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The anticipated depletion of our resources of natural gas and petroleum in a few decades has caused us to look for renewable sources of fuel. Among the possibilities is the chemical conversion of waste and grown organic matter into gaseous or liquid fuels. The overall feasibility of such a system is considered from the technical, economic, and social viewpoints. Although there are a number of difficult problems to overcome, this preliminary study indicates that this option could provide between 4 and 10 percent of the U.S. energy needs. Estimated costs of fuels derived from grown organic material are appreciably higher than today's market price for fossil fuel. The cost of fuel derived from waste organics is competitive with fossil fuel prices. Economic and social reasons will prohibit the allocation of good food - producing land to fuel crop production.

E-8463

INTRODUCTION

Since the early 1970's, it has become increasingly apparent that the known sources of natural gas and petroleum cannot meet the growing demand for these sources of energy. Thus, there has been a serious concern for developing renewable energy sources to relieve the severity of the anticipated shortfall. Among the suggested possibilities is the conversion of waste or grown organic matter to liquid and gaseous fuels. Such a proposal has received serious study by a number of independent organizations as reported in Ref. 1. Within the Federal Government, programs have been initiated to assess the technical feasibility and economic viability of this means of producing liquid and gaseous fuels. Until the formation of the new Energy Research and Development Agency (ERDA), most of this government effort was managed, or coordinated, by the National Science Foundation. This paper summarizes a preliminary study effort conducted at the Lewis Research Center and completed in 1975. The study was coordinated with the general solar energy program (Project RANN) of the National Science Foundation, which included feasibility assessments of bioconversion as an energy source.

A more comprehensive reporting of our study is contained in Refs. 2 and 3. Reference 3 reports the contractural effort of the Ohio Agricultural Research and Development Center of Wooster, Ohio whose contribution to this paper is gratefully acknowledged.

Figure 1 is a depiction of the overall system considered in this study. The sun is represented as the origin of all the energy that is stored in the grown or waste organic materials which can be chemically-converted to liquid or gaseous fuels. Tracing the flow diagram of Fig. 1 shows that the immediate organic harvests from photosynthesis can be blended with organic wastes at the point of "Conversion." In this paper, we present estimates of the annual magnitude of both these sources of organic material. Such estimates depend strongly on assumptions about the feasibility of collecting waste and the allocation of land for growing a crop. While these estimates are highly speculative, they lend some insight into the quantitative possibilities of such a system for impacting the nation's future fuel supplies. No estimates of crop yields from aquaculture are included.

Figure 1 shows a common conversion process for all of the sources of organic feedstock. Such systems are sensitive to the nature of the organic feedstock they are handling. Thus, cyclic changes in the character of the organic feedstock to a conversion plant could be an operational problem. In this paper, only two types of conversion systems are considered because of their advanced development: anaerobic digestion and pyrolysis. Some comparisons between the two processes are drawn on the basis of current technology.

We do not limit our discussion of the overall system or its components to purely technological issues. Where appropriate, social and economic issues are introduced. In fact, for any type of energy source, all of these issues must be considered in a system's evaluation. We will present preliminary cost estimates for fuel converted from waste and grown organics. These estimates were developed in Ref. 2. It is important to recognize that the economic information about the cost of growing and converting organic matter to fuel is preliminary and requires demonstration experience for verification. Nevertheless, a preliminary examination is valuable in determining whether a demonstration should be ventured.

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We will begin this preliminary assessment with an estimate of the yearly supply of organic material for conversion to fuel.

SOURCES OF ORGANIC MATERIAL

All suitable sources of waste (agricultural, urban, and industrial) will be included, but only soil crops will be part of the grown organic category.

Waste. It is difficult to make an accurate estimate of the amount of organic waste available in the contiguous United States. One published estimate by Anderson (Ref. 4) is summarized in Table I. Two columns are shown: one is an estimate of a "total potential" and the other is an estimate of "readily available" or collectable amounts of organic waste. These data can be interpreted as a maximum and minimum estimate of waste organic matter. The as-received energy value ranges from approximately 1.5×10^{18} joules (1.4×10^{15} Btu) per year to 9.5×10^{18} joules (9.0×10^{15} Btu) per year. In 1971, the U. S. consumed approximately 72×10^{15} Btu per year, so the energy equivalent of the waste is very significant.

