3 is a modification of an example, provided by Alexander, of common harvesting practices which result in the harvest of only 60% of the total biomass.

Figure III-3
SUGAR CROP COMPOSITION



Of the four components illustrated in Figure III-3, all of the attached trash and part of the green top will accompany the mature stalk to the mill. The proportion of lignocellulose to total fermentable solids in delivered material shifts roughly from 60/40 in sugar cane to 70/30 for energy cane. It should be noted that the "detached trash" fraction, already essentially dehydrated and lying on the field surface, does not go to the mill, but rather is raked and baled.

b. A word of caution

Generalizations about yields are not descriptive of specific locations and/or management methods. The above example provides a means of describing the opportunity. However, this opportunity is very location specific. The feasibility of harvesting the entire sugar plant depends on rainfall, terrain (slope of land), soil composition, plantation layout and other factors specific to each location.

c. Energy cane yields

Plantings of potentially high-yielding varieties of sugarcane were carried out by the Hawaiian Sugar Planters' Association as part of a recently-completed Biomass to Energy Project sponsored by the State of Hawaii and the U. S. Department of Energy.[27]

The reported experimental yields of the Hawaii sugarcane variety trials were somewhat less than the first-generation yields reported by Alexander in Puerto Rico and were significantly lower than the second-generation yields reported by Alexander. A range of experimental and projected commercial yields for sugarcane varieties is shown in Figure III-4 below.

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[27] Osgood and Dudley, previously cited.

3. Napier grass

One of the "energy grasses" which has been demonstrated and studied in Hawaii is napier grass (banagrass, also commonly discussed as a potential energy crop, is a variety of napier grass). A range of experimental and projected commercial yields for napiergrass is shown in Figure III-4 below.

4. Sweet sorghum

Sweet sorghum is currently grown in small quantities in Hawaii. Although not studied as extensively recently as some other potential energy crops (e.g. napier grass, eucalyptus, and leucaena), it has demonstrated good yields in Hawaii and elsewhere, its sucrose content makes it attractive from an ethanol production standpoint, and its protein content could provide an animal feed byproduct of some value. A range of experimental and projected commercial yields for sweet sorghum is shown in Figure III-4 below.

5. Eucalyptus

Eucalyptus has been demonstrated at several locations in Hawaii.[28] A range of experimental and projected commercial yields for eucalyptus is shown in Figure III-4 below.

6. Leucaena

Leucaena has been demonstrated at several locations in Hawaii. A range of experimental and projected commercial yields for leucaena is shown in Figure III-4 below.

7. A word of caution regarding comparisons of crop yields

The choice of biomass crop, crop yields, and delivered costs are highly site-specific. For example, some crops do better in sunnier, warmer locations while others flourish in cooler, wetter conditions. Although grasses generally achieve higher dry matter yields per acre per year than do trees, in specific locations (the eucalyptus plantings in Hamakua, for example) the trees out-performed the grasses. This illustrates the importance of using these estimates as a general guide from a statewide perspective rather than as an absolute relationship for all sites.

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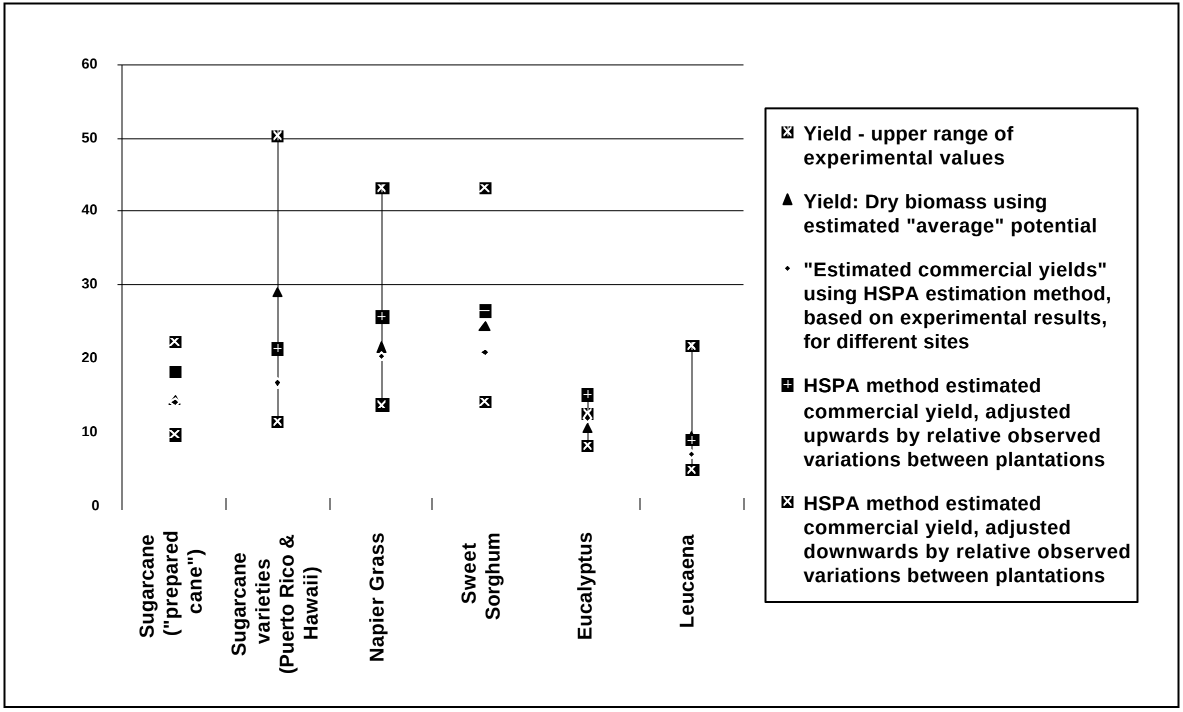
[28] Osgood and Dudley, previously cited.

Figure III-4

EXPERIMENTAL AND PROJECTED YIELDS FOR VARIOUS ENERGY CROPS



C. WASTES: MUNICIPAL SOLID WASTE, ORGANIC WASTE, AND NEWSPAPER

Organic wastes and municipal solid waste (MSW) – agricultural waste, green waste, and materials directed to landfills – contain significant amounts of cellulose, hemicellulose, and lignin. The diversion of these materials from landfills to ethanol production could make raw material available at a reasonable cost for conversion to ethanol (in some instances subsidized by tipping fees), and reduce the waste disposal problem.

In a sense, wastes such as paper and MSW will be available as long as there is a population and for this reason should be considered as sustainable as – and may be even more dependable a supply source than – cultivated biomass. These sources can also be considered as renewable since they are originally derived from crops and trees.

1. Municipal solid waste and organic waste

a. Composition

The composition of MSW varies substantially depending on location. In Hawaii, MSW contains almost 32% green material from yards, hotels, golf courses, parks, and construction sites. Paper and food wastes also contain significant amounts of lignocellulosic material. A detailed analysis of wastes deposited in the Kauai County landfill in 1990 was used as the basis for projections.[29] The detailed evaluation showed that almost 64% of the material disposed (wood, yard, green waste, food waste, and paper) had the potential to be used for ethanol production, as shown in Figure III-5.

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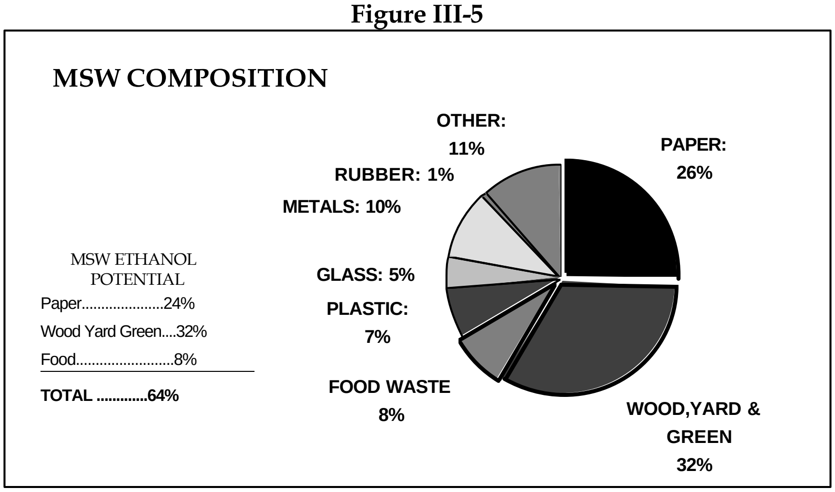
[29] *Analysis of Composition of Solid Waste for Kauai County* (1992).

Figure III-5



b. Quantity

A state-wide analysis of organic waste and MSW composition by island was carried out.[30] As shown in Table III-2, significant amounts of lignocellulose-containing MSW are produced.

Table III-2
QUANTITIES OF MUNICIPAL SOLID WASTE AVAILABLE IN HAWAII

ISLAND Population 1991	OAHU 836,231	MAUI 100,504	HAWAII 120,317	KAUAI 51,177
PAPER (tons per year)				
Old corrugated cardboard	71,200	26,500	15,200	7,800
Old newspaper	65,500	9,500	5,500	2,800
High-grade paper	26,500	23,500		700
Mixed paper	120,400	10,400	19,500	3,000
TOTAL PAPER	**283,600**	**69,900**	**40,200**	**14,300**
Other organics	244,300	58,100	36,100	14,000
Green waste	200,600	53,800	13,900	15,800
TOTAL OTHER	**444,900**	**111,900**	**50,000**	**29,800**
MSW w/ ethanol production potential	**708,500**	**181,800**	**90,200**	**44,100**
OTHER SOLID WASTE				
Glass	61,800	12,300	7,000	3,600
Aluminum	15,900	2,500	1,400	800
Tin		5,000		1,400
Metals (ferrous/non ferrous)	153,900	11,200	13,900	3,300
Mixed plastics	74,000	13,600	11,100	5,500
Batteries	12,000			
Tires	6,000	1,300		400
Construction demolition	93,200			
Others	335,900	45,300	15,500	21,200
TOTAL MSW (tons per year)	1,481,200	273,000	139,100	80,300

2. Newspaper and mixed waste paper

An independent study of magazine mail and newspaper volume in Hawaii estimated that we produce almost 2 pounds per capita of paper products per day. Much of this material does not presently enter the disposal system, but is potentially available. Almost 77% of the material in paper products is made up of sugars that can be converted to

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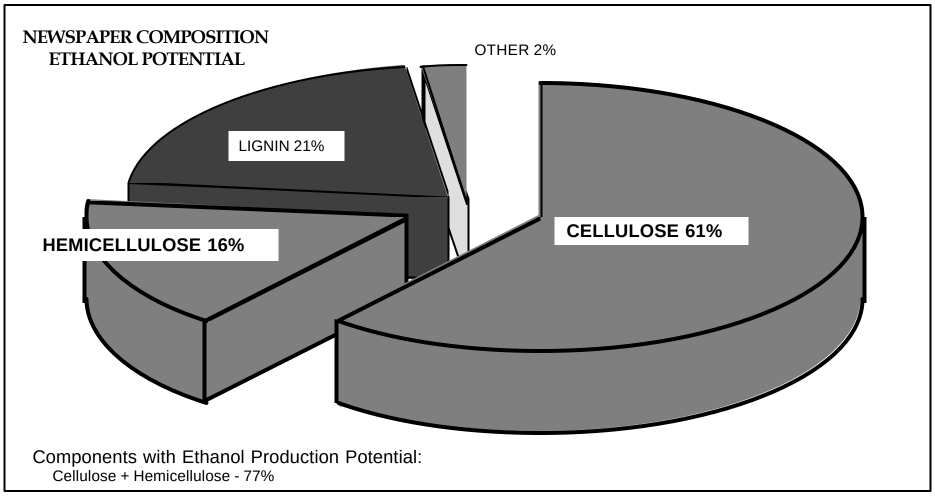
[30] Hildebrand, C. "Preliminary Report on Waste Streams State Wide for 1993." Department of Business, Economic Development and Tourism, State of Hawaii, August, 1993.

ethanol (see Figure III-6). The opportunity to use newspaper as a source of material for ethanol production should also be given a great deal of attention.

Figure III-6



At present, much of the newspaper collected in Hawaii is sold to Asian markets for about $8.00 per ton (FOB Hawaii).[31]

D. POTENTIAL GALLONS OF ETHANOL PER TON OF BIOMASS

On the basis of composition of each type of biomass, it is possible to estimate the ethanol potential per ton for the materials identified above. Figure III-7 provides a comparison of the potential ethanol yields, based on composition of biomass presented in Table III-1 and assumed conversion efficiencies presented in Table III-3. Additional detail is provided in the Appendix.

Table III-3
CONVERSION EFFICIENCIES ASSUMED IN FIGURE III-7
FOR SUCROSE, CELLULOSE, AND HEMICELLULOSE TO ETHANOL

CONVERSION EFFICIENCIES ASSUMED	LOW END OF RANGE	HIGH END OF RANGE	USED IN CALCULATIONS
Sucrose to glucose & fructose	99%	100%	99.5%
Cellulose to glucose	95%	100%	97.5%
Hemicellulose to xylose	50%	90%	70.0%
Glucose to ethanol	95%	100%	97.5%
Fructose to ethanol	95%	100%	97.5%
Xylose to ethanol	40%	90%	65.0%
Sucrose to ethanol	94%	100%	97.0%
Cellulose to ethanol	90%	100%	95.1%
Hemicellulose to ethanol	20%	81%	50.5%

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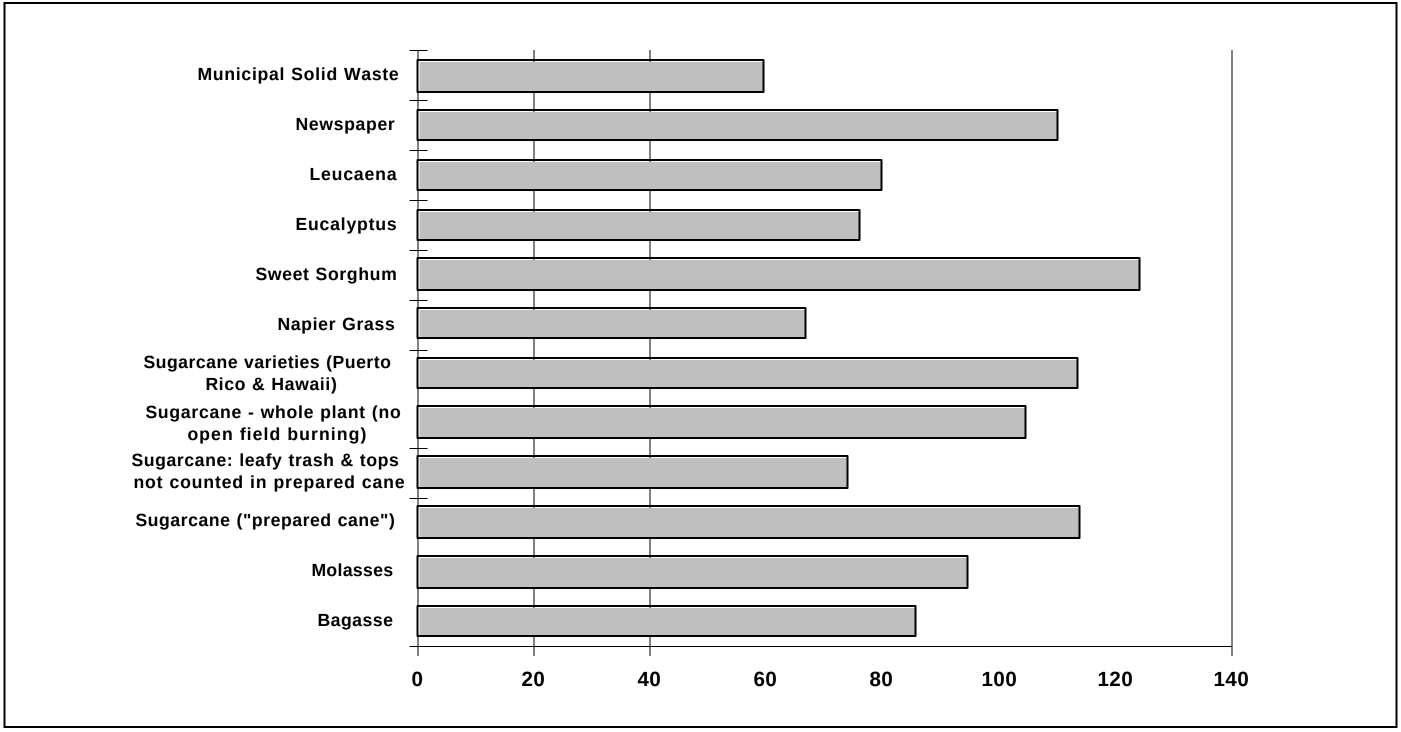
[31] Larson, David G. Market survey of newspaper prices from Hawaii. Personal communication, 1991.

Figure III-7
POTENTIAL GALLONS OF ETHANOL PER TON BIOMASS (DRY BASIS)



E. POTENTIAL GALLONS OF ETHANOL PER ACRE

There is a dramatic difference in the potential sugar yield per year and the yield per harvest for longer-rotation crops. As shown in Table III-4, the time to produce a harvestable crop varies from months (0.38 year, or about four and one-half months for sweet sorghum) to years (four to six years for leucaena and eucalyptus trees).

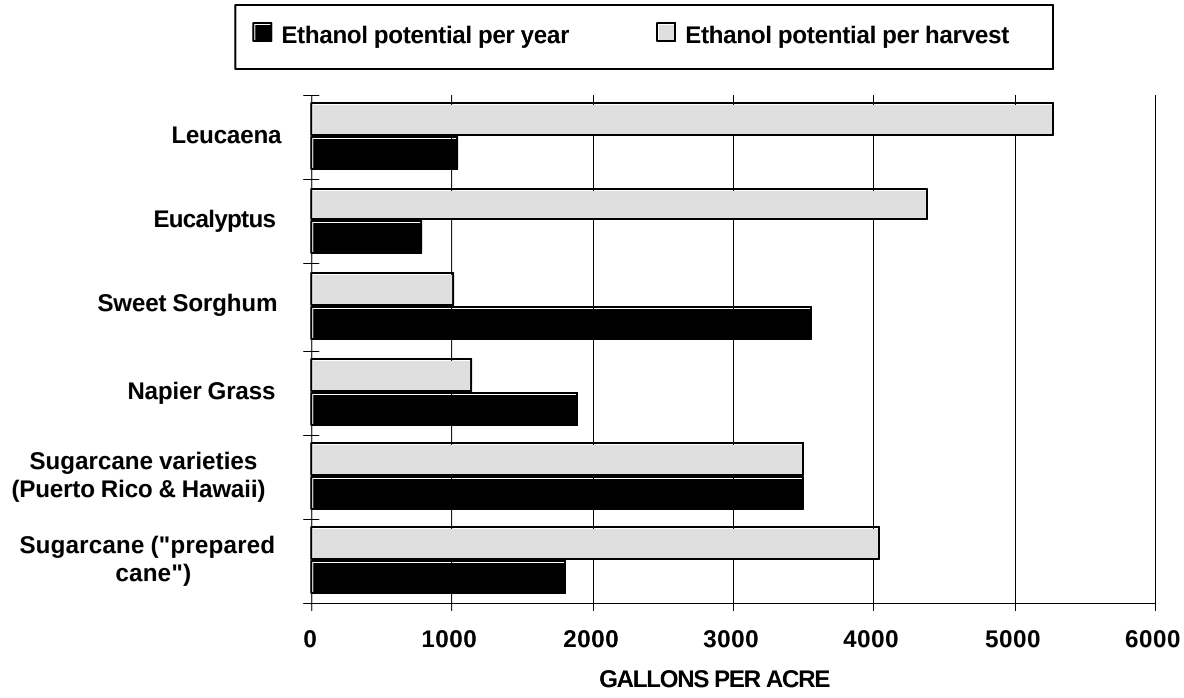
Table III-4
CROP PRODUCTION TIMES

Crop	Production time, years
Sugar cane (traditional varieties)	2.25
Other sugarcane varieties (including "energy cane")	1.00
Napier grass	0.60
Sweet sorghum	0.38
Eucalyptus	5.00
Leucaena	5.00

As shown in Figure III-8, the tree crops have the greatest projected yield per acre per harvest. However, trees are harvested less frequently than the grasses, and tend to have lower yields on a per acre, per year basis for most sites tested. Both relative and absolute yields may be expected to vary from site to site. Figure III-8 presents information on the basis of harvested acre as well as per acre per year.

Figure III-8

POTENTIAL GALLONS OF ETHANOL PER HARVEST AND PER YEAR[32]



F.

PRELIMINARY ECONOMIC SCREENING

In the process of gathering information for this evaluation, it became clear that there was only a limited amount of information on actual commercial-scale production, harvesting, transport, and processing costs for several of the feedstocks under consideration. Many of the crops under consideration have not been produced on a commercial scale in Hawaii.

The purpose of this study was to describe the opportunity in general terms. Actual costs and feedstock choices vary with location, and must be determined on a site-by-site basis. The figures presented in this section are provided for comparative purposes only.

1. Feedstock costs

a. Sugarcane (traditional varieties)

Sugarcane has been grown in Hawaii for over 150 years; as such, yields and costs of commercial production are well known within the industry. Figure III-9 shows the potential yields from an acre of harvested cane. However, the question of "ethanol from sugarcane" requires consideration of a number of variables, each of which has its own associated costs and side-effects. Possible approaches are shown in Table III-5.

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[32] Based on estimated "average" potential yields shown in Figure III-4 and conversion efficiencies shown in Table III-3.

