INTERNATIONAL DEVELOPMENT RESEARCH CENTRE

ENERGY FROM BIOMASS FOR DEVELOPING COUNTRIES

Report of the Energy from Biomass Project

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ENERGY FROM BIOMASS FOR DEVELOPING COUNTRIES

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Energy from Biomass for Developing Countries

SUMMARY

Biomass is renewable organic matter, produced by photosynthesis which converts solar energy into stored chemical energy, directly in the case of plants and indirectly in animals whose ultimate food source is plant material.

The first man consumed no more energy than the food he ate. Beginning with the use of fire and animal power, and followed by steam, oil, gas and electrical devices, per capita energy consumption on a world-average basis has increased 14-fold since the days of our primitive ancestors. But the growth rate of per capita energy use has been more than 50 times greater in the highly-developed nations than in the least-developed countries.

The industrial world now relies on fossil fuels for nearly 90% of its energy needs, while 80% of the energy used in developing countries still comes from biomass. The current oil crisis has prompted greatly intensified research into alternative energy sources, including direct sunlight and wind, water and nuclear power, with scant attention to biomass until very recently.

But to the overwhelmingly rural population of the developing world biomass remains a highly desirable, renewable source of energy. The challenge to provide it in suitable form on a sustained basis, and to develop efficient, convenient methods of converting it to energy in order to meet the ever-increasing needs, is an objective of the highest priority.

This paper reviews the current state of the art of energy production from biomass, with particular reference to the developing countries and to the needs of their rural communities. The extent, availability and productivity of different kinds of biomass -

trees, grasses, aquatic plants, and agricultural and animal residues - have been considered, together with their culture, management, harvesting and transportation. Various energy-conversion processes have been examined, from simple combustion and fermentation to the more sophisticated technologies which have as yet very limited relevance to the developing world.

From this appraisal of the potential of biomass for energy production it is evident that improvements in the generation of energy from biomass have been meagre in comparison with progress made in the utilization of commercial fuels. Lacking the support of profit-motivated institutions, sponsorship of donors such as IDRC is essential for sustained, well-focused research to enhance the value of biomass as fuel. Indications are that such research could quickly bring significant results in the form of reasonably-priced energy and increased self reliance to a large segment of the population in developing countries, especially to the rural people.

In addition to improving the utilization of biomass as fuel for the home, recent progress in coal gasification and liquefaction has raised the prospect of establishing medium sized units to manufacture liquid and gaseous fuels from lignocellulosic biomass to supply villages, small towns and industries.

The evaluation of the technical, social and economic implications of these different conversion systems for use in developing countries is recommended.

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ENERGY* FROM BIOMASS** FOR DEVELOPING COUNTRIES

Chapter I

Introduction

Compared with the challenge to secure food, shelter and health care in developing countries, energy needs have received scant attention. The 80% or so of the people who live in rural areas have been able, until recently, to gather fuel for cooking and heating in the nearby forest, or to burn agricultural wastes or dried dung. When it became apparent that non-commercial*** fuels were becoming scarce under the onslaught of a quickly growing population, it was widely assumed that cheap fossil fuels, mostly kerosene, would make up for the shortage.

The 1973 oil embargo and five-fold increase in the cost of fossil fuels dealt a damaging blow to industrialized countries from which they have not yet fully recovered. The catastrophic effect on the economies of oil-poor developing nations has not yet become fully apparent. It is obscured by the sketchy information available on the use of wood and other domestic non-commercial fuels which must be increasingly replaced by other sources of energy.

The shortage of free or cheap fuel has been building up for a long time. Rapid increase in population outpaced freely available wood supply. People searching frantically for anything which would burn, uprooted vegetation near populated centres and hungry goat, sheep and cattle completed the process of transformation into barren land. Mismanagement of forests and indiscriminate land clearing for agriculture has led to a situation where the fuel to cook the food is just as scarce as the food itself.

* Energy is the capacity for performing work.

** Biomass is the total amount of renewable organic matter, whether from plants (phytomass), or animals (zoomass).

*** Commercial energy is used throughout this paper to refer to sources of energy such as coal, oil, gas and electric power which are produced, distributed and sold by corporations and governments rather than by individuals. Non-commercial energy is energy from all other sources, such as fuelwood, crop wastes, dung, and human and animal power. Some authors use "formal sector" and "informal sector" instead of "commercial" and "non-commercial". "Non-commercial" is in fact a misnomer since there are monetary markets for these fuels (11).

The oil crisis highlighted a problem a long time in the making. It also made it clear that we rely too much on fossil fuels, which are lacking in many parts of the world and are being depleted at an increasingly rapid rate. The need to develop and better manage sources of energy which are sustainable and environmentally manageable is now recognized as a matter of extreme importance and urgency.

There is no need to fear a shortage of energy.

Apart from the fossil fuels and fissionable materials stored in the crust of our planet, the sun's radiation which constantly reaches the earth amounts to nearly 1,000 times the present primary energy used by mankind and the pull of the gravity of the moon creates additional energy potential in the form of tides.

Good progress is being made in the techniques of capturing the energy of sunrays for cooking, heating and industrial uses. Recently the generation of electricity from the action of sunrays on photovoltaic cells has shown promise for more widespread industrial application.

The heat of the sun also creates air currents which can be exploited with windmills, and the sun's heat evaporates water which returns to earth in the form of rain or snow and can be harnessed as water power.

The use of the sun's energy in the form of wind and water power has a long history. New research can be built on a solid foundation of knowledge and experience. In a tropical country most of the fuel to cook, to heat and for light is needed after sunset and people do not want to prepare a meal under the mid-day sun. Until simple and inexpensive means are found to temporarily store the radiant energy of the sun, the direct use of this energy source will remain limited.

Hydropower-generated electricity is not easy to deliver to the rural population either. Villages are clusters of a few to many hundreds of houses and most are remote from the generating site. Expensive transmission lines must be built and at least 1/3 of the energy is lost in transit. The cost to deliver the small and intermittent energy requirements in the form of electricity to the rural customer is beyond the reach of most villagers unless heavily subsidized. The World Bank estimated in 1971 that out of a population of 1½ billion in the rural areas surveyed, only 190 million or 12% had access to electricity (96).

Less than 2% of the sun's energy intercepted by plants is converted by the process of photosynthesis* into chemical energy, and is stored in the form of terrestrial and aquatic vegetation for food, feed, fuel and other uses until decomposed by microorganisms into inorganic materials.

The energy captured by photosynthesis is a small percentage of the total sun energy reaching our planet, but the total volume of biomass created is very large when compared with our needs for energy. It has been estimated that present U.S. consumption of energy is about equal to the net annual storage of solar energy in the U.S. biomass system (21).

Biomass is the basis for sustaining all life on this planet. With the discovery of fire a much larger range of biomass became available for food, and biomass has been used too as fuel to bring this transformation about and to keep man warm.

To control and shape his environment and to achieve goals other than those strictly related to survival, man has always searched for new sources of energy. The amount of work one human being can perform is pitifully small by the standards of energy consumption of today.

A hard-working person can deliver the equivalent of one Kwh per day, the energy contained in 125 grams or 0.000125 tonnes of coal (CE 0.000125), and can sustain 67 times that much effort (CE 0.009375) during one year. One way to add to one's muscle power is to control those of others. A widely practiced and exceedingly inhuman application of this technique became the institution of slavery.

*Photosynthesis is the process by which green plants utilize the sun's energy to convert carbon (from the carbon dioxide of the air) and water into wood fibre, leaves, flowers, fruit and seed.

Animals such as horses, camels, bullocks and mules were domesticated to add to the muscle power of man. A horse, walking at the speed of about 4 km/hour can deliver energy equivalent to 1/2 horsepower and can sustain it for 6 hours out of every 24. The daily output is equivalent to the energy contained in 560 grams of coal (= CE 0.0056).

Harrison Brown offers some perspective on energy consumption in human history (28). Let F represent per capita consumption of food energy (about 3,000 kcal/day) and let E represent total per capita consumption of energy. Primitive man, before the use of fire, consumed no more energy than he ate: $E = F$. After fire came into use, primitive man approximately tripled his energy consumption: $E \cong 3F$ (there are parts of the world where this formula remains valid today!). In early agricultural society, according to Brown, $E \cong 4F$. By 1200 A.D., with a world population of 400 million, $E \cong 8F$. By the beginning of this century, consumption had advanced in the industrialized world to $E \cong 25F$. In 1970,

$E \cong$ 83F in the United States;
$E \cong$ 50F in Swden;
$E \cong$ 14F, world average.

In the U.S., the coefficient 83 is divided into 10 for eating and 73 for other purposes.

Per capita energy consumption varies more widely than most other needs of people. Some societies have based their culture on the control of a large amount of energy generated from a vast array of fuels while others mainly depend on their muscle power and that of their draft animals.

The wide variations in energy consumption are illustrated by the following table (86).

Table 1. Per Capita Energy Consumption During 1974, in Kilogram Coal Equivalents

	Kg CE
World	2,050
North America	11,888
Central America	1,236
South America	804
Africa	377
Asian Middle East	944
Asia	516
India	188
U.S.A.	11,960
Canada	11,237

Differences in commercial energy consumption alone are even more extreme. In rural Africa they are about 1/60 of the global average, 1/6 of that of India and only 1/300 of the North American consumption (39).

A factory worker in the U.S. during 1974 used an average of 49,000 Kwh electricity, in effect the energy equivalent of 715 men helping him on the job all year long (53).

There may be some correlation between energy consumption and the quality of life, but it is not a very close one. In 1943 Leslie White, a renowned anthropologist, formulated his "Basic Law of Evolution" according to which: "other factors remaining constant, culture evolves as the amount of energy harnessed per capita per year is increased, or as the efficiency of the means of putting the energy to work is increased" (92). This theory has never been fully accepted by his fellow anthropologists and it is contradicted by many recent developments. The Swedes, who have a higher per capita income than the people of the U.S.A., use only 60% of the amount of energy per person that North Americans use. The total commercial energy consumption of China, with a population of 900 million, is said to be less than what the U.S. with a population of 230 million uses for air conditioning.

Worldwide energy consumption in 1970 was estimated to be the equivalent of 6,650 million tons of coal. About 80% was consumed by the one-third of the world's population who live in industrial countries.

Demand for energy is expected to increase to 10,000 million tonnes CE by 1980 and to reach 27,400 million tonnes CE by the year 2000. At the present time nearly 90% of the energy used in industrial countries comes from fossil fuels, while in the developing world 80% comes from biomass.

With the invention of the steam engine in 1765 by James Watt, in the industrialized countries first coal and then other fossil fuels such as oil, gas and the semi-fossil peat replaced biomass to provide the rapidly increasing energy requirements of industry.

Fossil fuels, including marginal, submarginal, and likely-to-be-discovered fossil resources, are expected to provide only a small fraction of the requirements projected for the end of the century. The handwriting is on the wall, we cannot rely on fossil fuel supplies much longer, and the sooner one switches to renewable fuel sources the better.

In the rural sector of the developing world biomass remains the single largest source of energy, and the challenge to provide the steadily increasing requirements on a sustained basis and in a form in which it can be used efficiently and under good control for the manifold requirements, has become an objective of the highest priority. This study reviews worldwide the "State of the Art" in this field.

For the overwhelmingly rural population of the developing world biomass is a highly desirable fuel. Where people work the land there are biomass fuels available in one form or another and they are mostly free. Using agricultural and animal wastes for fuel fits in well with the many other activities of the farmer, it provides at times a multiple use for his crop instead of only one and helps to keep his environment clean.

The energy needs of the city population are similar to those in industrial countries except that average per capita consumption is much more modest in tropical countries. The decision to secure fuel from a distribution network infers continued commitments which many people are justifiably reluctant to make. Charcoal, a smokeless, easily-controlled fuel which can be bought in very small volume, is widely used by those who make the transition from rural to city living.

Urbanization is rapid throughout the developing world, but 75% of the population still lives in rural areas in Asia, 91% in Africa, and 52% in Latin America. The share of energy consumption of the rural population is 23%, 4%, and 23% respectively (67).

Fifty per cent or more of the energy used by the rural population in the tropics is for cooking, a much smaller percentage for light, cultural and educational needs and about 25-33% for pumping water and operating agricultural and village industries.

Wood has been the conventional fuel in the rural sections of the developing countries, but little has been used for energy recently in the developed world as illustrated in Table 2, which is adapted from Earl (17) and others. The bulk of the wood used for energy in industrial countries is the byproduct waste from forest industries, including black liquor from pulp mills.

Table 2. Proportion of Total Energy Consumption Supplied by Fuelwood

(Earl's 1972/73 data unless otherwise noted)

	%
Tanzania	96
Nepal	96
Nigeria	91
Ivory Coast	71
Kenya	67
Brazil	59
India	30
Lybia	15
Finland	15
Venezuela	11
Canada	3.5 (1977)
Sweden	3
U.S.A.	1.4 (1977)
U.K.	0.1

There are indications of small but significant increases in the use of wood in some developed countries during the last few years.

Industrialized countries responded quickly to the recognition that the fossil fuel supply was in jeopardy. Funds for research into energy conservation, generation and distribution increased rapidly as indicated by the R and D budgets of the U.S. and Canada shown in Table 3(a).

Table 3(a). Expenditures on Energy Research and Development

U.S. Federal Government (10)

Fiscal Year	Million $
1973	652
1974	1,000
1975	1,810

Canada Federal Government (61)

1976	120
1977	130
1978	144

Not unexpectedly, after a long period of almost complete reliance on fossil fuels and preoccupation with the spectacular but somewhat speculative atomic fission and fusion opportunities, the bulk of research is still directed into development of these energy sources.

In North America less than 10% of government funds for energy research and development are earmarked for energy from renewable sources. They are spent for studying improved methods of harnessing wind, water power, tide, or heat generated by sunrays, or electricity on photovoltaic cells. Biomass, which was the principal source of energy until the invention of the steam engine in the 18th century, is a relatively neglected subject. Only a small though increasing fraction of all energy-related, government-sponsored research is directed into this field in North America. Non-governmental agencies and individuals however make a significant and growing contribution.

Table 3(b) shows the funding of the Fuels from Biomass Systems Branch of the United States Department of Energy (26).

Table 3(b). U.S. Federal Government Funds for Fuels from Biomass Systems Branch

Fiscal Year	Million $
1975	0.6
1976	4.6
1977	9.9
1978	20.2
1979	26.5

We found it difficult to obtain statistical information on energy research expenditure in developing countries, but indications are that funds are allocated in similar proportions but on a much smaller scale.

One hundred and fifty years ago research into the uses of coal speeded industrialization of Western Europe and created new techniques, and coal quickly replaced wood for fuel.

Seventy-five years later the discovery of the potential of liquid and gaseous fossil fuels opened up a whole new range of products, led to new modes of transportation, greater comfort and reduced environmental pollution. Today research aims to harness the energy from atomic fission and fusion in the expectation that this will help to satisfy the voracious appetite of industrial societies. A similar approach to fuel production from biomass holds promise to significantly improve the quality of life for people in the developing world, especially for the rural population, and to make rural living so attractive as to stem the alarming tide of migration to urban centres.

Chapter II

The Biomass Resource Base - Its Nature, Management and Harvesting

A. Introduction

Biomass is essentially stored chemical energy (30). It is produced by photosynthesis, directly in the case of plants and indirectly in the case of animals whose ultimate food-source is plant material.

The dry weight of all living phytomass (ie, plant matter) on the earth's land surface has been estimated as nearly 1,700 x 10^9 tonnes, produced at a rate of almost 100 x 10^9 tonnes per year (46).* Nearly all of this, together with undecomposed dead biomass in forest and field, as well as large quantities of aquatic vegetation, are potentially capable of being converted into some form of energy.

In actual fact, only a modest fraction of this biomass enters the human economy, and much of that fraction leaves the economy as waste (9). Of the forest biomass, which constitutes an estimated 98% of all living terrestrial plant matter, only 13% of the annual increment is currently harvested, 7% for industrial purposes and 6% for fuel (17). Nevertheless the uneven distribution and indiscriminate harvesting of forest biomass leads to the rapid destruction of forest capital, which not only reduces the future availability of biomass but has catastrophic environmental and social consequences in many parts of the world.

The animal kingdom represents a very much smaller potential for conversion into energy. Indeed, apart from work performed by animals and humans whose "fuel" is feed and foodstuffs, and from rare products such as fish oil, whale oil and tallow, most of the animal biomass used or likely to be used for energy production is in the form of excrement.

* In a recent comprehensive study, Rodin et al (73) estimate the world's land phytomass as 2,400 x 10^9 dry tonnes, with a primary production rate of 172 x 10^9 dry tonnes/yr.

Most industrial uses of biomass require quite specific properties in the materials employed, whether for food, fodder, construction materials, clothing, pulp and paper products, etc. For energy production, however, almost any part of a plant can be utilized - stems, foliage, bark, roots, even dead and decaying vegetation, as well as residues from numerous industrial processes.

Energy is thus the least demanding, as regards input materials, of all uses to which plant biomass can be put. Vegetation of any size from minute algae to giant trees and seaweeds can be utilized. The fact that tropical high forest stemwood comprises only 15% to 20% of the total dry-matter in trees compared with more than 30% in temperate forests (17), although a decided disadvantage for lumber and veneer production, is of little consequence for conversion to energy. In fact the rate of production of biomass, with due regard to the maintenance of site quality, is generally of much greater importance than the size and shape of the material produced.

1. Desirable Characteristics of Energy-Producing Vegetation (56)

Among the more important properties to be considered when selecting plants for energy biomass production are the following:

(1) A large proportion of available insolation must be absorbed by green tissue. This can be assisted by:
(a) Using plants with high photosynthetic efficiency - e.g. C 4 plants. These form a 4-carbon compound, and can convert 2 or 3% of available solar energy into plant material compared with less than 1% for most plants. Sorghum, millet and sugarcane are examples.

(b) Replacing each harvest with a new crop as quickly as possible. With most aquatic species this is not a problem. For terrestrial plants, those that have high sprouting potential following swathing or coppice cutting are preferable to those requiring planting or seeding.

(c) Using or breeding plants with leaves whose shape and orientation make maximum use of sunlight.