Grown. Depending on land availability, rainfall, climate, productivity, and economic factors, agriculture and silviculture could provide as much as, or more than, the amount of organic matter derived from waste. Agriculture or silviculture (tree farming) can be regarded as a means of converting solar energy into biomass through photosynthesis. (The same can be said for algae or plants grown in water.) In this process, radiant energy assists in the chemistry of fixing the carbon from the carbon dioxide of the atmosphere.

The ultimate theoretical efficiency of the conversion of total incident radiation by photosynthesis is estimated to be about 5.3 percent in Ref. 5, p. 92. For food agriculture in this country, the average efficiency falls far short of that figure - less than 1 percent. Translated in terms of yield per acre of a crop such as corn, the harvest amounts to about 13.5 to 22.4 metric tons of biomass per square hectometer-year (6 to 10 short tons/acre-yr) in the United States. Demonstrations of advanced agriculture have exhibited efficiencies in excess of 2 percent. This could amount to yields of approximately 44.8 to 67.2 metric tons per square hectometer-year (20 to 30 short tons/acre-yr) in the United States. Such a yield is realized through intensive cultivation and fertilization and is not a part of wide-spread agricultural practice anywhere in the United States. The Ohio Agricultural Research and Development Center extensively surveyed the biomass yields of various crops throughout the world. A few sample yields are given in Table II for grasses, tuberous and root crops, and cereals. Kenaf, which is frequently cited as an energy crop, shows yields of 18.5 to 29.2 metric tons per square hectometer-year (8 to 13 short tons/acre-yr). Expected progress in agricultural science such as genetics, holds promise for even greater yields per unit of land per year. With regard to improving the magnitude of plant yield it should be pointed out that agricultural science has been devoted to maximizing the protein yield of the plant species and not necessarily the cellulose production by the plant. In fact, little research has been pursued to maximize the biomass production of a plant during the growing season. It is possible that larger payoffs in biomass production could be realized if a research program devoted to this type of agriculture were instituted.

The total yields of grown biomass per year also depend on the total acreage that can be devoted to this enterprise. In view of the acute shortages of food and fiber throughout the world, it is becoming more and more difficult to find productive land that is not already in use. In fact, land once considered semimarginal in the United States is now being considered for food agriculture. Figure 2 is a 1965 United States Department of Agriculture inventory (Ref. 6) of cultivatable land and necessary water for 10 regions of the country. As is evident from the bar chart at the left of Fig. 2, almost one-half of rural land has unfavorable soil or adverse climate. It is not clear how much of the unfavorable land could be made productive.

Table III is a breakdown of land use in the United States according to information by the United States Department of Commerce, gathered in 1969 (Ref. 7). It seems possible that some of the grazing land could be used for a fuel crop. Also, selective species of trees or shrubs could be planted in some of the forest land, and their growth could be harvested at regular intervals as a valuable source of cellulose. There are approximately 303 million square hectometers (750 million acres) of forest land in this country, of which 206 million square hectometers (500 million acres) are classified as commercial timberland. According to Ref. 7, approximately 27 million square hectometers (67 million acres) are privately owned by producers of commercial wood products. Suppose that an equal acreage were dedicated to producing trees exclusively as a source of fuel. According to table II, the biomass yield for slash pines and sycamores grown in Southeastern USA ranges from 10.3 to 16.35 metric tons per square hectometer-year (4.6 to 7.3 short tons/acre-yr) of dry biomass. Assuming the heating value of a metric ton of biomass is 15.5×10^{9} joules, 27 million square hectometers (67 million acres) would produce the biomass equivalent in heating value of 4.3×10^{18} to 6.8×10^{18} joules per year (4.1×10^{15} to 6.5×10^{15} Btu/yr).

