A LONG-RANGE APPROACH TO THE NATURAL GAS SHORTAGE UTILIZING NONFOSSIL RENEWABLE CARBON

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INTRODUCTION

The production of substitute natural gas (SNG) from petroleum liquids, coal, and oil shale to alleviate the natural gas shortage has received considerable developmental effort. Commercial SNG processes based on these fossil feeds will undoubtedly play important roles in the future of the U.S. gas industry and help to maintain it as a methane marketer over the next few decades. But fossil feeds for the production of SNG are still finite natural resources, and ultimately depletion will occur. A very promising long-range practical solution to this problem is to convert a major source of continuously renewable nonfossil carbon to SNG.[1,2]

One source of nonfossil carbon that has been considered is organic wastes.[3] The growing environmental and pollution problems caused by the generation of organic wastes in the United States provides an opportunity to combine improved waste-disposal technology, for recycling valuable waste components into the economy, with energy recovery in the form of SNG. Table 1 summarizes the results of a recent study to survey the various types of organic wastes generated in the United States and the amounts that are collected and available for conversion to synfuels.[4] At SNG yields per ton of dry waste of 10,000 cubic feet, about 8.8 trillion cubic feet of SNG could be produced each year if all of the wastes could be processed. This is obviously not possible; all of the wastes could not be collected for this purpose even if laws were passed requiring total collection and a concerted effort were made to achieve it. However, if total collection did occur, the amount of SNG that could be produced would still fall far short of the U.S. annual demand for natural gas, which is currently about 24 trillion cubic feet. Organic wastes offer a significant source of supplemental synfuels, but are not the total answer to fossil fuel depletion. Another source of nonfossil renewable carbon must be utilized.

The most promising source of this carbon is water- and land-based biomass produced from ambient carbon dioxide and solar energy by photosynthesis.[1,2] Biomass is defined as all growing organic matter, such as plants, trees, grasses, and algae, and, in a real sense, is perpetually renewable. The production of SNG from low-cash-value, high-fuel-value biomass would offer a major, controllable, nonpolluting, storable source of fossil fuel substitutes. It has been estimated that 146 billion tons of biomass, most of which is wild and not controlled by man, is produced on the earth each year,[5] so at the same SNG yield used for organic wastes above, about 1.6% of this amount of biomass would provide enough raw material to meet all of our natural gas demand. With the advanced state of U.S. agricultural practice, it is conceivable that the conversion of solar energy to SNG via biomass could be achieved to establish what might be called "A Perpetual Methane Economy."

The concept of A Perpetual Methane Economy reduces itself to the development of suitable methods for planting, growing, harvesting, transporting, and converting biomass to SNG. The purpose of this paper is to review the important factors related to the development of this concept. Although liquid fuels and syncrudes can also be produced from biomass,[2] they are not included in the review.

Table 1. ESTIMATES OF AVAILABLE ORGANIC WASTES, 1971

Source	Total Organic Wastes Generated	Organic Solids Available
	10^6 tons/yr	
Manure	200	26.0
Urban Refuse	129	71.0
Logging and Wood Manufacturing Residues	55	5.0
Agriculture Crops and Food Wastes	390	22.6
Industrial Wastes	44	5.2
Municipal Sewage Solids	12	1.5
Miscellaneous Organic Wastes	50	5.0
Total	880	136.3
Net Oil Potential, 10^6 bbl	1098	170
Net Gas for Fuel Potential, 10^{12} CF	8.8	1.36

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SYSTEM DESIGN

The overall design of a biomass-to-SNG system depends on several parameters such as the type, size, number, and location of the biomass growth and processing areas. In the ideal case, the SNG production plants would be located in or near the biomass growth areas to minimize the cost of transporting the harvested biomass to the plants, all the nonfuel effluents of which are recycled to the growth areas. If this kind of "synfuel plantation" could be developed, it would be equivalent to an isolated system with inputs of solar radiation, air, carbon dioxide, and minimal water, and one output, SNG. A schematic design of such a system is depicted in Figure 1. The nutrients are kept within the ideal system so that the addition of external fertilizers and other materials is not necessary. Also, the environmental and disposal problems are eliminated.

Onsite production of synfuel from the biomass would be facilitated in land-based synfuel plantations and near water-based growth areas where the natural water currents might function as a transport vehicle for the biomass to move it to the conversion plant sites. The gasification plants would be strategically located onshore with respect to biomass supply, recycling, and SNG transmission or transportation facilities.