(2) Ability to conserve water requirements in arid areas - e.g. CAM plants which keep their stomata closed when the temperature is high, and thus greatly reduce water loss. Most of these however grow very slowly. Examples include the century plant, pineapple, and aloes.

(3) Minimum drain of nutrients from the soil, and ability to improve soil quality.

2. Methods of Converting Biomass into Energy

Processes for converting wood and other biomass into energy are described in detail in the next chapter. However it may be helpful to refer very briefly to these processes before considering the properties and characteristics of the various kinds of biomass available for energy production, since the nature of the biomass is often important in determining the conversion process used.

Burning, or complete combustion in the open air, is the simplest and oldest method of utilizing biomass for energy. Distillation or partial combustion in kilns to produce charcoal has also long been practiced. Other thermal and thermochemical conversion processes have been developed, using more elaborate equipment and technologies, for the production of gaseous and liquid fuels from biomass which are preferable to solids for many applications.

The use of the above processes is generally confined to terrestrial biomass with moisture contents normally less than about 30%. Bioconversion or fermentation processes are commonly employed (a) to convert plants with high sugar or starch contents (e.g. sugarcane and cassava) into ethanol (industrial alcohol); and (b) to produce biogas, which contains methane, from aquatic plants with large amounts of moisture, as well as biomass from animal sources and similar wastes.

3. Sources and Consumption of Energy

Data provided by Earl (17) show the world's recorded energy consumption in 1970, from various energy sources. For comparison, an estimate of the percentage of energy derived from these same sources in rural areas of the developing world, adapted from FAO data (4), is given below.

Table 4. Energy Consumption from Various Sources

	World Consumption		Rural Developing Areas
	Million tonnes coal equivalent	%	%
Non-Renewable Fuels	6,697	90	2
Hydroelectric	150	2	-
Geothermal	1	-	-
Wood and Charcoal	487	7	85
Dung	90	1	11
Agric. Waste	10	-	2
Total	7,435	100	100

These figures strikingly illustrate two facts: first, the overwhelming dependence of the world's energy-users as a whole on petroleum-related products; and second, the nearly equally dominant role of wood in supplying the energy needs of rural communities in developing countries.

4. Productive Capacity of Biomass

The heating value of wood, most agricultural residues, and similar biomass is roughly between 4,000 and 5,000 kilocalories per kilogram (k cal/kg), oven-dry weight. (For air-dried wood and green wood, the figures are approximately 3,000 k cal/kg and 2,000 k cal/kg, respectively). The following table, adapted from (56), shows yields of above-ground dry biomass and equivalent calorific values for a few representative species of plants among the many whose potential for energy production is being studied.

Table 5. Biomass (in dry tonnes) Available From Some Trees, Annual Crops, and Aquatic Plants

	tonnes/ha/yr	10^7 k cal/ha/yr
Aquatic Plants		
Water hyacinth	36 - 290*	15 - 122*
Fresh-water algae	88	36
Agricultural Crops		
Sugarcane	27 - 112	11 - 47
Sorghum	20 - 69	8 - 29
Trees		
Tropical rainforest	41	17
Eucalypts	20 - 48	8 - 17
Subtropical deciduous forest	24	10
Temperate zone tree species	7 - 22	3 - 9

*The higher figure (not from the reference quoted) has been reported for water hyacinth grown on sewage effluent.

It will be noted that the list is headed by aquatic plants, while trees tend to have lower yields, decreasing as the climate becomes colder and drier.

It is evident from the foregoing table that wide variations in biomass yields are encountered, even within a single species - a feature that is characteristic of studies of this kind. A great deal remains to be learned about the best combinations of climates, sites, genetic strains, cultural treatments, and the energy potential of the various parts of plants - stems, branches, foliage and roots.

Such knowledge is sadly lacking in the case of trees, which are much the most important source of biomass for energy production. But even less is known about the possibilities of most other biomass energy sources, especially in the developing world. We shall therefore start with a more detailed consideration of tree biomass. Many of the principles, if not the specifics of technology connected with wood as an energy source, apply in varying degree to other biomass forms.

B. Tree Biomass

1. The Biomass Resource Base

1.1 A Global Perspective

Inventories of the world's forest resources are both incomplete and imprecise. This is particularly true in the tropical regions (6). Moreover, standing timber has been surveyed and quantified almost entirely on a basis of its merchantable stemwood content, excluding all biomass except logs over a certain minimum diameter and other characteristics depending on the end products in view. Where the end use is primarily energy production, which is relatively free from constraints respecting the size, shape and other qualities possessed by the biomass, conventional forest inventory data may well be almost meaningless, and indeed highly misleading. Pending new surveys designed specifically for estimating forest biomass that is useable for conversion to energy, efforts are being made in some quarters to determine correction factors that may be applied to existing inventory data, in order to arrive at approximate estimates of biomass for energy purposes (80).

With all these limitations in mind it is hardly surprising that different authorities have arrived at rather widely divergent estimates of the forest biomass' potential for energy production, both on a global and a regional basis. This applies to the total biomass present on forest lands as well as to the annual rate at which it is being produced, or can be made to produce under different intensities of management and utilization.

Accepting Longman and Jenik's estimates (46), the total forest and savanna area of the world is 65×10^8 ha, carrying a biomass of $1,640 \times 10^9$ tonnes of dry matter. By contrast, the total area of tundra, steppe and agricultural land, 31×10^8 ha, supports a biomass of only 32×10^9 dry tonnes. Earl (17) points out that the reserve of energy held by the forests (conservatively estimated as equivalent to 271,000 million tonnes of coal) is more than 20 times greater than the world's current annual consumption of energy from all sources. The annual rate of production (by solar energy) of the world's forest biomass is

5 times the earth's hydro electric potential, and more than the world's total consumption of fossil fuels in 1970. However reassuring this picture may seem, there is little room for complacency when one realizes that most of this potential source of energy, apart from the portion now being utilized, is far removed from most of the world's population. The massive problem of distribution remains to be solved.

1.2 A Tropical Perspective

The largest reserve of renewable fuel is in the tropics, but this resource is being rapidly depleted (17). The overriding consideration must be to manage the land to bring out its optimum capacity without being overworked. In the final analysis the ultimate forest resource base is land, not biomass.

Based on the decidedly conflicting evidence available, the authors in an earlier study (6) estimated that the total forested area in the tropics amounts to some 2.5 billion ha,* or roughly half of the world's total. Very approximately, this is comprised as follows.

Table 6. Tropical Forested Areas of the World

	Million ha.
Mangrove forest (not estimated; probably 1% to 5% of total)	-
Tropical rain forest	650
Tropical forest with seasonal rainfall	1,450
Open woodland, savanna, shrub or protection forest	400
Total	2,500

* Rodin *et al* (73) estimate the total area of the world's tropical vegetation zone at 5.6 billion ha. This includes grasslands, bogs and other non-forest formations.

The total biomass contained in the tropical forest has been estimated as some 900 x 10^9 dry tonnes (46), or about half of all living plant matter.* The growing stock of stemwood in the forests of the developing countries (roughly equivalent to the tropics) is reported by FAO as amounting to 166 billion m^3 (6).

Of the 1,050 million m^3 of roundwood harvested annually in the developing world, some 860 million m^3, or 82%, are fuelwood (6). The remaining 18% is industrial wood; this small proportion means that industrial residues are at present relatively unimportant as a potential source of energy in comparison with fuelwood.

FAO (4) estimates that 86% of the wood consumed in developing countries is used as fuel, mostly outside commercial channels and therefore unrecorded. The best available data (FAO, 1975) indicate that about 1,200 million m^3 of wood are used as fuel in the developing world; presumably this includes some residues from industrial operations. By contrast, fuelwood consumption in the developed countries totals about 150 million m^3.

The term "fuelwood" includes both firewood and wood converted to charcoal. Little is known about the relative proportions of the two, but the use of charcoal is probably greater than is generally believed, and is increasing much faster than firewood (4).

Though other sources of energy may well become increasingly available, it is likely that hundreds of millions of people in the developing world will have no choice but to rely on wood in the forseeable future. There is still much room for increasing the woodfuel supply, for managing the biomass more productively, and for its more efficient conversion into energy. Most of the technical knowledge is now available. Although much needs to be done in adapting it to particular situations, the main information gap is institutional and economic in nature (4).

*According to Rodin et al (73) the total land phytomass in the tropical zone is 1,350 x 10^9 dry tonnes, of which 1,030 x 10^9 is forest biomass comprising about half of the world's total.

It should be noted that in many of the developed countries the forest was a major source of energy until quite recent times. Only 50 years ago half of all the wood cut in Canada was estimated to be fuelwood, while a century ago half of all the energy requirements of the United States was supplied by wood (78). The indications now are that the decline of wood for energy production in the industrialized world will be reversed, and that by the year 2000 the energy derived from wood in some developed countries will be twice its present level.

1.3 Sources of Tree Biomass Available for Energy Production

Without considering for the moment the economic aspects of supply, the major potential sources of tree biomass for energy include:

(a) Underutilized natural forests. Tropical forests often contain more than 100 species on a single hectare, only a few of which are used for industrial purposes in the present stage of development. The harvesting of wood for energy may improve the management of the forest.

(b) Industrial forest plantations. Biomass available for energy here would be much more limited, but pre-commercial or stand improvement thinnings would be readily adaptable to energy production. It should be noted that at present less than 1% of all tropical forests are man-made, and it is unlikely that industrial plantations will comprise more than 2% of the tropical forest by the year 2000 (6).

(c) Energy plantations or biomass farms, where trees are grown specifically for energy production. These are still largely in the conceptual stage and require much further research even in the developed countries, but in the longer term they may well be of tremendous significance.

(d) Fuel from the pruning, lopping, and pollarding of trees. These practices are defined in a later section.

(e) Industrial residues - principally logging waste left in the forest, and mill waste accumulated at sawmills and other manufacturing plants.

Although presently of minor importance relative to fuelwood in most developing regions, the advantages of utilizing wastes with no other practical use include (31):

(a) Conversion to energy by simple pyrolysis is fairly labour intensive, and thus adapted to the economics of many developing nations.

(b) Waste materials are often concentrated in fixed and highly accessible locations, making for easy collection.

(c) Many wastes have no other current use.

(d) Removal of wastes helps to clean the environment.

(e) Fuels derivable from wastes by simple pyrolysis can be produced in an ecologically clean and acceptable manner.

(f) Chipping or pelletizing (as is done with some agricultural wastes) enhances their portability and suitability for conversion to other forms of fuel.

Disadvantages might be:

(a) Some waste materials are widely scattered, and far from potential energy users.

(b) High moisture content is often present, increasing transport costs.

(c) High moisture content makes direct burning for energy impracticable.

(d) Seasonally produced wastes do not offer a steady supply of fuels, but under some conditions portable converting plants could partly offset this difficulty.

2. Rate of Production of the Biomass

The key to land productivity is its ability to provide sustained rapid growth in total harvestable biomass. Overcutting for fuel (or other uses) undermines land productivity by soil erosion, floods, desertification and impoverishing soil materials (19).

2.1 Natural Forests

The increment of forest biomass is extremely difficult to measure, especially in the tropics where growth is continous and annual rings are seldom identifiable in the wood. Figures given by Earl (17) for the annual increment of all wood above ground in the world's forest regions are reproduced below.*

Table 7. The World's Renewable Forest Energy Resource

Forest type	Area	Annual increment of wood† per ha		Total increment wood†		
	(ha × 10^6)	(m^3)	(tonnes)	(m^3 × 10^9)	(tonnes × 10^9)	(tonnes CE × 10^9)
Cool coniferous	800	4·1	3·0	3·3	2·4	1·4
Temperate mixed	800	5·5	4·0	4·4	3·2	1·9
Warm temperate	200	5·5	4·0	1·1	0·8	0·5
Equatorial rain	500	8·3	6·0	4·1	3·0	1·8
Tropical moist deciduous	500	6·9	5·0	3·5	2·5	1·5
Dry	1000	1·4	1·0	1·4	1·0	0·6
Totals and means	3800	4·7	3·4	17·8	12·9	7·7

† Estimated to include all wood above ground.

*In general, estimates by Rodin et al (73) of the total annual production of forest biomass are higher than Earl's.

From the above it will be seen that 9 billion m^3, or 51% of the world's total forest increment, is produced in the developing tropics. Of this, only 11% (1000 million m^3) is being used - 2% for industry and 9% for fuel. In terms of coal equivalent there is an unused increment of 3,500 million tonnes annually in the developing world, or nearly half of the world's total annual energy consumption in 1970.

The natural tropical forest biomass produces up to 50 tonnes (or 70 m^3) of dry matter/ha/yr, of a very diverse mix of plant material (6). The overall average increment of tree stems is estimated as 4 m^3/ha/yr, but production is probably double this in some forests, and might be more than doubled again under intensive management.

The dry weight of foliage and other litter falling to the ground annually is estimated as 9 to 14 tonnes/ha in tropical mixed and rain forests, 7 tonnes/ha in sub-tropical mixed forests, and 3 tonnes/ha in temperate hardwood forests (60). This biomass is potentially convertible into energy. However, as will be discussed in a later section, care must be taken that its removal does not lead to deterioration of soil quality.

The total annual production of carbon by the world's forest ecosystems is about double that obtained with other forms of land use, amounting to an estimated 36 x 10^9 tonnes, about half of which occurs in the tropics (17).

2.2 Plantation Forests for Industrial Wood

In tropical plantations stem growth exceeding 50 m^3/ha/yr has been obtained (6). It would appear that yields of 50 to 60 m^3/ha/yr of dry wood substance may be sustained, at least in the short term, under good management with fast-growing species such as gmelina and eucalyptus spp. carefully selected with regard to climatic and site conditions. Maximum yields in excess of 100 tonnes/ha/yr have been reported for eucalyptus species in Brazil (32).

2.3 Energy Plantations

Although gmelina energy plantations are reported in Nigeria and Malawi, little information is yet available regarding yields from tree plantations grown specifically for energy production in the tropics. However, increasing attention is being devoted to tree farms for energy production and other uses in various industrialized countries. In eastern Ontario, Canada, certain hybrid poplars show remarkable promise for rapid biomass production when grown alone or in combination with other crops. Poplar yields up to 10 tons/ha/yr above ground biomass have been obtained on 2-year rotations (8).

In the United States, the Mitre Corporation (51) estimates the productivity of the most promising species, when closely spaced and grown on short rotations, as 11 to 29 dry tonne equivalents (DTE) per ha per year. Yields might be doubled in 25 years, by concentrated research on species selection and improvement, and energy crop management. Conventional forest crops now yield about 4½ DTE/ha/yr.

The Mitre report also estimates that the quantity of energy produced in the form of wood biomass by energy farming is 10 to 15 times the amount of energy consumed in growing, irrigating, fertilizing, harvesting and transporting the biomass, depending on the productivity level achieved.

2.4 Combined Plantations

Plantations may be grown for the sole purpose of industrial wood production (with or without the possibility of using residual wastes for conversion to energy), or they may be grown with the exclusive object of energy production. A third possibility would be plantations designed with both objectives in mind. These could be either mixtures of appropriate species or monocultures in which the biomass from prescribed thinnings or prunings would be purposefully aimed at conversion to energy.

In some circumstances the maximum returns from forest lands might be obtained by the planting of "multi-purpose" species such as rubber trees which are used initially for latex production but, at the end of their useful life for this purpose, may be removed for conversion to energy. However, much research is likely to be needed to fully account for all the economic benefits.

2.5 Examples of Area and Biomass Requirements for Specific Energy Purposes

(a) Table 8 shows the area of forest required to supply charcoal for two specific purposes in Uganda, as estimated by Earl (17).

Table 8. Forest Areas Needed for Energy Proauction, Uganada

Purpose of Energy Requirement	Source of Biomass: Eucalyptus Saligna Plantation (ha)	Source of Biomass: Tropical High Forest (ha)
Town of 8,000 population	960	4,900
Smelter producing 100,000 tonnes of pig iron per year	28,000	140,000

(b) A 150 megawatt power station, with energy for power generation supplied entirely by direct combustion of wood, would require about 786,000 m^3 of air-dried wood per annum. Assuming that stems and branches with bark were all burned, and an increment of 20 m^3/ha/yr in energy plantations, an area of 38,650 ha would be needed for sustained production (17).

(c) In the United States the production of 1 quad of energy would require about 2½ million hectares of silvicultural biomass farms yielding 22 dry tonne equivalents/ha/yr (51). (One quad equals 25.2 x 10^{13} kcal; the total U.S. energy consumption is 75 quads annually.)

3. Availability of the Biomass for Energy Use

3.1 Natural Forest and Plantation Biomass

The actual availability of biomass for energy production from natural forests and industrial plantations in any one region at any given point in time is governed by the options available for higher-value alternative uses, by transportation facilities and costs, by the presence or absence of conversion plants using appropriate technologies, and many other factors. Individual studies of specific cases are needed to make any informed appraisals, and such studies are rare in the developing world.

In the case of energy plantations it may be presumed that all of the biomass produced will be available for conversion to energy. The potential productivity of such plantations has already been discussed.

Fuelwood production (also reviewed earlier) represents an important segment of the total biomass available for energy use. The amount of recorded fuelwood removals that is converted into charcoal probably does not exceed 18 million m^3/yr (17).

3.2 Biomass from Industrial Residues

In the developing world, increasing demands for energy and the rapidly diminishing availability of tree cover close to population centres, is putting a premium on other more accessible kinds of wood - e.g. tree farms, logging and mill residues, and used wood. In some countries more than half of fuelwood supplies now come from residues, shrubs, and tree crops; in the case of Sri Lanka from rubber and coconut plantations (4).

From the Georgia Institute of Technology's study in Ghana (31), where the annual cut of roundwood is about 10 million m^3, potential sources of forestry wastes for energy conversion are described as follows.