Figure III-9

PREPARED CANE TO ETHANOL DIAGRAM

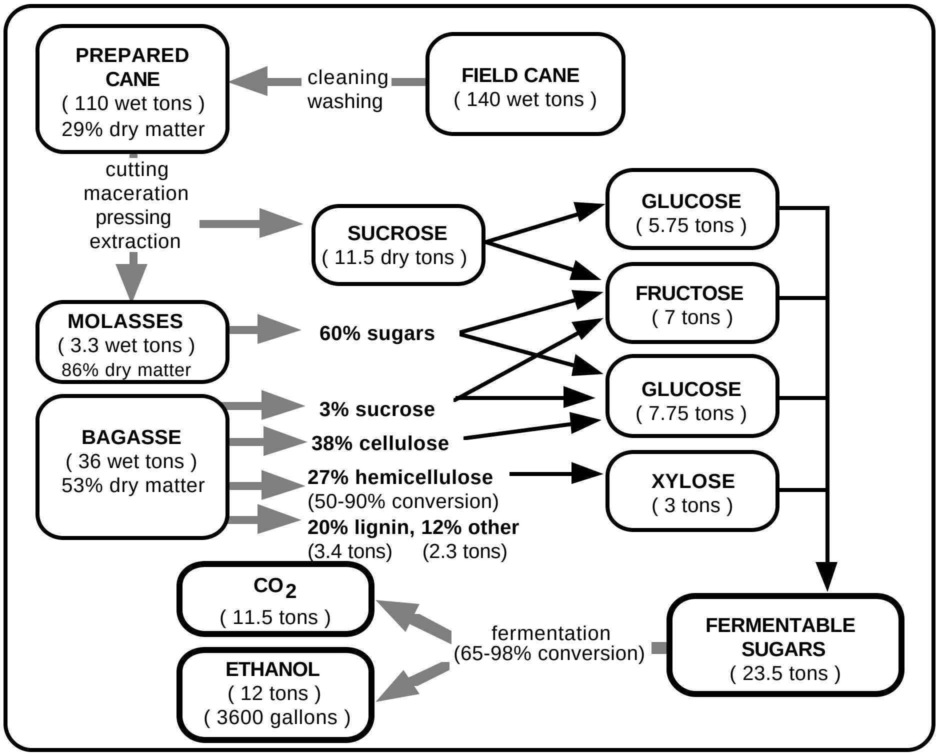

Table III-5

POSSIBLE APPROACHES TO ETHANOL FROM SUGARCANE

HARVESTING METHOD	PRODUCTS	ETHANOL FROM...
WITH OPEN FIELD BURNING	PRODUCING SUGAR, BAGASSE AND MOLASSES (BUSINESS-AS-USUAL)	NO ETHANOL PRODUCED
WITH OPEN FIELD BURNING	PRODUCING SUGAR, BAGASSE, AND ETHANOL	MOLASSES
WITH OPEN FIELD BURNING	PRODUCING SUGAR AND ETHANOL	ETHANOL FROM BAGASSE AND MOLASSES
WITH OPEN FIELD BURNING	PRODUCING ETHANOL	SUGAR, BAGASSE, AND MOLASSES
WITHOUT OPEN FIELD BURNING	PRODUCING SUGAR, BAGASSE, MOLASSES, AND UNBURNED LEAFY TRASH (LEAFY TRASH USED FOR ELECTRICITY GENERATION)	NO ETHANOL PRODUCED
WITHOUT OPEN FIELD BURNING	PRODUCING SUGAR, BAGASSE, MOLASSES, AND ETHANOL	UNBURNED LEAFY TRASH
WITHOUT OPEN FIELD BURNING	PRODUCING SUGAR, BAGASSE, AND ETHANOL	MOLASSES AND UNBURNED LEAFY TRASH
WITHOUT OPEN FIELD BURNING	PRODUCING SUGAR AND ETHANOL	BAGASSE, MOLASSES, AND UNBURNED LEAFY TRASH
WITHOUT OPEN FIELD BURNING	PRODUCING ETHANOL	SUGAR, BAGASSE, MOLASSES, AND UNBURNED LEAFY TRASH

The relative costs and returns of any of these scenarios are site-and technology-specific. For the purposes of this section, the costs of the various sugarcane-derived materials were considered separately, as described below:

Bagasse

For the purposes of the comparisons below, the cost per ton of bagasse was based on the cost that would be incurred in replacing the bagasse with #2 diesel, #6 fuel oil, or coal for electricity production (the low end of the range is for coal at $60 per ton; the high end of the range is for #2 diesel at $32.00 per barrel).

Molasses

Molasses cost per ton was based on the 1991 average return to growers of $40.00 per wet ton.[33] If the molasses was to be shipped to another location, rather than used at the point of production, the assumption of $40.00 per ton, which does not include consideration of transport costs, would be low.[34]

Prepared cane

For the purposes of the comparisons below, the cost per ton of "prepared cane" was based on Osgood and Dudley (1993) estimated sugarcane costs per acre, thus are consistent with napiergrass, leucaena, and eucalyptus estimated costs obtained from the same source. In subsequent calculations (such as those used to generate Figure III-10), an average of 50% irrigated and 50% unirrigated acreage was assumed.

When the dollars per ton figure used (from Osgood and Dudley, 1993) is compared to 1991 sugar production cost figures, adjusted for average yields over the period of 1981-1992, the estimated sugarcane costs per ton (used in this section) are about 16% less than might be expected. For the sake of consistency, cost figures used in this section have not been adjusted; the reader is cautioned, therefore, that these cost estimates may be somewhat low for a statewide average.

Sugarcane trash

“Sugarcane trash” refers to unburned leaves and trash not counted in prepared cane. These costs were based on an estimate of an increase of 50% in harvesting costs and an increase of 40% in hauling costs per acre,[35] using estimates of cost centers from Osgood and Dudley (1993).

There is some concern that harvesting without burning may lower recoverable sucrose yields by some percentage. The cost of reduction in recoverable sucrose yield has not been taken into account in the comparisons below.

Unburned sugarcane

The cost per ton of “unburned sugarcane” is the sum of the costs of “prepared cane” and the “unburned leaves,” determined on a per-acre basis then reduced back to a per-ton basis to maintain the relative proportions of the various parts of the plant.

b. Other sugarcane varieties

The costs of growing other sugarcane varieties are expected to be similar, on a per-ton basis, to costs of traditional sugarcane. On a per acre-basis, if the varieties are harvested more frequently (an annual harvest has been suggested by Alexander), costs per acre per year would be expected to be higher but costs per harvest and per ton would be expected to be less or the same (if annual harvests did not result in relative reductions in costs per ton as compared to the current two-year rotation, they probably would not be continued).

For the sake of comparisons below, the cost per ton of “other sugarcane varieties” was assumed to be the same as cost per ton for unburned sugarcane.

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[33] Personal communication, Hawaiian Sugar Planters' Association, 1994.

[34] Definition of “statewide” has not been changed to reflect recent plantation closings. For more information on what was included in “statewide average” figures, see tables in the Appendix.

[35] Kinoshita (1988), previously cited.

c. Napier grass, eucalyptus, and leucaena

The costs per ton for these crops were based on estimates by Osgood and Dudley (1993). These crops, particularly the tree crops, show potential for significant improvements in yields through species selection and improvement,[36] which would result in correspondingly lower costs per ton.

Table III-6
CULTIVATED FEEDSTOCKS:
ESTIMATED COST PER DRY TON AND PER ETHANOL GALLON

CROP	Estimated cost ($/ton dry matter), from Osgood and Dudley report (1993) on biomass for energy	Estimated feedstock cost ($/gallon ethanol potential)
Sugarcane (irrigated)	$86	$0.81
Napiergrass (irrigated)	$72	$1.20
Leucaena (irrigated)	$103	$1.43
Sugarcane (rainfed)	$77	$0.73
Eucalyptus (rainfed)	$71	$1.19
Napiergrass (rainfed)	$59	$0.83

d. Sweet sorghum

The costs per ton for this crop were set equal to the costs per ton of sugarcane, although there are indications from several sources (i.e. unpublished estimates of costs of sweet sorghum production in Hawaii) that cost of production of sweet sorghum on a commercial scale in Hawaii could be less than cost per ton of sugarcane. However, since the unpublished estimates were for specific sites, and this study is intended to utilize statewide averages wherever possible, estimated sweet sorghum costs were set equal to sugarcane costs per ton for the purposes of this evaluation.

e. Municipal solid waste and organic waste

Different types of municipal solid wastes and organic wastes are handled in different ways in different areas of the state. Although some waste-to-ethanol studies have included tipping fees (i.e. a fee is collected from the person(s) disposing of the organic waste at the collection site) in their cost analyses, such tipping fees may reduce the amount of material coming to the facility if there are cheaper (or free) alternatives such as public landfills, composting or disposing of the waste by illegal dumping. Therefore, although the potential may exist to collect fees for collecting these waste materials, such fees were not assumed in this analysis.

f. Newspaper

Newspaper is presently being sold for between $5.00 and $10.00 per ton.[37] Mixed waste paper, which is more difficult to recycle (and therefore generally costs less than newspaper), is also a potential feedstock for ethanol production and may cost less than the $5 to $15 per ton assumed.

g. Summary of feedstock costs

Estimated feedstock costs per ton and on a per-gallon-ethanol basis are shown in Table III-7 and in Figure III-10. The ranges shown are adjustments to the values discussed in the narrative above and are intended to indicate a range of costs which may be expected due to variations in yields between locations (assuming costs per acre to be relatively constant). Reported variations between sugarcane plantations in 1991 were used as the basis of the adjustments. (For more information, see tables in the Appendix.)

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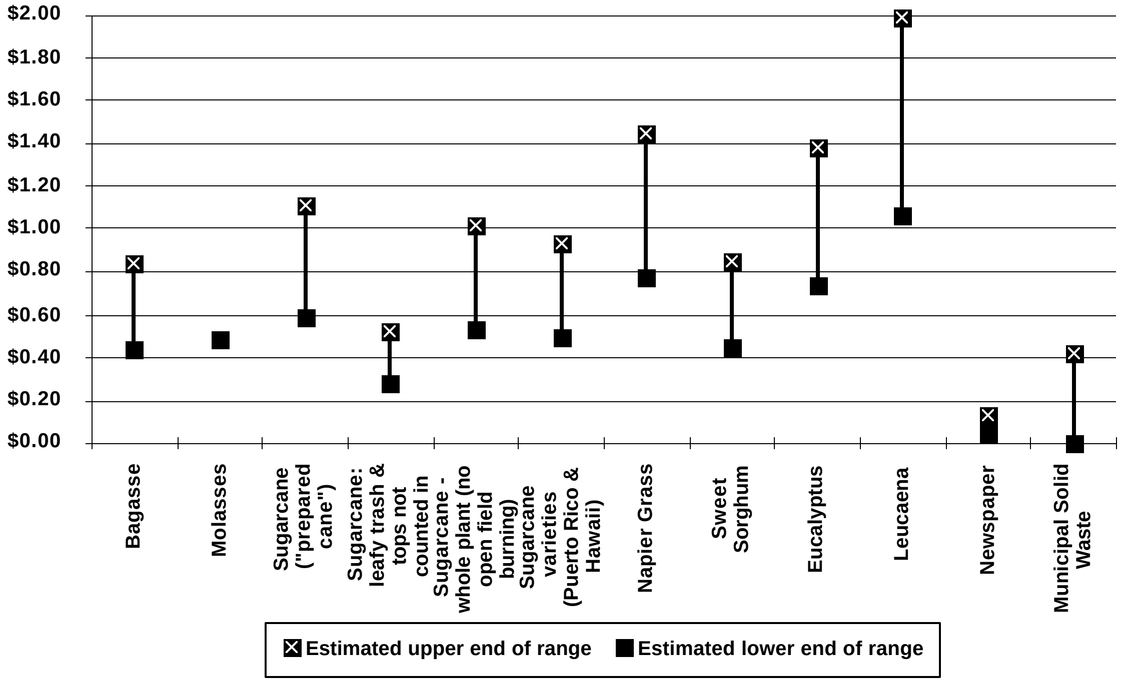
[36] Osgood and Dudley (1993), previously cited.

[37] Larson, David G. Market survey of newspaper prices from Hawaii. Personal communication, 1991.

Table III-7
RANGE OF ESTIMATED BIOMASS COSTS PER POTENTIAL ETHANOL GALLON

Estimated range, biomass cost for one gallon ethanol	Estimated upper end of range, feedstock cost per dry ton	Estimated lower end of range, feedstock cost per dry ton	Estimated upper end of range, feedstock cost per potential ethanol gallon	Estimated lower end of range, feedstock cost per potential ethanol gallon
Bagasse	$72	$38	$0.84	$0.44
Molasses	$46	$46	$0.49	$0.49
Sugarcane ("prepared cane")	$127	$67	$1.11	$0.59
Sugarcane: leafy trash & tops not counted in prepared cane	$39	$21	$0.52	$0.28
Sugarcane - whole plant (no open field burning)	$106	$56	$1.01	$0.54
Sugarcane varieties (Puerto Rico & Hawaii)	$106	$56	$0.93	$0.49
Napier Grass	$97	$52	$1.45	$0.77
Sweet Sorghum	$106	$56	$0.85	$0.45
Eucalyptus	$106	$56	$1.38	$0.74
Leucaena	$152	$81	$1.99	$1.06
Newspaper	$15	$5	$0.14	$0.05
Municipal Solid Waste	$25	$0	$0.42	$0.00

Figure III-10
ESTIMATED BIOMASS COST PER POTENTIAL ETHANOL GALLON



2. Plant size considerations and land area requirements

A critical consideration in a state the size of Hawaii is the acres in production required to meet the needs of a specific size processing plant or the needs of an identified market. Production on each island to meet the local demand and eliminate the cost of shipping may present the best opportunity.

Extensive discussions with developers of technology suggest that a plant producing 25 million gallons of ethanol per year might provide the optimal economy of scale for commercial production. This size plant corresponds to the acreages shown in Table III-8 below.

Approximately 100,000 acres were removed from intensive cultivation between 1968 and 1991,[38] with an additional 75,000 acres (Hamakua: 27,000; Mauna Kea Agribusiness/Hilo Coast Processing Company, 14,000; Oahu Sugar, 10,000; Waialua Sugar, 12,000; and Ka'u Agribusiness, 12,000) scheduled to discontinue or seriously considering possibly discontinuing sugar production over the next few years.

Table III-8
ACREAGE REQUIRED TO PRODUCE BIOMASS
FOR A 25 MILLION GALLON PER YEAR ETHANOL PRODUCTION FACILITY

BIOMASS MATERIAL	**ETHANOL POTENTIAL** (gallons per ton dry matter)	**ETHANOL POTENTIAL** (gallons per acre per year)	**TONS BIOMASS** required (dry, per year) for production of 25 million gallons ethanol	**ACRES REQUIRED** for biomass for 25 million gallon-per-year facility
Sugarcane ("prepared cane")	114	1,637	218,933	15,270
Sugarcane - whole plant (no open field burning)	105	1,967	238,655	12,709
Sugarcane varieties (Puerto Rico & Hawaii)	114	3,299	219,768	7,578
Napier Grass	67	1,449	372,670	17,257
Sweet Sorghum	125	3,037	200,290	8,231
Eucalyptus	76	792	327,054	31,547
Leucaena	80	736	312,397	33,956
Newspaper	110		226,260	--
Municipal Solid Waste	60		417,282	--

On the basis of the assumptions presented in this chapter, sugar cane varieties, sweet sorghum, MSW and paper wastes appear to have the most immediate potential to serve as sources of biomass for ethanol production.

The next step is to identify technologies for converting these feedstocks to ethanol, and estimated costs of conversion. These are discussed in Chapter IV.

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[38] Kinoshita, C. K. and Staackmann, M. 1994. Chapter 5 - Indigenous Biomass Energy Sources, input to Project 5 of the Hawaii Energy Strategy.

IV. ETHANOL PRODUCTION TECHNOLOGIES

A. STEPS IN THE ETHANOL PRODUCTION PROCESS

Figure IV-1 shows the various steps in a lignocellulosic biomass-to-ethanol conversion process. The starting material, "organic biomass," is in the top row on the left. This material is processed by treatments such as "crushing" and "grinding," with the resulting product being "prepared biomass." Then, the prepared biomass (shown in the second row) is subjected to a hydrolysis process, with the resultant products being cellulose, hemicellulose, and lignin. Cellulose and hemicellulose are shown in the third and fourth row, with their semi-hydrolyzed counterparts, hexosans and pentosans, and so forth.

Figure IV-1

BIOMASS CONVERSION PRODUCTS

MATERIAL	TREATMENT	PRODUCTS	VALUE/USE
ORGANIC BIOMASS	Crushing Grinding	Prepared Biomass	Raw Feedstock for Processing
Prepared Biomass	Hydrolysis	Cellulose Lignin Hemicellulose	6 carbon sugars fuel/chemicals 5 carbon sugars
Cellulose Hexosans	Continued Hydrolysis	Glucose	6 Carbon Sugars for Fermentation
Hemicellulose Pentosans	Continued Hydrolysis	Xylose Pentose Sugars	5 Carbon Sugars for Fermentation
Glucose	Yeast or Bacterial Fermentation	Stillage **ETHANOL** **CO_2**	Feed Ingredients Fuel Feedstock
Xylose Pentose Sugars	Bacterial Fermentation	Stillage **ETHANOL** **CO_2**	Feed Ingredients Fuel Feedstock
CO_2	Bioconversion	METHANE ALGAE	ENERGY Pharmaceuticals Commodities
ETHANOL	Chemical Conversion	**ETBE**	OCTANE ENHANCER
ALGAE	Processing Extraction	Pharmaceuticals ß CAROTENE Feed Ingredients	MEDICINE ANIMAL FEEDS

Intermediate products and process by-products (such as lignin, stillage, carbon dioxide, methane, algae, pharmaceuticals, feed ingredients, etc.) will be discussed in the section of this report which deals with markets and by-products.

B. PROCESS OPTIONS

There are many options available at each of the steps shown in Figure IV-1. Several government laboratories, academic institutions and private sector companies have devised various techniques to accomplish each of the steps required to process the biomass to ethanol. In many instances, organizations select a particular combination of steps and consider the sequence to be "their" system. Many of these entities are now seeking to build, license, or develop their technology in some fashion. Because of the relatively high cost of gasoline in Hawaii (as compared to elsewhere in the U. S.), opportunities to produce biomass year around, and the potential of land becoming available due to the decline of the sugar industry, Hawaii has gained the attention of several of these organizations.

This section of the report is devoted to the evaluation of a range of various approaches.

Caution is recommended in interpreting the information in this section. Because only limited information was provided by the developers of technologies, the evaluations are only approximations of the costs and yields from processes that appear to be ready for commercial scale development. The evaluations are only as good as the process information available. In no case was there sufficient information to conduct a rigorous comparison of the technologies. Material presented in this section indicates that a variety of approaches have potential to produce ethanol from biomass in Hawaii, although an assessment of the time frames to commercialization was beyond the scope of this report.

The options at each step of the biomass-to-ethanol processes are illustrated in Figure IV-2. "Systems" described in this section deal with various combinations of these options.

C. APPROACH TO EVALUATION OF SYSTEMS

The first step in system and technology comparisons was the development of a questionnaire. This questionnaire was forwarded to a comprehensive list of experts and technology owners. Quantitative, factual information was requested for each step of each of the systems. The success of this approach was limited for four primary reasons:

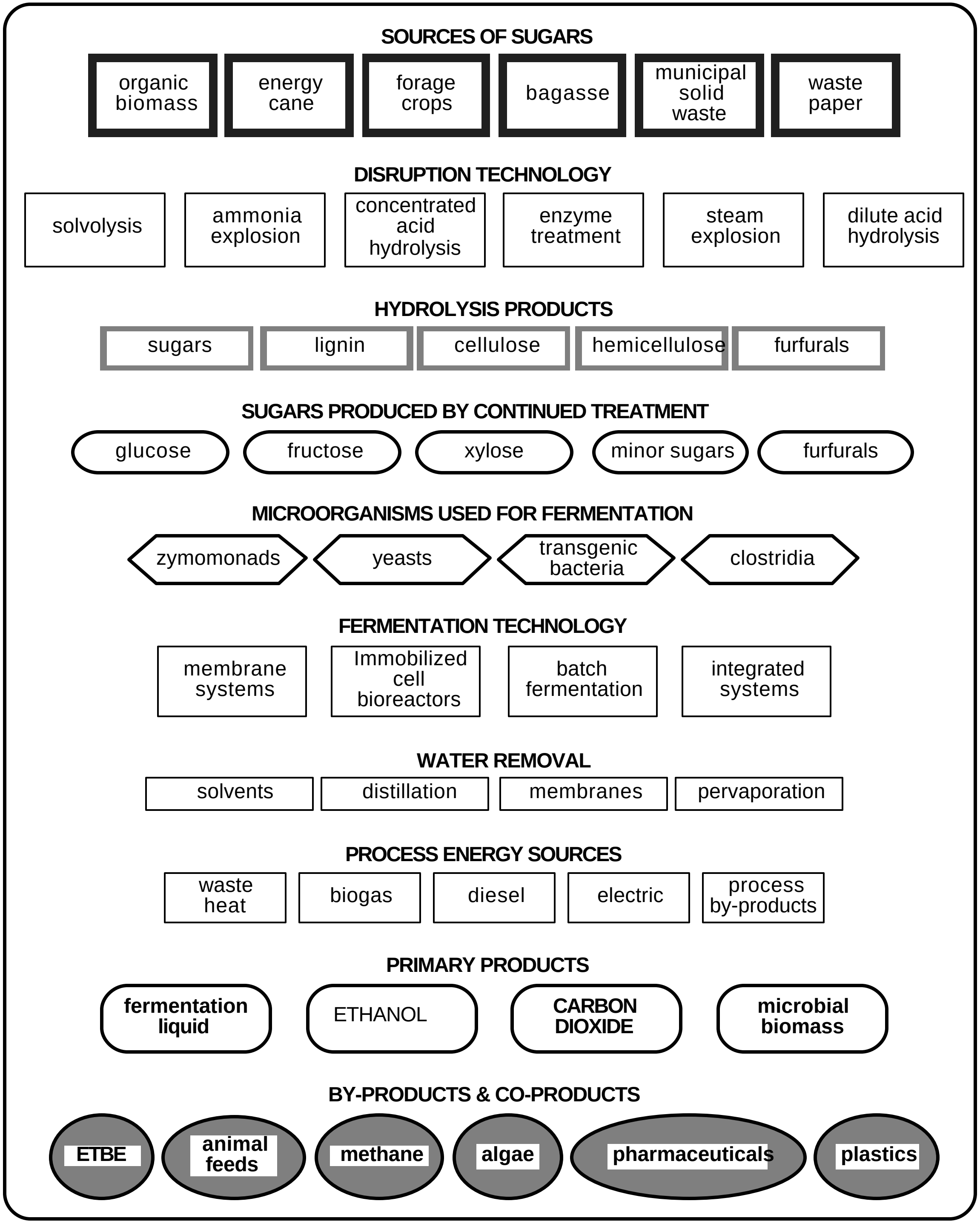
1) The slow response to questions from technology developers;

2) A reluctance to provide details that are considered proprietary;

3) The processes are at different stages of development, making extrapolations to commercial scale inconsistent across all processes; and

4) Different information sources and assumptions are used by the developers, providing no common base for comparison.

Figure IV-2



In no case were the questionnaire responses sufficient to conduct a detailed comparative analysis of the processes or even to compare the approaches to each step outlined in Figure IV-2. In the process of trying to obtain the specific details of each system it became clear that many of the technologies had not yet been demonstrated on a commercial scale and that much of the design information provided previously was based on laboratory or limited pilot data.

The limited success with the first questionnaire led to the development of a second survey requesting non-proprietary numbers. The results provided additional information; however, as there was still insufficient information on key points to complete the detailed comparisons, it was necessary to fill in missing pieces.

Due to the nature of this study, it was also necessary to rely on claims made by those most familiar with the various technologies. In most cases, these individuals were the developers of the technologies and the owners of the patent rights, and therefore may have been somewhat biased in their claims; it should be expected that some individuals may have been more conservative in their projections, and others may have been more optimistic.