The achievement of optimum system designs will be necessary to make the manufacture of SNG from biomass a commercial reality. The scope and size of commercial SNG plantations alone will demand careful planning and total integration of each operation because any errors in design will result in operating difficulties that can seriously affect the continuity of production, efficiencies, and economics.

The risks in such a large venture will have to be minimized by evolutionary development in a logical sequence of steps, such as system synthesis, preliminary analysis, small-scale demonstration, second-stage analysis, moderate- to large-scale demonstration over a prolonged time period, final analysis and system optimization, and full-scale commercialization. The business and political problems associated with each system cannot be overlooked either, because any new industry of

this magnitude will undoubtedly have its quota of skeptics among those who can benefit from the technology. The development program must produce the information needed to prove the viability of the concept beyond any doubt.

BIOMASS PRODUCTION

In the last few decades, the production of biomass for foodstuffs applications has been significantly improved through the use of modern techniques and equipment. Higher yields and more nutritious strains of crops have been developed as a result of these advanced methods, and much of the information could be applied to the development of low-cash-value, high-fuel-value biomass for SNG production. Also, our basic knowledge of photosynthesis has advanced so that specific biomass crops and growth methods can be optimized together to improve production.

A broad range of biomass production technology is available because the crops can either be land- or water-based. Suitable crops might include certain land-based, high-yield grasses and water-based algae, which can be grown in either fresh water or seawater. The goal of any program undertaken to develop and select the best biomass forms for SNG manufacture is to choose the highest yield, highest fuel-value crops that require minimum labor during planting, growth, and harvesting, and that not only survive but thrive in most climates. Also, it is desirable to use crops that have no large-scale markets as foodstuffs or materials. As expected, no one crop meets all of the desired characteristics, but, fortunately, numerous biomass species meet many of the idealized requirements.

A preliminary assessment of biomass production as it relates to SNG has been performed, and a few in-depth studies are in progress to assist in the selection of optimum biomass forms.[1,6] Some of the important parameters that were studied included biochemical energy transfer classification, solar energy capture efficiency, growth rate and cycles, yields, nutrient needs, water needs, carbon content and fuel value, insolation, temperature, and rainfall. These studies have attempted to quantify the relationship of these parameters and their importance in selecting the proper biomass types and production methods. It is not the purpose of this paper to review this information in detail; instead, the major conclusions will be summarized.

One major conclusion is that it appears sufficient yields of certain plants can be obtained to provide suitable raw material for conversion to large quantities of SNG. Examples of biomass that may prove to be optimum crops include land crops of Sudangrass, napiergrass, sorghum, sugarcane, sunflower, kenaf, and eucalyptus, sycamore, and poplar trees; freshwater crops of water hyacinth and the unicellular algae, Chlorella and Scenedesmus; and seawater crops such as Macrocystis pyrifera (giant kelp). Several of these crops are capable of production at yields of 20 to 30 tons dry organic matter/acre-year, and some have been reported to be produced at yields over 60 tons/acre-year. Also, the fuel values generally range from about 5000 to 8000 Btu/dry lb. These crops are believed suitable for SNG production.

Another important conclusion from these studies is that relatively large areas of land or water are needed to grow enough biomass to supply the U.S. fuel needs. For example, at a yield of 50 tons/acre-year of dry biomass, about 169,000 square miles are required at an overall thermal efficiency of conversion of 35% to SNG to replace all of the U.S. natural gas demand with SNG as indicated in Table 2.[1] This area corresponds to a square 411 miles on each edge and might be considered to be a major roadblock to commercialization of a biomass-to-synfuel industry. But, on further examination, it does not seem to be an insurmountable barrier, especially when considered in light of the problem solved. First, this area is about 5.6% of the Lower-48-State area. Idle farmland and deserts comprise about 6.4% of the Lower 48 States now. When compared with the surface areas of the oceans, a small portion of which might be devoted to biomass production, a

411-mile square seems to be an insignificant part of the whole. Also, it is possible to conceive of combined foodstuffs and biomass-for-fuel production, so some growth areas might serve dual functions. In some cases, symbiotic relationships might lead to further improvement in both biomass forms. Finally, it should be realized that the preliminary studies that have been made are based primarily on existing information. Major improvements in yield, fuel value, and other important properties might emanate from field-test programs.