Table 9. Biomass from Forestry Wastes Potentially Available for Energy, Ghana

Source	Green tonnes/yr (moisture content assumed = 50%)	Remarks
Sawdust	23,000	Produced by 51 sawmills.
Logging Wastes	365,000	No area or timber production given.
Reforestation Wastes	975,000	Brush, etc. cleared preparatory to planting 6,500 ha/yr.
Total	1,363,000	

4. Management of the Biomass

4.1 General

In many parts of the developing world, people living near the forest have long been accustomed to obtaining firewood without charge. Increasing demands for fuel and other free goods and services are now seriously eroding the forest resource and destroying the environment. Villagers are reluctant to give up their entrenched rights, thus creating a major social problem.

In order to change this attitude before forest destruction reaches the point of no return a more positive and imaginative approach than prohibitive legislation is needed in managing forests for energy production. An effective control system has been devised in several Indian states, whereby certain forest lands are placed under joint management between the forest department and communities. Local people are thus given a role in forest management within the framework of their established customs and practices (4, 71).

In other regions of the globe, current policies respecting timber harvesting regulations are based on existing biomass inventory and "first harvest" conditions, on the assumption that silviculture will remain unchanged from that applicable in the natural forest and that the over-riding objective is to maintain a constant harvest over long rotations

(50 to 100 years) selected with little regard to economic returns (62). The cost of intensive management, which is now becoming necessary, will provide a strong incentive to ensure optimum economic management of the forest land resource. In developed countries the use of biomass for energy could help stabilize the economy of the forest industry as a whole by using more waste for energy production in "boom" times, and more high-grade wood for energy in slack times, thus keeping men and equipment employed.

4.2 Natural Stands

The management of natural stands in the humid tropics, with their highly heterogenous mixtures of species of widely differing silvicultural characteristics and biomass properties, is a very complex operation. It has been under study by skilled silviculturists in various climatic and vegetative regions for decades. Yet, with few exceptions, manipulation of the natural forest has not been successful in promoting regeneration of favoured species (6). Some authorities despair of its achievement, and advocate the clearing of natural stands followed by planting. Others have faith in man's ability to manage these natural forests profitably on a sustained basis, especially having regard to the potentially serious, but largely unknown, effects of massive clearing on tropical ecosystems.

The increment of heterogenous tropical high forests can be increased beyond the natural rate by removal of slow-growing, moribund, and non-commercial stock, followed where necessary by enrichment planting of desirable species, or by plantations. The cleaning and thinning of natural forests to improve the final timber crop can result in substantial fuelwood gleanings, as has been practised in Europe for centuries. Even lightly-stocked savannas can support 8 to 20 tonnes of fuelwood/ha, which may be sold locally or converted to charcoal and transported to towns. Assisting these activities can provide social benefits and foster improved silviculture (17).

4.3 Industrial Plantations

In developing countries man-made forests are always established by planting rather than direct seeding because of abundant, low-cost labour (22). As a rule the management of plantations, whether monocultures or planned mixes of species, is easier than in natural stands and yields are more predictable. For tending as well as planting operations advantage can be taken of the availability of low-cost labour.

Although the proportion of man-made forests in the tropics is still very small it is increasing, and in several regions 2 or 3 rotations of tree monocultures have been successfully harvested. For industrial wood production, rotations of 5 to 20 years or more are usually required for trees to reach merchantable size, depending on the product desired (6).

Advantages of plantations listed by Earl (17) include:

(a) They permit close control of the nature and quality of the biomass, and species can be selected for rapid growth.

(b) Their growth rates are generally higher than in natural forests. Because of this, smaller land areas are needed for given biomass production.

(c) If land is available plantations can be located close to processing plants and markets.

(d) Under favourable conditions quick-growing plantations can be profitable undertakings. However plantations tend to be more prone to serious losses from forest pests, especially in monocultures.

4.4 Energy Plantations

The deliberate cultivation of vegetation for energy production is a means of converting solar energy into an easily-used fuel at a capital cost only slightly more than the real estate required to grow the biomass. This is appropriate for those developing countries where labour and land costs are low, energy cost is high, and sunshine and moisture are abundant (31).

In establishing community energy plantations in the developing countries the following points should be considered (4):

(a) The need for willing involvement of the people concerned, with recognition that wood is not free to be gathered at will.
(b) Availability of adequate technical support for site selection and provision of planting stock, and advice and supervision of planting, tending and harvesting. This implies subsidization, justified by improved environmental and socio-economic benefits.

For <u>any</u> energy plantation one should consider:

(a) The selection of appropriate species and sites.
In general the faster the growth the better, without regard to form or technological properties.
(b) Density, spacing and rotation periods to maximize dry-matter production.
(c) The possibility of joint production of other products with energy, e.g. poles, fodder, oils, fruit, etc., and amenity and environmental benefits.
(d) Availability and cost of alternative sources of energy.

Biomass production for energy only, under short-rotation management, has the following advantages compared with conventional (30-100 yr rotation) management (51):

(a) Higher yields per unit area.
(b) Smaller land requirement for a given output.
(c) Shorter time span from initial investment in stand establishment to cash flow from the harvested crop.
(d) Increased labour efficiency.
(e) Increased harvesting efficiency by adopting agricultural methods.
(f) Capacity of selected species to regenerate by coppicing - that is, by sprouting from stumps cut close to the ground and using the same root system for additional crops.

(g) Ability to take quick advantage of cultural and genetic advances.

The same authority (51) lists the following criteria for selecting species to be used for energy biomass production under short-rotation management:

(a) Rapid juvenile growth.
(b) Ease of establishment (from cuttings) and regeneration (by coppicing), both of which tend to favour hardwood species.
(c) Freedom from major insect and disease pests. Genetic diversity should be exploited to build in resistance to attack.

"Short" rotations are normally considered to be those in which the tree crop is harvested at intervals of 10 years or less. The term "mini-rotation" is commonly applied when the interval is less than 5 years. In general the shorter the rotation the greater is the density of planting - 3,000 to 190,000 stems per hectare compared with 1,500 to 5,000 for conventional plantations (51).

Nearly all the experimental evidence reviewed indicates great promise for energy biomass plantations managed on short and mini-rotations. It seems to be generally accepted that regeneration by the coppice system is desirable. However, there are some notable discrepancies in the results among the studies that are being conducted. In the United States ongoing research is not expected to provide substantial results for 10 years. With growing periods of 3 to 6 years, at least two rotations are needed to obtain reliable research results (30). This indicates the need for greatly intensified research, and when applied to the complex soil conditions in the tropics the problems requiring solution will undoubtedly be compounded.

4.5 Multiple-Use Plantations

Tree growing is an extensive use of land, incompatible with competing uses where pressure is heavy (4). However there is usually scope for energy plantations combined with amenity values along roads, canals, as windbreaks, and on marginal land, as well as when interplanted with agricultural crops.

The Georgia Institute of Technology (31) suggests that the use of highly-organized, labour-intensive farming methods (including conventional "non-till" and "organic" practices) in the developing countries could produce year-round, perpetually renewable sources of biomass for energy and food, and generate the continuous need for many new jobs. It is estimated that in Ghana a 40,000 ha (20 km square) "energy-food" plantation could produce the energy equivalent of 450,000 tonnes of coal with perhaps 50,000 tonnes of corn and 55,000 tonnes of peanuts. With a more capital-intensive enterprise the biomass could be converted into a number of more diversified energy forms, including methanol, charcoal and electric power.

Other examples of increased production from various tree and agricultural crop combinations have been discussed by the authors in an earlier publication (6).

4.6 Maximizing Energy Biomass Production from Individual Trees

Nearly all forest management systems, irrespective of silvicultural prescriptions, rotation lengths, or logging practices, involve the severance of the tree stems from their roots at or near ground level in the harvesting process. In most cases the plant is effectively put out of action, but an exception of increasing importance for energy production is the coppice system, whereby advantage is taken of the propensity of certain species to quickly reconstruct the aerial components of their biomass on the living foundations left in the soil. Two other more fundamental exceptions, in which only a part of the above-ground biomass is removed from the stem, are lopping and pollarding.

The lopping or pruning of branches from the lower part of the crown is usually practised in order to improve the quality of the stem for lumber or veneer manufacture. In Nepal, where the energy shortage has reached crisis proportions (19), the branches of trees are lopped for fuelwood, leaving only stubs which can be used for climbing when the cutting is repeated. Lopping should be carried out in such a way as to protect the growth capacity of the trees.

Pollarding consists of removing the upper part of the stem with its associated branches, thus promoting vigorous sprouting at the newly-formed top. It may be done for aesthetic reasons or for specialized kinds of wood production. The tops and sprouts are also reported to be used as fuel (29).

Although increasing attention is being given to methods of obtaining maximum sustained yields from energy plantations, we are aware of no studies that include the possibilities of lopping and pollarding, in comparison with coppicing and other management practices, with a view to maximizing biomass production from given rooting systems. This is an avenue of research that might well be explored, particularly in the developing world context, since both lopping and pollarding are highly labour intensive.

4.7 Maintenance of Soil Quality

The great bulk of plant biomass consists of carbon, hydrogen and oxygen derived from air and water. However, small but essential quantities of other elements are also present in the tissues, and these are mostly obtained from the soil in contact with the roots. One of the major concerns that has been expressed regarding the frequent removal of fast-growing biomass is the effect of sustained extraction of these elements on the nutrient properties of the soil.

Inputs of soil nutrients available to plants result from rainfall, dust, weathering of the parent soil material, fixation of atmospheric nitrogen by soil microorganisms, and soluble phosphorous produced by mycorrhizal fungi at the tree roots. Losses are mainly due to leaching and water runoff, volatilization of nitrogen and sulphur through burning and denitrifying organisms, and transfer to plant biomass (3, 60). In the natural state these processes are in fairly close balance.

Studies in various regions (mostly in the temperate zone) indicate that this equilibrium is substantially maintained when trees are logged at intervals of the order of 40 years or more. This appears to be true even with whole-tree harvesting - that is the complete removal of above-ground biomass from the site. Even though the foliage is particularly rich in nutrients such as nitrogen, potassium and phosphorous, its removal once every 40 years represents a loss of only 1/40th of the total nutrient content if the foliage is shed annually.

Loss of nutrients to the soil is accelerated by (a) shortening the rotation, and (b) increasing the proportion of total biomass removed, not only by loss in the biomass itself but by more frequent soil disturbance. This is especially true if below-ground biomass is removed, resulting in more leaching and streamflow loss (3). Exposure of tropical soil causes the soil porosity and "constitution" to deteriorate and may lead to erosion on slopes (60). "No-till" soil management, implying the least possible disturbance of the litter, reduces such damage as well as the harmful effects of sunlight getting below the surface: it would seem to be particularly applicable in the tropics.

There seems to be general agreement that in order to sustain production with whole-tree harvesting on short rotations, the application of external fertilizer will be necessary, and this can be a prohibitively expensive operation in developing countries. Moreover the application of fertilizer may not represent an absolute nutrient gain, since under some conditions the addition of one element may result in the loss of another. Also fertilizers made from effluent wastes may introduce disease, water pollution, and heavy metal toxicity (3).

When foliage and twigs are left on the forest floor the nutrient drain is greatly reduced. The length of rotation permissable under these conditions without additional fertilizer, for various combinations of plants and sites, requires much further study. In any event it is considered best to remove the bark in most cases, since tannins may retard the growth of the next crop, at least temporaily (70). Yet another method of sustaining fertility is to use plants with soil-enriching properties, such as the nitrogen-fixing leguminous species.

4.8 Other Environmental Impacts

The following observations apply to temperate North America - we are not aware of any studies of the environmental effects of producing tree biomass specifically for energy purposes in the tropics. However most of these points should be applicable at least to some degree under tropical conditions.

The Mitre study (51) classifies the environmental impacts of short-rotation forestry as low to medium, and notes a number of beneficial social and economic effects:

(a) The removal of logging residues should be aesthetically desirable; there may be some good and some adverse effects on wildlife.
(b) Forestry options for energy production are generally more attractive than alternative options such as mining and nuclear power generation. In comparative terms, forestry has a "benign" effect on the ecosystem.
(c) Short-rotation forestry permits a wide variety of options - e.g. multiple-product objectives such as pulp/sawtimber and biomass/sawtimber.

Other points that may be noted include:

(a) The area of land required to obtain a given quantity of biomass is reduced with short rotations and utilization of logging residues, leaving more land available for recreational and other uses.

(b) Opportunities for silvicultural management are enhanced.

(c) Fire and pest control is facilitated by waste removal.

5. Biomass Harvesting and Transport

5.1 General

In most parts of the developing world, and especially in rural communities, the logging and transportation of wood are basically manual operations, with or without the assistance of animal power. Industrialized nations on the other hand have largely converted to mechanization, and new developments in equipment and methods are steadily being introduced. Irrespective of the degree of mechanization, however, certain basic functions in the wood harvesting process can be identified.

(a) Felling - is the severing of tree stems from their roots. Hand tools include axes, machetes, and hand saws or hand-held power saws. Felling machines sever the stems with saws or shears, and may incorporate debranching and topping equipment unless whole-tree harvesting is practiced. Otherwise the limbs and tops are removed manually.

(b) The felled biomass is transported to the roadside or landing by skidding, that is dragging along the ground (usually with the butt end elevated where mechanical skidders are used); or by forwarding in vehicles which carry the biomass clear of the ground and thus cause less disturbance of the litter and surface soil. Various cable systems for skidding and forwarding are also in use.

(c) Where the feedstock for the processing plant is to be in the form of chips (as for pulp and some energy uses), chipping may be carried out at the roadside or nearby concentration points by portable chippers, in order to increase ease of loading and handling during transportation from roadside to mill.

Whatever harvesting methods are used, the question of energy balance should be kept in mind - that is the importance of getting the greatest possible amount of energy out of the biomass in relation to the energy input required for harvesting operations. This principle applies equally to the transportation and further processing of the biomass through to the final products.

5.2 Manual Harvesting

Because of the great variety of climatic and sociological conditions in the developing world, logging production varies greatly. Information on such production is scarce, and the adaptation of data obtained under the widely different conditions of developed countries is difficult. One point of interest is that the comparative work capacities of trained Scandinavian and Indian forest workers was found to be directly related to their body weights (22).

Most of our information on manual harvesting methods and production in developing countries is taken from FAO (22, 23).

The manual felling time for small - and medium-sized trees is about one-third as long with power saws as with bow saws. Bark can be removed with an axe or power saw. Regardless of the type of cutting tools used or volume harvested per unit area, there is remarkably little difference in cost of operations at the stump per unit of production. This averages about 30 to 50 cents per m^3.

Small trees or short wood can be packed manually to the roadside. One or two men can usually forward distances up to 100 m, on grades not exceeding 20%. Elephants have long been used for moving logs in Southeast Asia. Forwarding with a 2-ox team and trailer in Chile was found to be more sensitive to grade than carrying by hand, but the productivity was 2 to 3 times greater than that of a 2-man forwarding.

Mules or oxen are normally used for skidding in hot climates (for which horses are not suited), and can operate on down-grades of 15 to 35% depending on the smoothness of the ground. Machines have an important advantage under such conditions in that they require no rest periods, and road spacing can take this into account.

5.3 Mechanical Harvesting

Man-day productivity has been drastically increased in many industrialized countries by the introduction of harvesting machinery, but at present there are not the same pressures to mechanize forest operations in most of the developing world (22). In man-made forests farm tractors and trailers, either manually or mechanically loaded, can be used for forwarding, and choker skidders may be employed. In the high forest, heavy-duty crawler-tractor skidders are usually preferred. Skidding and forwarding machines can operate on down-grades up to 30% to 50%, forwarders being better adapted to the steeper grades. Cable yarding systems are more expensive, and are generally used only on steep slopes or very rough or swampy terrain for distances up to 900 metres, but usually much less.

In the highly industrialized nations a great variety of forest harvesting machines are in use, and many more are under development. Some combine two or more functions. For example, the feller-buncher accumulates bunches of cut trees or stems to load into forwarders or grapple skidders. The feller-forwarder fells trees, stows them in its own cradle and delivers them to landings.

Tree swathers with horizontal circular saws are now being developed in North America for continuous cutting of stems and bunching for skidding or forwarding. These are expected to harvest 300 or more trees 15 to 20 cm diameter per hour, at least 3 times as much as a feller-buncher.

Portable chippers now on the market can process 45 green tonnes of chips per hour from logs up to 56 cm diameter. The "Stumparvester", designed to recover biomass from stumps, is becoming common in Scandinavia. It has an output of 11 to 22 m^3 per day in spruce and pine.

The concept of harvesting large-scale energy plantations on short and mini-rotations is generally predicated on the use of self-propelled harvesting machines (51). Existing "corn combines" are not powerful enough, and apparently cannot be adapted for this purpose. Whatever equipment is used, stumps must be cut without mangling so as to permit coppice growth. A swather-chipper, now under development in the United States, would cut tree stems up to 30 cm diameter near the ground line, drum-chip them, and blow the chips into quick-dumping chip wagons of 10 tonnes capacity. The latter would convey the load to landings for transfer to conventional highway chip vans. In poplar hybrids of 130 green tonnes/ha it should be possible to swath and chip 35 green tonnes/hr. Even higher production rates are envisaged for other conceptual harvesting systems in biomass farms. All of these however are likely to be beyond the reach of the developing world for many years to come.

5.4 Transportation

Methods of conveying biomass from the forest to the point of utilization in developing regions vary from back-packing of firewood by human beings to the employment of massive trucks and vans usually associated with the industries of the developed nations. Where suitable waterways exist logs may be floated, or towed by tugboats in rafts or barges.

Typically, in rural areas of developing countries where wood is carried by animals or humans, all fuel requirements of villages within or adjoining forests are met by wood. In India, where dung is often burned as an alternative to wood, recent studies show that within 10 km of a forest, about 70% of the fuel comes from the forest. Beyond that distance the proportion drops rapidly, until at 15 km it is almost nil (4).

For commercial fuelwood, transport distances by roadway may be 100 km, but a more normal limit is 50 km. Wood is a relatively energy-inefficient fuel with a high ratio of weight to heat output; thus it can seldom absorb transport costs over any but short distances. This subject is dealt with in more detail in the next section.

6. Costs of Producing Useable Biomass

6.1 General

The two major factors influencing the commercial viability of energy farming are biomass productivity and land availability. Other important considerations are crop management, harvesting, and storage (51). However, it is very difficult to evaluate real economic costs associated with biomass production. They depend on many unknown variables, including benefits to conventional forestry operations and to regional development.