Generally, the financial return on fuel crop per acre would be substantially below that of a food crop just because of market conditions. According to Ref. 3, a representative 1974 open-market value of a metric ton of the total corn plant (including kernels) was \$52.36. On an energy basis, the value of a ton of corn biomass would be approximately \$3.50 per million Btu's. Obviously the cost of the raw biomass alone far exceeds the cost of any of the liquid or gaseous fuels used today. Such a price for a food crop precludes its competitiveness as feedstock for conversion to fuel on the open market. According to some economic studies performed by the Ohio Agricultural Research and Development Center (Ref. 3), the forseeable inflationary spiral of fertilizer and tractor fuel costs would discourage farmers from becoming involved in fuel crop production. However, a future national policy could conceivably subsidize fuel crop production and thus override the economics of a competing free market.

It seems clear that efforts in agriculture or silviculture to produce fuel crops will not develop spontaneously under current market conditions. In contrast, it seems to be certain that waste will become a viable source of organic materials for fuel conversion or direct burning.

ENERGY POTENTIAL

The combined potential of organic waste and a "grown" source of organic matter from 27 million square hectometers (67 million acres) of forest crops constitutes a sizable nondepleting energy source. From the "collectable" estimate in Table I and the lowest estimate of the annual biomass yield from 27 million square hectometers (67 million acres) of forest, the total energy equivalence is $(4.3\times1.47)\times10^{18}$ joules per year $= 5.8\times10^{18}$ joules per year (5.5×10^{15} Btu/yr). As the other extreme of this estimate, we will sum the total potential of organic waste with the largest anticipated harvest of grown biomass from the 27 million square hectometers (67 million acres) of forest land. The resulting total is $(6.8 + 9.5)\times10^{18}$ joules per year $=$ 16.3×10^{18} joules per year (15.5×10^{15} Btu/yr). The ranges of these estimates correspond to 7.5 to 21 percent of the 1971 United States consumption of energy. This estimate reflects the as-received heating value of the dry organic material. If it were converted to a gaseous or liquid fuel, the energy equivalence of the fuel would be approximately one-half these values, or 4 to 10 percent of United States energy consumption. For easier comparison, these estimates are summarized in Table IV. Potentially then, the combination of waste and grown organics could provide a significant segment of the United States energy consumption.

In considering the energy potential of a grown source of biomass, the question arises regarding the comparison of energy output to the energy input required to produce the crop. In Ref. 3, this question was studied. The results of the study revealed that the ratio of the energy content of the harvest to the energy input varies from 12 for corn to 25.3 for slash pines. Conversion of the biomass to gaseous or liquid fuels will reduce the energy output-input ratio by at least the conversion efficiency. Thus the energy content of the fuel will be approximately 6 to 12 times the energy used to farm the crop.

CONVERSION PROCESSES

In the INTRODUCTION, it was mentioned that we would consider just two conversion processes - fermentation (anaerobic digestion) and pyrolysis. These processes will be discussed briefly in this section.

Fermentation. It has been recognized for many years that organic matter can be converted to more useable forms by fermentation. The principal fermentation products that have been considered for fuel use are methane, ethyl alcohol, and hydrogen. At the present stage of development, the conversion to methane by anaerobic fermentation appears a viable route to pursue for efficient energy extraction.

Anerobic fermentation - the action of various microorganisms upon organic matter in the presence of water and in the absence of oxygen - produces primarily methane and carbon dioxide gas. The methane is insoluble in the reacting mixture and may be readily removed and collected. The carbon dioxide and other impurity gases may be scrubbed from the mixture so that nearly pure methane gas is readily attainable.

Such fermentation processes have been known for a long time and have been in use for many years for treating domestic sewage (see Buswell, Ref. 8). The goal in these applications to date has been in the reduction of the volume of solids and of the biological oxygen demand of the waste. The goal for efficient energy extraction would be to maximize the production of fuel gases at a minimum cost.

As discussed previously, essentially two types of organic material have been considered as possible feedstocks for conversion to methane by the biological process: organic wastes and specially grown crops. While the anaerobic digestion process would be essentially the same for either type of feedstock, there are some differences worth recounting. The waste feedstock will be variable in composition with time. The microbial population may not rapidly adapt to such changes. The possibility of toxic material in wastes could cause problems in digester behavior. Also, the possibility of a buildup of toxic material in the resultant sludge that must ultimately be disposed of, must be considered. The specially grown crop feedstock should not have these problems. The relatively constant feed composition should make digester control easier. The resultant sludge should be an ideal fertilizer since it will be feeding back much of the same inorganic elements it extracted from the soil during growth.