Table 2. POTENTIAL SNG PRODUCTION FROM BIOMASS*

	AVERAGE AREA REQUIRED, sq miles		
PERCENT OF PRESENT DEMAND†	10 ton/acre-yr	25 ton/acre-yr	50 ton/acre-yr
1.66	12,000	5,000	2,800
10	72,000	30,100	17,000
50	361,500	150,500	84,500
100	723,000	301,000	169,000

*Based on indicated dry yields at overall thermal efficiency of conversion to SNG of 35% and fuel value of 6500 Btu/dry lb.

†Calculations based on annual demand of 22×10^{12} cubic feet.

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No field tests of any significant size are yet in progress to optimize biomass production methods and specific biomass crops for SNG manufacture. However, the U.S. Navy has announced plans to begin such a program with giant kelp off the California coast.[7]

BIOMASS CONVERSION TO SNG

Methane can be produced from biomass by digestion, pyrolysis, and hydrogasification as shown in Figure 2. Digestion is a biological process that occurs in the absence of oxygen and in the presence of anaerobic organisms at ambient pressures and at temperatures of 95°to150°F. The biomass is supplied to the anaerobic digesters as a water slurry and is converted to an intermediate-Btu gas (450 to 800 Btu/cubic foot) that is essentially a two-component gas containing methane and carbon dioxide. This product is easily upgraded to pipeline gas (SNG) by removal of carbon dioxide in conventional amine scrubbers or by other methods. IGT's Biogas™ Process (Figure 3) is an example of such processes.[3]

Biomass can also be converted to SNG by pyrolysis. Pyrolysis consists of thermal decomposition of the feed at low pressure in the 900° to 1700°F range. However, the initial product gas is generally a low-Btu gas (100 to 450 Btu/cubic foot) that contains low concentrations of methane and higher concentrations of carbon monoxide, carbon dioxide, and hydrogen. In addition, by-products of char and oxygenated liquids are formed; these are often used to supply the heat for the pyrolysis units. If SNG is the desired end product, the pyrolysis gas must first be adjusted in composition by "shifting" the molar ratio of hydrogen to carbon monoxide in a shift converter to about 3:1, which corresponds to the stoichiometric ratio needed to convert the carbon monoxide to methane in the methanator. The gas is then scrubbed to remove carbon dioxide, and the resulting gas, which contains methane, carbon monoxide, and hydrogen, is methanated to yield SNG. The process developed by West Virginia University for solid-waste pyrolysis should also be suitable for biomass pyrolysis.[8]

In the hydrogasification process, part of the biomass feed is first converted to hydrogen by partial oxidation or steam-reforming followed by shifting to increase the hydrogen content as high as

possible. The hydrogen-rich gas is then reacted with the remaining biomass at 500° to 1500°F and 500 to 2500 psi to hydrogenate it and yield a product gas high in methane. The gas is then upgraded to SNG by shifting, scrubbing, and methanating as in the pyrolysis process.

As might be expected, each of these three processes is not energetically suitable for all types of biomass. Some types of biomass, especially those in the water-based category, usually contain large quantities of intracellular water, as high as 90 to 95%. If this type of feed is pyrolyzed or hydrogasified, the water must be removed before thermal treatment, or a large amount of feed energy is consumed in the process simply in driving off the water before gasification.[1] The curves in Figure 4 illustrate the effect of moisture content on the energy available for conversion of heat-dried biomass to SNG. For example, if a biomass containing 70% moisture is heat-dried to a moisture content of 30%, only 62% of the energy content is available for conversion to SNG. Anaerobic digestion is preferred for those feeds high in moisture because the process requires large amounts of water. Air-drying of biomass is the most economical drying method if it is needed.

Table 3 lists representative examples that have been reported of methane-containing products made from various biomass plants. Available information on actual experimental data is limited because the biomass-to-synfuels concept has only recently begun to receive attention. Only a few research groups are developing data at present, but the data base is expected to expand rapidly in the near future.