In countries with undeveloped forest areas which are also deficient in fossil fuels and other sources of energy, forests commonly provide the cheapest fuel in rural communities. This is reflected in Table 10, adapted from Earl (17).

Table 10. Average Market Prices of Selected Fuels and Power

Fuel	E. Africa (1970)	Nepal (1973)	India (1973)
	(Cost per tonne coal equivalent, $U.S.)		
Wood	14	45	43
Charcoal	22	34	49
Kerosene	57	74	64
Electricity	135	240	401

Earl also makes the following observations (17):

(a) The cost of producing fuelwood from eucalyptus plantations in Uganda (1970) was U.S. $4/tonne CE, but was less than $2/tonne where taungya was practised.

(b) The cost of transport is the most critical factor determining whether fuelwood will be competitive with other fuels; therefore moisture content should be reduced to the minimum.

(c) Storage costs are also lowered if wood is dry. Where it can be stacked for a few days before moving, initial rapid drying will reduce the weight considerably.

(d) The cost of producing charcoal is about \$20 to \$25 per tonne in representative developing countries.

6.2 Costs of Wood Residues and Natural-Stand Biomass

In view of the paucity of information on costs of mill and logging residues for energy production in tropical regions, a recent estimate of such costs in Canada is given in Table 11, together with costs of energy biomass from trees in natural stands not presently utilized for other purposes (47). It should be understood that these figures are broad averages, subject to wide variation according to alternative uses available and other factors.

Table 11. Wood-Residue and Natural-Stand Biomass Costs, Canada

	\$ per oven-dry ton
Mill Residues	1.50 to 9.00
Forestry Operations (logging) Residues	15.00 to 34.00
Natural Stands -	
(i) Unutilized trees in currently logged areas	16.00
(ii) Wood available in areas currently not being logged.	36.00 to 48.00

6.3 Cost of Biomass Grown in Energy Plantations

In the temperate zones, where labour costs are high and rotations long, compound interest often makes investment in growing timber unattractive unless the many ancillary benefits are also quantified and the increase in the value of the land is taken into account. It has been reported that in developing countries with low-cost labour (e.g. Indonesia) plantations yielding 25 m^3/ha/yr can be established at about one-tenth the cost of that in developed countries (17). However financial returns from well-managed natural forests may be higher than from plantations. In either case there can be many indirect benefits to the environment from forests, which are not usually considered in cost-benefit studies.

Current production costs from silvicultural energy farms in the United States are estimated as about $2 per 250,000 Kcal; these could be halved if productivity were doubled (51). The main costs are associated with crop management - fertilizers and irrigation account for up to 40% of the total, and capital only 10%.

Other North American studies indicate that the cost of producing biomass from energy plantations ranges from $20 to $42 per oven-dried tonne (47). These figures could be reduced by $10 to $20/ODT by careful selection of fast-growing species in areas close to conversion plants. Production costs from mini-rotation plantations have been estimated as about $6/ODT (51). Yet another study which assumed short-rotation silviculture, a 30-mile one-way haul distance, and a biomass moisture content of 50%, indicated harvesting and transport costs of $25/ODT.

6.4 Effect of Transport Distance on Cost

Virtually all of the tree biomass used for energy in the rural developing world is in the form of either wood or charcoal. Four tonnes of dry wood produce about one tonne of charcoal, but the latter has nearly twice the calorific value of the same weight of dry wood (17). At short transport distances it is cheaper to use wood, but as the distance increases the point is reached where charcoal becomes cheaper. The critical distance depends on the production cost and weight (including moisture) of the wood, the cost of making charcoal, the efficiency of using the fuel, transportation charges and many other factors.

A table showing production and transport costs of fuelwood and charcoal in East Africa is reproduced below, from Earl (17).

Table 12. Production and Transport Costs, U.S. $ per tonne of fuelwood and charcoal (excluding overheads and profit) in East Africa in 1970. (Wage rate US $0.72 per man/day)

	Fuelwood: Plantation without *taungya*	Fuelwood: Plantation with *taungya*	Fuelwood: Natural forest	Charcoal: Plantation without *taungya*	Charcoal: Plantation with *taungya*	Charcoal: Natural forest
Royalty/net cost of raw material	2·38	1·08	0·14	9·52	4·32	0·56
Conversion costs	1·08	1·08	1·08	10·18	10·18	10·18
Total costs at site	3·46	2·16	1·22	19·70	14·50	10·74
Costs including transport 35 km	6·96	5·66	4·72	23·20	18·00	14·24
Costs including transport 70 km	10·46	9·16	8·22	26·70	21·50	17·74
Costs including transport 100 km	13·46	12·16	11·22	29·70	24·50	20·74

(Transport costs U.S. $0.10 per tonne/km. Assumes 3 stacked m^3 per tonne at 30 per cent moisture content.)

Since weight for weight charcoal contains about twice the energy of wood, 100 km is about the "point of difference" in this example, assuming that wood and charcoal are used with the same efficiency.

A second example from Earl (17), also based on East African data for 1970, is shown in the following chart. This gives a critical distance of 82 km.

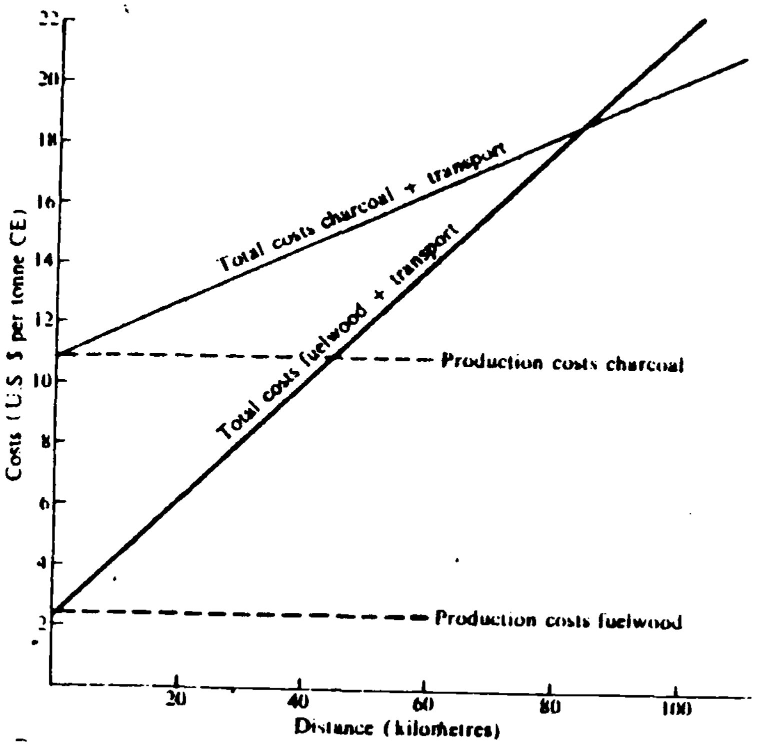

FIGURE 1. NET PRODUCTION COSTS (US$) PER TONNE CE OF FUELWOOD AND CHARCOAL FROM NATURAL FOREST, EAST AFRICA (1970).

Consumer preference is a governing factor in determining the market price, and this is influenced by qualities such as cleanliness of burning and ease of handling as well as calorific value. Liquid and gaseous fuels, both of which can be made from tree biomass, have properties which are much preferred to solid fuels for many purposes, notably industrial uses and space heating, and powering transport equipment.

Fluids and gases are also much more readily transportable than solids and, other things being equal, it is economically feasible to transport them to far greater distances. However the cost of their conversion from tree biomass is much higher than charocal and, with the possible exception of certain small units for domestic or local use, they are unlikely to enter the long-distance energy transportation economies of developing countries to any signficant extent in the foreseeable future.

C. Grass Biomass

1. Introduction

According to Longman and Jenik (46) the areas of the world's natural grassland formations and those supporting a high proportion of herbaceous growth are estimated as follows:

Table 13. World Areas of Savanna and Natural Grasslands

	Area (10^8 ha)
Savanna	15
Tundra and alpine grassland	8
Steppe and other temperate grassland	9
Total	32

Earl's estimate of the planet's grassland area is 26×10^8 ha, a figure in reasonably close agreement with the above considering that the latter probably includes some areas in which trees (savanna) and mosses (tundra) comprise a significant part of the vegetation. It seems reasonable to conclude that the grassland area of the developing world approximates 1,500 million hectares.

In the tropics as in other regions, a sizeable fraction of the natural grass biomass is grazed by wild animals and by domestic livestock. Another and smaller fraction is harvested for use as fodder. At present however these appear to be the only ways in which natural herbaceous growth is converted into useful energy.

On the other hand, vast amounts of energy are wasted each year through fires on grass, brush and forest lands. Although we are not directly concerned with forest fires here, it is interesting to note that the average annual loss of energy in forest fires in Canada (which burned over some 900,000 ha/yr in the period 1965 to 1974) was calculated to be equivalent to more than 50 million barrels of furnace oil (94). This was based on an assumed average fuel load (i.e. the dry weight of all dead material on the forest floor) of 22 tonnes/ha, which is about half of the dry weight per hectare reported for 2-year old elephant grass (60).

Burning has long been regarded as an essential preliminary to cultivation in both forest and savanna (60). Carbon, nitrogen and sulphur in the living biomass and litter are lost, but not those in the humus where the soil fertility is temporarily enhanced. The alkaline ash raises the pH availability of cations in the surface soil - a very important effect on acid soils.

It has been estimated that shifting cultivators burn some 14 million ha of treed lands each year in the tropics and sub-tropics. Grasslands are burned annually over much larger areas to dispose of dry vegetation unpalatable to cattle, and to enhance the new growth of pasture. This severely inhibits the establishment of trees and other perennial plants, and is a major factor contributing to widespread desertification in semi-arid regions.

2. Productivity of Grass Biomass*

Some investigators have concluded that warm-season grasses, such as Bermuda grass and Sudan grass, are equally as well suited for energy plantations as the more promising tree species. Realistic yields in either case are estimated as 7 to 11 tons of dry matter/ha/yr, corresponding to the net conversion of 0.6 to 0.8% of the incident sunlight (78). Grasses grown on agricultural lands probably have a higher potential to produce biomass than forest lands. Each 0.4 ha of an energy plantation (in the U.S.) should supply fuel for two kilowatts of installed generating capacity. Thus a 500-megawatt power plant would consume the output from about 100,000 ha or 1,000 km^3 (78).

Natural grasslands generally have low yields as shown in Table 14, adapted from Nye and Greenland (60), and large-scale removal of biomass from them could precipitate ecological problems.

* Rodin et al (73) estimate that annual increment for the grass communities of steppes, prairies and savannas is between 20 and 55% of phytomass reserves, and for desert communities 30 to 75%. For communities of annual field crops it is 100%.

Table 14. Examples of Total Above-ground Biomass Weight in Tropical Forest and Savanna Fallows

Country	Annual Rainfall (cm)	Type of Fallow Vegetation	Oven-Dry Weight (tonnes/ha)
Moist Evergreen Forest:			
Ghana	165	40 - yr mature secondary forest	337
Congo	185	18 - yr secondary forest	146
Congo	185	5 - yr secondary forest	87
Moist Semi-Deciduous Forest:			
Congo	180	Elephant grass, 2 yrs old	40
Dry Forest and Savanna:			
Ghana	90-100	10-year old coastal thicket	58
Ghana	150	High-grass savanna,* undisturbed 20 yrs -	
		Herbs	9
		Trees	31
Ghana	150	Imperata cylindrica grass	3
Rhodesia	90	Natural grassland	2

3. Elephant Grass (Pennisetum purpureum)

The high productivity of elephant grass is apparent from the above table, exceeding that of any of the tree fallows listed on a basis of annual increment. It is native to Uganda, where it dominates wide areas in the southern part of the country as "derived" savanna (60).

In Egypt, experiments are under way with elephant grass grown in combination with food and other crops as a source of summer forage for domestic animals (16). The grass grows wild in Indoneisa and is now being introduced in forest plantations there to eliminate weeds, improve the soil, and provide cattle food. It is harvested and transported manually to the cattle stalls, where collection of dung for fertilizer is facilitated (34).

*High-grass savanna is much the most extensive formation in the dry-deciduous forest zone (60).

4. Potential of the Biomass for Energy Production

It would be naive to expect that any appreciable fraction of the enormous amount of energy released annually in wildfires and broadcast burns could be captured for useful purposes, although even this may not be beyond the scope of man's ingenuity if energy supplies become sufficiently critical. However, in view of the optimistic projections for energy farms using grass biomass in the United States, it is surely realistic to suggest that studies be made in developing regions to determine whether the energy yield from grass biomass is too low to be practical, or the grasses too difficult to harvest, for use as an energy source.

Elephant grass in particular seems to have adequate yield potential, provided that competing uses for the biomass, or for the quality of land required to grow it, do not make energy production a non-viable alternative. In areas where grass is customarily burned for pasture with serious adverse effects, or where herbaceous growth is unpalatable for animals (such as imperata grass), the harvesting of the vegetation for conversion to energy might be a gainful undertaking.

D. Aquatic Plant Biomass

1. Introduction

Aquatic vegetation can be divided into two broad classes - fresh-water, and marine or ocean plants. Rodin et al (73) estimate the total marine phytomass (i.e., the phytomass reserve in the oceans) as 0.17×10^9 dry tonnes, and that in the lakes and rivers as 0.04×10^9 dry tonnes. Thus the total aquatic phytomass reserve is less than 1/10,000th that of the land phytomass reserve. However, the annual primary production of marine phytomass (60×10^9 dry tonnes) is more than 300 times the oceans' phytomass reserve, while fresh-water phytomass production is about 1×10^9 dry tonnes per year. In total, aquatic vegetation contributes only a little more than 1/3 as much to the world's primary production of phytomass as terrestrial plants do.

It was once widely believed that most of the planet's living matter is concentrated in the seas. Present indications are that the total living biomass (plants and animals) on land is some 750 times greater than in the oceans (73).

Despite this reassessment of marine biomass reserves, the enormous possibilities of aquatic vegetation for contributing to the food supply of man and beast and for furnishing a wide variety of materials for industry are appreciated, but they remain largely untapped. Only very recently have steps been taken to investigate the huge potential of water-plant biomass for energy production (95).

In the warm waters of the tropics aquatic weeds exist and multiply in abundance (57), and some species produce more biomass on a given area than even the most prolific of their terrestrial counterparts. Particularly relevant locations include China, the Philippines, Thailand, Malaysia, Bangladesh, India, Sri Lanka, Sudan, Zaire, Zambia, Guyana, Panama and Mexico (57).

In some of these countries aquatic plants are used to a varying extend for food, animal feed, fertilizer, and water purification. However in most parts of the world the nuisance value of water weeds far exceeds their benefits: they impede navigation, irrigation and fish culture projects; interfere with hydroelectric production; and may contribute to the spread of diseases such as the debilitating schistosomiasis which is prevalent in many developing countries (57).

Some industrialized nations such as the United States have spent large sums in an effort to get rid of water weeds (notably the water hyacinth), and more recently Egypt and the Sudan have jointly embarked on a similar project in the upper waters of the Nile. Now in both cases the development of projects to convert the waste materials to biogas by anaerobic digestion is under study (95).

Obviously there is no need for immediate concern regarding the establishment, culture and productivity of aquatic plant biomass - suitable water areas are the prime requirement. Most of the species useable for energy production are essentially a free crop requiring no seed, tillage or fertilizer. Indeed they thrive on nutrients from domestic and agricultural wastes and sewage effluents. They are highly effective in removing nutrients, heavy metals and other chemical elements from waste water, making them a potentially valuable source of protein fertilizer when free of toxic metals. However the process of water purification does not include the removal of certain micro-organisms such as coliform bacteria (5, 95).

The solid (dry-matter) content of aquatic weeds varies from about 0.5% to 15% of their fresh weight (57). This very high moisture content makes them unsuitable for most energy-conversion processes unless they are pre-dried by pressure (which itself is energy-consuming) or by spreading in the sun (which is time and space-consuming). Therefore, irrespective of the scale of operations, anaerobic fermentation appears to be the only feasible process, since the moisture content of the biomass is in any case very high while fermentation is taking place.

2. Fresh-Water Plants

The two categories - fresh-water plants and marine plants - are not mutually exclusive, since some closely-related species can be found in each, and some, like the water hyacinth, will grow in brackish water though not in sea-water (5).

2.1 Vascular Plants

Among the many fresh-water plants that possess vascular systems (i.e. specialized tissues for conveying fluids between different parts of the organism) two appear to be of particular importance from the standpoint of potential for conversion into energy. These are the water hyacinth and the duckweeds. Both are free-floating; the absence of roots attached to the soil is of some advantage in harvesting.

(a) Water Hyacinth (Eichhornia crassipes)

The water hyacinth is a native of South America, but is now widespread on all continents between latitudes 32 deg. N and 32 deg. S. (88,95). It is a fleshy plant measuring several inches across, and so firm that it is possible to walk across dense floating masses (2).

This water weed is one of the most prolific plants known; a single pair can produce 1,200 offspring in 4 months. Stands of 470 tonnes/ha have been recorded, with a weight gain of 4.8% per day. When grown on warm sewage effluent, up to 800 kg dry matter/ha/day (or 292 tonnes/ha/yr) may be produced (57).

The fresh plant contains approximately 95.5% moisture, 3.5% organic matter and 1% ash (2). When grown on sewage, the dry biomass contains 17 to 22% crude protein, 15 to 18% fibre, and 16 to 20% ash. Nitrogen and potassium are each about 3% (95). Water hyacinths absorb metals selectively into their roots, which may make recovery from effluents possible and also reduces the toxicity in the other portions of the plant.

In addition to the uses for aquatic weeds already mentioned, the possibilities of water hyacinth for pulp and paper manufacture have been extensively tested in the United States. So far however the results have been disappointing (88).

The prospects for conversion to energy on a commercially viable basis, using anaerobic fermentation, are much more promising. Each dry Kg of water hyacinth yields about 370 litres of biogas containing 60% to 80% methane, with a fuel value of 5,300 Kcal/m^3. The residual sludge makes a valuable fertilizer, retaining most of the nitrogen, all the phosphorous, and other minerals (95). In landlocked areas, the return of this sludge to the soil preserves the whole nutrient cycle.