D. ASSUMPTIONS USED IN EVALUATIONS

Dr. Hans Grethlein, at the Michigan Biotechnology Institute (MBI), has developed an approach using data from the more complete systems to fill in missing parts from less complete technologies. This method was of great help in these evaluations, and in some cases this information was used directly.[39, 40] Grethlein compared performance of systems producing 25 million gallons per year using corn stover as the source of biomass substrate.

A similar approach was used in this study. Information provided by the questionnaire respondents was for plants of many different sizes and capacities. Scaling factors of 0.7 and 0.9 were used for the plant and personnel, respectively. For the purposes of the comparison, prepared cane was identified as the baseline feedstock. Other assumptions common to the evaluations are shown in Table IV-1.

Table IV-1
EVALUATION ASSUMPTIONS

Power Law Scaling Factor	0.7	Process cost only (biomass $0)	$0
Contingency	10 %	Biomass cost 1	$50
Start-up factor	5 %	Biomass cost 2	$108
Working Capital	7.5%	Denaturant Cost, $/gal	$0.87
Operating Days per Year	330	Denaturant Use	5 %
Personnel Scaling Factor	0.9	Fringe Benefits	25 %
Property Tax & Insurance	1.5 %	Capital Charge, %/yr.	16 %

E. TECHNOLOGY REVIEW

The material below is presented primarily as a comparative review of technology. Although most of the technologies described below are associated with a specific company, additional information from the technical literature and projections on capital and operating costs in Hawaii were used to complete the comparative evaluations. Because much of the information provided was incomplete, the extrapolations below cannot be used to reach final conclusions regarding economic performance of a specific technology in Hawaii. The results should not be considered to be representative of the current status of this technology.

The information below is for comparative purposes only, and may not represent the actual performance of any specific proprietary technology in Hawaii.

1. Simultaneous saccharification and fermentation

This technology is largely associated with the research and development program of the National Renewable Energy Laboratory (NREL) in Golden, Colorado. This institution has had a long history of involvement in developing technology for producing ethanol from lignocellulosic biomass. In a succession of development steps, they have settled

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[39] Grethlein, H.W. and T. B. Nelson. (1992) “Projected Process Economics for Ethanol Production from Corn.” Final Report under Agreement No. 58-1935-2-020, July 17, 1992 to the United States Department of Agriculture, Agricultural Research Service, North Atlantic Area, Eastern Regional Research Center, Philadelphia, Pennsylvania.

[40] Grethlein, H.E. and T. Dill. (1993) “The Cost of Ethanol Production from Lignocellulosic Biomass – A Comparison of Selected Alternative Processes.” Final Report to the U. S. Department of Agriculture, Agricultural Research Service, under Specific Cooperative Agreement No. 58-1935-2-050, April 30, 1993.

on the process of Simultaneous Saccharification and Fermentation (SSF).[41, 42, 43] A 1988 paper by Wright, Wyman and Grohman[44] provides a useful overview. Quoting selectively from this publication,

> "...All enzymatic processes consist of four major steps that may be combined in a variety of ways — pre treatment, enzyme production, hydrolysis and fermentation. · · ·The key to increasing the digestibility of lignocellulose lies in increasing the cellulose surface area that is accessible to enzymes · · ·by carrying out a pre hydrolysis (dilute 1.1% sulfuric acid at 160° C for 10 minutes) the hemicellulose fraction is removed (93% of the xylan is hydrolyzed resulting in fully digestible cellulose pulp) enlarging pore size and thus opening the structure to attack by enzymes · · ·the degree of digestibility is almost directly proportional to the fraction of xylan removed. Cellulose is then broken down by enzymes. In the SSF process enzymes that break down cellulose are produced separately by the fungus *T. reesei.* Yeast and the enzymes are added to the remaining material where the enzymes digest the cellulose to produce glucose. Glucose is then fermented by yeast or other microorganisms to produce ethanol."

Essential elements of the SSF approach are presented in Figure IV-3.

As presented, this is not a complete system; however, it describes an approach to pre-treating and processing biomass that distinguishes this process from the others evaluated. The unique aspect of the NREL approach is that the microorganisms and the enzymes are present in the same system. By converting the sugars to ethanol as they are formed, this reduces the inhibitory effect of sugar build up on enzyme performance. Wright et al comment (28):

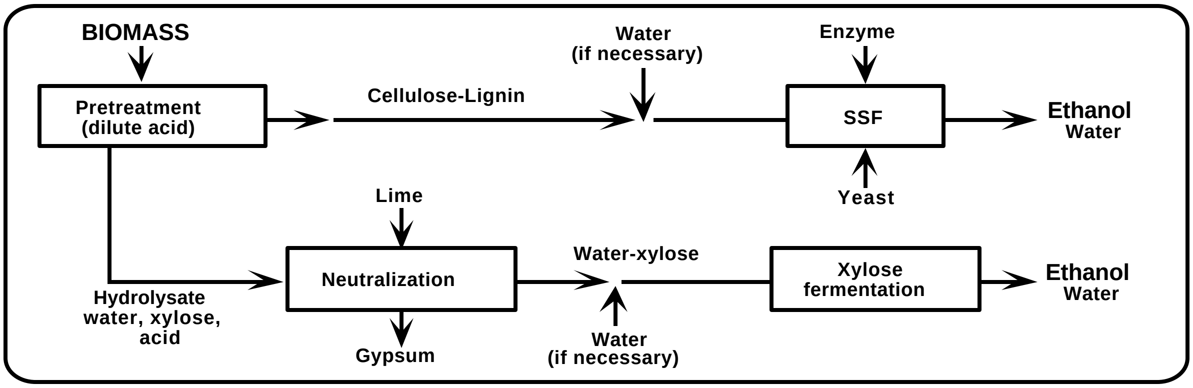
> "...simultaneous saccharification and fermentation systems offer large advantages over separate saccharification and fermentation systems for the production of ethanol from lignocellulosic materials because of their great reduction of the cellulase enzyme complex."

A very important issue is identified by the statement:

> "The performance of SSF appears to be limited by the performance (combined temperature and ethanol tolerance) of the yeast rather than by the performance of the enzyme."

A solution to this problem will be discussed under the section "Technology for Hawaii."

Figure IV-3
SIMULTANEOUS SACCHARIFICATION AND FERMENTATION



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[41] Wyman, C. E., and N. D. Hinman. (1990) "Ethanol - Fundamentals of Production from Renewable Feedstocks and Use as a Transportation Fuel" in *Applied Biochemistry and Biotechnology*, The Humana Press Inc., 24/25, 735:753.

[42] Wright, J. D. (1988) "Economics of Enzymatic Hydrolysis Processes," Prepared for the National AlChE Meeting 6-10 March 1988, New Orleans, SERI/TP-231-3310, UC Category: 246 DE88001134, 1:47.

[43] Wright , J D. (1989) "Evaluation of Enzymatic Hydrolysis Processes," in *Energy from Biomass and Wastes* (D. L. Klass, ed.) Institute of Gas Technology, Chicago, 1247: 1276.

[44] Wright, J.D., et al. (1988) "Simultaneous Saccharification and Fermentation of Lignocellulose" in *Applied Biochemistry and Biotechnology*, The Humana Press Inc., 75:90.

Information provided and available was for a facility producing about 58 million gallons per year, as shown in the Appendix. Cost savings may be possible on the basis of scale and financing mechanisms. Scaling factors for facilities and personnel were used to generate the performance estimates for systems producing 5 and 25 million gallons per year; results are presented in Tables IV-2 and IV-3.

2. Concentrated acid hydrolysis, neutralization and fermentation

The Tennessee Valley Authority (TVA) began developing technology for conversion of cellulosic feedstock to fuel ethanol in the 1950s. TVA focused on developing dilute and concentrated acid hydrolysis technology.[45] Much of the work at TVA focused on processing biomass feedstocks and effluent to multiple products. The TVA programs have developed and evaluated many of the technical options for converting cellulose bound in biomass to sugars, bioconversion of those sugars to ethanol and other chemicals, and waste utilization for conversion of co-products from waste effluent.[46, 47, 48, 49] A summary of the process follows:

First, the biomass is collected, dried, and milled to pass through a 4 mesh screen. Then the material is transferred to a first stage hydrolyser or large vat. Sulfuric acid (7.65% by weight) is added to the vat which is heated to 100° C for 2 hours. About 75% of the hemicellulose is hydrolyzed to xylose. The remaining solids (lignin and cellulose) are removed in a screw press and transferred to a separate vessel where additional acid and much of the acidified xylose are added back to increase the sugar concentration.

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[45] Goldstein, I. S. and J. M. Easter. “An Improved Process for Converting Cellulose to Ethanol.” *Technical Association of Pulp and Paper Industry Journal*, August, 1992, 135-140.

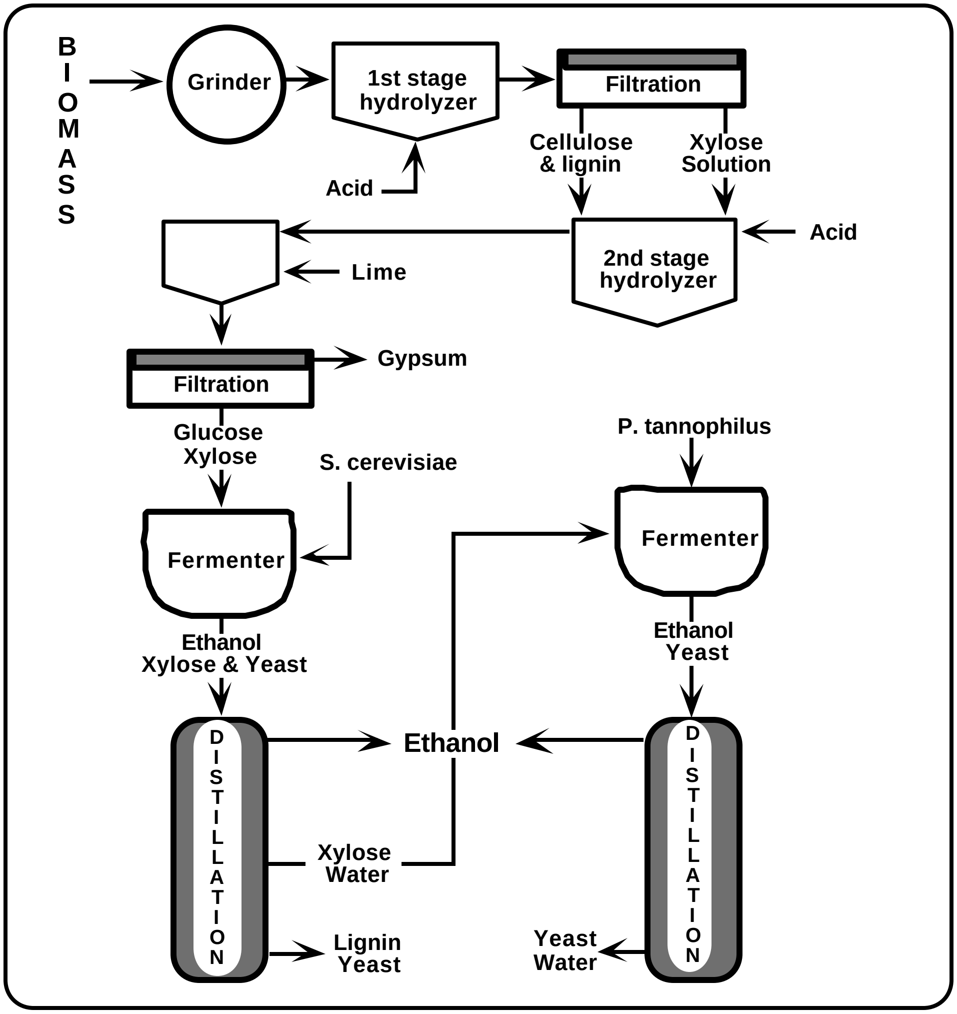
[46] Bulls, M.M., T.M. Shipley, J.W. Barrier, R.O. Lambert and J.D. Broder. “Comparison of MSW Utilization Technologies — Ethanol Production, RDF Combustion, and Mass Burning.” Tennessee Valley Authority Biotechnical Research Dept., Muscle Shoals, Alabama, Presented at the Southern Biomass Conference, Baton Rouge, Louisiana.

[47] Barrier, J. W., M. R. Moore, and J. D. Broder. “Integrated Production of Ethanol and Co-Products from Agricultural Biomass.” Tennessee Valley Authority Biomass Program, Muscle Shoals, Alabama, April, 1986.

[48] Broder, J. D. and J. W. Barrier. “Producing Ethanol and Coproducts from Multiple Feedstocks.” Tennessee Valley Authority, Muscle Shoals, Alabama, for the International Summer Meeting of the American Society of Agricultural Engineers, Rapid City, S. D., June 26-29, 1988.

[49] Broder, J. D., J. Wayne Barrier and M. M. Bulls. “Producing Fuel Ethanol and Other Chemicals from Municipal Solid Wastes.” Tennessee Valley Authority Biotechnical Research Dept., Muscle Shoals, Alabama, Prepared for the 1991 International Summer Meeting of The American Society of Agricultural Engineers, June 1991.

Figure IV-4
CONCENTRATED ACID HYDROLYSIS, NEUTRALIZATION AND FERMENTATION



The temperature is again raised which results in the hydrolysis of the remaining cellulose to glucose. The result is a mixture of 5 carbon (pentose) and 6 carbon (hexose) sugars in acid solution. Lime is added to neutralize the acid, producing gypsum, which is removed in a rotary filter. The remaining solution stream contains both glucose (11.6%) and xylose (9.0%)

Fermentation is also conducted in steps. First, glucose is fermented to ethanol by the yeast *Sacromyces cerevisiae*. The mixture is then distilled to remove the ethanol leaving the unconverted xylose behind. A second yeast *Pachysolen tannophilus* which ferments xylose to ethanol is added to the remaining solution. Ethanol produced from xylose is then distilled. Lignin and cellular material remaining is dried and burned in a boiler to provide process energy or produce electricity. The process is shown in Figure IV-4.

Grethlein et. al. made a number of assumptions in their theoretical cost evaluation of the TVA process.[50] Further assumptions have been made in this study regarding financing, start up time, and working capital. Estimated costs for plants producing 5 and 25 million gallons per year using this process are presented in Tables IV-2 and IV-3.

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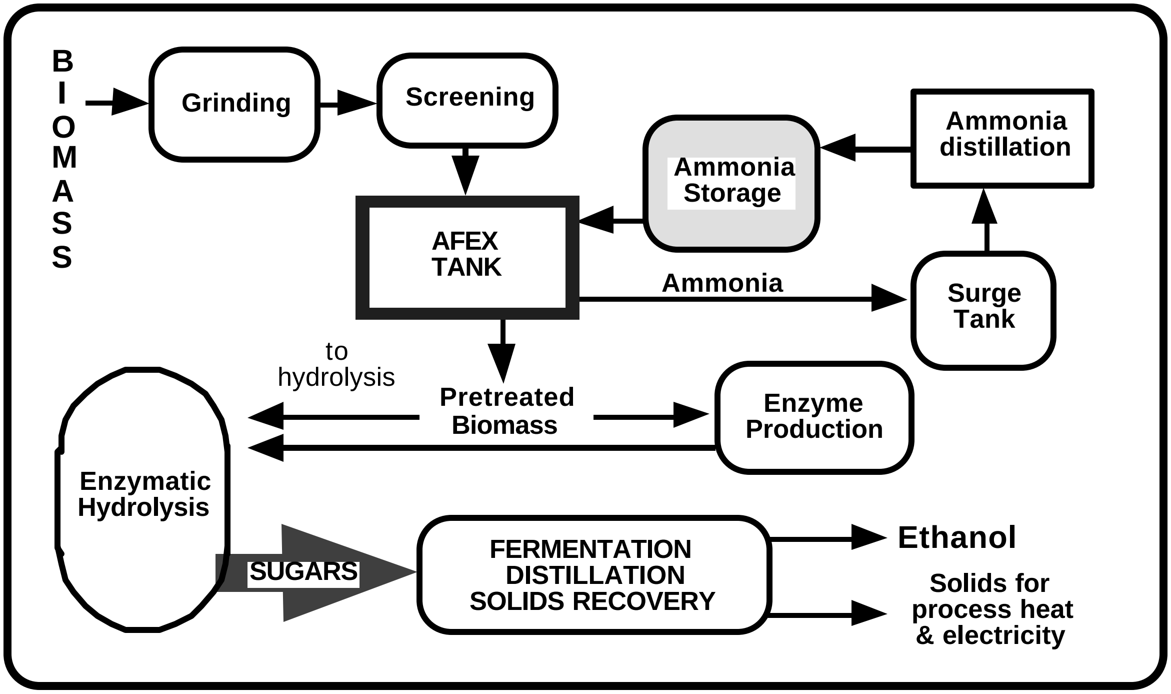
[50] Grethlein, H.E. and T. Dill. (1993) “The Cost of Ethanol Production from Lignocellulosic Biomass – A Comparison of Selected Alternative Processes.” Final Report to the U. S. Department of Agriculture, Agricultural Research Service, under Specific Cooperative Agreement No. 58-1935-2-050, April 30, 1993.

3. Ammonia disruption, hydrolysis and fermentation

The development of this technology and its application in converting lignocellulosic material to animal feed was described in the technical literature in the late 1980's. Ammonia is used to pre treat the lignocellulosic biomass.[51, 52, 53] The biomass is ground and milled to small particles. Ammonia is then infused at high pressures for about 30 minutes at temperatures ranging from 25-90° C (Figure IV-5).

In this process, ammonia infused at elevated pressure and temperature swells and de crystallizes the cellulose/hemicellulose complex so the biomass is very accessible to the enzyme cellulase. When the pressure is released the ammonia virtually explodes or gassifies. It is then recaptured in a surge tank and recycled. Hydrolysis of cellulose and hemicellulose to sugars is accomplished by adding enzymes that are produced separately on site to the ammonia treated biomass. This process does not degrade protein which can be recovered as an animal feed ingredient. Fermentation is accomplished sequentially as with the concentrated acid hydrolysis process above.

Figure IV-5
AMMONIA DISRUPTION, HYDROLYSIS AND FERMENTATION



Information provided by Grethlein,[54] technical publications,[55, 56] and local cost estimates were used to complete the economic projections in Tables IV-2 and IV-3.

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[51] Dale, B. and M. Holtzapple. "Technical Summary of Ammonia Freeze Explosion." Report, Dept. of Chem. Engineering, Texas A&M University, March 1989.

[52] Dale, B.E. "Biomass Refining: Protein and Ethanol from Alfalfa." *I&EC Product Research & Development,* 1983, vol. 22, p. 446.

[53] Óoltzapple, M. (1988) "Conversion of Grass to Highly-Digestible Animal Feed, Protein Concentrate, and Ethanol." Report, Dept. of Chem. Engineering, Texas A&M University, June, 1988.

[54] Grethlein, H.E. and T. Dill. (1993) "The Cost of Ethanol Production from Lignocellulosic Biomass – A Comparison of Selected Alternative Processes." Final Report to the U. S. Department of Agriculture, Agricultural Research Service, under Specific Cooperative Agreement No. 58-1935-2-050, April 30, 1993.

[55] Dale, B. and M. Holtzapple. "Technical Summary of Ammonia Freeze Explosion." Report, Dept. of Chem. Engineering, Texas A&M University, March 1989.

[56] Dale, B. E. "Biomass Refining: Protein and Ethanol from Alfalfa." *I&EC Product Research & Development,* 1983, vol. 22, p. 446.

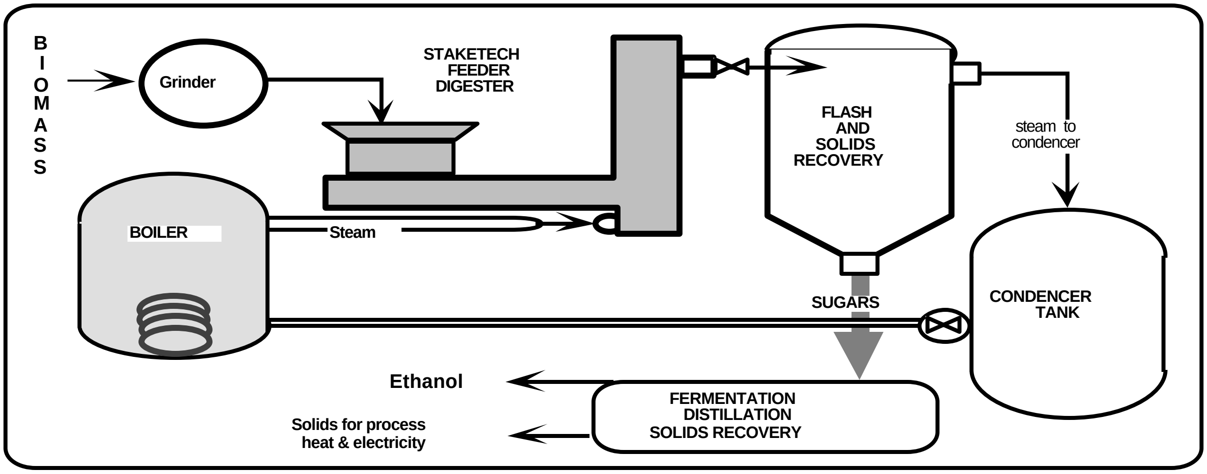
4. Steam disruption, hydrolysis and fermentation

Stake Technology Limited, of Norval, Ontario, Canada has been one of the pioneering firms involved with processing of lignocellulosic biomass. The company initially was involved with preparing cattle feed from wood chips using steam to disrupt the crystalline cellulose structure in a fashion similar to ammonia explosion. The Stake Tech people have been involved in sustaining an interest in ethanol in Hawaii for decades and have provided a great deal of information.[57, 58] Figure IV-6 below summarizes the key elements of the process.

In the steam explosion process, biomass is chopped to an appropriate size and fed into a high pressure reaction cylinder. The solids are moved continuously through the steam reactor tube with an auger and pushed through an orifice where the material literally explodes into a flash tank, where the exploded biomass and steam are recovered. When the pressure is released it causes the deacetylation and auto hydrolysis of the hemicellulose to xylose. The lignin is also melted in this treatment and the remaining biomass becomes a viscous slurry of cellulose and polysaccharides that are available for enzyme digestion to component sugars (primarily glucose).

Figure IV-6

STEAM DISRUPTION, HYDROLYSIS AND FERMENTATION



When the biomass exits the recovery tank it can be fermented and distilled to produce ethanol. It should be noted that volatile organics such as furfural, an inhibitor of microbial fermentation, are also formed. In order to compare the performance of this approach, information provided by Stake Tech was combined with estimates of the costs elements not described by the company and estimates of costs in Hawaii. The projections for a steam disruption, hydrolysis and fermentation plant producing 5 and 25 million gallons of ethanol per year are presented in Tables IV-2 and IV-3.