Table 3. EXAMPLES OF FUEL GAS PRODUCTION FROM BIOMASS

Biomass	Conversion		Fuel Products[a]
	Reaction	Approximate Conditions	
Pine Bark[9]	Pyrolysis	900°C, ambient pressure	Low-Btu gas, char, oil[b]
Rice Straw[9]	Pyrolysis	200°-700°C, ambient pressure	Low-Btu gas, char, oil[b]
Cellulose (Refuse)[10]	Hydrogasification	540°C, 1000 psi	High-Btu gas (after CO_2), char
Wood (Excelsior), Paper[11]	Digestion	30°C, 30 days	Intermediate-Btu gas
Grass[12]	Digestion	48°C, 10-28 days	Intermediate-Btu gas
Water Hyacinth[c, 12]	Digestion[d]	48°C, 28 days	Intermediate-Btu gas
Seaweed Algae[e, 12]	Digestion	33° and 48°C, 20-50 days	Intermediate-Btu gas
Unicellular Algae[f, 13]	Digestion	35° and 55°C, 30 days	Intermediate-Btu gas

[a]Low-Btu gas, 100-450 Btu/CF; intermediate-Btu gas, 450-800 Btu/CF; high-Btu gas, >800 Btu/CF.

[b]Minor product.

[c]Eichhornia crassipes.

[d]After caustic treatment.

[e]Macrocystis pyrifera; commonly called giant kelp; grown in seawater.

[f]Principally Scenedesmus spp. and Chlorella spp.; grown in fresh water.

ECONOMICS AND ENERGETICS

The economics of biomass conversion to SNG are in a preliminary stage of development. However, some idea of the cost structure can be obtained from existing information. Table 4 illustrates the energy cost of several selected biomass species. With the exception of the edible portion of corn,

whose energy cost was calculated from current market prices, the price range varies from $0.42 to $1.88/million Btu, which places biomass energy in a range competitive with the current costs of fossil fuel energy. Of course, the cost of converting biomass to SNG must be added to the biomass energy costs.

Table 4. SELECTED COST ESTIMATES OF BIOMASS ENERGY

Biomass	Yield, dry tons/acre-yr	Fuel Value, Btu/dry lb	Estimated Cost, $/10^6 Btu
Corn	2.27*	6,500*	9.70†
Corn Silage[15]	15.9	6,500	1.31
Corn Silage[15]	6.5	6,500	1.88
Conifer[15]	–	7,000	1.25-1.75
Poplar[15]	10	7,800	0.90-1.00
Sugarcane[6]	25	7,500	0.63
Kenaf[6]	20	7,500	0.61
Kenaf[6]	6	7,500	1.40
Land or Water Based[1]	20	8,000	0.79-1.46‡
Land or Water Based[1]	50	8,000	0.42-0.87‡
Land Based[6]	30	7,500	0.65

*Assumed values based on current yield and market information.[14]

†Calculated from assumed values and market price of $3.53 per bushel of No. 2 yellow corn (Chicago).[14]

‡Calculated from Table 11 in Reference 1.

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A few cost estimates have been reported on the conversion of biomass to SNG as shown in Table 5. There is a wide diversity of plant sizes, conversion efficiencies, and capital requirements in this particular tabulation, but the SNG price ranges from only $0.73 to $3.50/million Btu. One of the available SNG-from-coal projections is also included in this table for comparison.

An interesting factor in the production of biomass alluded to in Table 4 concerns the energy budget of the system, i.e., the total energy into the system and the product energy returned. Few studies of this type have been made. One of the in-depth studies computed the energy budget of U.S. corn production and included all of the nonsolar energy inputs into the system such as electric power, equipment fuels, and the energy needed to manufacture ammonia fertilizer which is made primarily from natural-gas-derived synthesis gas.[17] Some of the information developed in this study has been converted to thermal energy production efficiency (energy in/energy out) and nonsolar energy input/lb of corn produced and plotted versus year (Figure 5). Less energy was expended to produce a pound of corn in 1940, which means that the energy input is utilized less efficiently today.

This kind of energy budget treatment is directly related to SNG because one of the important factors that has largely been ignored in the development of new energy supplies concerns the net

Table 5. PRELIMINARY COST ESTIMATES OF BIOMASS-DERIVED SNG

Biomass	Biomass Yield, dry ton/acre-yr	Biomass Fuel Value, Btu/dry lb	Gasification Process	SNG Production, CF/day	Area Required, acre	Eff, %[e]	Capital Requirement, $	SNG Cost, $/$10^6$ Btu
Land or Water Based[1]	20	8,000	Digestion	$1.0 \times 10^{9,a}$	3.26×10^6	35	1.6×10^9	1.10-1.77
Land or Water Based[1]	50	8,000	Digestion	$1.0 \times 10^{9,a}$	1.30×10^6	35	0.98×10^9	0.73-1.17
Giant Kelp, Floating[16]	2.8[b]	5,160[c]	Digestion	$3.56 \times 10^{9,d}$	64.0×10^6	70	5.0×10^9	2.48
Giant Kelp, Anchored[16]	49	5,160	Digestion	19.2×10^9	22.4×10^6	62	105×10^9	3.50
Land Based[6]	30	7,500	Air Dry. Pyrolysis	$76.0 \times 10^{6,a}$	89.6×10^3	69	0.325×10^9	2.09
Coal[6]	-	-	Hydro-gasification	250×10^6	-	-	0.350×10^9	1.61