In terms of areal productivity, one hectare of water hyacinths fed on sewage nutrients and yielding 0.8 tonnes of dry plant material per day could produce nearly 200 m^3 of methane daily with a fuel value of more than 1½ million Kcal. On a yearly basis these figures are equivalent to about 70,000 m^3 and 550 million Kcal respectively (57, 95).

The harvesting of water hyacinth and most other aquatic weeds can use either labour- or capital-intensive techniques. Shoreside harvesting requires the moving of the floating plants to the harvester on shore - this can be done manually from boats. For large-scale weed-removal operations in the U.S. elaborate cranes with clamshell buckets, mechanical conveyors, and pumps have all been employed. Mobile harvesters lift and carry the plants to the shore.

Choppers are sometimes incorporated in harvesting machinery, or they may be operated on land at the water's edge. Chopping makes the weeds easier to handle and reduces the bulk to less than 1/4 of the original volume.

Dewatering is necessary for most current end-uses of water weeds, or before transporting to refuse dumps. Up to 70% of the water is removed in this process, which can be carried out in small portable presses, suitable for developing countries and capable of pressing 4 tons of chipped water hyacinth per hour. Although water removal is not needed for anaerobic fermentation, the chopping of water hyacinths is required (57).

(b) Duckweeds (Lemnaceae)

About 40 species of duckweeds are known; they occur in fresh water world-wide. They are small and fragile, varying from pinhead size to a few millimetres across, without distinct stems or leaves and with nearly invisible flowers. They cluster in colonies, forming a scum on the water surface.

Although their rate of biomass increase is less than the water hyacinth's, growth is extremely vigorous and year-round in the tropics. Some species can double their numbers in 3 days or less. Wolffia arrhiza, the world's smallest flowering plant, can produce 265 tonnes fresh weight/ha/yr, equivalent to 10.5 dry tonnes. The average moisture content is about 96% (or nearly the same as the water hyacinth), but in other species it is as low as 90% (50,57).

Large quantities of various species of duckweed are used in tropical Africa and Asia for fertilizer and animal fodder, as well as by humans in Southeast Asia for cakes and as a "poor man's" vegetable. The nutrient value for both man and beast exceeds that of most agricultural crops. Duckweeds are particularly high in protein (typically 37 to 45%), and in nitrogen (6 to 7%). They are also promising for the recovery of nutrients from waste water, and their ability to concentrate metals is high. (50,57).

Although techniques for growing and harvesting duckweeds have not yet been perfected, they are relatively easy to harvest by skimming with rakes or nets. Other advantages in comparison with water hyacinth for biogas production are a generally higher dry-matter content, a high nitrogen content which is needed by bacteria for fermentation, and the elimination of the necessity for chopping or shredding (57, 76).

Much research needs to be done, however, to ascertain the true value of duckweed biomass for energy production. Water milfoil, hydrilla, and alligator weed are other aquatic plants whose potential for this purpose may be worthy of investigation.

2.2 Non-Vascular Plants

(a) The Algae

The algae, like the fungi, belong to the primitive order of Thallophytes. Some are fresh-water and some are marine plants. Their range of sizes and shapes is tremendous - from microscopic, unicellular organisms to huge seaweeds 60 to 90 metres or more in length. Some are free-floating and some are attached to the bottom. All however (unlike the fungi) have chlorphyll, and all lack true leaves, stems, roots and vascular systems.

(b) Microalgae

Among the fresh-water species of algae only the microalgae, ranging from 2 to 100 microns in diameter, will be considered as these are the only ones whose potential for biomass production is being investigated.

These microscopic plants, the largest of which are just barely visible, have a short life span and an impressive reproduction rate because of their efficiency in fixing solar energy. They have a very high protein content (50% to 60%) and the annual production of protein is as much as 22 tonnes per hectare. They purify water containing organic wastes, but growing them requires more elaborate techniques and equipment than conventional agriculture (10).

Experimental evidence indicates that average dry-matter yields of some 20 gm/m^2/day of microalgal biomass are possible. This is equivalent to 73 tonnes/ha/yr, but caution must be exercised when extrapolating the results of short, small-scale experiments in terms of long-term commercial operations (50). As with water hyacinth the greatest productivity is obtained when the plants are grown in sewage effluent.

Microalgae are being used in Taiwan for hog feed, and studies to extend their use for animal feeds are in progress. Some attention is also being given to the possibilities of mass cultivation of algae for energy production. One authority estimates that all the gas needs of the United States could be provided by 5% of the country's land area if used for growing algae and floating plants in sewage ponds, and converting the biomass to methane. However the costs of production by fermentation of algae ($1.50 to $2.00 per 250,000 Kcal) are higher than from solid wastes because of the higher costs of producing algae (9).

The harvesting of algae represents the greatest energy consumption requirement from external sources. The larger microalgae can be harvested by mechanical filtration, which is cheaper than by centrifuging or flocculation (50).

Further investigation of the potential of microalgae for energy production seems to be justified, but this use will have to compete with the value placed on the biomass for livestock feed (50).

3. Marine Plants

The oceans cover more than 70% of the surface area of the globe, and thus most of the solar energy reaching the earth falls at sea. Nations and industries must therefore "go to the oceans" if they wish to utilize a large fraction of the world's naturally received solar energy (93).

At the Ocean Energy and Food Farm Project in California, seaweeds grown in "ocean farms" are considered the most promising means of capturing and storing vast amounts of the solar energy falling on the seas, in a form that can be used for food, animal feed, methane and other fuels, fertilizer, plastics, and "nearly all the other products now obtained from the basic agricultural and energy supply sectors" (93).

The plant on which attention is now being concentrated is the giant California kelp (Macrocystis pyrifera). The kelps are large brown algae, attaining lengths up to 65 metres. They are usually found in the colder seas - a fact which may restrict the possibilities of their use for energy production in most of the developing world. They are however cultivated commercially in the Philippines, Japan and Taiwan where average yields of 0.5 to 4 grams dry weight/m^2/day have been reported. In the northeastern United States small-scale experiments have shown yields of 5 to 10 times this amount (33). These latter figures are roughly comparable with those anticipated from fresh-water microalgae in the tropics.

Adverse water temperatures and the large-scale operations envisaged in the California experiments combine to give the latter little relevance to the present situation in developing countries. However it may be of interest to note that the Ocean Farm Project forsees, before the end of the century, the demonstration of an ocean farm covering some 40,000 ha. This would yield almost 10 million Kcal/yr of food, plus nearly 100 million Kcal/yr in the form of methane, for each hectare of cultivated ocean. On this basis, all of the United States' present annual food and natural gas energy requirements could be produced from an area of ocean surface approximately 750 Km square. Low-temperature, low-pressure anaerobic digestion technology would be used for the production of methane from the kelp biomass (93).

E. Biomass From Agricultural Crops

1. General

1.1 The Biomass Resource Base

Practically all of the plant biomass produced by farmers throughout the world is technically capable of being converted into some form of energy, whether the primary purpose of the crop be for food, animal feed, fibre, drugs and medicines, or other products. While global figures for agricultural production are not directly related to biomass quantities actually available for energy, the following data from FAO (24) do indicate the relative potential, in various regions of the world, for energy production from several crops which are now used, or give promise of being useable, for this purpose:

Table 15. Production (in million tonnes) of Representative Agricultural Crops,1975

Crop	World Total	Developing World Total	Africa	Latin America	Near East	Far East
Sugarcane	652	541	24	279	9.5	225
Cassava	105	104	43	32	1.1	28
Rice, paddy	344	192	5.0	14	4.8	169
Mixed Grains	6.5	0.2	-	-	0.2	-
Cotton	35	16	1.4	4.4	4.1	5.7
Coconuts	30	30	1.6	2.0	-	24
Palm Oil	2.9	2.9	1.1	0.1	-	1.6

Maize, millet, jute, sisal, and many other crops cultivated on a sizeable scale in developing countries might be added to the list.

1.2 Productivity and Availability of the Biomass for Energy

With rare exceptions only that poriton of an agricultural crop which is not used for the customary primary product is available for other purposes, including energy production. In this case, as with other biomass sources, energy must compete with such alternatives as fertilizer, feed, pulp, and a variety of industrial uses. The usual uncertainties of fluctuating demands for these products are, in the case of agriculture, compounded by wide differences in crop yields from year to year according to weather conditions.

The ratio of the annual biomass production per plant to the amount actually used for the primary product (that is, the ratio of the residual to the harvested product) varies greatly with different kinds of crops, as does the overall biomass yield itself. Sugarcane and cassava are discussed in separate sections below. Data based on information from Ghana, regarding other crops given in the preceding table are summarized from (31):

<u>Rice</u> - The total biomass yield averages about 7 to 9 tonnes/ha/yr, of which some 85% is residue in the form of straw, with an additional 3% to 5% of husks.

<u>Coconuts</u> - The yearly production of nuts from coconut plantations is about 25 tonnes/ha. Husks and shells comprise about 85% of the total weight.

<u>Oil Palm</u> - Plantations produce about 4½ tonnes of bunches/ha/yr, 55% of which is residue.

The possibilities of several cereal or grain straws for conversion to energy are being considered in North America. It is reported that the average annual production of straw in Western Canada is 4½ tonnes/ha, and that pelletized straw has an energy content of about 4,000 Kcal/kg (10). Annual yields per hectare in the United States are given as 4½ tonnes for wheat straw, 7 tonnes for rice, 5½ tonnes for corn, and 27 tonnes (total weight) for sorghum (8).

For reasons already given it is extremely difficult to obtain reliable data on the quantity, distribution and availability of various agricultural wastes. Earl (17) considers it "fairly safe to assume that the total (world) consumption of agricultural wastes, e.g. bagasse, cotton sticks, and hay, as fuel is not more than 10 million tonnes of coal equivalent", and he gives the same figure for projected consumption in the year 2000. Zumer-Linder (98), referring to India alone, quotes an estimate of the consumption of vegetable wastes such as bagasse, cotton sticks and hay as totalling 27 million tonnes/yr (or about 17 million tonnes CE). A recent study indicates that 1.4 billion tonnes (850 million tonnes CE) could be used as fuel annually in the United States (8).

Clearly there is wide scope for updating and refining estimates of the contribution that agricultural wastes are making, and potentially can make, towards solving the world's energy problems.

2. Sugarcane (*Saccharum officinarum*)

Sugarcane is one of the most efficient plants known for using solar energy to convert carbon dioxide and water into biomass by photosynthesis. In Iran yields of up to 218 tonnes/ha have reported, but the average for the developing world is between 45 and 50 tonnes per hectare annually (24). The biomass furnishes approximately equal quantities of cane sugar and cellulosic residue (bagasse). The sugar is extracted from the cane, and the residual bagasse is used as a source of fibre for manufacturing pulp and paper, or as a fuel to operate the sugar refinery.

Brazil has taken the initiative in converting sugarcane to ethanol by aerobic fermentation. Initially only the biomass surplus to other uses was diverted to ethanol production, the amount available depending on current sugar and bagasse demands. However Brazil's ethanol motor-fuel program has progressed so well that sugarcane is now being grown specifically for this purpose (58). This is a rare example of an agricultural crop being raised deliberately for conversion to energy in a form other than food for powering human and animal muscles.

The Brazilian government is currently revising its program so as to increase the alcohol content of gasoline to 20% by the early 1980's. In terms of sugarcane production this will require about 1.3 million hectares (77).

According to Brazilian scientists an energy strategy based on biomass is a natural course of action for Brazil because of the availability of land and water, and an ideal climate for growth. The growth potential of trees is also among the highest in the world. It has been estimated that less than 2% of the land area could provide enough fuel to replace all imported petroleum (77). The example which has been set by Brazil and the results it obtains from its biomass programme should be of great assistance to other developing countries in solving their energy problems.

3. Cassava (Manihot spp)

This plant is indigenous to tropical America but is now being cultivated in small holdings throughout the tropics. Brazil, Indonesia and Zaire are the largest producers, and the roots have become a very important source of food in many developing countries.

From the point of view of photosynthetic conversion of solar energy cassava is not as efficient as sugarcane, but it does produce more starch per unit area under relatively dry conditions than any other known crop. This makes it particularly suitable for the production of ethanol by aerobic fermentation. The average starch content is about 30%, although some of the new commercial varieties contain as much as 38% (40). The dry weight is about 40% of the fresh weight (24).

Cassava will grow in relatively poor soils because its root structure seems to act as a scavenger for nutrients. However it does respond well to irrigation and the application of fertilizers. Yields of 15 to 40 tonnes/ha have been reported (40).

Because it will grow on poorer sites than sugarcane and much larger areas of suitable land are available, cassava is being considered as a potential raw material for ethanol production in Brazil.

4. An Example of Potential Energy Production from Agricultural and Forestry Wastes

The Georgia Institute of Technology's study in Ghana (31) presents an interesting plan for converting certain agricultural and forestry wastes into energy, based on the biomass available in, and tailored to the conditions specific to, that country. All the biomass required is surplus to any practical use at present. A labour-intensive pyrolitic conversion system would be used, and most of the components would be fabricated in Ghana.

Table 16. Quantities of Agricultural Residues Available and Areas Required to Produce Them, Ghana

Biomass	Weight (green tonnes/yr) (assumed moist. cont. 50%)	Area from which Recovered (acres)
Rice straw and husks	469,000	165,000
Coconut wastes	622,000	82,000
Oil Palm wastes	21,000	19,700
	1,112,000	266,700
To this is added reforestation wastes, logging wastes, and sawdust	1,363,000	
Total biomass	2,475,000	

All the above, if converted by the pyrolitic process proposed, could yield 310,000 tonnes of charcoal and 250,000 tonnes of oil annually. The energy thus provided would exceed the total energy produced in Ghana in 1973, which was nearly 1/3 of all the energy (equivalent to 1.45 million tonnes of coal) consumed in the nation that year.

F. Biomass From Other Plants

Beyond question there are many plants, not included in the categories we have considered, that merit study from the standpoint of energy production. For example members of the milkweed family are rich in latex from which oil can be extracted by distillation. Bush clover and sago palm are other possibilities whose potential as a source of energy remains largely unexplored.

G. Biomass From Animal Sources

1. Resource Base Potential and Productivity

Unlike most plants, members of the animal kingdom are incapable of using the free energy of the sun for manufacturing their own body biomass; their energy must be supplied from external sources in the form of food. Therefore it is most unlikely that any animals will ever be deliberately raised for the energy that can be derived from their carcasses; this would be a highly inefficient way of using the initial energy input.

It is also true that practically no parts of the carcasses of animals raised for other purposes are likely to be available for conversion to energy, either in developed or developing countries. In the former, abbatoir residues are nearly all used by various industries - there is not enough true waste to be of any significance. In developing countries most of the internal organs are habitually used as food, and the skins for leather, clothing and shelter. The bones may be ground up for fertilizer, but otherwise they have very little energy value (61).

The only biomass of animal origin that has any significance for energy production is excrement. Besides its great importance as a fertilizer, animal dung has been used for centuries as fuel in many developing countries. The growing scarcity of firewood is resulting in the diversion of higher proportions of dung from fertilizer to fuel, often with disastrous effects on crop productivity. In the semi-arid tropics, ICRISAT estimates that 75% of the cow dung is burned today instead of being used as fertilizer (6). Each tonne of cow dung burned may mean a loss of about 50 kg of food grain (4).

Viewed in world perspective, the populations of the principal kinds of animals whose potential for dung production for energy purposes merits consideration in developing countries are given by FAO (24) as follows:

Table 17. Representative Animal Populations (in million head), 1975

Animal	World Total	Developing World Total	Africa	Latin America	Near East	Far East
Cattle	1,201	685	122	260	45	257
Buffalo	132	99	-	-	3.8	95
Horses, Mules, Asses	121	73	14	43	11	5
Camels	14	13	6.8	-	4.4	2.0
Pigs	674	120	6.7	71	0.2	41
Sheep and Goats	1,447	745	203	165	203	174

The productivity of most of these and of some other members of the animal kingdom, in terms of dung production and the moisture and nitrogen contents of the excreta, is shown in the following table compiled by Makhijani (48).

Table 18. Estimated Annual Production of Dung per Head, Indicating Moisture and Nitrogen Contents

Animal	*Fresh Manure per 1,000 kg Liveweight (kg/yr)*	*Assumed Average Liveweight (kg)*	*Fresh Manure Production Assumed per Head (kg/yr Except Item 7)*	*Assumed Moisture Content of Fresh Manure (Percent)*	*Nitrogen Content Percentage of Dry Matter*	
					Solid and Liquid Wastes	*Solid Wastes Only*
1. Cattle	27,000	200	5400	80	2.4	1
2. Horses, mules, donkeys	18,000	150	2700	80	1.7	1 1
3. Pigs	30,000	50	1500	80	3.75	1 8
4. Sheep and goats	13,000	40	500	70	4.1	2 0
5. Poultry	9,000	1.5	13	60	6.3	6 4
6. Human feces without urine		40 to 80	50 to 100	66 to 80	–	5 to 7
7. Human urine	-	40 to 80	18 to 25 kg dry solids/yr	–	15 to 19 (urine only)	

On a dry weight basis the energy content of chicken, cattle, and hog manure varies from about 3,500 to 4,500 Kcal/kg (83) and one tonne of cow manure is equivalent to 0.58 tonnes of coal (17).

There are few uses for animal dung other than fertilizer and fuel. The biogas conversion process is inexpensive and yields both these products. It is therefore not unreasonable to assume that a much larger proportion of the total biomass that can be collected could be made available for this purpose than is the case with most other kinds of biomass we have considered.

Using data from the two tables above, it may not be too unrealistic to suggest that, of the estimated 278 million tonnes of dry dung produced annually by the 257 million head of cattle in the Far East (most of which are in India) one-half could be collected for biogas conversion. This would be equivalent to about 80 million tonnes of coal. Assuming that 50% of this energy were converted to biogas, the net energy available would be 40 million tonnes CE/yr, or about 1/4 of the world's consumption of hydroelectric power in 1970.