5. Acid disruption and transgenic microorganism fermentation (Quadrex process)

BioEnergy International, L.C., is a subsidiary of Quadrex Corporation, a publicly held company. They have the exclusive worldwide license for a constructed set of genes that when inserted into a microorganism has the ability to ferment both pentose (5-carbon) sugars and hexose (6-carbon sugars).[59, 60, 61, 62, 63]

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[57] StakeTech, Program Description. Stake Technology Limited, 2838 Highway 7, Norval, Ontario, Canada, L0P 1K0, 1993.

[58] Taylor, John D. June 3,1993, questionnaire response from StakeTech.

[59] Grethlein, H.E. and T. Dill. (1993) “The Cost of Ethanol Production from Lignocellulosic Biomass – A Comparison of Selected Alternative Processes.” Final Report to the U. S. Department of Agriculture, Agricultural Research Service, under Specific Cooperative Agreement No. 58-1935-2-050, April 30, 1993.

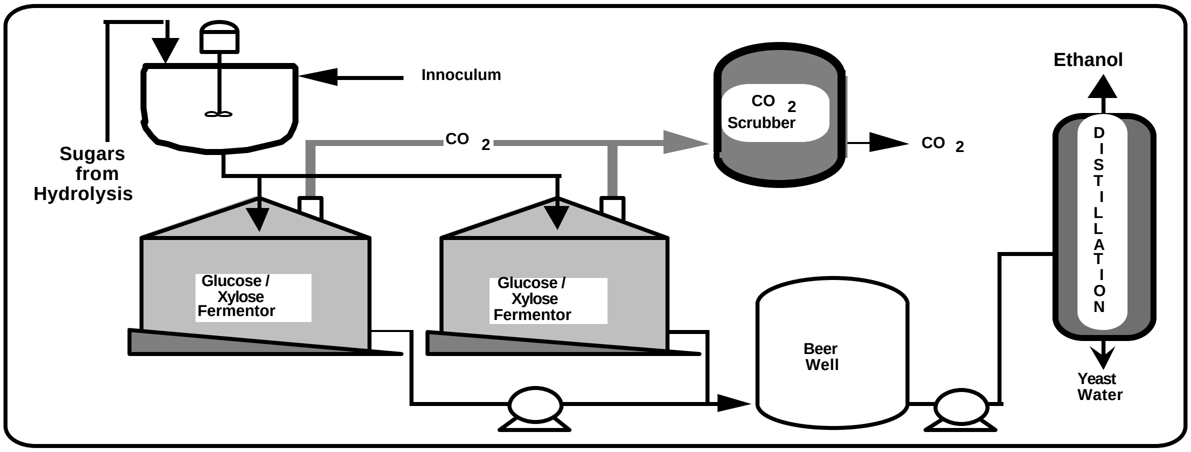
[60] BioEnergy International, Project Information.

[61] Derrickson, W.B. and D.E. Fowler. “Ethanol from Biomass Technology.” presented to Pacific International Center for High Technology Research, May 14, 1992.

[62] Derrickson , William B., President, Quadrex, personal communication, May 21, 1992.

This genetic construct, developed by Dr. Lonnie Ingram and co-workers at the University of Florida, was issued U. S. Patent No. 5,000,000 in 1991. This patent outlines the methodology for constructing a unique portable operon for ethanol production, which consists of alcohol dehydrogenase II, and pyruvate decarboxylase genes from *Zymomonas mobilis,* which is inserted into the genome of a host cell such as *E. coli, Erwinia* or *Klebsiella*.[64, 65] This system is designed to enhance ethanol production by diverting pyruvate to ethanol during growth under either aerobic or anaerobic conditions. This allows lactose, glucose, xylose, arabanose, galactose and mannose to be converted to ethanol without producing organic acids.

Figure IV-7
ACID DISRUPTION AND TRANSGENIC MICROORGANISM FERMENTATION



BioEnergy also has the exclusive worldwide rights to all improvements under an on-going research agreement. A simplified view of the downstream process is shown in Figure IV-7 (feed preparation and hydrolysis are not shown).

BioEnergy states that its "...new organisms offer, for the first time, the ability to economically ferment five-carbon sugars to ethanol as well as offering the opportunity to hydrolyze economically the cellulose with enzymes." Complete data on the BioEnergy system and associated costs were not available. Again, Grethlein's approach was used to project performance of a 5- and a 25-million gallon per year ethanol plant in Hawaii, as shown in Tables IV-2 and IV-3.

6. Concentrated acid hydrolysis, acid recycle and fermentation

Recognizing that the cost of acid, chemicals for neutralizing the acid, and gypsum disposal costs were constraints to using concentrated acid to hydrolyze lignocellulosic biomass, several laboratories have been investigating methods for separating and recovering acid from the hydrolysis mixture.[66, 67] This approach contrasts with those described previously in that it uses concentrated acid hydrolysis with almost 100% acid recycle. Some of the most notable work in developing this technology has been the work done at the Tennessee Valley Authority and the University of Southern Mississippi.[68, 69] Also active in this area is Arkenol Inc., a Nevada corporation, which was formed in 1992 to develop

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[63] BIOENERGY. "Ethanol from Biomass Technology." View Graph copies presented to PICHTR. May 14, 1992.

[64] BioEnergy International, Project Information.

[65] Derrickson, W.B. and D.E. Fowler. "Ethanol from Biomass Technology." presented to Pacific International Center for High Technology Research, May 14, 1992.

[66] Numan, R. P., S. R. Rudge, and M. R. Ladish. (1987) "Sulfuric acid-sugar separation by ion exclusion." Reactive Polymers, 5: 55-61.

[67] Nanguneri, S. R. and R. D. Hester. (1990) "Acid / Sugar separation using ion exclusion chromatography resins, A process analysis and design." Separation Science and Tech. 25, 1829-42.

[68] Hartfield, S. and R. Hester. (1993) "Separation of acid and sugar by ion exclusion chromatography, An application in the conversion of cellulose to ethanol." Proceedings, First Biomass Conference of the Americas, Burlington Vermont, August, 1993: 1078-1083.

[69] Hester, R. D., S. Hartfield, and G. E. Farina. (1993) "A process for separating acid - sugar mixtures using ion exclusion chromatography." Proceedings, Tenth International Symposium on Alcohol Fuels, Colorado Springs, Colorado. November, 1993: 716-723.

"thermal host" industrial applications and facilities for the co-generation electric power industry. Biomass-to-ethanol was selected as one of the complementary activities[70] for development.

The process is made up of six basic unit operations:

1. Feedstock preparation;
2. Hydrolysis;
3. Separation of the acid and sugars;
4. Acid recovery and recycle;
5. Fermentation of the sugars; and
6. Distillation.

Incoming biomass feedstocks are ground to reduce the particle size for introduction into the process equipment. The pre-treated material is then dried to a moisture content consistent with the acid concentration requirements for de crystallization (separation of the cellulose and hemicellulose from the lignin), then de crystallized and hydrolyzed (degrading the chemical bonds of the cellulose) to produce hexose and pentose sugars at the high concentrations necessary for fermentation. Insoluble materials, principally lignin, are separated from the hydrolysate by filtering and pressing and further processed into fuel or other uses.[71, 72] A schematic of the concentrated acid hydrolysis, recycle, and fermentation process is provided in Figure IV-8.

Commercially available resins are used to separate the acid from the sugar without diluting the sugar. The separated sulfuric acid is recirculated and re-concentrated to the level required by the de crystallization step. Any acid left in the sugar solution is neutralized with lime to make hydrated gypsum, $CaSO_4$, $2H_20$, an insoluble precipitate that is separated from the sugar solution. In some cases this material can be sold as an agricultural soil conditioner.

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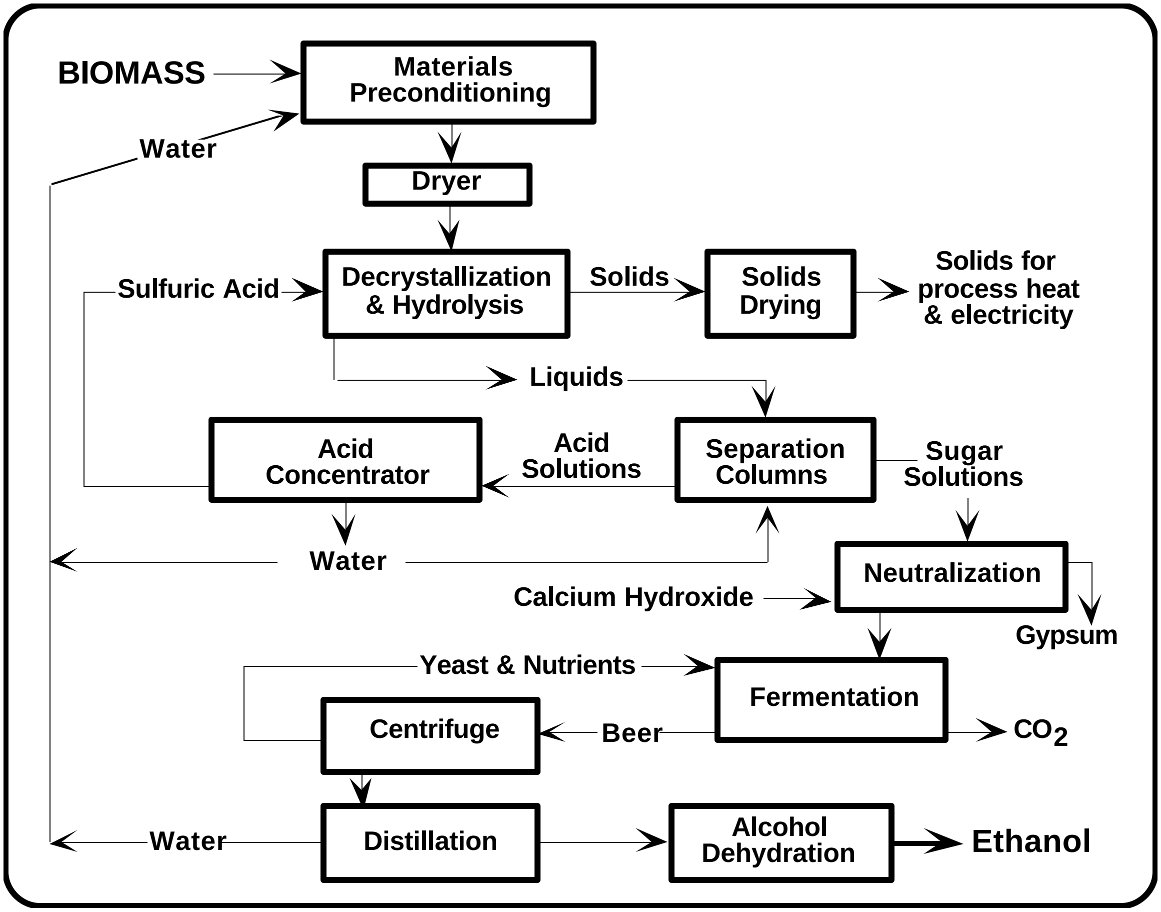
[70] ARKENOL Inc., Mark Carver, 23293 S. Pointe Dr., Laguna Hills, CA 92653. Personal Communication, May 13, 1993.

[71] ARKENOL Inc. View Graph copies presented to PICHTR. April, 1993.

[72] Carver, Mark. (1993) General Manager, ARKENOL Inc. response to questionnaire. August 1993.

Figure IV-8
CONCENTRATED ACID HYDROLYSIS, ACID RECYCLE AND FERMENTATION



At this point the process yields a stream of mixed sugars (both C-6 and C-5) for fermentation. The sugars are mixed with nutrients and inoculated with yeast that converts both C-6 and C-5 sugars to fermentation beer (an ethanol, yeast and water mixture) and carbon dioxide. Tables IV-2 and IV-3 presents analyses of the acid hydrolysis/recycle system producing 5 and 25 million gallons per year. Much of the basic process and financial information was provided by Arkenol[73] although, as in other analyses, Hawaii-specific information was included as well.

Yeast is separated from the fermentation beer by a centrifuge and returned to the fermentation tanks for reuse. Ethanol is separated from the beer by conventional distillation technology and dehydrated to 200 proof with conventional molecular sieve technology. Evaluations of the 5 and 25 million gallon per year production systems are presented in Tables IV-2 and IV-3.

7. Acidified acetone extraction, hydrolysis and fermentation

Dr. Laszlo Paszner has developed a unique approach to the pre-treatment and hydrolysis of biomass for ethanol production.[74, 75, 76, 77] The process, known as ACOS (Acid-Catalyzed Organosolv Saccharification), involves pre-treatment and grinding of biomass to make the material available for processing. The Organosolv process is shown in Figure IV-9.

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[73] ARKENOL Inc. Concentrated Acid Hydrolysis. “History, Technology and Projects” Corporate publication, 1993.

[74] Paszner Technologies, Inc., Dr. Lazlo Paszner, 2683 Parkway Drive, Surrey, B.C., V4P 1C2 Canada. Description of the ACOS Process. Personal communication. November 20, 1993.

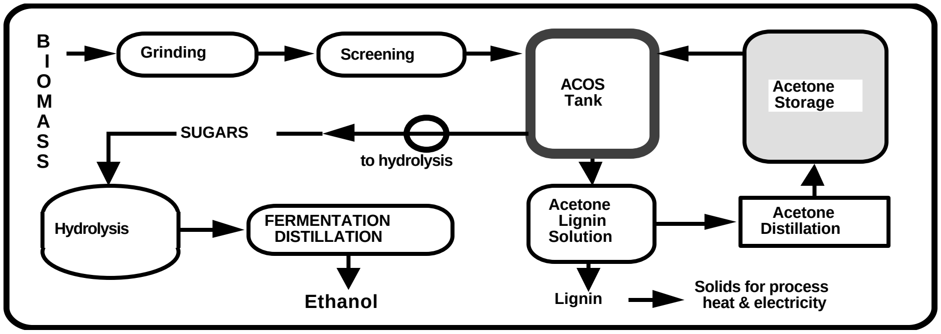
[75] Paszner Technologies, Inc. Dr. Laszlo Paszner, 2683 Parkway Drive, Surrey, B.C., V4P 1C2 Canada, Description of the ACOS Process. Technical Literature, 1993.

[76] Paszner, Laszlo. Paszner Technologies, Inc., response to questionnaire, November 1993.

[77] Prasner, L. et al, (1986) “High-Yield Organosolv Process for Conversion of Cellulosic Biomass to Ethanol" in *Energy from Biomass and Wastes*_ (D. L. Klass, ed.), Institute of Gas Technology, Chicago, 1279: 1318.

The lignin in the biomass is extracted by subjecting the material to acidified acetone at elevated temperature and pressure. Acetone is distilled from the lignin acetone mixture, leaving the lignin available for generation of electricity or process heat. The remaining residue consists of cellulose and hemicellulose that are now easily hydrolyzed to produce sugars for fermentation. The process has been designed to allow continuous extraction of the lignin, hydrolysis of the cellulosic material and fermentation of the sugars to ethanol. Based on information provided by Paszner, and estimates for system capital and operating costs in Hawaii, projections for an ACOS type facility producing 5 and 25 million gallons of ethanol per year are shown in Tables IV-2 and IV-3.

Figure IV-9
ACIDIFIED ACETONE EXTRACTION, HYDROLYSIS AND FERMENTATION



8. Traditional fermentation of sugars to ethanol

Fermentation of sugars to ethanol, using commercially-available fermentation technology, provides a fairly simple, straightforward means of producing ethanol with little technological risk. The system modeled assumes the molasses is clarified, then fermented via cascade fermentation with yeast recycle. The stillage is concentrated by multi-effect evaporation and a molecular sieve is used to dehydrate the ethanol.[78]

F. SUMMARY OF TECHNOLOGY COMPARISONS

1. Developmental status of technology options

Although some of the steps in each process have been demonstrated at the pilot-scale or even commercial-scale level (e.g. grinding, screening, pre-hydrolysis, fermentation, distillation, etc.), the integrated systems described in subsections 1 through 7 of the previous section have not yet been demonstrated at a commercial scale. The newly developed steps in the technologies evaluated are generally at the early or late pilot scale stage of development.

The information below is for comparative purposes only, and may not represent the actual performance of any specific proprietary technology in Hawaii. As described earlier in this chapter, data from more complete systems was used to fill in missing parts from less completely described technologies. Due to uncertainties associated with pilot-scale results, and subsequent efforts to evaluate the technologies on a comparative basis, the extrapolations below should not be taken as final conclusions regarding performance of specific technologies in Hawaii.

2. Ethanol production costs and sensitivity analysis

As stated above, the purpose of these evaluations is to estimate the relative economic performance and appropriateness of the various technologies and to develop a rough estimate of the costs of production of ethanol from biomass sources in Hawaii. Tables IV-2 and IV-3 and Figure IV-10 provide summaries of the evaluation results and indicate the relative sensitivities of the processes to facility size and feedstock cost. Since the costs used in these comparisons are best estimates and may not be consistent for all technologies and processes, these estimates cannot be taken as an endorsement of one process over another. A more detailed site- and technology-specific analysis would be required for detailed comparisons of the processes.

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[78] Personal correspondence, Carroll R. Keim, April 1994.

Table IV-2
ETHANOL PLANT CAPITAL AND PROCESS COSTS[79]
(biomass costs not included)

	PROCESS COST ONLY (biomass = $0 /ton)					
	25 MILLION GALLONS PER YEAR			5 MILLION GALLONS PER YEAR		
PROCESS	**CAPITAL (million $)**	**$/gallon ethanol**	**Biomass tons/day**	**CAPITAL (million $)**	**$/gallon ethanol**	**Biomass tons/day**
1. Simultaneous saccharification and fermentation	$81	$0.94	820	$26	$1.34	164
2. Concentrated acid hydrolysis, neutralization and fermentation	$99	$1.66	952	$32	$2.13	190
3. Ammonia disruption hydrolysis and fermentation	$124	$1.25	863	$40	$1.83	173
4. Steam disruption, hydrolysis and fermentation	$110	$1.09	814	$36	$1.61	163
5. Acid disruption and transgenic microorganism fermentation	$127	$1.30	838	$41	$1.90	168
6. Concentrated acid hydrolysis, acid recycle and fermentation	$72	$1.31	833	$23	$1.64	167
7. Acidified acetone extraction, hydrolysis and fermentation	$88	$1.19	779	$29	$1.61	156

Table IV-3
ETHANOL PLANT PERFORMANCE SUMMARY, BIOMASS COST INCLUDED

	Biomass cost: $50 / ton (dry matter)		**Biomass cost: $108 / ton** (dry matter)	
PROCESS	Ethanol $/gallon, 25 million gallon per year plant	Ethanol $/gallon, 5 million gallon per year plant	Ethanol $/gallon, 25 million gallon per year plant	Ethanol $/gallon, 5 million gallon per year plant
1. Simultaneous saccharification and fermentation	$1.48	$1.88	$2.11	$2.51
2. Concentrated acid hydrolysis, neutralization and fermentation	$2.28	$2.76	$3.01	$3.49
3. Ammonia disruption hydrolysis and fermentation	$1.81	$2.40	$2.48	$3.06
4. Steam disruption, hydrolysis and fermentation	$1.63	$2.15	$2.25	$2.77
5. Acid disruption and transgenic microorganism fermentation	$1.86	$2.45	$2.50	$3.10
6. Concentrated acid hydrolysis, acid recycle and fermentation	$1.86	$2.19	$2.50	$2.83
7. Acidified acetone extraction, hydrolysis and fermentation	$1.70	$2.13	$2.30	$2.72

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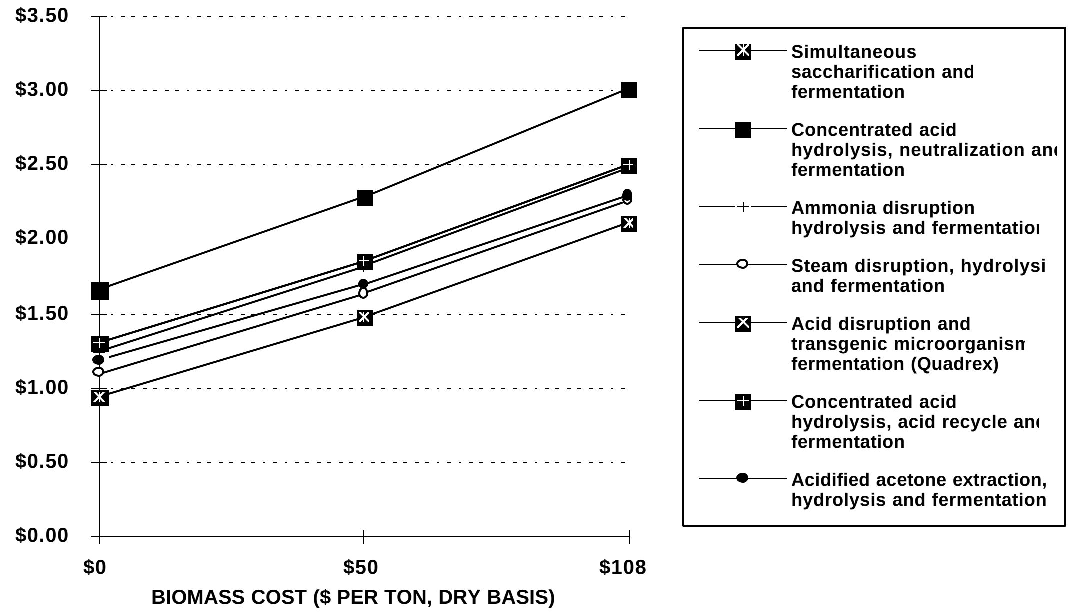
[79] In constructing these tables it was necessary to rely on claims made by those most familiar with the various technologies. It should be expected that some individuals may have been more conservative in their projections, and others may have been more optimistic. Also, these analyses were not site-specific; significant differences would be expected for different sites, feedstocks, financing, etc.

Figure IV-10
ETHANOL PRODUCTION COST SUMMARY FOR 7 TECHNOLOGIES
(feedstock costs ranging from $0 to $108 per ton)



NOTE: In constructing this chart it was necessary to rely on claims made by those most familiar with the various technologies. It should be expected that some individuals may have been more conservative in their projections, and others may have been more optimistic. Also, these analyses were not site-specific, and significant differences would be expected for different sites, feedstocks, financing costs, labor costs, and so forth. These costs should be viewed as first-cut estimates only.

The analysis does indicate that there are a variety of technologies that may produce ethanol, depending on amounts paid for feedstock, at costs ranging from less than $1.00 to over $3.00 per gallon. This is represented graphically in Figure IV-10. **Note that these ethanol production cost estimates do not take into account any potential revenues from by-products.** By-products and markets for those products are discussed in Chapter V.

G. CONCLUSIONS REGARDING ETHANOL PRODUCTION TECHNOLOGIES

As described in the previous sections, there are several approaches to the production of ethanol from lignocellulosic biomass. However, since the level of uncertainty associated with the analyses may be greater than the apparent differences between the technologies, it is not clear from this analysis what process is the “best.”