[a]Biomass is assumed to be gasified onsite at growth area; transportation costs of biomass and SNG not included.

[b]Calculated from referenced area of 250 miles x 400 miles in which it was estimated that 80% of kelp is harvested.

[c]Calculated from referenced information which indicates kelp yield of 1.8×10^8 dry tons/yr, conversion of 70% of its energy content to SNG, and SNG yield of 1.3×10^{12} CF/yr.

[d]As liquefied SNG.

[e]Calculated from ratio of energy produced as SNG and fuel value of biomass feed; $100\ E_p/E_f$.

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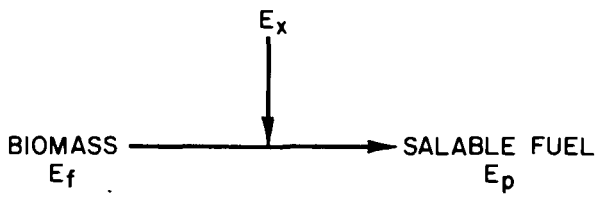
energetics of the system.* Valid comparisons of different systems cannot result from only synfuel cost estimates and capital and operating cost projections; these factors do not necessarily correlate with net energy production. Nor can valid comparisons be made simply by calculating the thermal efficiency or the energy in and out of a process. All of the energy inputs involved in planting, harvesting, transportation, fuel production, and recycling of product streams should be considered. It is essential that these factors be lumped together with economics in the fully integrated system. Since the primary objective is to produce new fuel supplies, more fossil fuel substitutes must be produced as salable end products than the fossil fuels consumed in the system. Even then, the selection of the best of several systems is a difficult one to make.

For example, let E_f, E_x, and E_p represent the energy content of the dry biomass, the sum of the external nonsolar energy inputs into the total system, and the energy content of salable fuels, respectively. Diagrammatically, the system can be represented as follows:



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Then the ratio, $(E_p - E_x)/E_x$, which can be termed the Net Energy Production Ratio, indicates how much more (or less) salable fuel energy is produced than that consumed in the integrated system if the external energy consumed is replaced, and it is assumed that the biomass feed energy is zero. This is a reasonable assumption because the energy value of the biomass is derived essentially 100% from solar radiation. Net Energy Production Ratios greater than zero indicate that an amount of energy equivalent to the sum of the external energy inputs and an additional energy increment of salable fuel are produced; the larger the ratio, the larger the increment. The ratio $100\ E_p/E_f$ is the Fuel Yield Efficiency and is a measure of how much biomass energy is diverted to other than salable fuels in the system. The ratio $100\ E_p/(E_f + E_x)$ is the overall Fuel Production Efficiency of the system.

*The rationale presented here is also applicable to synfuels from fossil feeds.

In Table 6, a comparison of selected end product costs, as either SNG or biomass energy, and the calculated Net Energy Production Ratio for each end product is presented. A correlation exists between these ratios and the biomass energy costs listed, namely, the higher the energy cost, the lower the ratio. However, the corresponding correlation does not apply to the listed SNG cases. The Net Energy Production Ratio is therefore a useful tool when considered together with the energy costs to evaluate synfuel systems and, especially, to bring out the importance of the external energy inputs.

Table 6. COMPARISON OF ESTIMATED END PRODUCT COST AND NET ENERGY PRODUCTION RATIO

Biomass	Conversion Process	Fuel Efficiency Yield, %[a]	End Product	End Product Cost, $/10^6 Btu	Net Energy Production Ratio[b]
Rice (U.S.A.)[18, 19]	None	–	Rice	26.70[c]	0.67 to 0.80[e]
Corn (U.S.A.)[17]	None	–	Corn	9.70[d]	1.82[f]
Giant Kelp, Floating[16]	Digestion	70	LNG	2.48	5.07[g]
Land Based[6]	None	–	Biomass	0.65	17.40[h]
Land Based[6]	Air Dry, Pyrolysis	69	SNG	2.09	2.34[i]
Land or Water Based[20]	Digestion	35	SNG	0.73 to 1.77	3.79[j]

[a] $100\ E_p/E_f$.