2. Cattle

In India, which probably accounts for about 2/3 of the world's annual consumption of cow dung as fuel (17), 98% of the dung cake so used does not enter commercial channels (81). This makes it particularly difficult to arrive at meaningful estimates of both production and consumption. Singh (81) reports that total production estimates in India vary from 345 to 1,490 million wet tonnes/yr. His own estimate is 575 million wet tonnes/yr, corresponding to about 115 million dry tonnes annually. Estimates of the proportion that is diverted to fuel range from 20% to 50%.

Earl (17) suggests that the total world consumption of cow dung for fuel is not less than 150 million dry tonnes/yr of which 67% is in India, 9% in Turkey and 7% in Pakistan. He assumes that this figure will be unchanged by the year 2000. Arnold and Jongma (4) estimate that the total use of cow dung in parts of Asia, the Near East and Africa may be of the order of 80 million tonnes/yr dry weight. This is a considerably lower figure than Earl's.

3. Other Animals

Domestic livestock other than cattle (with which buffalo may be included) are of much less importance and are usually ignored in statistics of dung production for energy purposes. Pigs have a relatively high ratio of dung to liveweight, and the manure has a high nitrogen content (48). The husbandry of sheep and goats, which are commonly associated with nomadic populations in the east, is such that the collection of dung is difficult in comparison with animals that spend much of their time in stalls or pens.

Game animals are even less promising as a potential source of energy. However if proposals for game farming in East Africa materialize (38) they should not be excluded from future consideration.

4. Domestic and Sewage Wastes

A variety of waste materials from household and barnyard, including vegetable as well as animal biomass, may be included in the feedstock for biogas plants. Nightsoil (human feces) produces nearly 4 times as much gas as cow dung alone on a dry-weight basis. Even a 25:75 mixture of nightsoil and cow dung increases the volume of gas produced by nearly 60 per cent (81). Both the social and the possibly beneficial health implications of this practice must of course be taken into consideration.

Sewage effluents consisting mainly of biomass are readily adaptable to biogas conversion. Municipal solid wastes in St. Louis, Missouri, are being used for power generation, with a heating value of about 2,500 Kcal/kg (10). In the developing countries, however, less than 7% of the population now have sewage disposal facilities (50). Thus there is little prospect that sewage effluents will make a significant contribution to the energy requirements of those countries in the near future.

Chapter III
Technologies for Converting Biomass into Energy

A. Introduction

It is the purpose of this chapter to examine the technologies which are concerned with the conversion of renewable biomass into more convenient and efficient gaseous, liquid, or solid fuels, and to determine if these technologies have potential application in the developing countries where traditional fuels are relatively inefficient and are becoming quite scarce and expensive. In most countries various forms of biomass are available, or presumably could be made available, but, because of the bulk and relatively low heating value of these materials, they cannot be economically transported very far from the source. A process is therefore needed for converting bulky biomass, as it is formed in nature, into clean, efficient, energy-intensive fuels which can be used as replacements for petroleum products in providing heat and light in the rural villages, and in providing fuel for small engines. It is expected that the economics of some processes, especially those which are labour-intensive, may be quite different and even more favourable in the developing countries.

1. Energy Usage in the Developing Countries

The energy requirements of a family in a rural village of a developing country are relatively small compared to those of an urban family in highly industrialized society. These requirements also vary considerably from one country to another, as does the type of fuel available. India may be considered as a typical example of a developing country where there is a serious fuel shortage and some information will be given regarding the fuel situation in that country.

According to the 1971 census 80% of the population in India lives in rural villages (85). Their pattern of fuel consumption is shown in Table 19.

Table 19. Pattern of Fuel Consumption in Rural India

Fuel	Percentage share
A. Commercial	
Soft coke	1.6
Kerosene	3.8
Electricity, gas, etc.	*
B. Non-commercial	
Firewood	58.6
Dung cake	21.0
Vegetable wastes	15.0
Charcoal, vegetable oil, etc.	*
Total	100.0

* Negligible

These data indicate that commercial fuels, which are common in urban areas, only account for 5.4% of the total energy needs of the rural population. The census also found that 77% of the firewood, 98% of the dung cake, and all of the vegetable wastes are not monetized, i.e. 80% of the fuel requirements of the villages is essentially free. However the effective utilization of these fuels is believed to be very poor, because of their much lower system efficiency.

The traditional use of cow dung as a fuel in India has been increasing because of the growing scarcity of firewood and other fuels and is now believed to require 30-50% of the total dung available (85). This wasteful practice is of concern to the authorities because it deprives the soil of an important source of nutrients and organic matter which are needed for improving fertility. An alternative method of recovering energy from this material without destroying its fertilizer value will be discussed below.

2. Review of Technology Available for Converting Biomass to a More Convenient Fuel

For the purpose of this review it has been considered appropriate to discuss the various technologies for converting biomass into a more convenient form of energy under the following four categories:

(1) Thermal Conversion Processes
(2) Thermochemical Conversion Processes
(3) Fermentation Processes
(4) Novel Unproven Concepts

B. Thermal Conversion Processes

1. Complete Combustion

1.1 Technology

The simplest and most direct method of recovering energy from biomass in the form of heat is by the traditional method of complete combustion, i.e. burning in the presence of air until all of the organic material has been converted to carbon dioxide and water. The burning process can take place under a variety of conditions and in a variety of furnaces, from an open pot which is the least efficient, to a fluidized bed combustion unit which is the most efficient.

Combustion begins after the residual moisture has been driven off and the temperature of the fuel has been raised to the ignition point (590^{o}C), i.e. the temperature at which rapid decomposition of the organic matter takes place, giving rise to large volumes of gaseous decomposition and distillation products. Most of these gases are combustible but they are evolved so rapidly that a portion of them escape without being ignited. They also carry off small particles of unburned or partially burned solid material which are visible as smoke. This rapid and incomplete combustion results in a considerable loss in efficiency. After all of the volatile materials have been removed the residual carbon burns more slowly and more efficiently.

The rate of combustion is controlled almost entirely by the amount of air available at the combustion site. If there is an excess of air, combustion will take place rapidly and more or less completely, but these advantages are offset to some extent by the heat lost in warming the excess air to the combustion temperature. In commercial boilers it is therefore essential not only to use a minimum excess of air but to mix it with the fuel as thoroughly as possible. Considerable wasteage of heat cannot therefore be avoided in an open fire, or even in a stove which is not air tight.

The efficiency of combustion is also dependent on the size of the fuel particles and on their moisture content. It is, for example, believed that it is economically attractive to grind wood down to a certain size but the energy consumed in pulverizing the wood below this size is in excess of that gained from the increased combustion efficiency.

Freshly cut "green" wood and all other forms of biomass such as straw, animal dung, etc., have a high moisture content, i.e. 20-80%, based on their oven-dry weight. Drying of these materials is difficult and requires considerable time. It should also be noted that dry lignocellulosic materials rapidly re-absorb moisture from the atmosphere until they reach an equilibrium moisture content of 10-22%, depending on the ambient relative humidity. This contributes greatly to transportation and storage problems, especially in tropical countries, and makes it rarely possible to obtain a moisture-free fuel from any form of biomass.

The presence of moisture in these fuels reduces their heating value, not only by the amount of heat required to evaporate the free water, but, in addition, some heat is required to free the bound water from the wood cells. The effect of moisture content on the heating value* of wood is shown in Figure 2 (18). These results indicate that it is essential to remove as much moisture as possible prior to combustion, and that it is inefficient to burn biomass with a moisture content in excess of 30%.

* See definitions, Appendix I.

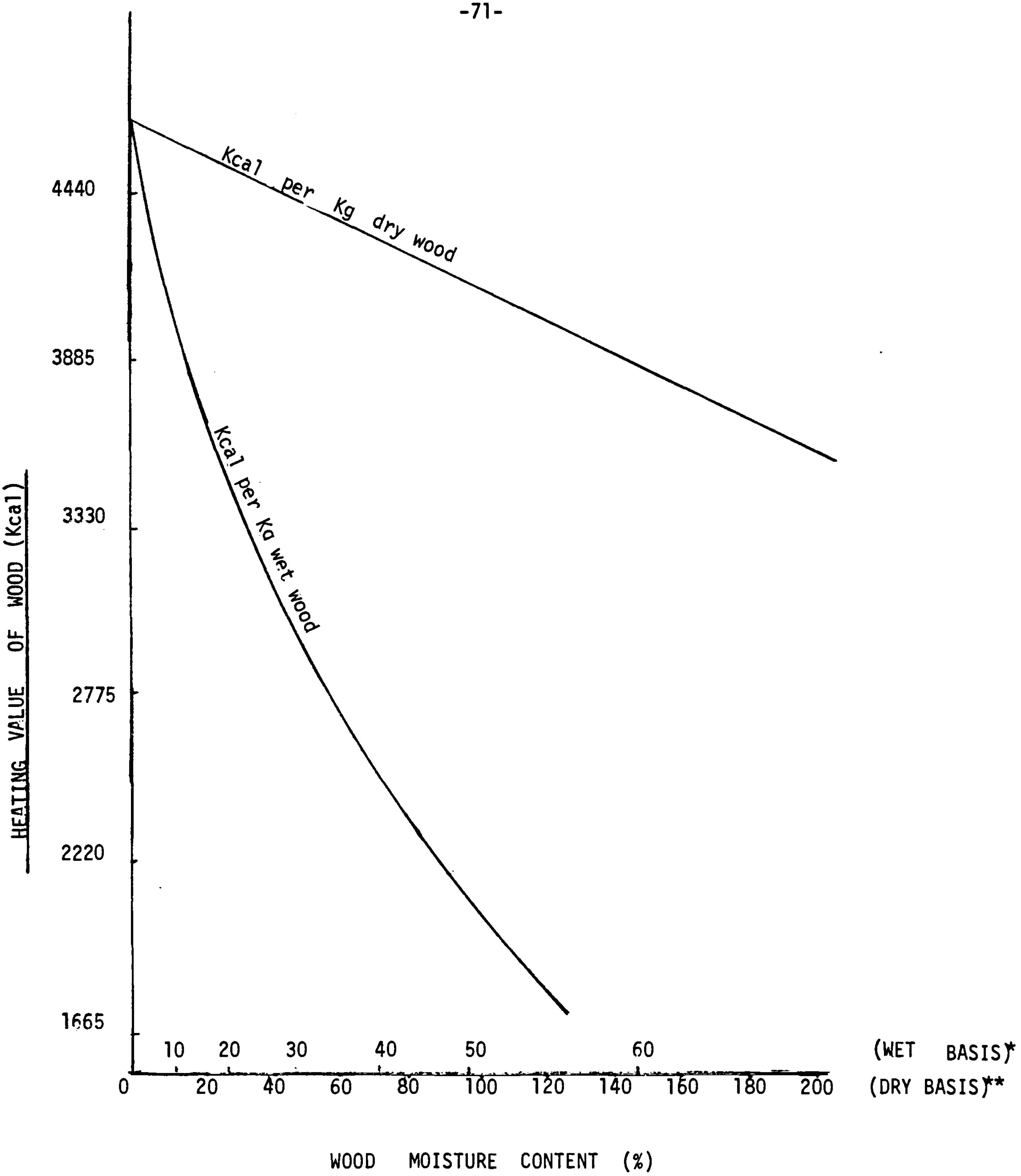

FIGURE 2. EFFECT OF WOOD MOISTURE CONTENT ON ITS HEATING VALUE.

$$\text{* WET BASIS} = \frac{\text{Wet Weight} - \text{Dry Weight}}{\text{Wet Weight}}$$

$$\text{** DRY BASIS} = \frac{\text{Wet Weight} - \text{Dry Weight}}{\text{Dry Weight}}$$

The calorific value* of all fuels is basically a function of their carbon and hydrogen content and may be calculated from the percentage of these two elements. Lignocellulosic materials, however, in addition to carbon and hydrogen, contain a high percentage of molecular oxygen, whereas fossil fuels contain essentially none. The presence of oxygen in the molecule lowers its heating value and thus reduces the temperature in the furnace. This may cause a reduction in the efficiency of the boiler, depending upon its design and operating conditions (52).

It should also be noted that some tropical woods contain certain chemicals which, on combustion, give rise to toxic vapours. This possibility would have to be investigated before proposing any change in fuel supply.

The system efficiency* is also dependent to a very large extent on the type of combustion unit. In the rural villages of the developing countries partially-dried animal dung or wood is burnt in a "chula" with an average efficiency of about 5-11% when used for cooking (48, 64). Conventional wood-burning stoves with a controlled air supply likewise only have an efficiency of about 12.5% when used for cooking, or about 50% when used for space heating (12).** Gas burners, on the other hand, have an efficiency of about 45% when used to cook food or heat water because the flame can be controlled and it can be applied more directly to the surface which is being heated (14). The system efficiency of charcoal has been estimated to be 20-35%, because it burns with essentially no smoke or flame and the heat generated can be confined to a limited area.

* See definitions, Appendix I.

** It has been reported that a locally-produced cooking and heating stove for houseboats in Kashmir operates at higher efficiency than this. Outside air controlled by a simple check-valve is introduced at the base of the fuel. Condensed liquids in the smoke pipe drain off beyond the cabin wall, thus minimizing corrosion problems (72).

This wide variation in system efficiency is of primary importance in assessing the value of converting biomass into a more convenient and controllable solid, liquid, or gaseous fuel. The conversion process may or may not require some energy but in any case there will be a net loss in gross fuel value. However, in most cases, there will be a substantial improvement in system efficiency which will more than offset this loss and will result in a much higher net fuel value. The conversion of wood into charcoal is a typical example which will be discussed in more detail in a later section.

On an industrial scale the use of wood, or straw, or other forms of biomass as a fuel has been largely restricted to those industries which have them available as wastes. Thus there have not been any major improvements in the design of the equipment used for burning solid fuels until recently, when it has become more economical to use these wastes. The conventional Dutch oven type of furnace is therefore being replaced by fluidized bed units which are more efficient because of two major changes in design, i.e. (a) the fuel is burnt in suspension, thus permitting very intimate mixing with the optimum ratio of air and (b) the boiler is separated from the combustion chamber so that the heat is transported by the hot combustion gases. This provides a more flexible system with respect to the type of fuels which can be accomodated. The efficiency of a fluidized bed wood waste combustion unit is claimed to be equivalent to that of an oil or gas fired boiler (97). It is therefore possible to estimate the value of a ton of wood waste from the cost of a thermal equivalent of fuel oil, at various price levels per gallon, as shown in Table 20 (97).

It is apparent that direct combustion is a complex process which can vary greatly in efficiency, depending upon a number of independent factors. In the developing countries the efficiency that is obtained by burning partially dried solid fuels in a open fire is probably the lowest possible, in spite of the fact that fuel is very scarce in many of these areas and the labour involved in collecting the fuel represents a substantial portion of the family productivity.

Table 20. Value of a Tonne of Wood Waste as a Function of Fuel Oil Costs (97)

Moisture Content of Wood Waste	Average K.cal content /Tonne	Equivalent #2 Oil	Comparable Value of one Tonne of Wood Waste ($)				
			30¢ Oil*	35¢ Oil*	40¢ Oil*	45¢ Oil*	50¢ Oil*
50% Moisture 50% Dry Wood	2.23×10^6	62.7 gal	18.81	21.95	25.08	28.22	31.25
30% Moisture 70% Dry Wood	3.35×10^6	94.6 gal	28.38	33.11	37.84	42.57	47.30
10% Moisture 90% Dry Wood	4.46×10^6	125.4 gal	37.62	43.89	50.16	56.43	62.70

* Oil costs are expressed as cents per U.S. gallon

1.2 Suitability for Direct Combustion

Consideration will be given to the suitability of the various types of biomass which are available, or may be potentially available, to a rural community.

1.21 Wood

Wood has been a primary fuel since man discovered fire but it does have some undesirable characteristics, e.g. when harvested it has a moisture content of approximately 50%, it is difficult and slow to dry, it is costly to transport because of its bulk, and it burns with a long flame and considerable smoke, both of which result in a loss of combustion efficiency; the efficiency is also reduced by the presence of moisture and thus it must be sheltered from the rain during storage. The hygroscopic nature of wood also makes it virtually impossible from a practical point of view to maintain it in an oven-dry condition.

The principal advantages of wood as a source of fuel are that it is socially and environmentally acceptable, it is not particularly hazardous, and it can be burnt in small and simple equipment which can even be home made. The only byproduct is a small amount of ash which has some value as a fertilizer as it contains all of the potassium and other minerals which were present in the original wood.

1.22 Residues from Agricultural Crops

Cereal straws, husks, hulls, and stalks all have a heating value similar to wood, i.e. 4440 - 5000 Kcal per Kg, depending on their ash content, and have similar advantages and disadvantages when used as a fuel by direct combustion. The relatively higher bulk of these materials causes greater transportation and storage problems, and burning in a primitive type of stove as used in rural villages is much more difficult and less efficient than burning wood. Most of these problems could be solved by compacting or pelletizing these residues but this requires relatively large and expensive equipment which would have to be purchased and operated on some type of community basis.

It has been reported that pelletizing only requires 2% of the energy content of the biomass unless considerable moisture is present in which case it may require up to 8% (7). Although pelletizing does improve the transportation and storage of biomass, its primary purpose is to improve the conversion technology, e.g.:

(a) Pellets have a higher heat content per unit volume.
(b) Pelletizing removes most of the residual moisture in the biomass.
(c) Pellets have a uniform size which is essential for use in automatic handling equipment.

Most forms of biomass, with the exception of municipal trash, can be pelleted without the addition of a supplementary adhesive since the lignin and moisture both act as natural binders. Pelletizing equipment is now being manufactured by three different firms in the U.S.

1.23 Grasses

Elephant grass and certain other grasses in developing countries appear to have potential for fuel, but insufficient information is available to determine whether the energy yield from them is high enough to be economical, or what harvesting methods should be used.

1.24 Fresh-water and Marine Plants

As noted earlier in this report the potential yield of biomass from both fresh-water and marine plants is very great. However, the extremely high water content of many of these plants as harvested, and the difficulty in drying them in the sun, may preclude their use as a fuel by direct combustion techniques. Other methods of converting these wet crops into energy are considered to be more promising and will be discussed in a later section.