The established technical feasibility of the production of methane by anaerobic fermentation needs to be supplemented both by engineering data and economic analyses of those systems that hold promise of contributing significantly to our gaseous fuel requirements.

Anaerobic fermentation to methane as an industrial process (or on an industrial scale) today is carried out only in treatment of various types of wastes such as municipal sewage and some animal (see Steffen, Ref. 9) and vegetable wastes. There is no effort beyond batch operation of laboratory scale digesters for using specially grown crops as a feedstock.

Current operating practice for digesters consists of a set of empirical rules concerning such items as organic and hydraulic loading rates, uniformity of loading, temperature control and pH control. These factors are discussed in Refs. 10-14. Empirical procedures have been developed for the startup of digesters and for the recovery of digesters that have failed or are on the verge of failure. One of the greatest problems is the early detection of impending process failure so that proper control measures may be applied to prevent failure. The restarting of a failed digester requires considerable time.

Pyrolysis. Pyrolysis is basically the thermal decomposition of large organic molecules into smaller molecules, principally CH_4, CO, and H_2 as is described by Shafizadeh (Ref. 15). The organic molecule cellulose first decomposes to levoglucosan, which in turn breaks into smaller hydrocarbons, hydrogen, carbon oxides, alcohols and ketones. If these products are exposed to oxygen at high temperature, combustion takes place. For example, in the combustion of wood, the overall process comprises three stages: pyrolysis of cellulose, diffusion of gaseous pyrolysis products, and finally the oxidation of the pyrolysis products. Thus, in order to recover the pyrolysis products as fuels, it is important that the cellulose molecules be heated and decomposed in an oxygen-free or oxygen-poor (partial combustion) atmosphere so that the products are not immediately and totally consumed by combustion. Various processes have been developed to accomplish a non-combustive pyrolytic decomposition. The process heat is supplied from external thermal sources or is recuperated from the pyrolysis reaction.

The technology of pyrolysis is well-developed and commercial installations for waste disposal are in operation. Not much is known yet about fuel conversion operations in a pyrolytic reactor. Some experience reported by Mallan and Finney (Ref. 16) showed that solid organic waste was converted to char (18 percent), gas (26 percent) and oil (48 percent) in those mass-fraction percentages. The oil is refineable into the general classes of petroleum products.

Pyrolytic reactors needed for fuel conversion would have to possess much larger capacities and improved efficiencies over existing commercial units. In large scale units, designers will have to contend with such problems as feed systems, bed geometry, operational stability, and maximum recuperation of thermal energy.

Comparison of Fermentation and Pyrolysis. Actual experience with the two processes reveals that fermentation is superior with regard to energy efficiency, and environmental impact. Pyrolysis offers the advantages of being less expensive for initial plant cost and the process is more responsive to controls and can be programmed to produce liquid, gaseous and solid fuels in varying proportions. The fermentation process produces gaseous fuel only. The inherent advantages of each conversion process makes it likely that both will have a useful place in the conversion of organics to fuel.

ESTIMATED COST OF FUEL FROM ORGANICS

A cost estimate has been made (1974 dollars) in which the principal cost items have been included. The principal assumptions, cost data, and method of analysis are described in Ref. 2. It turns out that the dominant cost for the grown organic conversion is the feedstock itself. From data in Ref. 3, the feedstock cost \$36 per metric ton or \$2.16 per million Btu's. Other items, such as plant cost, operation, transportation, insurance and taxes, etc. are less influential. For waste organic feed, generally the waste comes free except for the expense of collecting it and separating it. These handling costs are the more significant in setting the output fuel cost for waste conversion. The estimated fuel costs for waste and grown organic feed converted in a pyrolytic reactor are \$0.77 and \$5.09 per million Btu's, respectively. If fermentation conversion is used, the fuel from waste would cost \$2.76 per million Btu's and the fuel from grown organics would cost \$7.08 per million Btu's. Obviously, the fuel derived from grown organics is expensive compared to today's (1976) fuel costs. However, the fuel from waste is cost-competitive. These fuel costs must be interpreted as preliminary estimates based upon the best existing information. A demonstration program would be required to verify these estimates.