[b] $(E_p - E_x)/E_x$.

[c] Average price of $20.00/100 lb and 7500 Btu/dry lb assumed.

[d] From Table 4.

[e] Calculated from References 18 and 19 that state that 1/5 to 1/3 of energy input returned as end product. NEPR = (0.2 – 1.0)/1.0, and (0.33 – 1.0)/1.0.

[f] Calculated from in-depth analysis in Reference 17 for year 1970 that states that 2.82 kcal returned/kcal input: NEPR = (2.82 – 1.0)/1.0.

[g] Calculated from Table 1 in Reference 16 utilizing reported estimate that 16.48% of end product fuel content consumed by system: NEPR = (1.0 – 0.1648)/0.1648.

[h] Calculated from Table 5, p. 51, in Reference 6, using reported estimate that total energy yield for case analyzed was 45 X 10^7 Btu out and 2.45 X 10^7 Btu consumed: NEPR = (45 – 2.45)/2.45.

[i] Calculated from conditions assumed in Reference 6: 5.6% biomass energy content required as energy input in growth phase, 15.0% of biomass energy content required as energy input on gasification, and Fuel Yield Efficiency of 69.0%: NEPR = (0.69-0.206)/0.206.

[j] Calculated from conditions assumed in Reference 20 for waste conversion in which 2.7% of feed energy equivalent required as external energy input on gasification, Fuel Yield Efficiency is 35%, and assuming 5.6% of biomass energy content is required as energy input in growth phase as in Reference 6: NEPR = (0.35 – 0.073)/0.073.

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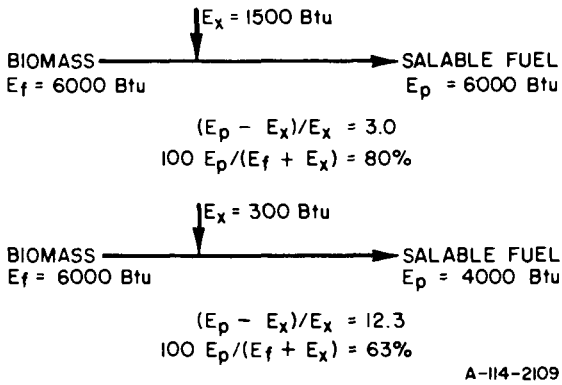
For biomass having an energy content of 6000 Btu/dry lb, a plot of Net Energy Production Ratio versus the total external energy input as a percentage of the feed energy equivalent (100 E_x/E_f) provides the two curves shown in Figure 6 for Fuel Yield Efficiencies of 66.6% and 100%. If the following two systems selected from Figure 6 are compared, which is preferred?

Is the first system preferable because it has a higher Fuel Production Efficiency, or is the second system preferable because it has a higher Net Energy Production Ratio? Consideration of this kind of information in conjunction with economics is necessary to make an intelligent choice. Also, in this simplified treatment, the boundary is not drawn regarding the size of the system. Thus, tractors may be used to plant and harvest biomass. The fuel requirements of the tractors are certainly part of E_x, but is the energy expended in manufacturing the tractors also part of E_x? In-depth studies are necessary to decide these questions.

ENERGETICS OF TWO SELECTED SYSTEMS



SUMMARY

The concept reviewed in this paper to attain A Perpetual Methane Economy by conversion of biomass to SNG is technically feasible. After suitable development, the commercialization of an SNG industry using low-cash-value, high-fuel-value biomass raw materials will probably be economically attractive and permit conservation of our valuable fossil fuel reserves. Since the basic technology is already on hand, large-scale programs to refine the technology and to develop intergrated systems should be started without delay before fossil fuel depletion causes greater energy supply problems.