1.25 Animal and Human Wastes

India appears to be one of the few countries in which a systematic attempt has been made to determine the extent of use of non-commercial fuels. The survey indicated that 120 million tons of wood, 50 million tons of dry dung, and 30 million tons of vegetable wastes were burned each year, mostly in the villages where 80% of the population is located (48).

The direct combustion of dung is a very wasteful process, not only because of the inefficiency of combustion but because the nitrogen content is destroyed by burning. Phosphorous and potassium remain in the ash but it is not generally recovered for use as a fertilizer. It is estimated that these losses amount to approximately 500,000 tons of nitrogen, 300,000 tons of phosphorous, and 500,000 tons of potassium per annum (66). There is also the water content of the dung to be considered as this amounts to a considerable loss of valuable moisture in areas where it is needed. The alternative method of converting dung to a combustible gas, i.e. biogas, and conserving all of the nutrients for subsequent use on the land is much preferred and will be discussed in a later section.

2. The Pyrolysis of Biomass into Charcoal and Various Combustible Liquids and Gases (Wood Distillation)

When wood or other lignocellulosic biomass is heated in the absence of air it breaks down both physically and chemically into a complex mixture of liquids and gases and a residual char, commonly known as charcoal. This process is known as "Pyrolysis". It can be carried out under a wide variety of conditions, the two extremes being either to maximize the production of charcoal, or to convert the total organic portion of the biomass into combustible liquids and gases. The latter process is usually referred to as "Gasification".

By comparison with the relatively slow fermentation methods of converting biomass into gaseous and liquid fuels, which will be discussed later, pyrolysis or gasification offers high reaction rates in relatively small plants and the capability of converting a wide variety of feedstocks into a single product or a variety of products. These products will be discussed in the natural sequence in which they occur as products of the pyrolysis reaction.

2.1 Charcoal

The production of charcoal in simple earthen pits has been carried out for hundreds of years primarily for use as a fuel because of its improved burning properties. Towards the end of the 19th century more sophisticated equipment was introduced in order to recover the methanol, acetic acid and other byproducts which were needed by other industries. Thus "wood distillation" became a thriving chemical industry until the mid thirties when it was discovered that methanol and acetic acid could be synthesized more economically from petrochemical feedstocks. While the demand for charcoal in the industrialized countries declined because of the convenience, availability, and low cost of the petroleum fuels, charcoal still remains one of the most important fuels in the small rural households in the developing world.

Charcoal is comparatively easy to ignite and burns evenly with essentially no smoke or flame. This flameless combustion makes it possible to control and utilize the heat more effectively because it is concentrated within a smaller area than is possible with wood where the flames dissipate the heat in all directions.

Charcoal is a non-hygroscopic fuel and therefore can be maintained in a relatively dry condition with a minimum of protective measures. The absence of any significant amounts of moisture or molecular oxygen in the charcoal is also an advantage because of their adverse effects on heating value. Charcoal has a calorific value of 7240 Kcal/kg, and a system efficiency in an open cooker of 20-35%, thus giving a net average fuel value of 1950 Kcal/kg (4). By comparison, air dry wood (moisture content, 25-30%) has a calorific value of 3500 Kcal/kg and a system efficiency of 5-10% thus giving an average fuel value of 260 Kcal/kg. Thus the relative superiority of charcoal as a fuel over wood is 1950/260 or approximately 7.5/1. This advantage becomes even more important as the distance between the fuel source and the point of use increases, and transportation charges become a significant factor in the overall cost of the fuel.

2.2 Charcoal Production Technology

The process of converting wood to charcoal takes place in two stages, i.e. the "drying" and the "coaling" stage. The heat needed for drying and to initiate coaling is furnished by burning part of the wood. This is controlled by regulating the amount of air entering the kiln. After an initial surface zone of dry wood has been established, further heating breaks down the wood to charcoal and this process continues progressively throughout the kiln charge.

The manufacturing process has evolved slowly over the past 200 years from crude earthen pit kilns to modern beehive kilns which are reasonably efficient and controllable. This type of equipment works well with forestry wastes, particularly the limbs and branches of trees, but is not suited for finely divided agricultural wastes. The charcoal produced by these kilns is suitable for domestic consumption without briquetting or further processing.

The yield of charcoal is approximately 30% of the dry weight of the wood and the density varies from 0.2 from softwoods to 0.5 from the heavy hardwoods. Its texture ranges from "soft and crumbly" to "hard and brittle", and is dependent on the carbonization conditions and the original wood density. The briquetting of charcoal greatly improves its handling properties but adds considerably to the cost as a 10% starch binder is required.

2.3 Recent Developments in Charcoal Production Technology

The production of charcoal is of particular interest to the developing countries because of its superior fuel properties as compared with wood and other forms of biomass. In many of these countries the manufacture of charcoal is being carried out on a small scale in relatively unsophisticated equipment. This type of operation is quite labour-intensive, the yield of charcoal is poor, and there is virtually no recovery of byproducts .

More recently, and especially since the energy crisis, new and improved technologies for charcoal production are being developed. Their primary objective is to develop a continuous process which will be more efficient with respect to labour and the recovery of charcoal and other gaseous and liquid fuels.

It is beyond the scope of this study to review all of the new technologies in this field and hence this discussion will be restricted to three typical processes each representing somewhat different objectives.

2.31 The Nichols - Herreshoff Furnace Process, Nichols Engineering and Research Corporation, Belle Mead, New Jersey

This process produces only charcoal and a gaseous fuel, the latter having a calorific value of approximately 1780 Kcal/m^3. This is in excess of the heating requirement for drying the wood and, if used for in-plant steam generation, is capable of producing 7500 lbs of high pressure steam per ton of wood processed. Assuming a charcoal yield of 30% by weight, the total energy recovery from the wood is about 67%, as compared with approximately 44% when only the charcoal is recovered as in a conventional charcoal kiln (52).

2.32 The Tech-Air Process, Tech-Air Corporation, Atlanta, Georgia (42).

This process was developed by the Georgia Institute of Technology to convert waste biomass into more convenient and more efficient fuels. It consists of a steady-flow continuous low-temperature pyrolysis in a porous vertical bed but the actual details have not been disclosed. The advantages of the process are its simplicity and its low temperature operation which result in a very economical design. It has been operated on a scale of 50t/d using a variety of feeds including peanut hulls, wood chips, pine bark and sawdust, municipal wastes, nut hulls, and cotton gin wastes.

Using a dry feed a total energy recovery of 92% can be obtained in the form of charcoal (35%), oil (35%), and a combustible gas (22%). In actual practice some of the combustible gas is used to dry the feed down to moisture content of about 4%, thus reducing the energy recovery to 70-92%, depending on the moisture content of the feed.

The recovery of 70% of the original fuel value in the form of high calorie charcoal and fuel oil, and the successful operation of this process on the relatively small scale of 50t/d, are attractive features from the point of view of application in the developing countries. It has also been reported that, on this scale, the equipment is portable so that when the supply of biomass is exhausted at one location it can be moved to another. Unfortunately no information is available at the present time as to capital or operating costs.

2.33 The Occidental Flash Pyrolysis Process, Occidental Petroleum, La Verne, California

The primary objective in this process is to convert municipal waste into a petroleum-type fuel oil. Since municipal waste, on an ash and moisture free basis, consists largely of cellulosic materials, it is expected that the process should work at least equally well, if not better, on biomass feed. The principle of the process is to provide a short residence time flash pyrolysis that converts finely shredded wood waste into a char, a combustible liquid, and a medium heating value flue gas. The gas is recycled for use as a transport medium and is eventually burned to provide heat to dry the feed. The char is also burned to provide heat to the pyrolysis reaction. The yield of products is shown in Table 21.

Table 21. Yield of Products, Occidental Flash Pyrolysis Process

	Calorific Value	Yield from 100 kg dry feed (kg)	Energy Recovered (kcal)
Char	4570 Kcal/kg	20	91,400
Oil	5900 Kcal/kg	40	236,000
Gas	3385 Kcal/m^3	30	119,470*
Water		10	
		100 kg	446,870 Kcal

* The weight per m^3 of gas, i.e. 0.85 kg, was calculated from the composition, as reported by Occidental Research Corporation (65).

Assuming that the cellulosic wastes used as feed have a calorific value of 4720 Kcal/kg, this represents an energy recovery of approximately 94%.

A 200 t/d demonstration plant has been constructed at San Diego, California on behalf of the Environmental Protection Agency and the City of San Diego and this plant is in the early stages of operation. The feed is to be a highly cellulosic municipal solid waste and the char is to be recycled internally as a heat source.

The cost of a 1000 t/d plant for processing municipal waste has been estimated to be $25.2 million dollars but a substantial part of this cost is for separating and recovering the glass and metal values. This equipment would not be required if uncontaminated biomass is used as raw material. The principal advantage of this process is the production from biomass of a synthetic oil which is comparable in most respects to "Bunker C" fuel oil. Because of the relatively high calorific value of this oil, i.e. 5900 Kcal/kg, as compared with biomass (4700 Kcal/kg) and the other advantages of transporting and burning a liquid fuel, the process appears to have excellent potential, particularly in areas where the supply of biomass is a considerable distance from the point of use.

2.4 Wood Distillation

Wood distillation is a more sophisticated version of the traditional process for manufacturing charcoal and differs from it in that most of the volatile products, in particular methanol and acetic acid, are recovered and sold as pure chemicals (Table 22), (17). As referred to earlier the synthesis of methanol and acetic acid from petrochemical feedstocks has caused the wood distillation industry in the industrialized countries to virtually disappear. It has been suggested, however, that with the increasing price of coal and oil over the next few years the products of wood distillation may again become competitive in the overall situation with the corresponding chemicals produced from coal and oil. This situation may already exist in the developing countries where petroleum costs are higher and labour costs are lower in relation to the cost of other commodities.

Table 22. Average Products Available from Tropical Woods

	Yields per 1000 kilograms of dry wood
Charcoal	300 kg
Gas (calorific value approximately 2500 Kcal/m^3)	140 m^3
Methyl alcohol	14 litres
Acetic acid	53 litres
Esters (mainly methyl acetate and ethyl formate)	8 litres
Acetone	3 litres
Wood oil and light tar	76 litres
Creosote oil	12 litres
Pitch	30 kg

The wood distillation process may otherwise be justified in areas which have a plentiful supply of wood but which are too far from the areas of consumption. In such cases the energy consumed in transporting the wood may equal or exceed the energy content of the delivered wood. The principal products of the wood distillation process, i.e. charcoal, methanol, and oil, not only have a much higher calorific value than wood but also can be used much more efficiently as a fuel so that the net transportation cost per unit of heat will be correspondingly lower. This is illustrated by the following Tables 23 and 24.

These estimates indicate that, on a weight basis, the products of wood distillation, i.e. charcoal, methanol, and pyrolytic oils have net fuel values approximately 4 to 5 times greater than that of the original wood. This represents a saving in transportation costs of approximately 75-80%. It will therefore often be cheaper to use these pyrolysis products rather than wood when transportation costs are substantial (17).

There is a loss in "gross" energy content when wood is pyrolysed into charcoal, methanol, and pyrolytic oils, but there may be an overall gain in using the products of pyrolysis because they can be burnt much more efficiently. Table 24 illustrates this point.

Table 23 A Comparison of the Fuel Value of Wood and the Products of Wood Distillation

Fuel	Calorific Value* (Kcal/kg)	System Efficiency* (%)	Effective Calorific Value* (Kcal/kg)	Fuel Value Compared to Wood
Wood	4718	11**	519	1.0
Charcoal	7215	27.5***	1984	3.8
Methanol	4756	45****	2140	4.1
Pyrolytic Oils	6382	45****	2862	5.5

* See definitions, Appendix I.

** References (48, 64).

*** The system efficiency of charcoal when used for cooking food has been reported to be 20-35% (4). An average figure of 27.5% was therefore used in this calculation.

**** It has been assumed that methanol and pyrolytic oils can be used as effectively as natural gas when used to heat water or cook food, i.e. about 45% (14).

Table 24. Relative Calorific Values and Effective Calorific Values of One Tonne of Wood and Its Pyrolysis Products

		Calorific Value (Kcal)	System Efficiency	Effective Calorific Value (Kcal)
Wood	(1000 Kg) x 4718	4,718,000	(.11)	518,980
Principal Pyrolysis Products				
(1) Charcoal	(300 Kg) x 7215	2,164,500	(.275)	595,237
(2) Pyrolytic Oil	(70.4 Kg) x 6382	449,292	(.45)	202,181
(3) Methanol	(11.2 Kg) x 4756	53,267	(.45)	23,970
		2,667,059		821,388

Relative Calorific Values (Pyrolysis Products/Wood) $= \frac{2,667,059}{4,718,000} = 0.56$

Relative Effective Calorific Values (Pyrolysis Products/Wood) $= \frac{821,388}{518,980} = 1.58$

The above estimates indicate that only 56% of the calorific value of the wood is recovered when it is converted into charcoal, pyrolytic oils, methanol, etc. However, because these pyrolytic products can be burnt more efficiently, the effective calorific value is 1.58 times greater than that of the original wood.

Because of this substantial gain in efficiency, it is suggested that wood distillation may provide an economic solution to the problem of providing fuel to communities which are too distant from forested areas to take advantage of the available wood. Wood distillation plants are traditionally small and labour intensive as compared with modern chemical plants, but depending on the availability of capital, labour, and raw materials, these may not be serious disadvantages in certain situations.

2.5 Pyrolysis of Biomass from Agricultural Sources

Wood is the most consolidated form of biomass available and is therefore best suited for the production of charcoal. Agricultural residues and all types of terrestrial and marine plants are similar to wood in composition and therefore will produce essentially the same decomposition products when subjected to pyrolysis. They differ markedly from wood, however, in such characteristics as physical form and water content and are inferior to wood in these respects. Provided that the water content is controlled within reasonable limits they could be used for the manufacture of charcoal. The quality of the charcoal produced from these sources, however, would be adversely affected by their small particle size and low density and it would therefore probably be necessary to briquet the resulting charcoal before it could be shipped and used.

3. Gasification - the Complete Conversion of Biomass into a Combustible Gas

The complete conversion of coal or wood into a combustible gas is a well-known process which has been successfully used to provide fuel for motor vehicles in many countries during periods of oil shortage. The gasification units were rather heavy (100 kg minimum) and were therefore more suitable for trucks and buses than for private cars (Fig. 3). During 1941 the Swedish state railway operated more than 100 trains with "producer" gas from wood charcoal and thereby demonstrated that this is a viable alternative in those countries which have to import their petroleum but have ample supplies of wood or other forms of biomass. It has been estimated that under normal running conditions 1 tonne of charcoal is equivalent to 720 litres of gasoline (68). At a retail price of $1.00/imp. gal. this is equivalent to a value of $158.40 per tonne of charcoal.

During the past 4-5 years there has been a revival of interest in the gasification of wood and municipal wastes, presumably as a result of the oil crisis. The current interest in this process, however, is in the production of a low or medium BTU gas for direct use as an industrial fuel, or for upgrading into substitute natural gas of pipeline quality which can be fed into existing systems, or for use in the synthesis of methanol or other chemicals. A number of organizations have recently become interested in this concept and have constructed, or are in the process of constructing, pilot plants to evaluate the first stage of the process, i.e. the production of a combustible gas. It is beyond the scope of this study to review all of this development work and therefore only single examples will be provided to illustrate the basic process and examine its potential in the developing countries.

3.1 The Production of a Low BTU Gas

The first stage of the gasification process is similar to pyrolysis in that the wood is dried and the volatile content removed by partial combustion or by heating, leaving behind a residue of charcoal.

$$\text{Drywood} + \text{Heat} \longrightarrow C + CO + CO_2 + CH_4 + \text{Tars}$$

If the heating is continued in the presence of a limited amount of air the charcoal can be completely converted into "producer" gas which is essentially a mixture of carbon monoxide and nitrogen.

$$C + O_2 \rightleftarrows CO_2 + 394 \quad \text{KJ/mole} \qquad (1)$$

$$C + CO_2 \rightleftarrows 2CO - 172 \quad \text{KJ/mole} \qquad (2)$$

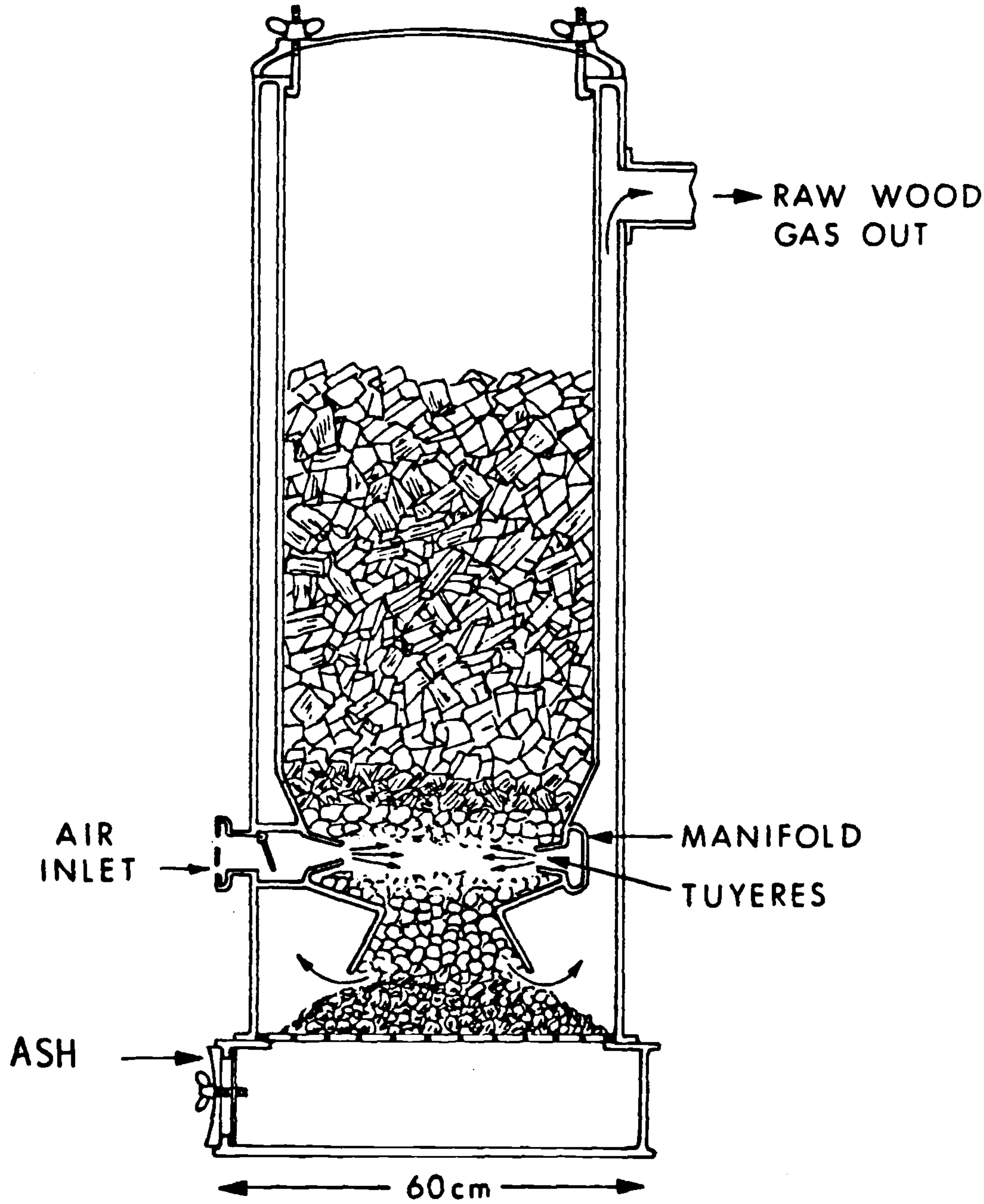

FIGURE 3

AUTOMOTIVE WOOD GAS GENERATOR, CIRCA 1945.
(25 lbs. wood = 1 gallon gasoline, 2.5 kg = 1 liter petrol)

(From Reed, 68)

However, if at some point during this reaction, water or steam is sprayed over the incandescent charcoal, then "water gas", a mixture of carbon monixide and hydrogen, is formed.

$$H_2O + CO \rightleftharpoons CO_2 + H_2 - 2.85 \text{ KJ/mole} \quad (3)$$

$$H_2O + C \rightleftharpoons CO + H_2 - 1.75 \text{ KJ/mole} \quad (4)$$

Under operating conditions it is more practical to alternate these reactions and thus form a mixture of "producer" gas and "water" gas.