OVERALL EVALUATION

This preliminary study has considered several factors of a technical and non-technical nature, that influence an overall opinion regarding the viability of a system to produce fuel from solid organic feedstocks. Reference 3, by Roller, et al. is a comprehensive study about the possibility of growing the organic feedstock. They are negative in their appraisal of such a possibility. In the summary of Ref. 3, the authors state: "The conclusion is drawn that climate, land availability and economics of agricultural production and marketing, food demand, fertilizer shortage and water availability all combine to cast great doubts on the feasibility of producing grown organic matter for fuel, in competition with food, feed or fiber, on U.S. acreages."

In Ref. 2, it is suggested that silviculture on some of the existing forest acreage might be a source of grown organic feedstock and would have minimum impact on the land used in food production now or in the future. Kemp, et al. (Ref. 17) have proposed forest plantations as a source of fuel for large (1000 MW) electric power plants.

Less controversial is the utilization of agricultural, industrial, and domestic waste as a conversion feedstock. However, crop residues are used to replenish soil organic matter and prevent erosion. According to Ref. 6 only Class I land can sustain semi-continuous crop residue removal without seriously impairing the agricultural value of the land. From Department of Agriculture estimates, Class I land comprises 5.5 percent of non-Federal rural land in the United States (Ref. 3).

Before a conclusive judgment can be made about the possible use of a grown source of organic feedstock in fuel conversion, a demonstration phase experience must be tried to test its viability. Inasmuch as it appears very likely that organic waste will be converted to fuel, such available facilities can be used to convert grown organics also. Use of existing conversion equipment will enable the complex systems comprising agriculture, collection transportation and distribution to interface. Reliable operational and economic data would result from such an operation.

Estimates of the collectable waste and the silviculture harvest derived from 67 million acres (arbitrarily selected for estimate purposes) indicate that these sources could provide a fuel output which is roughly 4 to 10 percent of the energy consumed in the United States during 1971 (see table IV). This is not an insignificant magnitude. Furthermore, the source of the fuel is essentially renewable for the grown source and the collection of waste is an energy-recovery measure. This appreciable potential source of clean (sulfur-free) fuel possible from a combination of grown and waste organics matter suggests that a demonstration size system should be evaluated.

REFERENCES

1. "Inventory of Current Energy Research and Development," Report prepared for Subcommittee on Energy of Committee on Science and Astronautics, U.S. House of Representatives, 93rd Congress, by Oak Ridge National Laboratory and National Science Foundation, vol. 1, pts. 1 and 2, Jan. 1974.

2. Graham, R. W., Reynolds, T. W., and Hsu, Y. Y., "Preliminary Assessment of Systems for Deriving Liquid and Gaseous Fuels from Waste or Grown Organics," NASA TN D-8165 (1976).

3. Roller, W. L., et al., "Grown Organic Matter as a Fuel Raw Material Resource." NASA CR-2608 (1975).

4. Anderson, L. L., "Energy Potential from Organic Wastes: A Review of the Quantities and Sources," U.S. Bureau of Mines, Invest. Circ. 8549 (1972), p. 131.

5. Sci. Amer. 225, No. 3 (1971).

6. "Soil and Water Conservation Needs - A National Inventory," U.S. Dept. Agriculture Misc. Publ. No. 971 (1965), p. 5, fig. 4.

7. Statistical Abstracts of the United States 1974, U.S. Department of Commerce, Bureau of Census, 1974.

8. Buswell, A. M., "Production of Fuel Gas by Anaerobic Fermentation," Ind. Eng. Chem. 22, No. 11, 1168 (1930).

9. Steffen, A. J., "Waste Disposal in the Meat Industry (A Comprehensive Review of Practice in the United States)," Pure Appl. Chem. 29, 173 (1972).