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FIG. 1. SCHEMATIC DIAGRAM OF BIOMASS-TO-SNG SYSTEM

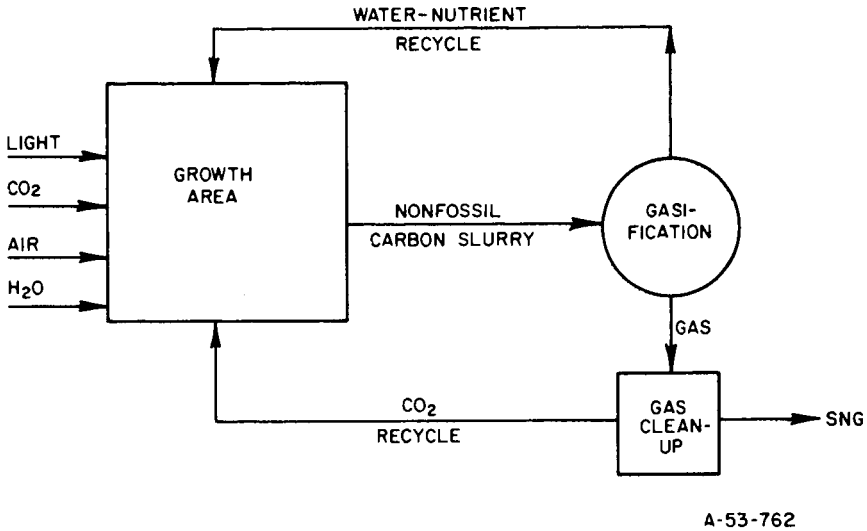

FIG. 2. SCHEMATIC DIAGRAM OF THE THREE PRINCIPAL METHODS OF METHANE PRODUCTION FROM BIOMASS

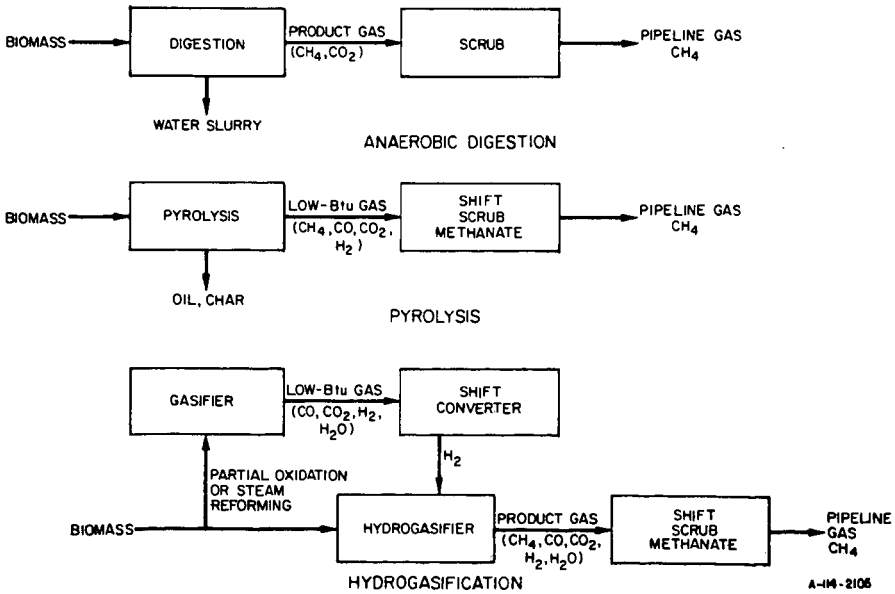

Fig. 3. EXAMPLE OF BIOGAS™ PROCESS DESIGN USING BIOMASS FEEDS

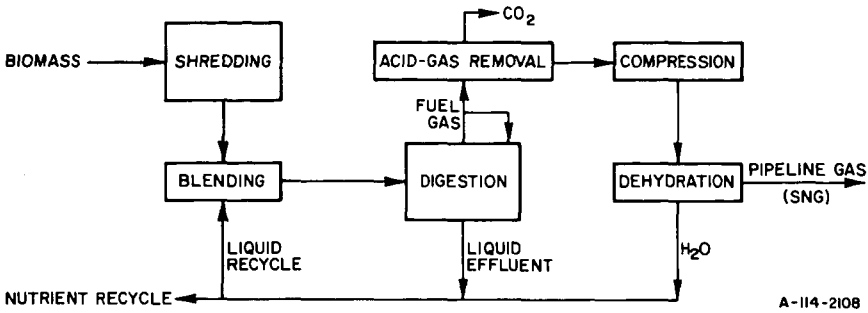