In spite of the previously-described uncertainties, variations in levels of optimism, etc., the analyses resulted in similar cost projections. This similarity lends a degree of confidence that, as the technologies mature, ethanol production costs in Hawaii will fall within this range.

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V. MARKETS AND VALUES FOR ETHANOL AND CO-PRODUCTS

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A. MARKETS FOR ETHANOL FUEL

Possible markets for ethanol fuel include use as a transportation fuel, fuel additive, for use in manufacturing a fuel additive, or as a fuel for electricity production. The potential market sizes, competition, and incentives for six possibilities are discussed briefly below. (For more detailed information on calculations and applications of tax credits and/or exemptions, see Appendix.)

1. As a blending agent (10%) with gasoline

a. Market: 382 million gallons of gasoline were sold in the state in 1992. A 10% blend with all gasoline would require about 38 million gallons per year.

b. Competition: 1) Locally-available gasolines; and
2) Ethanol from out of state

1) Locally-available gasolines

$ 0.85 rack price (approximately)
\+ 0.09 retail overhead
\+ 0.184 Federal tax
\+ 0.325 State and County fuel tax (Honolulu rate)
\+ 0.039 State 4% tax
$ 1.49 retail gasoline price per gallon

Gasohol to compete with local gasoline:

$ 0.788 for 0.9 gallon $0.875 (unleaded regular + 2.5¢[80]) gasoline
\+ 0.163 for 0.1 gallons ethanol (this is the maximum possible, which will still result in the same "bottom line" price to the consumer)
\+ 0.09 retail overhead
\+ 0.130 Federal fuel tax
\- 0.01 Federal small producer credit (for facilities of less than 30 million gallons per year; credit applies only to the first 15 million gallons)
\+ 0.004 Federal income tax on credits
\+ 0.325 State and County (Honolulu rate) fuel tax
\+ 0.00 4% State excise tax (gasohol is exempt)
$ 1.49 retail gasohol price per gallon
(Ethanol would have to be produced for less than $1.63 per gallon.)

2) Ethanol from out of state:

Current prices for ethanol on the mainland range from $1.11 in South Dakota to $1.46 in the state of Washington.[81]

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[80] According to 1990 correspondence from Pacific Resources, Inc., it would cost an additional 2 to 2.5 cents per gallon of gasoline to reduce the vapor pressure of the base gasoline for blending with ethanol.

[81] "U.S. Market Fuel Ethanol." New Fuels Report. April 18, 1994. Volume 15, Number 6.

$1.10 - $1.40 per gallon (approximate 5-year range);
\+ 0.10 to $0.20 shipping from West Coast to Hawaii (assumes parcel tanker shipments, includes terminal costs in Hawaii, does not include terminalling costs on the West Coast)

$ 1.20 to $1.60 per ethanol gallon for Hawaii ethanol to compete with ethanol from out of state.
(Ethanol would have to be produced for less than $1.30 per gallon.)

c. **Incentives:**
5.4¢/fuel gallon Federal excise tax (fuel tax) partial exemption (See federal fuel tax amounts listed above:
gasoline, $0.184 per gallon;
\- gasohol, $0.130 per gallon;
= partial exemption for gasohol, $0.054 per gallon);
10¢/ethanol gallon small producer Federal income tax credit (minus a percentage because credit is taxable)

2. **As a blending agent (10%) in unleaded mid-grade and premium gasoline**

a. **Market:** About forty-two percent of the gasolines sold in Hawaii in 1992 were mid-grade and premium blends. A 10% blend with all mid-grade and premium gasolines would require about 17 million gallons of ethanol per year.

b. **Competition:**
1) Locally-available mid-grade and premium gasoline; and
2) Ethanol from out of state

1) Locally-available mid-grade and premium gasolines
$ 0.89 rack price (approximate)
\+ 0.10 retail overhead
\+ 0.184 Federal tax
\+ 0.325 State and County (Honolulu rate) fuel tax
\+ 0.041 State 4% tax
$ 1.54 retail gasoline price per gallon

Maximum allowable cost of ethanol to compete with mid-grade and premium gasolines:

$ 0.788 for 0.9 gallon $0.875 (unleaded regular + 2.5¢) gasoline
\+ 0.204 for 0.1 gallons ethanol at $2.04 per gallon
\+ 0.10 retail overhead
\+ 0.130 Federal fuel tax
\- 0.01 Federal small producer credit (for facilities of less than 30 million gallons per year; credit applies only to the first 15 million gallons)
\+ 0.004 Federal income tax on credits
\+ 0.325 State and County (Honolulu rate) fuel tax
\+ 0.00 4% State excise tax (gasohol is exempt)
$ 1.54 retail gasohol price per gallon
(Ethanol would have to be produced for less than $2.04 per gallon.)

2) Ethanol from out of state: Same as 1.b. above.

c. **Tax incentives:** Same as 1.c. above.

3. **For use in light-duty flexible-fueled vehicles (FFV)**

Most major auto manufacturers have designed special "flexible-fuel vehicles" which are capable of operating on mixtures of 85% alcohol and 15% gasoline. A mixture of 85% ethanol and 15% gasoline is known as "E85" and is considered an alternative fuel. The Federal government has identified increased use of alternative fuels as a means to meet national energy security, economic, and environmental goals in both the Clean Air Act Amendments of 1990 and the National Energy Policy Act of 1992 (EPACT). As described in a Congressional Research Service Issue Brief,

> "The Energy Policy Act of 1992 sets a national goal of 30% penetration of nonpetroleum fuels in the light-duty vehicle market by 2010 and requires that, in sequence, the Federal government, alternative fuels providers, State and local governments, and private fleets buy alternative fuel vehicles in percentages increasing over time. The Act also creates tax incentives for vehicle buyers and for alternative fuel service station operators."[82]

State government fleets are required to begin purchasing these vehicles in model year 1996.

Ethanol is one of several alternative fuels. Other choices are methanol, liquefied petroleum gas (also commonly referred to as LPG or propane), natural gas, electricity, and biodiesel. Each of the fuels has benefits and disadvantages. It is unknown at this time what will be the demand for each of the alternative fuels (or for alternative fuels in general).

a. **Market:** Unknown. Based on number of alternative-fueled vehicles purchased. Fuel use per vehicle: less than 500 gallons gasoline (694 gallons E85, containing 590 gallons ethanol) per year. A 1 million gallon per year facility would provide more than enough fuel for 1695 cars.[83] Theoretical maximum (if all gasoline-powered vehicles eventually used 85% ethanol) is projected to be more than 450 million gallons per year of ethanol. Current demand is zero.

b. **Competition:**
1) Locally-available gasolines; and
2) Ethanol from out of state

1) Locally-available gasoline

$ 0.85 rack price (approximate)
\+ 0.09 retail overhead (approximate)
\+ 0.184 Federal tax
\+ 0.325 State and County fuel tax (Honolulu rate)
\+ 0.039 State 4% tax
$ 1.49 retail gasoline price per gallon

1.39 gallons E85 = 1 gallon gasoline. Since it takes more gallons of E85 to go the same distance, fuel cost per E85 gallon should be less. For fuel costs to be equivalent on a mile-for-mile basis, E85 retail price may not exceed $1.07 per gallon.

Maximum allowable cost of E85:

$ 0.1275 for 0.15 gallon gasoline (at 85¢/gallon gasoline)
\+ 0.70 for 0.85 gallon ethanol (at 82¢/gallon ethanol)
\+ 0.09 retail overhead
\+ 0.184 Federal fuel tax
\- 0.459 Federal tax credit
\- 0.085 Federal small producer credit
\+ 0.19 Federal income tax on credits
\+ 0.325 State and County fuel tax
$ 1.07 per gallon E85
(Ethanol would have to be produced for less than $0.82 per gallon.)

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[82] Congressional Research Service Issue Brief Number 93009, updated 01/01/94.

[83] These estimates are for flexible-fueled vehicles. Dedicated vehicles would have better fuel economy.

2) Ethanol from out of state: Same as 1.b. above (less than $1.30 per gallon).

c. Incentives: 54¢/gallon Federal income tax credit;
10¢/gallon small producer Federal income tax credit
(minus a percentage because credits are taxable);
Deductions for alternative fuel refueling facilities; and
Deductions for alternative fuel vehicles.

4. For use in buses

Ethanol-powered buses and trucks are in use in revenue service in several locations across the United States and in other countries (e.g. Brazil and France). Several federal programs have increased the use of alternative fuels in buses over the past several years. In 1988, the National Alternative Motor Fuels Act provided for transit agencies to begin to utilize alternative fuels in their fleets. In 1990, the Clean Air Act Amendments targeted particulate emissions from urban transit buses as an air pollution reduction objective. Alcohol fueled buses are one approach to reducing emissions of particulates. (Other options include advanced electronic engine controls, engine re-design, particulate traps, "clean diesel" fuels, catalytic converters, and various combinations of these systems.) The National Energy Policy Act of 1992 also contains provisions for alternatively-fueled buses.

Full-size transit buses which run on 100% ethanol[84] are available for approximately $40,000.00 more than for a regular bus (regular buses cost over $200,000.00).

a. Market: Unknown. Based on number of vehicles purchased. Current demand is zero. A 1 million gallon-per-year ethanol plant would provide enough fuel for about 35 buses. A 5 million gallon-per-year ethanol plant would provide enough fuel for about 178 buses.

b. Competition:
1) Locally-available diesel fuel; and
2) Ethanol from out of state

1) Locally-available diesel fuel[85]

$ 1.16 rack price (approximate)
0.00 Federal tax
0.00 State and County fuel tax
$ 1.16 per gallon diesel

It takes approximately 1.8 gallons of ethanol go as far as 1 gallon diesel.[86] Since it takes more gallons of ethanol to go the same distance, fuel cost per ethanol gallon should be less. For fuel costs to be equivalent on a mile-for-mile basis, the total price of the E100 fuel should not be more than $0.69 per gallon.

Maximum allowable cost of ethanol to compete with diesel for use in transit buses:

$ 1.11 (1 gallon ethanol at $1.11 per gallon)
\- 0.54 Federal tax credit
\- 0.10 Federal small producer credit
\+ 0.224 Federal income tax on credits
$ 0.69 per gallon total price of E100 fuel
(Ethanol would have to be produced for less than $1.11 per gallon.)

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[84] "100% ethanol" and "E100" also refer to blends of 95% ethanol with 5% denaturant.

[85] Assumes fuel used for a federally nontaxable purpose, such as by a state or local government.

[86] U. S. Department of Energy. *Alternative Fuels Data Center Update.* Spring 1994. Volume 3, Issue 1.

2) **Ethanol from out of state:** Same as 1.b. above.

c. **Tax incentives:** Same as 3.c. above.

5. As a feedstock in the production of ETBE (ethyl tertiary butyl ether)

Ethyl tertiary butyl ether (ETBE) is a gasoline additive made from ethanol and isobutylene. ETBE is an octane enhancer (raises the octane rating of the fuel) and an oxygenate (makes the fuel cleaner-burning). The November/December 1993 issue of *Fuel Reformulation* pegged the value of one gallon of ETBE at 130% the value of one gallon unleaded regular gasoline.

a. **Market:** If ETBE was blended into all mid-grade and premium gasolines at the rate of 17.2 per cent, demand for ethanol to make the ETBE would be about 12.5 million gallons per year.

b. **Competition:**
1) Locally-available octane enhancers;
2) ETBE or other octane enhancers from out of state; and
3) ETBE for export

1) Locally-available octane enhancers

Depends on refinery processes. If a competitive cost for ETBE is 130 per cent of unleaded regular, ETBE cost per gallon would be $1.10.

$ 0.238 (0.68 gallons isobutylene[87] at approximately $0.35 per gallon[88])
\+ 0.113 Processing cost (estimated)
\+ 0.928 Ethanol cost (0.42 gallons ethanol at $2.20 per gallon)
\- 0.2268 Federal tax credit for ethanol used in ETBE
\- 0.042 Federal small producer credit
\+ 0.094 Federal income tax on credits
$ 1.10 ETBE
(Ethanol would have to be produced for less than $2.21 per gallon.)

2) ETBE or other octane enhancers from out of state

Depends on refinery processes. If a competitive cost for ETBE is 130 per cent of unleaded regular, and average price of unleaded regular is about 49 cents per gallon, ETBE could be shipped in for about 85 cents per gallon. However, the current situation with impending reformulated gasoline regulations – requiring lower vapor pressures (ETBE has a low vapor pressure), use of oxygenates (ETBE is an oxygenate) and a requirement for a certain percentage of oxygenates to be “renewable” (ETBE is usually made from ethanol which is considered “renewable”) – may increase the value / price of ETBE.

3) ETBE for export

Depends on refinery processes. If unleaded regular on the mainland is about 49 cents, and a competitive cost for ETBE on the mainland is 130 per cent of unleaded regular (or about 64 cents), and shipping cost from Hawaii to the Mainland is about 10¢ per gallon, ETBE cost per gallon before shipping should be less than $0.54.

$ 0.238 (0.68 gallons isobutylene at approximately $0.35 per gallon)
\+ 0.113 Processing cost (estimated)

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[87] Tshiteya, R. et al. 1991. Properties of Alcohol Transportation Fuels. Alcohol Fuels Reference Work #1. Prepared by Meridian Corporation for the U. S. Department of Energy.

[88] Gorden, M. et al. 1989. Feasibility of the Production of Fuels and Co-products from Biomass.

\+ 0.354 Ethanol cost (0.42 gallons ethanol at $0.84 per gallon)
\- 0.2268 Federal tax credit for ethanol used in ETBE
\- 0.042 Federal small producer credit
\+ 0.094 Federal income tax on credits
$ 0.53 ETBE
(Ethanol would have to be produced for less than $0.84 per gallon.)

6. For use in electricity generation

Electric utilities and combustion turbine manufacturers have evaluated the use of alcohols (methanol and ethanol) in combustion turbines. Combustion turbines operating on alcohols have shown higher efficiencies, longer operating life, and reduced emissions of NOx.[89]

a. Market: If ethanol is used in a 25,000 kW steam injected combustion turbine, fuel consumption is projected to be about 0.119 gallons per kilowatt-hour,[90] or almost 3000 gallons per hour at that operating rate. Statewide electricity consumption in 1992 was over nine and one-half billion kWh.

b. Competition:
1) Conventional fossil fuels (fuel oil, diesel, and coal);
2) Direct combustion of biomass;
3) Other alternative energy sources for electricity generation.

Note that in the ethanol production process, lignin is a by-product which may also be burned to produce electricity. Although not explicitly valued in this section, its electricity production value may be included by reducing the projected ethanol price by the value of the lignin, then comparing that result to the target ethanol prices identified here.

1) Conventional fossil fuels

If #6 fuel oil is $18.00 per barrel, ethanol competing with fuel oil would have to be produced for not more than...

$ 0.22 (equivalent value per gallon ethanol on energy content basis)
\+ 0.126 if electricity is generated from a "dedicated feedstock supply system," Federal credit of 1.5¢ per kilowatt-hour generated (8.4 kWh per gallon ethanol x 1.5 ¢/kWh = 12.6¢/gallon ethanol)
\+ 0.54 Federal income tax credit for ethanol used as fuel
\+ 0.10 Federal credit for small (less than 30 million gpy) producers
\- 0.268 Federal income tax on credits
$ 0.72 per gallon ethanol
(Ethanol would have to be produced for less than $0.72 per gallon.)

If diesel is $28.00 per barrel,

$ 0.40 (equivalent value per gallon ethanol on energy content basis)
\+ 0.126 if electricity is generated from a "dedicated feedstock supply system," Federal credit of 1.5¢ per kilowatt-hour generated (8.4 kWh per gallon ethanol x 1.5 ¢/kWh = 12.6¢/gallon ethanol)
\+ 0.54 Federal income tax credit for ethanol used as fuel

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[89] Electric Power Research Institute. 1980. AP-1712. “Test and Evaluation of Methanol in a Gas Turbine System;” and personal communication, General Electric representative M. Hirakami, 1992.

[90] Based on a General Electric LM2500 combustion turbine running at 3600 RPM with shaft output of 31,200 HP.

\+ 0.10 Federal credit for small (less than 30 million gpy) producers
\- 0.268 Federal income tax on credits
$ 0.87 per gallon ethanol
(Ethanol would have to be produced for less than $0.87 per gallon.)

If coal is $30.00 per ton,[91]

$ 0.11 (equivalent value per gallon ethanol on energy content basis, assuming coal at 21 million Btus per ton)
\+ 0.126 if electricity is generated from a "dedicated feedstock supply system," Federal credit of 1.5¢ per kilowatt-hour generated (8.4 kWh per gallon ethanol x 1.5 ¢/kWh = 12.6¢/gallon ethanol)
\+ 0.54 Federal income tax credit for ethanol used as fuel
\+ 0.10 Federal credit for small (less than 30 million gpy) producers
\- 0.268 Federal income tax on credits
$ 0.61 per gallon ethanol
(Ethanol would have to be produced for less than $0.61 per gallon.)

2) Direct combustion of biomass

If biomass is $50.00 per ton dry matter,

$ 0.232 (equivalent value per gallon ethanol on energy content basis)
+0.00 If electricity is generated from a "dedicated feedstock supply system," Federal credit of 1.5 ¢ per kilowatt-hour generated. However, if biomass for direct combustion is also from a "dedicated feedstock supply system," it would be eligible for the credit as well so there would be no net advantage for ethanol with respect to this credit.
\+ 0.54 Federal income tax credit for ethanol used as fuel
\+ 0.10 Federal credit for small (less than 30 million gpy) producers
\- 0.224 Federal income tax on credits
$ 0.65 per gallon ethanol
(Ethanol would have to be produced for less than $0.65 per gallon.)

7. Summary of potential markets for fuel ethanol

As illustrated above, and summarized in Table V-1 below, there are several potential markets for fuel ethanol. The "target price" for ethanol varies, according to the competition and applicable tax incentives, from as low as around 60 cents per gallon to over $1.50 per gallon.

In Chapter IV, it was stated that "...there are a variety of technologies that may produce ethanol, depending on amounts paid for feedstock, at costs ranging from less than $1.00 to over $3.00 per gallon." Since a portion of the projected range of sales prices is consistent with a portion of the projected range of production costs, this first-cut estimate indicates that ethanol production for certain markets may be economically feasible.

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[91] This differs from the coal price ($60 per ton) assumed in Chapter III, due to the assumption that a utility which purchases coal for baseload power generation may face lower prices per ton than plantations replacing bagasse with coal.

Table V-1
ESTIMATED "COMPETITIVE PRICE" FOR FUEL-GRADE ETHANOL IN VARIOUS HAWAII APPLICATIONS

PRODUCT	VS:	% ETHANOL BY VOLUME IN PRIMARY PRODUCT	COMPETITIVE RETAIL PRICE FOR PRIMARY PRODUCT (With ethanol cost added)	ESTIMATED RETAIL PRICE FOR PRIMARY PRODUCT (Without ethanol cost added)	COMPETITIVE PRICE FOR QUANTITY OF ETHANOL USED IN PRIMARY PRODUCT	COMPETITIVE PRODUCTION PRICE PER GALLON OF ETHANOL
	-	%	$ per gallon	$ per gallon	$ per gallon	$ per gallon
Gasoline (all grades)	-	0%	$1.49	$1.49	-	-
Gasoline (mid-grade & premium)	-	0%	$1.54	$1.54	-	-
Ethanol shipped from the mainland	-	100%	$1.30	-	$1.30	$1.30
Hawaii Gasohol	Gasoline (all grades)	10%	$1.47	$1.30	$0.16	$1.63
Hawaii mid-grade & premium with ethanol	Gasoline (mid-grade & premium)	10%	$1.54	$1.34	$0.20	$2.04
E85	Gasoline (all grades)	85%	$1.07	$0.37	$0.69	$0.82
Diesel for use in city buses	-	0%	$1.16	$1.16	-	-
E100	Diesel for use in city buses	100%	$0.70	($0.42)	$1.11	$1.11
ETBE	Octane enhancers	42%	$1.11	$0.18	$0.93	$2.21
Fuel oil (#6 distillate)	-	0%	$0.43	$0.43	-	-
E100	Fuel oil (#6 distillate)	100%	$0.22	($0.50)	$0.72	$0.72
Diesel (#2 distillate)	-	0%	$0.67	$0.67	-	-
E100	Diesel (#2 distillate)	100%	$0.37	($0.50)	$0.87	$0.87
Coal	-	0%	$30.00	$30.00	-	-
E100	Coal	100%	$0.11	($0.50)	$0.61	$0.61

Also, ethanol is only one possible output from the biomass conversion systems described in this report. Revenues received from the sale of other byproducts could help to pay for a portion of the feedstock and operating costs. In Chapter IV, the “ethanol production cost” did not take into account potential returns from sale of byproducts, and assumed that the only revenue coming into the system was from the sale of ethanol; therefore, the ethanol price had to be set high enough to cover 100% of the costs.

In certain cases, production and sale of co-products could reduce the ethanol sales price required for an economically feasible system.

Although it is beyond the scope of this project to evaluate the outputs from all possible combinations of feedstocks and technologies (once again, this would vary by site as well), what follows is a general discussion of possible co-products, markets and values.

B. CO-PRODUCTS AND BY-PRODUCTS

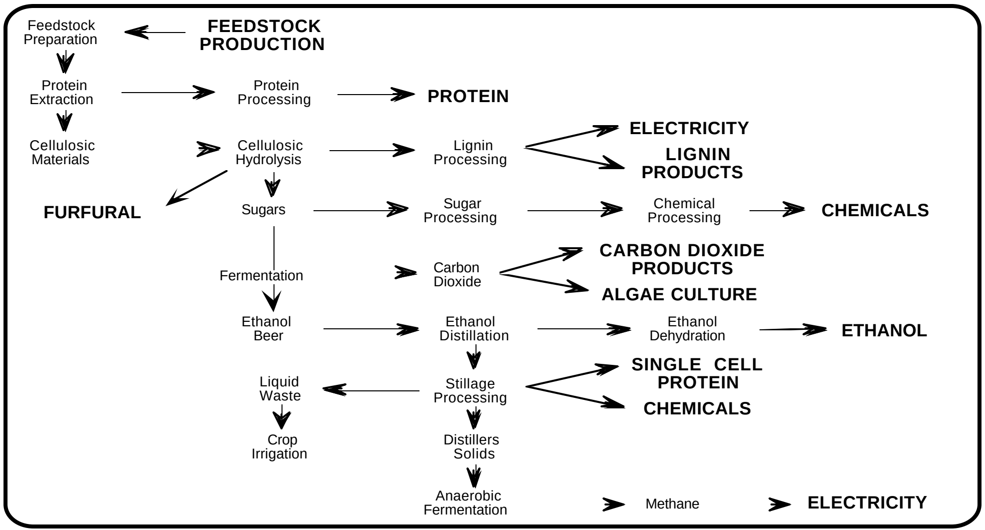
Each feedstock source and processing technology combination will produce slightly different outputs and co-products. For example, a feedstock with high levels of protein has potential to produce a high-protein animal feed supplement. A process with an overall lower energy demand, if combined with feedstocks high in lignin content, may produce greater quantities of electricity for sale to the utility.