10. McCarty, P. L., "Anaerobic Waste Treatment Fundamentals. 1," Chem. Microbiol. 95, No. 9, 107 (1964).

11. McCarty, P. L., "Anaerobic Waste Treatment Fundamentals. 2," Environ. Requir. Cont. 95, No. 10, 123 (1964).

12. McCarty, P. L., "Anaerobic Waste Treatment Fundamentals. 3," Toxic Mater. Contr. 95, No. 11, 91 (1964).

13. McCarty, P. L., "Anaerobic Waste Treatment Fundamentals. 4," Process Design 95, No. 12, 95 (1964).

14. Pfeffer, J. T., "Reclamation of Energy from Organic Refuse," Illinois University (PN-23117619; EPA-670/2-74-016) (1974).

15. Shafizadeh, F., Advances in Carbohydrate Chemistry, M. L. Wolfram and R. S. Tipson, eds., Academic Press, N. Y., 1968, pp. 419-474.

16. Mallan, G. M. and Finney, C. S., "New Techniques in the Pyrolysis of Solid Waste," Am. Inst. Chem. Engrs., 73rd National Meeting, Minneapolis, 1972.

17. Kemp, C. C., Szego, G. C., and Fraser, M. D., "The Energy Plantation," J. Appl. Polymer Sci., Appl. Polymer Symposia No. 28, 11 (1975).

TABLE I. - ESTIMATES OF ORGANIC WASTE IN UNITED STATES

[From Bureau of Mines Information Circular 8549, Ref. 4.]

	Total potential	Readily available
Yield, tons/yr:		
Agricultural and food wastes	390×10^6	22.6×10^6
Animal wastes	200×10^6	26.0×10^6
Urban wastes	129×10^6	71.0×10^6
Logging and wood manufacturing residue	55×10^6	5.0×10^6
Industrial wastes	44×10^6	5.2×10^6
Municipal sewage solids	12×10^6	1.5×10^6
Miscellaneous organic wastes	50×10^6	5.0×10^6
Total yield, millions of tons/yr	880×10^6	136.3×10^6
Total energy content (as received), J/yr (Btu/yr)	9.49×10^{18} (9×10^{15})	1.47×10^{18} (1.4×10^{15})
Converted high-energy gas volume, m^3 (ft^3)	1500×10^8 (5300×10^9)	230.7×10^8 (815×10^9)
Energy content of gas, J/yr (Btu/yr)	4.6×10^{18} (4.4×10^{15})	7.4×10^{17} (0.7×10^{15})

TABLE II. - ANNUAL BIOMASS YIELDS OF SEVERAL CROPS

[From Ref. 3.]

Crop	State	Number of years of data	Total plant yield	
			Metric tons per hectare-year	Short tons per acre-year
Corn, kernels	Ohio	5	-----	-----
	Iowa	4	-----	-----
	Georgia	4	-----	-----
Alfalfa, whole	Ohio	4	13.66	6.1
	Indiana	4	13.65	6.1
	Wisconsin	(a)	-----	-----
Kenaf, stems	Maryland	5	18.52	8.3
	Florida	6	29.19	13.0
Kenaf, aerial	Indiana	3	20.83	9.3
Napier grass, whole	Puerto Rico	1	42.3	19.0
Slash pine, wood and	Southeastern	(a)	15.75	7.05
bark	United States	(a)	10.30	4.6
Potatoes, tuber	Maine	(a)	6.62	2.95
	Michigan	4	9.15	4.08
	Idaho	(a)	11.04	4.90
Sugar beets, roots	Kansas	2	16.72	7.5
	California	2	15.29	5.8
Sycamore, aerial	Georgia	1	16.35	7.3

[a]No years specified.

TABLE III. - SUMMARY OF LAND USE IN UNITED STATES

[Departments of Commerce 1969 data; from Ref. 7.]