Fig. 4. EFFECT OF FEED MOISTURE CONTENT ON ENERGY AVAILABLE FOR SNG PRODUCTION

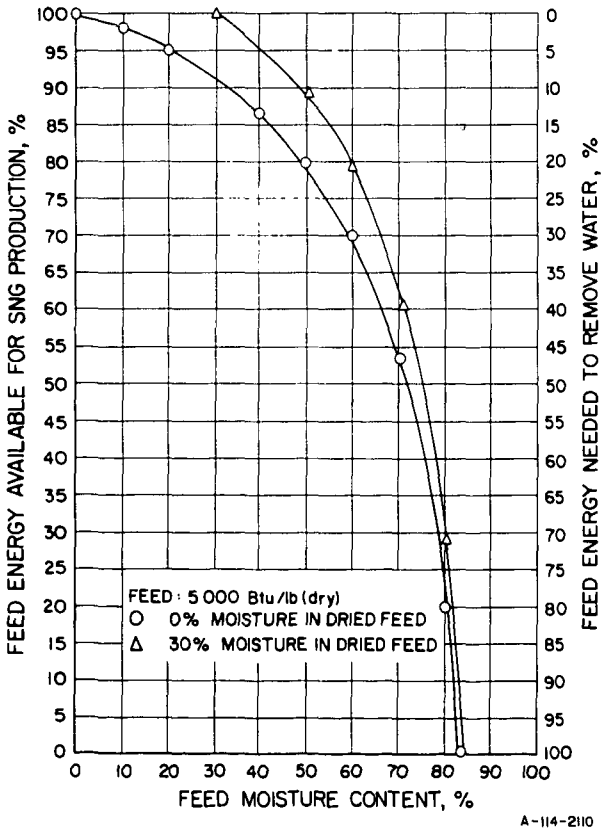

Fig. 5. THERMAL ENERGY PRODUCTION EFFICIENCY AND ENERGY INPUT FOR U.S. CORN FROM 1945 TO 1970

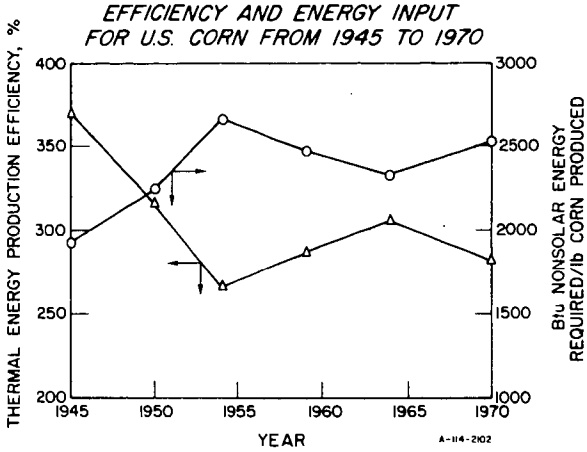
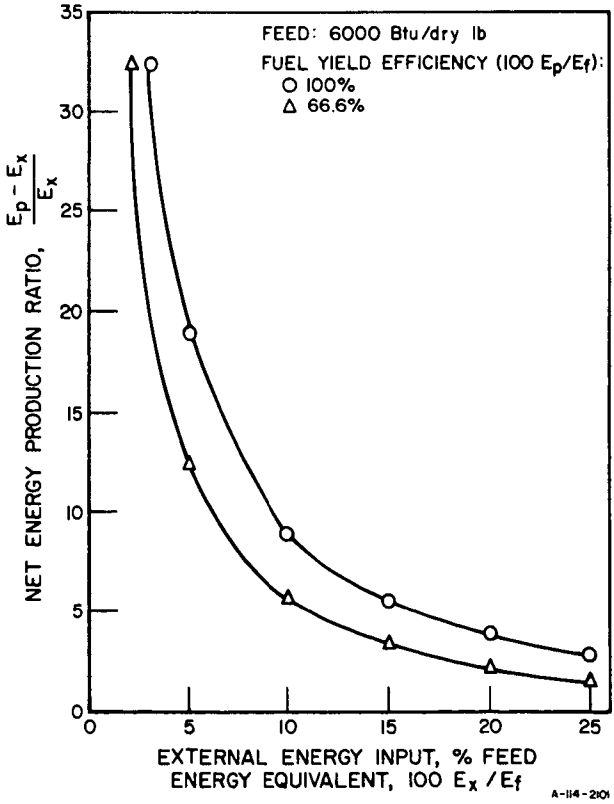
Fig. 6. NET ENERGY PRODUCTION RATIO vs. EXTERNAL ENERGY INPUT