Figure V-1 illustrates a "crop refinery" concept.[92] This is analogous to an oil refinery which uses crude oil as a feedstock to produce a variety of refined products (gasoline, jet fuel, fuel oil, etc.) Revenues from all of the products contribute to the overall economic viability of the refinery.

If an oil refinery considered itself simply an "oil to gasoline" production plant, tried to price its gasoline to cover all of the costs of the refining process, and disposed of the other products (jet fuel, diesel, fuel oil, etc.) as waste products, the process would be extremely inefficient, the price of gasoline would be very high, and the problems of disposing of the unused portions of the crude oil would be expected to be substantial, to say the least.

A discussion of "biomass to ethanol" may be, in its own way, as narrowly focused as the "oil to gasoline" production plant described above. Although actually designing the crop refinery outlined above is beyond the scope of this project, a general discussion of each of the possible by-products or co-products of such a system is provided below.

Figure V-1
CROP REFINERY



Modified from "An integrated forage crop refinery system"
TVA Agriculture Research Branch. April 1985.

1. Protein

Protein- Some sources of lignocellulosic biomass (e.g. sorghum) can contain as much as 15% protein based on dry weight. This protein may be used in a marketable animal feed supplement. In a 1983 paper, Dale and others [93], [94] have pointed out that "protein is a valuable component of biomass that is currently neglected in current fuels and chemicals from biomass schemes." In this paper Dale provided some representative data on crop composition, a summary of which is presented in Table V-2 below.

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[92] Broder, J. D. and J. W. Barrier. "Producing Ethanol and Coproducts from Multiple Feedstocks." Tennessee Valley Authority, for the International Summer Meeting of the American Society of Agricultural Engineers, Rapid City, S. D., June 26-29, 1988.

[93] Dale, B. E. "Biomass Refining: Protein and Ethanol from Alfalfa." *I&EC Product Research & Development*, 1983, vol. 22, p. 446.

[94] Holtzapple, M. (1988) "Conversion of Grass to Highly-Digestible Animal Feed, Protein Concentrate, and Ethanol." Report, Dept. of Chem. Engineering, Texas A&M University, June, 1988.

The material described is independent of the grain in the crop. For example, in this analysis sorghum residue contains approximately 10% protein based on dry weight. A well-balanced plant protein is worth approximately $0.75 per pound. In this case, a ton of dry sorghum residue might contain 200 pounds of protein, for a total value of $150.00. If the extraction costs are reasonable, plant residues may be processed to provide protein for an animal feed industry.

Protein is also contained in stillage from the fermentation process (see section on stillage).

Table V-2
PROTEIN CONTENT OF SELECTED PLANT MATERIALS

Material	Cellulose (% by weight, dry basis)	Hemicellulose (% by weight, dry basis)	Lignin (% by weight, dry basis)	Protein (% by weight, dry basis)	Other (% by weight, dry basis)
Alfalfa (leaves)	22.2%	11.0%	5.2%	**28.5%**	33.1%
Alfalfa (stalks)	48.5%	6.5%	16.6%	**10.5%**	17.9%
Sorghum residue (leaves)	25.6%	40.0%	7.8%	**10.4%**	16.2%
Sorghum residue (stalks)	26.1%	31.1%	8.0%	**9.3%**	25.5%
Corn residue (leaves)	33.2%	31.1%	7.4%	**7.1%**	21.2%
Corn residue (stalks)	43.1%	10.5%	9.6%	**3.4%**	33.4%
Sudan grass (leaves)	35.8%	29.5%	10.9%	**6.7%**	17.1%
Sudan grass (stalks)	44.1%	21.3%	9.1%	**5.1%**	20.4%

2. Lignin

Lignin is a component of lignocellulosic biomass which generally passes through the biomass to ethanol conversion system unchanged. For a plant producing 25 million gallons per year of ethanol (using assumptions stated in Chapter IV), lignin production would be about 100 tons per day. Lignin has an energy value that varies by source, from about 9,100 Btu per pound of lignin from northern red oak to 11,300 Btu per pound of lignin from softwood.[95] Another reference quotes a heat content of 12,700 Btu per pound of "milled wood lignin."[96]

Extraction of lignin in the processing of biomass to ethanol has the potential to provide a high energy compound for the production of process heat and generation of electrical energy.

Lignin may also be processed to specialty polymers, electrically conducting polymers, or phenolic resins, which may be used as glues or binders in production of plywood and fiberboard.

3. Furfural

Hydrolysis of biomass can result in soluabilizing or liberating the sugars that constitute cellulose and hemicellulose. Xylose, the primary sugar in hemicellulose, can be further processed in the presence of acid to furfural.

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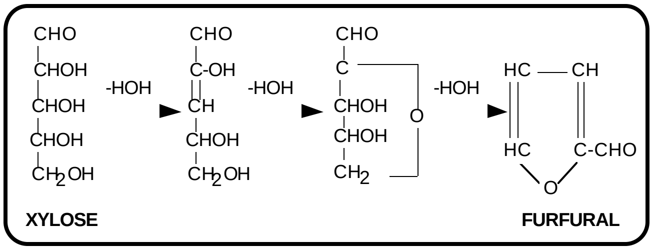
[95] American Society of Mechanical Engineers. *Thermodynamic Data for Biomass Materials and Waste Components.*

[96] Falkehag, Ingemar. 1975. Lignin in Materials. Printed in *Proceedings of the Eighth Cellulose Conference.* Applied Polymer Symposia, No. 28.

Figure V-2
XYLOSE TO FURFURAL



This compound can be used as a selective solvent for refining high quality lubricating oils. Hydrogenation of furfural at 200° C produces furfural alcohol which can be refluxed to produce commercial resins. Furfural can also be used to produce low temperature adhesives and protective coating for wood; it also has application in the production of nylon.

4. Carbon dioxide

For every pound of ethanol produced, approximately one pound of carbon dioxide is produced from the fermentation process. For a 25 million gallon per year plant, carbon dioxide production would be about 250 tons per day.

a. Direct sale

Carbonation. Carbon dioxide has only limited market as a beverage carbonating agent in Hawaii.

Compression to make dry ice. Dry ice is used as a cooling agent in some industries.

b. Conversion to other products

Carbon dioxide may also be directed to the production of algae or methane.

5. Algae

In photosynthesis, plants and other chlorophyll containing organisms – including algae – use energy provided by sunlight to covert carbon dioxide to sugars. This is done by the reduction of CO_2 (removing oxygen and adding hydrogen).

$$6\,CO_2 + 6\,H_2O + \text{Light} \longrightarrow 6\,O_2 + C_6H_{12}O_6$$

carbon dioxide + water + sunlight --------> oxygen + sugar

As a result of photosynthesis, carbon dioxide (considered a pollutant) is converted to valuable oxygen and sugars that living forms use as a source of energy. CO_2 is utilized 100% by aquatic algae to produce biomass by photosynthesis. Appropriate selection of algae has the potential to produce pharmaceuticals, animal feed ingredients, and energy products.[97, 98, 99, 100, 101, 102] The abundance of sunlight available in Hawaii makes this possibility particularly intriguing.

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[97] Becker, E.W. "Nutritional Properties of Microalgae: Potentials and Constraints." (1986) *Handbook of Microalgal Mass Culture.* CRC Press, Inc. Boca Raton, Florida. pp. 339-419.

[98] Ceferri, Orio, and Tiboni, Orsola. (1985) "The Biochemistry and Industrial Potential of Spirulina." *Annual Review of Microbiology.* Vol. 39: 503-526.

[99] Cohen, Zvi, etal. (1987). "Fatty Acid Composition of Spirulina Strains Grown Under Various Conditions." *Phytochemistry.* Vol. 26.

[100] Materassi, R. et. al. (1986) "Some Consideration on the production of Lipid Substances by Microalgae and Cyanobacteria" in *Algae Biomass.* pp 619-626. Elsevier/North Holland Biomedical Press.

[101] Richmond, A. (1986) "Microalgae of Economic Potential." in *Handbook of Microalgae Mass Culture.* CRC Press, Inc. Boca Raton, Florida. pp. 199-243.

6. Stillage

Fermentation (conversion of sugars to ethanol and carbon dioxide) is carried out by a variety of microorganisms. These microorganisms contain nitrogen, phosphorous, potassium, trace minerals, and, on a dry weight basis, may contain up to 70% protein and a variety of vitamins and fatty acids.

Animal feeds. Processing produces a protein rich powder (sometimes referred to as single cell protein). Depending on species these can be used as substitutes for soy protein or fish meal in formulating feeds for animals and aquatic species.

Anaerobic digestion to produce methane. Stillage may be anaerobically processed to produce methane.

7. Methane

Methane may be used for the generation of electricity or as a feedstock for production of other materials. Methane is not a direct product of the biomass to ethanol production process, but could be produced via anaerobic digestion of stillage and/or conversion of carbon dioxide.

Proprietary designs of systems that have the capacity to convert CO_2 to methane have been developed at the experimental level.[103, 104, 105, 106, 107, 108, 109]. As this technology continues to improve, methane from carbon dioxide may become an important source of energy for biomass conversion systems.

After microbial biomass is removed the resulting "beer" must be distilled. The liquid remaining is rich in nutrients and contains particulate material that must be disposed of or utilized. When combined with other organic wastes, this material is a particularly good substrate for anaerobic fermentation to produce methane. The resulting methane may be used for process heat or to produce electricity.

8. Electricity

a. Production

There are several possibilities for production of electricity within the plant: direct incineration of lignin, incineration of stillage (the stillage would have to be dried first), or use of methane (from anaerobic digestion of stillage and conversion of carbon dioxide) in natural gas engines or gas turbines.

b. Sale to utilities

Electricity not used in the plant may be sold to a local electric utility. The amount received in payment from the utility varies from island to island and between negotiated power purchase agreements. (A power purchase agreement is a

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[102] Vaughn, S. R., R. M. McDonald, P. E. Donnelly, N. A. Hendy, and R. A. Mills. (1984) "The Biomass Refinery as a Route to Fuel Alcohol from Green Crops." *Proceedings Communications,* Vol. III, May 21-25, 1984, Ottawa, Canada, C-34, PP. 26-32.

[103] Hayes T. D. and H. R. Isaacson. (1987) "New Concept for the Production of High-BTU Gas from Anaerobic Digestion," in *Biotechnological Advances in Processing Municipal Wastes for Fuels and Chemicals*, Noyes Data Corporation 355:374.

[104] Jee, H., Yano, T., Nishio, N. and Nagai, S. (1987) "Biomethanation of H2 and CO2 by Methanobacterium thermoautotrophicum in membrane and ceramic bioreactors." *Journal of Fermentation Technology.* No. 4. Vol. 65: 413-18.

[105] Ng, T. K., Bassat, A., and Zeikus, J. G. (1981) "Ethanol production by thermophilic bacteria: fermentation of cellulosic substrates by cocultures of Clostridium thermocellum and Clostridium thermohydrosulfuricum." *Applied and Environmental Microbiology*. No. 6, Vol. 41:1337-43.

[106] Ng, T. K., Weimer, P. J., and Zeikus, J. G. (1977) "Cellulolytic and physiological properties of Clostridium thermocellum." *Arch. of Microbiology.* Vol. 114: 1-7.

[107] Ng, T. K., Zeikus, J. G. (1982). "Differential metabolism of cellobiose and glucose by Clostridium thermocellum and Clostridium thermohydrosulfuricum." *Journal of Bacteriology.* No. 3. Vol. 150:1391-9.

[108] Wiegel, J., Ljungdahl, L. G., and Rawson, J. R. (1979). "Isolation from soil and properties of the extreme thermophile Clostridium thermohydrosulfuricum." *Journal of Bacteriology.* No. 3, Vol. 139:800-10.

[109] Zeikus, J.G. (1980). Chemical and Fuel Production by Anaerobic Bacteria. *Annual Review of Microbiology.* Vol. 34: 423-64.

contract between the independent power producer (IPP) and the utility.) An important factor in utility payments to IPPs is whether the contract is for firm power (available upon demand by the utility) or not.

Another option would be to sell biomass-derived fuel (pellets, oils, etc.) to the utility for use in their own facilities, if a long-term contract could be worked out that was acceptable to both parties.

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VI. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

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A. SUMMARY

The previous sections have provided a perspective on biomass sources, costs, and technologies for the production of ethanol from biomass in Hawaii.

1. Biomass sources

There are several possible sources of raw materials for the production of ethanol; they include municipal solid waste, newspaper, tree crops such as leucaena and eucalyptus, sweet sorghum, grass crops such as napier grass and sugarcane, and by-products of agricultural processes, such as sugarcane molasses or leaves and tops of the sugarcane plant. Each material has a different ethanol production potential, and has different acreage requirements for a given quantity of ethanol produced.

The raw material necessary for the production of ethanol in Hawaii is either available in Hawaii or may be grown in Hawaii. It is projected that sufficient quantities of feedstock could be produced to satisfy the requirements of several commercial-scale ethanol production facilities.

The costs of various feedstocks show a wide variation, from cultivated feedstock with projected costs of over $100 per ton in some locations to waste feedstocks available almost for free.

2. Technologies for ethanol production

These analyses are not the site-specific, in-depth analyses that would be required prior to actual construction of an ethanol production facility; the uncertainty associated with the figures quoted here must be taken into account in interpreting the results.

Due to the nature of this study, it was necessary to rely on claims made by those most familiar with the various technologies. In most cases, these individuals were the developers of the technologies and the owners of the patent rights, and therefore may have been somewhat biased in their claims; it should be expected that some individuals may have been more conservative in their projections, and others may have been more optimistic.

The use of this information from these sources was both necessary and appropriate for this study. It is the responsibility of the reader to keep in mind the source of the information and approach taken when interpreting the results.

Each of the various technologies and resulting projected costs were identified in Chapter IV. For the sake of simplicity, and to avoid overemphasizing the apparent differences between the various technologies, the highest projected production cost per gallon and the lowest projected production cost per gallon have been used in Table VI-1 to indicate a range of "pre-feasibility" estimated ethanol productions costs.

As shown in Table VI-1, the projected cost of ethanol produced from a variety of feedstocks and processes ranges from $0.94 per gallon to over $3.00 per gallon.

Table VI-1
ETHANOL FEEDSTOCK AND PRODUCTION COSTS

BIOMASS MATERIAL	$/gallon for feedstock cost alone (high end of range)	$/gallon for feedstock cost alone (low end of range)	$/gallon processing cost (high end of range)	$/gallon processing cost (low end of range)	Total $ per gallon (high end of range)	Total $ per gallon (low end of range)
Bagasse	$0.84	$0.44	$1.66	$0.94	$2.49	$1.38
Molasses	$0.49	$0.49	$1.02	$0.52	$1.51	$1.01
Prepared cane	$1.11	$0.59	$1.66	$0.94	$2.76	$1.53
Leafy tops and trash not counted in prepared cane	$0.52	$0.28	$1.66	$0.94	$2.18	$1.22
Unburned sugarcane	$1.01	$0.54	$1.66	$0.94	$2.67	$1.48
Sugarcane varieties (Puerto Rico & Hawaii)	$0.93	$0.49	$1.66	$0.94	$2.59	$1.44
Napier Grass	$1.45	$0.77	$1.66	$0.94	$3.10	$1.71
Sweet Sorghum	$0.85	$0.45	$1.66	$0.94	$2.50	$1.39
Eucalyptus	$1.38	$0.74	$1.66	$0.94	$3.04	$1.68
Leucaena	$1.99	$1.06	$1.66	$0.94	$3.65	$2.00
Newspaper	$0.14	$0.05	$1.66	$0.94	$1.79	$0.99
Municipal Solid Waste	$0.42	$0.00	$1.66	$0.94	$2.07	$0.94

Assuming 25 million gallon-per-year ethanol production facility

3. Markets and values for ethanol

Markets and values for ethanol indicate that locally-produced ethanol could compete price-wise in a variety of applications[110] if it could be produced for between $0.65 per gallon to over $2.00 per gallon (this includes consideration of tax incentives - see Chapter V for more detail on method of application of incentives). It appears that, in order for Hawaiian ethanol to compete with current mainland prices, ethanol production costs would have to be less than $1.30 per gallon.

The production of marketable products, in addition to ethanol, from the biomass-to-ethanol facility could potentially increase the profitability of the ethanol production facility and/or decrease the break-even sales price of the ethanol.

B. CONCLUSIONS

As stated earlier in this report,

> **"The objective of this study is to provide a first-cut estimate of the feasibility of producing ethanol in Hawaii, and to identify the most promising feedstocks and technologies for ethanol production.**
>
> **If it appears that ethanol production in Hawaii may be feasible, more detailed and/or site-specific analysis may be warranted."**

The following section summarizes conclusions that may be drawn from this study.

1. Feasibility of producing ethanol in Hawaii

Due to the availability of raw materials, and the existence of technology for ethanol production, it appears that ethanol production in Hawaii is technically feasible.

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[110] See Table V-1.

Projected ethanol production costs range from less than $1.00 per gallon to over $3.00 per gallon, depending on cost of feedstock, conversion technology, and scale of facility. Projected value (marketable price) for the ethanol ranges from under $0.65 per gallon to over $2.00 per gallon. The overlap between projected production cost per gallon and projected return per gallon indicates that ethanol production in Hawaii may be economically feasible, with the proper selection of feedstocks and processes.

Therefore, more in-depth site-, technology-, and feedstock-specific analyses appear to be warranted.

2. The most promising feedstocks

Feedstocks which are already available – as wastes or by-products from other processes – appear to provide the lowest-cost near-term alternative. These wastes, however, are limited in amount, and may not be available in concentrated amounts close to the ethanol production facility.

Several cultivated crops appear promising, although the economics of cultivating these crops for ethanol production alone appear marginal. The production of higher-value products, such as food, feed, pharmaceuticals, or sugar, together with the production of ethanol, could be economically viable.

3. The most promising technologies for ethanol production

Given the uncertainty in the cost projections for the various technologies, the general conclusion that may be drawn is that there are several apparently viable options ready for commercialization, with projected ethanol production costs in the range of economic feasibility.

The production of a variety of products, in addition to ethanol, may improve the overall economic feasibility of a biomass-to-energy facility, and may influence the ultimate decisions regarding optimal feedstocks, technology and location.

Therefore, more in-depth site-, technology-, and feedstock-specific analyses appear to be warranted.

C. RECOMMENDATIONS

1. Conduct site-, technology-, and feedstock-specific analyses

As discussed numerous times throughout this report, the actual feasibility of ethanol production at any particular site cannot be determined without conducting specific analyses. The values used in this effort were "state averages" wherever possible, which understates the potential at some locations and overstates the potential at other locations.

2. Improve economics of ethanol production in Hawaii

The results of this study indicate that cost reductions could improve the economic viability of ethanol production. Specific elements that appear to be significant are the following:

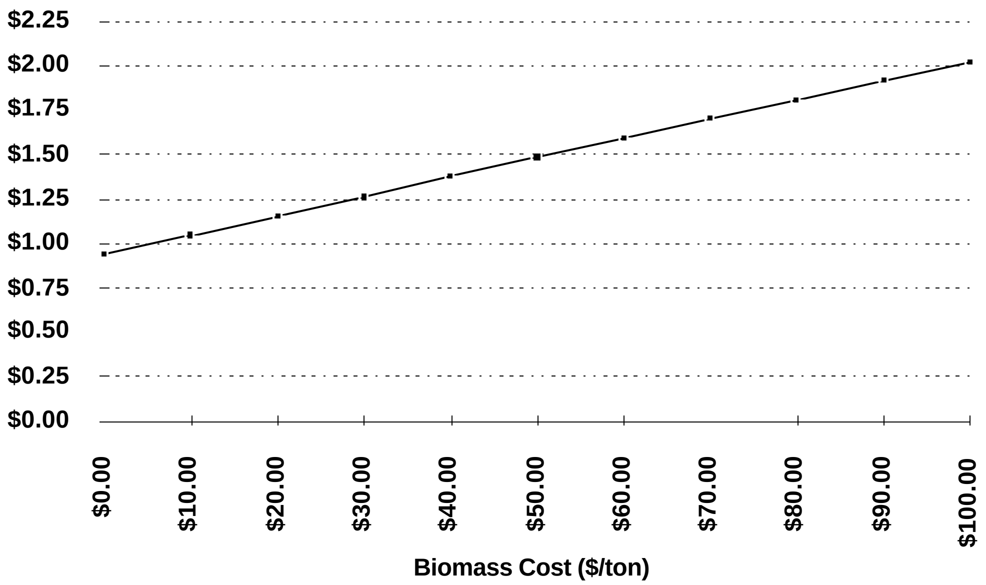
- Lower cost feedstock;
- Improved processing technology;
- Production and marketing of by-products; and
- Federal and State tax incentives.

The following is a discussion of the above-listed options.

a. Lower cost feedstock

Figure VI-1 below shows the relationship of feedstock price to the cost per gallon using one of the more promising technologies. If feedstocks were supplied at costs as low as five dollars per ton, the cost of producing the ethanol is projected to be about $1.00 per gallon. At a feedstock cost of $80.00 per ton, the cost of ethanol production, in a plant producing 25 million gallons per year, is projected to be about $1.80 per gallon.

Figure VI-1
IMPACT OF BIOMASS COST ON ETHANOL PRODUCTION COST



The most immediate opportunities for low-cost feedstock would be the use of municipal solid waste, paper waste, and green waste to augment the biomass crops. Use of these materials may have the added advantage of providing tipping fees as a means of offsetting production costs.

The establishment of biomass-to-ethanol businesses may depend on the continuous availability of biomass at a reasonable cost in close proximity to the production plant. As technologies for the production of products of value from wastes continue to improve, it may be possible to envision competition for all lignocellulosic wastes, resulting in reduced pollution problems and lower costs of waste disposal for communities. If a community is interested in developing a waste-to-ethanol industry, the establishment of policies to facilitate this effort may improve the feasibility of waste-to-ethanol facilities in that region. Source separation of waste paper and green waste could reduce front-end costs.

b. Improved processing technology

Technical improvement in the biomass conversion processes may have positive impacts on capital and operating costs of various systems. Also, designs which are specifically geared towards optimal use of Hawaii's feedstocks and natural resources may result in lower overall costs. Several examples of these types of improvements are listed below.

1) Processing plants: appropriate scale for available feedstock

Processing plants will most likely be located on all islands and located central to locations where the resource base is adequate to sustain the biomass requirements for the scale that the plant requires to be profitable.