Type of land	Amount of land	
	hm^2	Acres
Farmland:		
Cropland including idle cropland and cropland used for pasture	155.5×10^6	384×10^6
Pasture grassland	218.6	540
Forest and woodland (not pasture)	20.2	50
Farmsteads and other land	11.3	28
Woodland pasture	25.1	62
	430.7×10^6	1064×10^6
Land not in farms:		
Grazing land	116.6×10^6	288×10^6
Forest land	192.3	475
Other land (urban, roads, parks)	176.9	437
	485.8×10^6	1200×10^6
Available land which could be used in agriculture:		
Grazing land	116.6×10^6	288×10^6
Forest land not grazed	192.3	475
	308.9×10^6	763×10^6

TABLE IV. - ESTIMATED ENERGY CAPABILITY OF WASTE AND GROWN ORGANIC MATERIALS

	Energy content of organic matter			Energy content in fuel, converted efficiency = 0.5	
	Waste	Grown	Total	Total	Fraction of U.S. energy consumption, %
Minimum	1.5×10^{18}	4.3×10^{18}	5.8×10^{18}	2.9×10^{18}	4
Maximum	9.5×10^{18}	6.8×10^{18}	16.3×10^{18}	8.2×10^{18}	10
	Energy data in J/yr			Based on 1971 consumption	

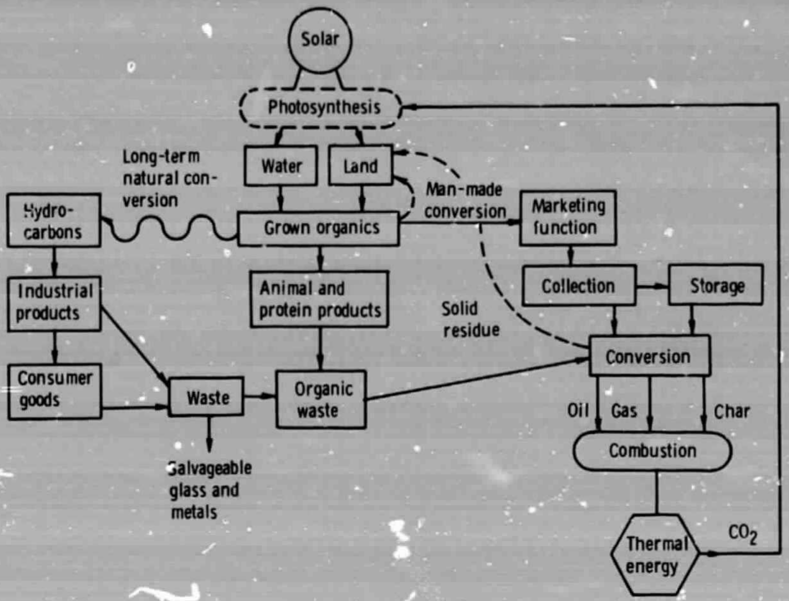

Figure 1. - Diagram of principal elements in system for producing clean fuel from organic matter.

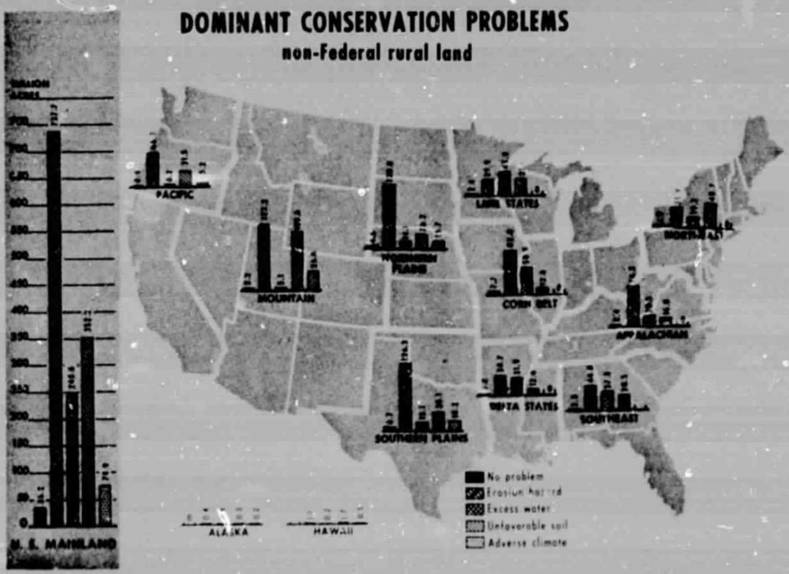

Figure 2. - Inventory of land capabilities for 10 regions of U. S. mainland, Alaska, and Hawaii. (From ref. 6.)

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