2) Pre-treatment

Pre-treatment is essentially cleaning, cutting or grinding the feedstock to sizes that are appropriate for subjecting to acid, heat, ammonia, or other treatments that liberate sugars. Using the existing cleaning and chopping sections of the sugar mill to pre-treat the crude biomass could be a real opportunity to reduce the amount of capital investment required.

3) Hydrolysis

There are many approaches to the process of converting cellulose, hemicellulose, and complex sugars to monosaccharides suitable for fermentation. With cost the primary concern, Hawaii must concentrate on options that require low energy and are not highly dependent on expensive imports. Growing appropriate strains of microorganisms to produce cellulose- and hemicellulose-hydrolyzing enzymes may provide a real advantage. This is one area where a small amount of local research might show a significant benefit.[111]

4) Fermentation

Once the sugars are liberated, they are available to be fermented to ethanol. There are two key aspects of this situation: (1) microorganism(s); and (2) fermentation system design.

There are a wide variety of microorganisms that convert pentose or hexose sugars to ethanol.[112, 113, 114]. An organism that can convert both kinds of sugars may be beneficial but is certainly not an economically limiting factor.[115] Of greater concern are issues such as efficiency of conversion of sugars to ethanol, tolerance of the organism to ethanol and sugar concentrations, the time required for fermentation, resistance to contamination, and safety from accidental spillage.

Batch reactors are notoriously vulnerable to problems in these areas. Immobilized cell bioreactors developed in Hawaii and elsewhere offer potential to reduce fermentation times from days to hours and afford an opportunity to operate continuously with low probability of contamination.[116, 117]

5) Alcohol concentration

Even the most effective fermenting microorganisms seldom achieve alcohol concentrations exceeding 10%. Selecting microorganisms with higher tolerances to ethanol concentration may provide a distinct advantage.[118, 119]

Cost effective removal of water or alternative methods of concentrating ethanol can also have important economic impacts. Pervaporation technology (causing ethanol to evaporate and condense using membrane technology) is a promising area of emphasis. The energy required to distill ethanol from the beer (post fermentation mixture) is considerable. Hawaii has a particular advantages in this area. Use of solar energy or sunlight to provide the heat for

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[111] Stuart, Dorsey, President Neugenesis, 2800 Woodlawn Drive, Honolulu, Hawaii 96822, personal communication.

[112] Gordon, J., Jiminez, M., Cooney, C., and Wang, D. (1978). “Sugar Accumulation During Enzyme Hydrolysis and Fermentation of Cellulose.” *Biochemical Engineering: Renewable Resources.* No. 1981. Vol. 74: 91-7.

[113] Messing, R. and R. A. Shleser. "A Two Stage BioReactor Using Microporous Matrix For Conversion of Organic Waste to Pure Methane,” NSF SBIR Phase I Final Report Aquacultural Concept Inc., Hawaii, Nov. 1986.

[114] SERI. “Yeast Metabolism of Xylose.” Science & Technology Brief, Solar Energy Research Institute, Golden, CO., Biofuels/6, 1985.

[115] BIOENERGY. “Ethanol from Biomass Technology.” View Graph copies presented to PICHTR. May 14, 1992.

[116] Messing, R. and R. A. Shleser. "A Two Stage BioReactor Using Microporous Matrix For Conversion of Organic Waste to Pure Methane,” NSF SBIR Phase I Final Report Aquacultural Concept Inc., Hawaii, Nov. 1986.

[117] Kossen, N. W. F. (1986) “The Characteristics of Immobilized Cell Particles,” in *Process Engineering Aspects of Immobilized Cell Systems* (C. Webb, G. M. Black, and B. Atkinson, eds.), 103.

[118] Messing, R. and R. A. Shleser. "A Two Stage BioReactor Using Microporous Matrix For Conversion of Organic Waste to Pure Methane,” NSF SBIR Phase I Final Report Aquacultural Concept Inc., Hawaii, Nov. 1986.

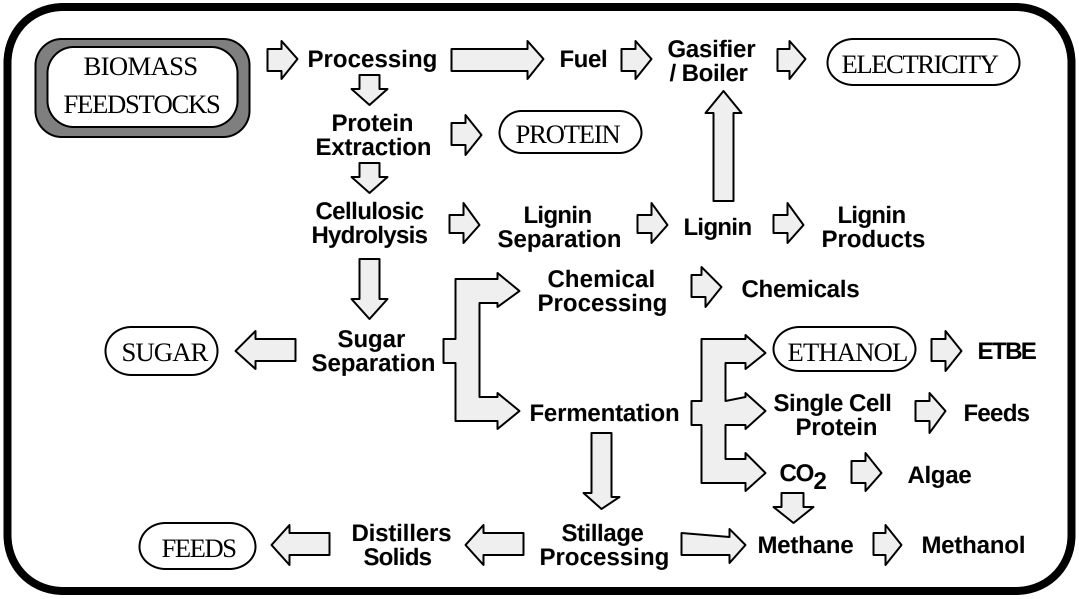
[119] Dorsey, Stuart. President, Neugenesis. 2800 Woodlawn Drive, Honolulu, Hawaii 96822, personal communication.

distillation may provide significant cost savings. This should be evaluated when siting and designing processing facilities.

c. Production and marketing of by-products

Options for optimizing the resources bound in the biomass feedstock are illustrated in Figure VI-2.

Figure VI-2



d. Federal and State tax incentives

As illustrated in Chapter V, there are several tax benefits currently available. In the short term these may assist in the establishment of an ethanol industry. Since most of the benefits are from Federal sources and several Federal programs are designed to encourage agriculture, rural employment, and energy security, these may last for some time.

Additional government support for agriculturally-based fuels and other products may also be justified by the creation (or maintenance) of agricultural employment and the establishment of local fuels production capability.

The following suggested tax incentives at the state level may increase the economic competitiveness of a local ethanol industry and reduce the likelihood of ethanol being shipped in from out-of-state.

1) State certified facility fund

A State fund could be set up, whereby a tax on gasoline used in the state of Hawaii would be collected and set aside for payment of production incentives to ethanol producers located in Hawaii. The fund could be administered by a state agency such as DBEDT. Payments could be geared to provide locally-produced ethanol with an advantage over ethanol shipped in from the mainland.

A “certified ethanol production facility” would be defined as a facility located in Hawaii and which produced ethanol of fuel grade ethanol. The ethanol produced must be derived from organic compounds. Certification would also require that 100% of the ethanol produced was fermented, distilled, and dehydrated at the facility.

(This recommendation is patterned after legislation passed by the State of Nebraska in 1993, Assembly Bill 864.)

2) Distributor incentive

Distribution of ethanol could be encouraged by providing distributors of gasoline containing 10% or more ethanol with a tax credit. This would provide the distributors with a positive incentive to learn about gasohol and could avoid some of the negative publicity campaigns experienced in other states.

3. Demonstrate and develop technology

At present no complete system has been built or run at a commercial scale that is appropriate for Hawaii. Building a pre commercial scale demonstration facility will be essential to validate assumptions and refine costs. Recognizing that technology is continually evolving, and that there will be opportunities for cost-effective innovations, perhaps the most productive approach will be to integrate all information available and design a system for Hawaii. A meeting would be held with those individuals representing emerging technologies with near term potential. The design would be refined, then implemented in the form of a pre commercial demonstration facility supported by private, Federal, and State interests. Performance and costs would be refined and validated. Based on demonstration results, private sector interests would invest in one or more strategically located production plants.

a. Support construction of a demonstration facility

This evaluation suggests that there are numerous technical approaches to producing ethanol from biomass. A plant producing about 25 million gallons per year may produce ethanol at costs ranging from $1.20 to $2.00 per gallon. Current availability of Federal and State tax concessions and benefits should make the potential very attractive. At the local level it is clear that nothing short of constructing pre-commercial or commercial scale plant will overcome the skepticism generated from past experience.

A cooperative effort between government and the private sector could be initiated to validate the economics and, if positive, encourage the establishment of a commercial scale ethanol demonstration. This might consist of utilizing existing sugar mills; this would have the advantage of providing a location for large scale ethanol production demonstration, and could also establish a location for technical education.

b. Utilize federal cooperation and support

Federal programs to develop, demonstrate, and implement the production of ethanol from biomass crops may be utilized for this effort. Joint public-private partnerships could bring together scientific expertise, business and economic resources in the design of a technology demonstration project. If the design is promising, the U. S. Department of Energy may be interested in providing funding for the construction of the facility.

Success in either of the above approaches may be sufficient to convince local interests with facilities, land resources, and crop production experience to participate in the development of ethanol. Active encouragement and participation by the state may increase the success of these efforts.

4. Combine elements to create a system specifically for Hawaii

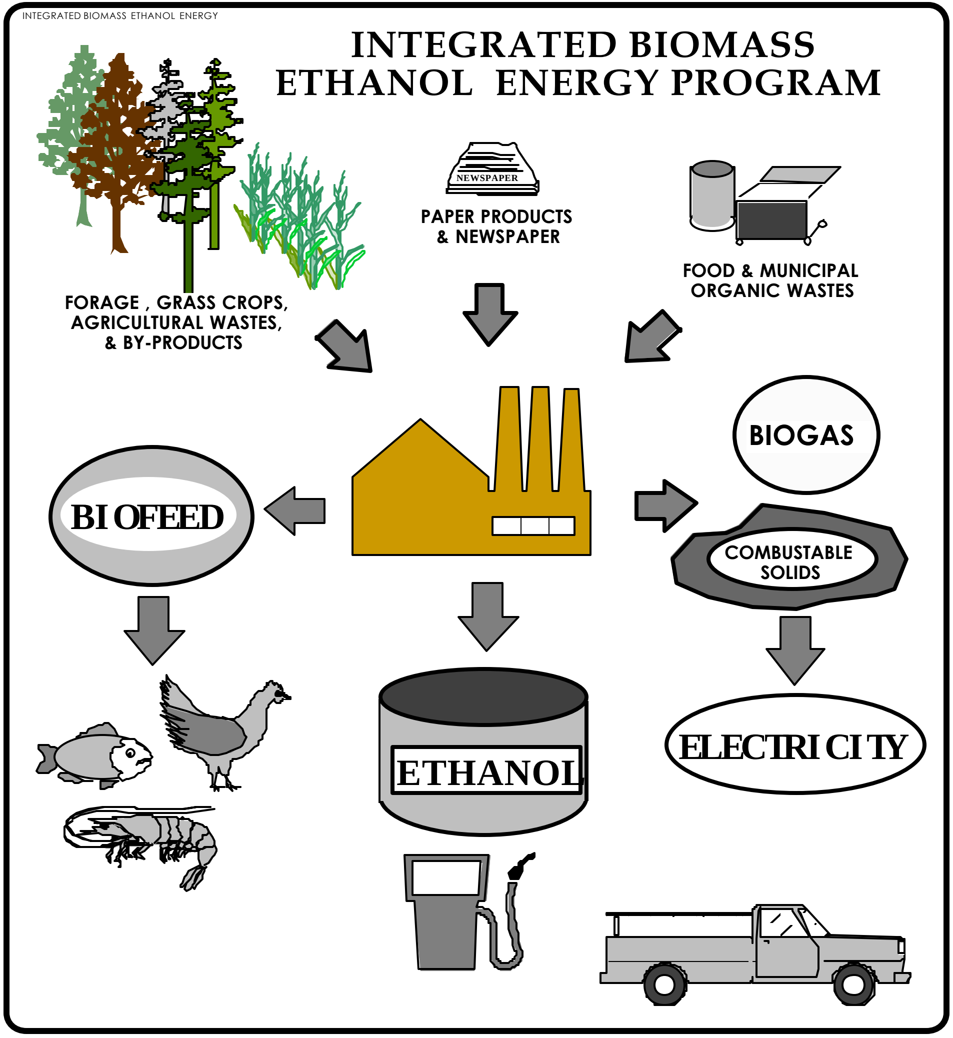
The original intent of this study was to compare the cost of alternative processes for the conversion of lignocellulosic biomass to ethanol. In the process of evaluating the various approaches it became clear that the technology selected for Hawaii must be appropriate for the sources of feedstock and sensitive to the resource base and the economic conditions in each location. As a result, a “System for Hawaii” concept is shown that is intended to be sensitive to the sources of biomass and the physical and economic operating environment in the State. The system shown below selects elements from the various systems that are:

1) Economically most effective; and

2) Consistent with the feedstock, operating conditions, and economic needs in Hawaii.

The system that will evolve in Hawaii will likely be integrated to use a variety of biomass sources as feedstocks and will generate products and co-products that make optimal use of the resource base as well as respond to market opportunities for the products. This is illustrated in Figure VI-3.

Figure VI-3



5. Develop markets for ethanol produced in Hawaii

Without demand for the ethanol, sale of the product would be difficult at best and unlikely at worst. Possible markets have been briefly described in Chapter V; the actual development of those markets, however, has not been discussed here. Market development activities may increase the likelihood of attracting investors to build ethanol production facilities.

Working from where Hawaii is now (no ethanol production and zero use of ethanol as fuel; lingering public suspicion of ethanol-blended gasoline) to the desired result (a healthy ethanol industry) will take a concentrated, organized effort to develop three key elements:

1a. Public acceptance and support of ethanol as a fuel or fuel component;

1b. A stable, commercial-sized local market for the product; and

1c. Economically sound local ethanol production facilities using locally-produced feedstocks.

These elements are listed in the order in which they may be expected to occur, since

- The goal is local production of ethanol using locally-produced feedstocks.
- However, investors will not be interested in investing in local ethanol production facilities unless there is a local market.
- And, it will not be possible to develop a local market for the product without public support and acceptance of ethanol as a fuel.

a. Public education

Public acceptance of ethanol as a fuel will be essential in politicians' as well as retailers' willingness to support ethanol or ethanol blended fuel. Therefore, one of the first activities for the promotion of the use of ethanol as a fuel or fuel component is public education. The sooner this is accomplished, the sooner the other elements may occur.

An ethanol education program established within the state may facilitate communication with and between schools, the university, industry, and the legislature regarding the use and production of ethanol. Several veterans of ethanol and oxy-fuels programs suggest being proactive ("ahead of the curve") in educating the public, mechanics, and gasoline retailers. Hawaii is fortunate in that information is available from the 44 states in which ethanol blends are sold.

b. Mandates

1) State fleet ethanol use requirement

All State owned vehicles powered by gasoline fuel could be required to use gasoline containing ethanol.

2) Ethanol blending requirement

There appears to be a significant amount of concern and support for the local agricultural sector. A proposal that would support local agriculture – but that would not cost motorists any extra – may be successful. The acceptability of a mandate may be increased if it only focuses on mid-grade and premium gasolines (thus giving the public a choice). If these are the targeted grades, the price protection provisions of the mandate may not have to be as stringent, since only "luxury" grades are affected.

Success of this proposal would be dependent upon a knowledgeable, supportive public (see recommendation above for public education) and a program which is structured to protect against increased costs to motorists.

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APPENDICES

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REFERENCES

Alexander, A. G. 1984. *Energy Cane as a Multiple-Products Alternative.* Hawaii Natural Energy Institute Symposium Paper No. 2.

Alexander, A.G. 1982. *Production of Sugarcane and Tropical Grasses as a Renewable Energy Source.* Final Report to the U.S. Department of Energy. DOE/ET/20071--T5.

Alexander, A.G. 1985. *The Energy Cane Alternative.* Sugar Series #6. Elsevier Science Publishing Co., Inc. New York, New York. pp. 1- 479.

Alexander, Alex. 1982. *Report to U.S. Department of Energy, Production of Sugarcane and Tropical Grasses as a Renewable Energy Source.*

Alexander, Alex. 1986. *Evaluating Varieties as Sugar and Biomass Co-Production Systems.* Inter-American Sugar Cane Seminars. Miami , Florida.

American Society of Mechanical Engineers. *Thermodynamic Data for Biomass Materials and Waste Components.* Sponsored by the ASME Research Committee on Industrial and Municipal Wastes.

Analysis of Composition of Solid Waste for Kauai County (1992).

Antal ,Michael. 1992. Hawaii Natural Energy Institute, University of Hawaii, Personal Communication.

ARKENOL Inc. Concentrated Acid Hydrolysis. "History, Technology and Projects," corporate publication, 1993.

ARKENOL Inc. View Graph copies presented to PICHTR. April, 1993.

ARKENOL Inc., Mark Carver, 23293 S. Pointe Dr., Laguna Hills, CA 92653. Personal Communication, May 13, 1993.

Atkinson, B., F Mavituna, (1983), "Ethanol (Raw Materials)," in Biochemical Engineering and Biotechnology Handbook, The Nature Press, 1015:1030.

Atlas of Hawaii. (1973) University of Hawaii Press, R. W. Armstrong, editor.

Bagley, M. H. and W. K. Hashimoto. (1990) "Energy Inventory of Hawaiian Sugar Plantations — 1989." *Energy Report 29, Experimental Station, HSPA*, September 1990.

Barnes, A. C. (1974) "The Sugar Cane." *The World Crop Series.* Leonard Hill Books, International Textbook Company Limited, London.

Barrier, J. W., M. R. Moore, and J. D. Broder. "Integrated Production of Ethanol and Co-Products from Agricultural Biomass." *Tennessee Valley Authority Biomass Program,* Muscle Shoals, Alabama, April, 1986.

Becker, E.W. "Nutritional Properties of Microalgae: Potentials and Constraints." (1986) *Handbook of Microalgal Mass Culture.* CRC Press, Inc. Boca Raton, Florida. pp. 339-419.

Beguin, P. (1990) "Molecular Biology of Cellulose Degradation," in Annual Review of Microbiology. Vol. 44: 219-48.

Bergson, P. W. et al, (1989) "Dilute Acid Hydrolysis of Biomass for Ethanol Production," in Energy from Biomass and Wastes (D. L. Klass, ed.) Institute of Gas Technology, Chicago, 1277:1296.

BioEnergy International, Project Information.

Bioenergy International, 1901 N.W. 67th Place, Suite E, Gainesville, FL 32606. Personal Communication, August 3, 1992.

BIOENERGY. "Ethanol from Biomass Technology." View Graph copies presented to PICHTR. May 14, 1992.

BIOENERGY. Fact Sheet (1992).

Biological Science. (1986) W.W. Norton & Company, Publisher.

Broder, J. D. and J. W. Barrier. "Producing Ethanol and Coproducts from Multiple Feedstocks." *Tennessee Valley Authority*, Muscle Shoals, Alabama, for the International Summer Meeting of the American Society of Agricultural Engineers, Rapid City, S. D., June 26-29, 1988.

Broder, J. D., J. Wayne Barrier and M. M. Bulls. "Producing Fuel Ethanol and Other Chemicals from Municipal Solid Wastes." Tennessee Valley Authority Biotechnical Research Dept., Muscle Shoals, Alabama, Prepared for the 1991 International Summer Meeting of The American Society of Agricultural Engineers, June 1991.

Bulls, M.M., T.M. Shipley, J.W. Barrier, R.O. Lambert and J.D. Broder. "Comparison of MSW Utilization Technologies — Ethanol Production, RDF Combustion, and Mass Burning." Tennessee Valley Authority Biotechnical Research Dept., Muscle Shoals, Alabama, Presented at the Southern Biomass Conference, Baton Rouge, Louisiana.

Buzzanell, P., F. Gray, R. Lord, and W. Moore. *Sugar and Sweetener– Situation and Outlook Report."* (1992) Commodity Econ. Div., Econ. Research Service, U.S. Department of Agriculture, December 1992, SSRV17N4.

C. Brewer & Co., Ltd. "Feasibility Study for Hilo Coast Processing Company Pepeekeo, Hawaii 11.4 Million Gallon per Year Motor Fuel Grade Ethanol Plant" Vol. 1, Honolulu, HI, May, 1981.

C. Brewer and Company, Ltd. 1981. *Feasibility Study for Hilo Coast Processing Company. 11.4 Million Gallon Per Year Motor Fuel Grade Ethanol Plant.*

Carver, Mark. (1993) General Manager, ARKENOL Inc. response to questionnaire. August 1993.

Ceferri, Orio, and Tiboni, Orsola. 1985. "The Biochemistry and Industrial Potential of Spirulina." *Annual Review of Microbiology.* Vol. 39: 503-526.

Chen, Charles S., etal. 1980. *Hawaii Ethanol from Molasses Project - Final Report.* Report to the U.S. Department of Energy under Contract No. DE-AC03-79ET23141. April 1980.

Chereminisoff et al. 1976. *Woodwastes Utilization & Disposal.* Technomic Publishing Company, Inc. Westport.

Clausen, E. C. and J. L. Gaddy. 1987. "The Production of Chemicals and Fuels by Acid Hydrolysis and Fermentation of MSW," in *Biotechnological Advances in Processing Municipal Wastes for Fuels and Chemicals*, Noyes Data Corporation 387:405.

Clausen, E. C. and J. L. Gaddy. 1989. "Ethanol from Biomass by Concentrated Acid Hydrolysis and Fermentation" in *Energy from Biomass and Wastes* (D. L. Klass, ed.) Institute of Gas Technology, Chicago, 1319:1342.

Clausen, E.C. and J. L. Gaddy, 1987. "The Production of Chemicals and Fuels from Municipal Solid Waste," in *Global Bioconversions*, Vol. II, Donald L. Wise, Ed. CRC Press, Inc. Boca Raton, Fla. 62:73.

Cohen, Zvi, et. al. 1987. "Fatty Acid Composition of Spirulina Strains Grown Under Various Conditions." *Phytochemistry.* Vol. 26.

Congressional Research Service Issue Brief Number 93009, updated 01/01/94.

Crabb, T. 1994. Personal communication.

Cysewski, G. R. and C. R. Wilke. 1974. "Rapid Ethanol Fermentations employing Cell Recycle and Vacuum Fermentations" Biotechnol. Bioeng. 18: 1297.

Cysewski, G. R. and C. R.Wilke. 1974. "Fermentation Kinetics and Process Economics for Production of Ethanol." Lawrence Berkeley Lab. Report, 4480, March 1976.

Dale, B. and M. Holtzapple. "Technical Summary of Ammonia Freeze Explosion." Report, Dept. of Chem. Engineering, Texas A&M University, March 1989.

Dale, B. E. 1983. "Biomass Refining: Protein and Ethanol from Alfalfa." *I&EC Product Research & Development,* 1983, vol. 22, p. 446.

Dale, Bruce E. 1983. Biomass Refining: Protein and Ethanol from Alfalfa. *I&EC Research and Development.* 22, 466.

Delta-T Corporation. 1992. "Ethanol Production." 212 Fairfax Way, Williamsburg, VA 23185.

Department of Business and Economic Development. 1989. *Hawaii's Sugar Industry and Sugarcane Lands: Outlook, Issues and Options.* State of Hawaii, April, 1989.

Department of Business, Economic Development & Tourism. 1991. *The State of Hawaii Data Book – A Statistical Abstract.* 1991.

Department of Planning and Economic Development. 1981. *Hawaii's Sugar Industry – Problems, Outlook and Urban Growth Issues.* April 1981.

Derrickson , William B., President, Quadrex, personal communication, May 21, 1992.

Derrickson, W.B. and D.E. Fowler. "Ethanol from Biomass Technology." Presented to Pacific International Center for High Technology Research, May 14, 1992.

East-West Center Program on Resources: Energy and Minerals. 1993. *Fossil Energy in Hawaii.* Report prepared for the State of Hawaii, Department of Business, Economic Development, & Tourism.

Electric Power Research Institute. 1980. AP-1712. "Test and Evaluation of Methanol in a Gas Turbine System."

Ensminger, M.E., and C.G. Olentein (1978) *Feeds and Nutrition.*

Falkehag, Ingemar. 1975. "Lignin in Materials." Printed in *Proceedings of the Eighth Cellulose Conference*. Applied Polymer Symposia, No. 28.

Farone, Dr. William. 1994. Correspondence with Dr. Robert Shleser dated March 26, 1994.

Fowler, David B., Managing Director BIOENERGY. Letter to Andrew Trenka, V.P. PICHTR, Aug. 3, 1992.

Fuels & Transportation Division. 1991. "Properties of Alcohol Fuels: Alcohol Fuels Reference Work #1." Meridian Corporation, 4300 King Street, Alexandria, VA, prepared for Biofuels Systems Division, Office of Alternative Fuels, U.S. Department of Energy, July, 1991.

Gavett, E. E. 1989. "The Economics of fuel Ethanol: A Comparison of Three Major Studies" in *Energy from Biomass and Wastes* (D. L. Klass, ed.). Institute of Gas Technology, Chicago, 1235:1243.

Goldstein, I. S. and J. M. Easter. "An Improved Process for Converting Cellulose to Ethanol." *Technical Association of Pulp and Paper Industry Journal*, August, 1992, 135-140.

Gorden, M., et al. 1989. "Feasibility of The Production of Fuel and Co-Products from Biomass." *Report to the Fifteenth State Legislature in Response to House Concurrent Resolution No. 85, H.D. 1 Urging Continued Research into Programs for the Development of New Energy Systems and Sources which could Replace Petroleum Fuels, thereby lowering the Cost of Energy Required by Sugar Factories and Field Equipment.* Prepared for Department of Business and Economic Development, State of Hawaii, 1:40.

Gordon, J., Jiminez, M., Cooney, C., and Wang, D. 1978. "Sugar Accumulation During Enzyme Hydrolysis and Fermentation of Cellulose." *Biochemical Engineering: Renewable Resources.* No. 1981. Vol. 74: 91-7.

Gowan, M. 1987. "Cane Energy Utilization Symposium." A Report from the 2nd Pacific Basin Biofuels Workshop, Vol. II: Presented papers, Bioenergy Systems and Technology Project, 936-5709, RONCO Consulting Corp., LAC-5709-C-00-5067-00, April, 1987.

Grethlein, H.E. and T. Dill. 1993. "The Cost of Ethanol Production from Lignocellulosic Biomass – A Comparison of Selected Alternative Processes." *Final Report to the U. S. Department of Agriculture, Agricultural Research Service*, under Specific Cooperative Agreement No. 58-1935-2-050, April 30, 1993.

Grethlein, H.W. and T. B. Nelson. 1992. "Projected Process Economics for Ethanol Production from Corn." *Final Report under Agreement No. 58-1935-2-020, July 17, 1992 to the United States Department of Agriculture, Agricultural Research Service*. North Atlantic Area, Eastern Regional Research Center, Philadelphia, Pennsylvania.

Hartfield, S. and R. Hester. 1993. "Separation of acid and sugar by ion exclusion chromatography, An application in the conversion of cellulose to ethanol." *Proceedings, First Biomass Conference of the Americas*. Burlington, Vermont. August, 1993: 1078-1083.

Hawaii Natural Energy Institute. 1980. *Hawaii Ethanol From Molasses Project. Phase I - Final Report.*

Hawaiian Sugar Planters' Association. 1978. "Approximate Composition of Sugarcane and Leaf Trash on Dry Weight."

Hawaiian Sugar Planters' Association. Personal communication, 1994.

Hawaiian Sugar Planters’ Association. 1991. 1992. *Hawaiian Sugar Manual*. HSPA, 99-193 Aiea Heights Drive, Aiea, Hawaii, 96701.

Hawaiian Sugar Planters’ Association. *Energy Inventory of Hawaiian Sugar Factories -- 1980*. Unpublished HSPA data for calendar year 1981. D. Murata and C. M. Kinoshita. 1981.

Hawaiian Sugar Planters’ Association. *Energy Inventory of Hawaiian Sugar Plantations -- 1981*. Unpublished HSPA data for calendar year 1981. C. M. Kinoshita. 1982.

Hawaiian Sugar Planters’ Association. *Energy Report 19*. Unpublished HSPA data for calendar year 1982. C. M. Kinoshita. September 1983.

Hawaiian Sugar Planters’ Association. *Energy Report 21*. Unpublished HSPA data for calendar year 1983. C. M. Kinoshita. November 1984.

Hawaiian Sugar Planters’ Association. *Energy Report 22*. Unpublished HSPA data for calendar year 1984. C. M. Kinoshita. December 1985.

Hawaiian Sugar Planters’ Association. *Energy Report 23*. Unpublished HSPA data for calendar year 1985. C. M. Kinoshita. December 1986.

Hawaiian Sugar Planters’ Association. *Energy Report 24*. Unpublished HSPA data for calendar year 1986. C. M. Kinoshita. December 1987.

Hawaiian Sugar Planters’ Association. *Energy Report 26*. Unpublished HSPA data for calendar year 1987. M. H. Bagley, W. K. Hashimoto, and C. M. Kinoshita. February, 1989.

Hawaiian Sugar Planters’ Association. *Energy Report 27*. Unpublished HSPA data for calendar year 1988. M. H. Bagley and W. K. Hashimoto. December 1989.

Hawaiian Sugar Planters’ Association. *Energy Report 29*. Unpublished HSPA data for calendar year 1989. M. H. Bagley and W. K. Hashimoto. September 1990.

Hawaiian Sugar Planters’ Association. *Energy Report 30*. Unpublished HSPA data for calendar year 1990. M. H. Bagley and W. K. Hashimoto. November 1991, revised February 1992.

Hawaiian Sugar Planters’ Association. *Energy Report 31*. Unpublished HSPA data for calendar year 1991. L.A. Jakeway, M. H. Bagley, and W. K. Hashimoto. October 1992.

Hawaiian Sugar Planters’ Association. *Energy Report 32*. Unpublished HSPA data for calendar year 1992. W. K. Hashimoto and L.A. Jakeway. July 1993.

Hayes T. D. and H. R. Isaacson. 1987. “New Concept for the Production of High-BTU Gas from Anaerobic Digestion,” in *Biotechnological Advances in Processing Municipal Wastes for Fuels and Chemicals*, Noyes Data Corporation 355:374.

Hester, R. D., S. Hartfield, and G. E. Farina. 1993. “A process for separating acid - sugar mixtures using ion exclusion chromatography.” *Proceedings, Tenth International Symposium on Alcohol Fuels.* Colorado Springs, Colorado. November, 1993: 716-723.

Hildebrand, C. “Preliminary Report on Waste Streams State Wide for 1993.” Department of Business, Economic Development and Tourism, State of Hawaii, August, 1993.

Hirakami, M. General Electric. 1992. Correspondence with Roy Mushrush, used with permission.

Holtzapple, M. 1988. “Conversion of Grass to Highly-Digestible Animal Feed, Protein Concentrate, and Ethanol.” Report, Dept. of Chem. Engineering, Texas A&M University, June, 1988.

Hubbard, H. and C. M. Kinoshita. 1993. *Investigation of Biomass for Energy Production on Molokai.* Hawaii Natural Energy Institute. Report, September 1993.

Jakeway, Lee, HSPA. 1993 correspondence with Shleser, Robert A.

Jee, H., Yano, T., Nishio, N. and Nagai, S. 1987. "Biomethanation of H_2 and CO_2 by Methanobacterium thermoautotrophicum in membrane and ceramic bioreactors." *Journal of Fermentation Technology.* No. 4. Vol. 65: 413-18.

Katzen, R. 1990. "Ethanol from Ligno-Cellulose Utilization of Agricultural and Forest Residues." *Raphael Katzen Associates International, Inc., Cincinnati, OH*, Prepared for the Agro-Industrial Revolution Conference, June 24-27, 1990. Washington, DC.

Keany, Francis. 1994. Personal communication.

Keim, Carroll R. Personal communication, April 1994.

Kinoshita, C. K. 1988. "Composition and processing of burned and unburned cane in Hawaii." *International Sugar Journal*. Volume 90, Number 1070.

Kinoshita, C. K. and Staackmann, M. 1994. "Hawaii Energy Strategy Development Project 5: Transportation Energy Strategy." Hawaii Natural Energy Institute input to Parsons, Brinckerhoff, Quade and Douglas, Inc. under subcontract.

Kinoshita, Charles M. 1990. *Cogeneration in the Hawaiian Sugar Industry.* A publication of the Hawaii Natural Energy Institute for the Office of Energy of the United States Agency for International Development / Tennessee Valley Authority, through a subcontract from the Hawaiian Sugar Planters' Association. Contract No. TV-73595A.

Kossen, N. W. F. (1986) "The Characteristics of Immobilized Cell Particles," in *Process Engineering Aspects of Immobilized Cell Systems* (C. Webb, G. M. Black, and B. Atkinson, eds.), 103.

Kung, L. and Stanley, R. W. 1982. "Effects of Stage of Maturity on the Nutritive Value of Whole-Plant Sugarcane Preserved as Silage" *Journal of Animal Science.* November 1982.

Larson, David G. Market survey of newspaper prices from Hawaii. Personal communication, 1991.

Madson, P. W., and J. E. Murtagh. "Fuel Ethanol in USA: Review of Reasons For 75% Failure Rate of Plants Built." Raphael Katzen Associates International, Inc., Cincinnati, OH. International Symposium on Alcohol Fuels — Firenze '91.

Materassi, R. et. al. (1986) "Some Consideration on the production of Lipid Substances by Microalgae and Cyanobacteria" in *Algae Biomass.* pp 619-626. Elsevier/North Holland Biomedical Press.

Merriam, B. 1994. Personal communication.

Messing, R. and R. A. Shleser, "A Two Stage BioReactor Using Microporous Matrix For Conversion of Organic Waste to Pure Methane," NSF SBIR Phase I Final Report Aquacultural Concept Inc., Hawaii, Nov. 1986.

Michigan Biotechnology Institute. Descriptive material on the Michigan Biotechnology Institute provided by Jeff Lievense, Ph.D., September, 1993.

Mok, William Shu-Lai and Antal, Michael Jerry. 1992. "Uncatalyzed Solvolysis of Whole BIomass Hemicelluloase by Hot Compressed Liquid Water." *Hawaii Integrated Biofuels Research Program, Final Subcontract Report Phase III.*

Moon, G. D., J. R. Messick, C. E. Easley, B. S. Sheoff, J. C. Haban, W. W. Kline, H. W. Hicks, and R. Katzen. (1978) "Grain Motor Fuel Alcohol Technical and Economic Assessment Study." Raphael Katzen Associates. AN493 Dec. 31, 1978. *Report to DOE Contract No. EJ-78-C-01-6639.*

Nanguneri, S. R. and R. D. Hester. 1990. "Acid/Sugar separation using ion exclusion chromatography resins, a process analysis and design." *Separation Science and Tech*. 25, 1829-42.

Ng, T. K., Bassat, A., and Zeikus, J. G. 1981. "Ethanol production by thermophilic bacteria: fermentation of cellulosic substrates by cocultures of Clostridium thermocellum and Clostridium thermohydrosulfuricum." *Applied and Environmental Microbiology*. No. 6, Vol. 41:1337-43.

Ng, T. K., Weimer, P. J., and Zeikus, J. G. 1977. "Cellulolytic and physiological properties of Clostridium thermocellum." *Arch. of Microbiology.* Vol. 114: 1-7.

Ng, T. K., Zeikus, J. G. 1982. "Differential metabolism of cellobiose and glucose by Clostridium thermocellum and Clostridium thermohydrosulfuricum." *Journal of Bacteriology.* No. 3. Vol. 150:1391-9.

Numan, R. P., S. R. Rudge, and M. R. Ladish. 1987. "Sulfuric acid-sugar separation by ion exclusion." *Reactive Polymers*, 5: 55-61.

Osgood, R. 1994. Personal communication.

Osgood, R. V. and Dudley, N. S. 1987. "Comparative Yield Trials with Tree and Grass Energy Crops in Hawaii: a Preliminary Report on Current Research" report 88-04 of *Cane Energy Utilization Symposium Proceedings*.

Osgood, Robert V. and Dudley, Nicklos S. 1993. *Comparative Study of Biomass Yields for Tree and Grass Crops Grown for Conversion to Energy.* Final report from the Hawaiian Sugar Planters' Association under State of Hawaii contracts 18817, 20033, 22823, 27626, and 32116 from September 1985 to November 1993.

Osgood, Robert. 1993. Hawaiian Sugar Planters' Association, personal communication.

Pacific Resources, Inc., correspondence, 1990.

Paszner Technologies, Inc. Dr. Laszlo Paszner, 2683 Parkway Drive, Surrey, B.C., V4P 1C2 Canada, Description of the ACOS Process. Technical Literature, 1993.

Paszner Technologies, Inc., Dr. Laszlo Paszner, 2683 Parkway Drive, Surrey, B.C., V4P 1C2 Canada. Description of the ACOS Process. Personal communication. November 20, 1993.

Paszner, L. et al, 1986. "High-Yield Organosolv Process for Conversion of Cellulosic Biomass to Ethanol" in *Energy from Biomass and Wastes* (D. L. Klass, ed.), Institute of Gas Technology, Chicago, 1279: 1318.

Paszner, Laszlo. Paszner Technologies, Inc., response to questionnaire, November 1993.

Paturau, J. M. (1989) "By-products of the Cane Sugar Industry (an introduction to their industrial utilization)." Sugar Series #11. Elsevier Science Publishing Co., Inc. New York, New York.

Peterson, J. N. and B. H. Davison. "Modeling of an Immobilized-Cell/Three-Phase Fluidized-Bed Bioreactor." *Applied Biochemistry and Biotechnology,* Vol. 28/29, 1991, pp. 685-697.

Phillips, V. 1994. Personal communication.

Plucknett, D. L., O. R. Younge, T. Izuno, Y. N. Tamimi, S. M. Ishizaki. (1972) "Sorghum Production in Hawaii." University of Hawaii, Hawaii Agricultural Experiment Station, Research Bulletin 143. April 1972.

Prebluda, H. J. et al, 1981. "Perspectives on the Economic Analysis of Ethanol Production from Biomass" in *Biomass as a Nonfossil Fuel Source* (D.L. Klass, ed.), American Chemical Society Symposium Series, 144:199.

Raphael Katzen Associates International, Inc., Cincinnati, OH. 1987. "Grain Motor Fuel Alcohol Technical and Economic Assessment Study." *Prepared for U.S. Department of Energy, Office of Technical Programs Evaluation.* Washington, DC. under Contract No. EJ-78-C-01-6639, December 1978.

Reed, R. H. 1983. "Blue-green Algae: Prospects and Perspectives." *Plants and Soils.* Vol. 89.

Richmond, A. 1986. "Microalgae of Economic Potential." in *Handbook of Microalgae Mass Culture.* CRC Press, Inc. Boca Raton, Florida. pp. 199-243.

Roberts, R.R. and H.W. Hilton. 1988. "Sugarcane Bagasse as a Potential Source of Ethanol and Methanol Biofuels," *Final Report of the Feasibility and Production of Alcohol Fuels from Sugarcane Bagasse Project*, Prepared for the Department of Business and Economic Development, State of Hawaii, 1:53.

Roberts, Robert. 1979. HSPA/HNEI *Alcohol Production from Molasses - Selection of Efficient Yeast Strains.* HNEI- 79-04.

Rockwell, P. J. 1976. "Single Cell Proteins from Cellulose and Hydrocarbon,." in *Economic Potential of Single-cell Protein.* Noyes Data Corp., Park Ridge, New Jersey. pp. 125-36.

Seki, A. 1982. "Biomass Resource Potential for Selected Crops in Hawaii." Hawaii Natural Energy Institute, University of Hawaii at Manoa, 2540 Dole Street, Holmes Hall 246, Honolulu, HI 96822. June, 1982.

SERI. "Yeast Metabolism of Xylose." *Science & Technology Brief*, Solar Energy Research Institute, Golden, CO., Biofuels/6, 1985.

Shigeta, Diane. Alexander and Baldwin. Personal communication, 1990.

Shleser, R., Messing, R . 1987. "Bioreactor Systems for Production of Methane and Ethanol," *NSF SBIR Phase II Grant Proposal*, Aquacultural Concept Inc., Hawaii.

Sloane, George. 1979. HSPA/HNEI *HSPA Molasses and Alcohol Stillage Characterization Project - Final Report.* HNEI- 79-03.

Smith, G. A., M. O. Bagby, R. T. Lewellan, D. L. Doney, P. H. Moore, F. J. Hills, L. G Campbell, G. J. Hogaboam, G. E. Coe and K. Freeman. 1987. "Evaluation of Sweet Sorghum for Fermentable Sugar Production Potential." *Crop Science*, Vol. 27, No. 4, pp. 788-793, 1987.

StakeTech, Program Description. Stake Technology Limited, 2838 Highway 7, Norval, Ontario, Canada, L0P 1K0, 1993.

State of Hawaii, Department of Business, Economic Development & Tourism, *DATA BOOK 1992*, table 556.

Stuart, Dorsey, President Neugenesis, 2800 Woodlawn Drive, Honolulu, Hawaii 96822, personal communication.

Swain, R. L. 1987. "Molecular Sieves – A New Option for Ethanol Dehydration." *Alcohol Outlook,* December 1987.

Swain, R. L. 1988. "Ethanol Dehydration Technology: State of the Art." National Alcohol Fuels Meeting and Exhibition, Washington, DC, May 16-18 1988.

Swain, R. L. Bibb, P.E., president, Delta-T Corporation, Personal communication, March 25, 1992.

Szmant, H. H. 1986. *Industrial Utilization of Renewable Resources - an Introduction.* Technomic Publishing Company, Inc. Lancaster, PA. pp. 1-188.

Taylor, John D. June 3,1993, questionnaire response from StakeTech.

Tigney Technology Inc. "A Technical Analysis of Partitioning and Transformations of Sugarcane Bagasse and Leaves by the Tigney Refinery System." Prepared for the Hawaiian Sugar Planters Association, Aiea, Hawaii, January 28, 1991.

Tsao, G. T. 1987. "Ethanol and Chemicals from Cellulosics in Solid Wastes," in *Biotechnological Advances in Processing Municipal Wastes for Fuels and Chemicals,* Noyes Data Corporation 375:386.

Tshiteya, R. et al. 1991. *Properties of Alcohol Transportation Fuels. Alcohol Fuels Reference Work #1.* Prepared by Meridian Corporation for the U. S. Department of Energy.

U. S. Department of Energy. *Alternative Fuels Data Center Update.* Spring 1994. Volume 3, Issue 1.

"U.S. Market Fuel Ethanol." *New Fuels Report*. April 18, 1994. Volume 15, Number 6.

Unisyn Bioconversion Technology. 1991. "An Inventory of and Potential Uses for Organic Waste in Hawaii." Report to the Department of Business and Economic Development, State of Hawaii, June 1991.

VanDillewijn, C. 1952. *Botany of Sugarcane*.

Vaughn, S. R., R. M. McDonald, P. E. Donnelly, N. A. Hendy, and R. A. Mills. (1984) "The Biomass Refinery as a Route to Fuel Alcohol from Green Crops." *Proceedings Communications,* Vol. III, May 21-25, 1984, Ottawa, Canada, C-34, PP. 26-32.

Whitesell, C. D., D. S. DeBell, T. H. Schubert, R. F. Strand and T. B.Crabb. (1992) "Short-Rotation Management of *Eucalyptus:* Guidelines for Plantations in Hawaii." *Pacific Southwest Research Station*, Albany, California, November 1992.

Wiegel, J., Ljungdahl, L. G., and Rawson, J. R. (1979). "Isolation from soil and properties of the extreme thermophile Clostridium thermohydrosulfuricum." *Journal of Bacteriology.* No. 3, Vol. 139:800-10.

Wright , J D. 1989. "Evaluation of Enzymatic Hydrolysis Processes," in *Energy from Biomass and Wastes* (D. L. Klass, ed.) Institute of Gas Technology, Chicago, 1247: 1276.

Wright, J. D. 1988. "Economics of Enzymatic Hydrolysis Processes," Prepared for the National AlChE Meeting 6-10 March 1988, New Orleans, SERI/TP-231-3310, UC Category: 246 DE88001134, 1:47.

Wright, J.D., et al. 1988. "Simultaneous Saccharification and Fermentation of Lignocellulose" in *Applied Biochemistry and Biotechnology*, The Humana Press Inc., 75:90.

Wyman, C. E., and N. D. Hinman. 1990. "Ethanol - Fundamentals of Production from Renewable Feedstocks and Use as a Transportation Fuel" in *Applied Biochemistry and Biotechnology*, The Humana Press Inc., 24/25, 735:753.

Yost, J. G. and K. Hahn. 1993. "Ethanol Production from Mixed Waste Paper: A Pre-Feasibility Study." Economic Research Associates, for the Nebraska Energy Office, March 1993.

Yu, Ernest, Vice President, Stake Technology Limited. 1993. Cost Estimates of Corn Stover-to-Alcohol Plant. Facsimile Transmissions, February 12, 1993 and March 1, 1993. Norval, Ontario.

Zeikus, J.G. 1980. Chemical and Fuel Production by Anaerobic Bacteria. *Annual Review of Microbiology.* Vol. 34: 423-64.

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