It should be noted that the formation of producer gas (Reaction 2) and water gas (Reactions 3 and 4) both require heat and that this heat is supplied by the complete combustion of part of the charcoal (Reaction 1). Thus the efficiency of gasification will not exceed about 70% since some additional energy is required to maintain the high temperatures in the pyrolysis zone.

This dual reaction concept has been applied by Moore Canada in the development of their process to produce a combustible gas with a somewhat higher BTU content (52).* Both air and steam are used as oxidants and, as a result of the simultaneous water gas reaction, the product gas contains higher levels of CO and H_2 than conventional wood pyrolysis gas (Table 25). Their gasification unit is basically a conventional moving bed reactor with a star valve at the top capable of feeding wood refuse up to 20 cm in diameter (Fig. 4). The maximum temperature inside the reactor is approximately 1200°C so that the ash and non-combustible contaminants are discharged from the bottom in granular form rather than as a molten slag. The product gas leaves the top of the reactor at a temperature of 93°C and is passed through a wet scrubber to remove a condensate of water and tars. It is then cooled and passed through a dry scrubber after which it may be stored, or burnt in a special burner to provide heat or generate steam in a package boiler. Because it is a very clean gas, free of metallic impurities, it has also been recommended for use in a gas turbine to generate electricity.

* This process has been taken over and is now being developed by Westwood Polygas Limited.

Table 25. Analysis of Pyrolysis Gas

	Moore Process (Wood Waste) Volume (%)	Purox Process (Municipal Refuse) Volume (%)
Hydrogen	18.3	26.0
Carbon Monoxide	22.8	40.0
Carbon Dioxide	9.2	23.0
Methane	2.5	5.0
Hydrocarbons	0.9	5.0
Oxygen	0.5	0.5
Nitrogen	45.8	0.5
BTU per cu. ft.	150-170 (1335 - 1512 Kcal/m^3)	350 (3114 Kcal/m^3)

3.2 The Production of a Medium BTU Gàs

It is evident from the composition of conventional pyrolysis gas that its relatively low BTU value is due to a very considerable extent to its high nitrogen content (37). This problem is overcome in the Purox process by using pure oxygen for combustion in place of air, thus essentially eliminating nitrogen from the system and resulting in a more combustible gas with a heating value of approximately 350 BTU per cu. ft. The Purox reactor is a conventional moving bed pyrolysis unit which has been designed specifically for the recovery of heat from municipal refuse, but it could be adapted to lignocellulose biomass. The oxygen is introduced near the base of the reactor and travels upflow, counter-current to the downflowing refuse. The refuse passes through successive stages of drying, reduction, and oxidation, until it finally is removed at the bottom at a temperature of 1650^{o}C in the form of a molten non-leachable slag, which is quenched and discarded. The gas is released from the top at a temperature of 93-260^{o}C after which it is passed through a water scrubber to remove particulate matter, chlorides, and some organic compounds, which are recovered and burnt as fuel. The gas is then passed through an electrostatic precipitator to remove an oily mist after which it is a clean-burning fuel gas with the composition shown in Table 25.

The process has been operated successfully by Union Carbide Corporation in a 5 ton/day pilot plant at Buffalo, N.Y. and a 200 ton/day demonstration plant at South Charleston, West Virginia using solid municipal waste as a feed. One ton of refuse required 0.2 ton of oxygen and produced 0.7 ton of medium BTU fuel gas, 0.22 ton of sterile residue, and 0.28 ton of wastewater. The efficiency of conversion was about 75-80%, the remainder of the energy being consumed in the process (27).

The cost/benefit ratio of the use of oxygen to produce a medium BTU pyrolysis gas from wood waste does not appear to have been established at the present time. If the gas is to be used directly as a fuel, the additional cost of oxygen may not be practical. However, if the gas is to be upgraded into substitute natural gas for transmission in pipelines, or for ultimate conversion into chemicals, it is probable that the additional cost of oxygen will be more than offset by the cost of removing the nitrogen from conventional wood pyrolysis gas.

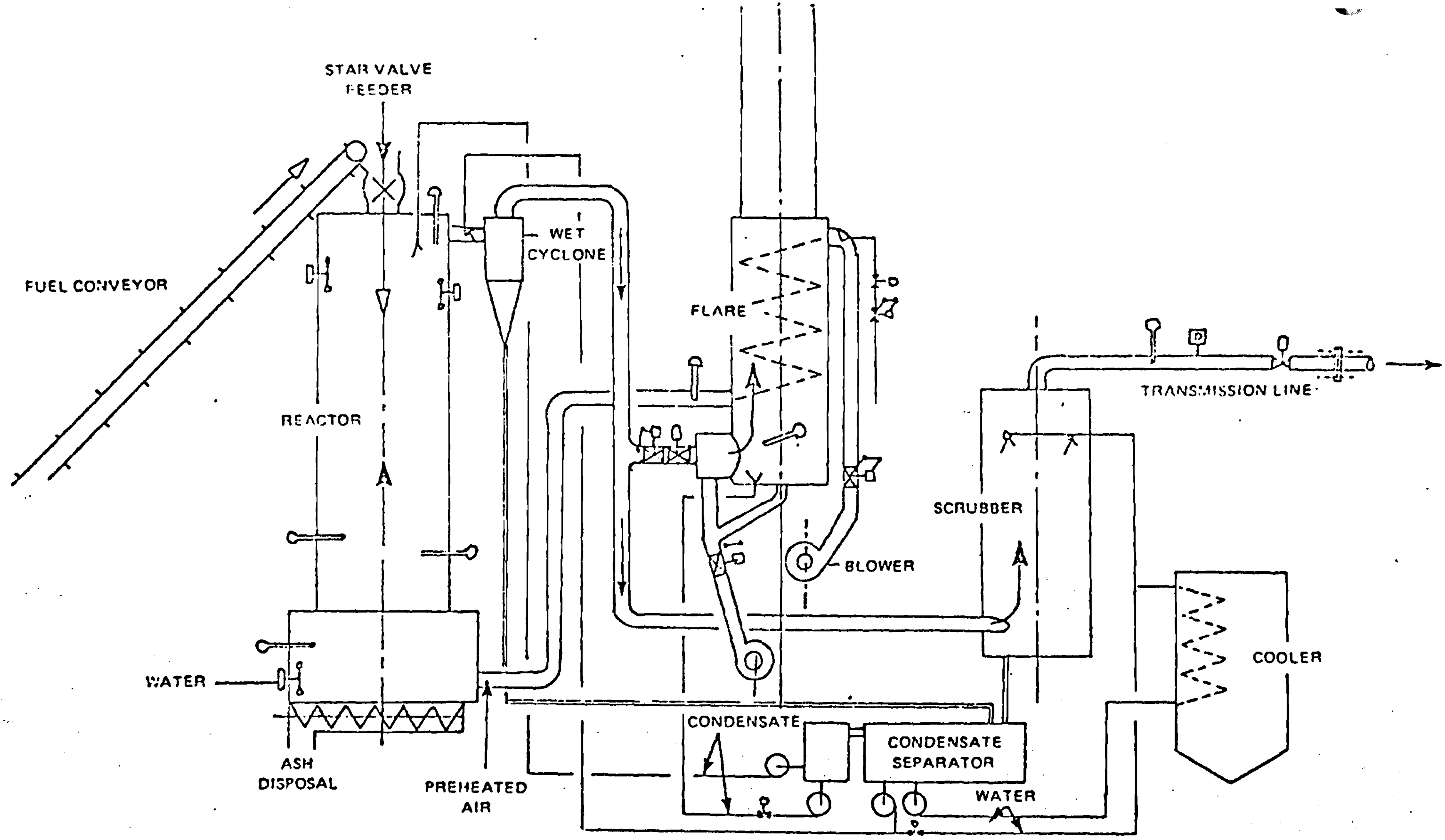

FIGURE 4 WOOD GASIFICATION SYSTEM (MOORE CANADA, LIMITED)

3.3 The Production of Substitute Natural Gas

The process of converting a low or medium BTU pyrolysis gas into a high purity methane of pipeline quality involves various chemical reactions and is called methanation. The crude gas from the wood gasification plant is first processed to remove water vapour, tars, nitrogen, and carbon dioxide. The clean gas, containing primarily CO and H_2, is then processed in a shift reactor to react part of the CO with water to form additional hydrogen, so that the final gas contains H_2 and CO in the proper ratio of 3:1.

$$CO + H_2O \longrightarrow H_2 + CO_2$$

Since additional CO_2 is formed in the shift reactor, the gas must again be "scrubbed" before it goes to the synthesis convertor. The following methanation reaction takes place in the convertor after which the product gas must be cooled and then dried to meet the requirements of the pipeline transmission companies.

$$3H_2 + CO \longrightarrow CH_4 + H_2O + 52.69 \text{ Kcal}$$

The technology for these reactions is available from similar processing steps in the conversion of coal to synthetic natural gas. It is obvious that the cost of producing methanol from biomass will be much higher than that from coal because of the much lower purity of the pyrolysis gas. However it is probable that this extensive beneficiation will not be required if the gas is only to be used as a fuel.

C. Thermochemical Conversion Processes for Methanol Production

1. Use of Methanol as a Domestic Fuel

Methanol has always been regarded as an excellent fuel because it burns cleanly and can be readily transported and stored, although it has only about 50% of the calorific value of gasoline on a volume and weight basis. From an historical point of view methanol was used as a fuel during most of the eighteenth century, when it was eventually replaced by kerosene. Around 1850 it was used exclusively in Paris for cooking, heating, and lighting, because it was more economical to distill wood in the Provinces and transport the alcohol to Paris, than to transport the wood to Paris and then have to dispose of the ashes (69). This earlier and persisting use of methanol as a fuel for various domestic purposes, with no apparent problems, suggests that it may well be used again to replace kerosene in the rural communities of the developing countries.

2. Use of Methanol as a Motor Fuel

Interest in the use of methanol and ethanol as alternative motor fuels has gone through many cycles from 1910 to the present time. As compared with gasoline, both methanol and ethanol have certain advantages which, to a very large extent, are a reflection of their physical and chemical properties (36).

Methanol has a high heat of vaporization which results in cooler fuel mixtures and a lower temperature of combustion. These lower temperatures may cause starting problems but they also result in lower nitrogen oxide emissions. This is quite important because these compounds are the major contributors to photochemical smog.

Methanol also has a much lower calorific value than gasoline so fuel consumption will be higher on a weight or volume basis and larger gas tanks will be required. However specific energy consumption (per km) will be lower because of higher compression ratios and the use of simpler emission control systems. Because of its slower burning characteristics methanol is a high octane fuel and therefore should not require aromatic supplements which are normally added to low-lead and lead-free gasoline for improving octane quality. Thus even the partial use of methanol should reduce the carcinogenic risk caused by the presence of these aromatic compounds in the fuel and in the exhaust gases.

One potential problem with gasoline-methanol blends is the possibility of phase separation in the presence of small amounts of water. This could cause serious problems in carburetors and fuel tanks and therefore some method of keeping water out, or some additive to dissolve it in the fuel mixture, would have to be developed. Test data by a number of organizations have indicated that up to 20% methanol can be added to the gasoline without requiring any engine modifications but above this level some minor adjustments to the carburetor and fuel system are necessary.

Another potential problem is toxicity. However, methanol has been used extensively during the past 150 years and there is no medical evidence to indicate that the addition of methanol to gasoline would materially change the hazards associated with the handling of this fuel (54).

3. Current Technology for Methanol Production

As referred to earlier methanol was originally produced on a limited scale in wood distillation plants as a byproduct of the production of charcoal and hence the common name "wood alcohol". During the 1920's a process was developed for producing "synthetic" methanol by passing a mixture of hydrogen and carbon monoxide over a catalyst at high temperatures and pressures. The hydrogen and carbon monoxide were produced by the reaction of steam with coke; charcoal produced from biomass would have served equally well except for its much higher cost. This process was used until the 1940's when natural gas became available in quantity and the process was then changed from using "water gas" produced from coke to "synthesis gas" produced by the reforming of methane. This is easily the most economical and most direct process known at the present time and all of the current production of methanol is based on the use of natural gas as a raw material.

The impending shortage of petroleum has caused experts in many countries, particularly the U.S., to advocate the use of methanol as a partial or complete replacement of gasoline as a fuel for motor vehicles. The completion of such a program would create an enormous demand for methanol, far beyond the current resources of natural gas to supply it. Serious consideration has therefore been given to the possibility of using coal or biomass as a raw material. The gasification of coal is a relatively old and well established process which has been used in Germany and South Africa for the production of synthetic gasoline. Thus the technology for manufacturing methanol from coal is available but so far no plants have been built because of the much higher cost of production as compared with the current process using natural gas.

4. Production of Methanol from Biomass

The production of methanol by "wood (or biomass) distillation" has already been discussed in Section B2.4.

The technology for producing methanol by the chemical conversion of wood pyrolysis gases is similar to that used for coal but additional processing steps are involved because the quality of the pyrolysis gas from wood is much lower than that available from coal. This is due to its high carbon dioxide content which results from the high oxygen content of the biomass and has no calorific value. However, because of the availability of forest and municipal wastes on a renewable basis, a number of organizations have studied the feasibility of producing methanol from these raw materials, e.g.:

(a) The State of Maine has large forest reserves available and has considered the possibility of manufacturing methanol from diseased timber stands as an answer to its energy problems.

(b) The City of Seattle, Washington sponsored an investigation of 12 different methods of disposing of their municipal wastes and concluded that the production of methanol and/or ammonia were the only processes which would return a profit.

(c) Prof. Thomas B. Reed of the Energy Laboratory, Massachussetts Institute of Technology, also estimated the cost of producing methanol from municipal waste, wood, and coal. His calculations indicated that the production of methanol from wood at the 300t/day production level is not profitable at current prices for methanol.

(d) The U.S. Forest Products Laboratory sponsored a study of the economics of producing methanol and other chemicals from wood waste, which was carried out by Raphael Katzen Associates (37). They also concluded that the production of methanol was not practical unless it was part of a large complex for producing a variety of chemicals from wood waste (Table 26).

Table 26 Cost of Production of Methanol from Natural Gas, Coal and Wood

Feedstock	Plant Investment (million $US)	Production Cost (cents per US gallon)	Gross Profit (cents per US gallon)	Net Profit (cents per US gallon)	Selling Price
50 million US gal/yr capacity					
Natural gas @ $1.75/mcf	23.1	32.0	14.0	7.0	46.0
Coal @ $38/Ton	74.4	53.4	44.6	22.3	98.0
Wood Waste @ $34/ODT	64.0	59.6	38.4	19.2	98.0
200 million US gal/yr capacity					
Natural gas @ $1.75/mcf	61.0	25.8	9.2	4.6	35.0
Coal @ $38/ton	178.0	41.4	26.6	13.3	78.0
Wood waste @ $34/ODT	169.0	57.8	25.2	12.6	83.0

Other studies which have been carried out recently show cost figures ranging from 28 cents per gallon to 42 cents per gallon, depending on differences in process and plant capacity. There does however appear to be a concensus that the process is not viable in North America under present conditions. It may however be viable in other countries where there are other important considerations such as a shortage of foreign exchange to buy petroleum imports. In such cases it may be desirable to use methanol produced indigenously even though it costs more than imported gasoline.

It is also expected that the economics of producing methanol from wood waste will become more favourable in the future as the costs of coal and natural gas increase. Possibly in anticipation of this the U.S. Dept. of Energy is planning to build a prototype plant to produce medium BTU gas from wood waste. This would also serve as a prototype for methanol manufacture since the technology for converting gas to methanol is already available.

D. Fermentation Processes

The conversion of all living matter by microorganisms into simpler chemicals, and ultimately into carbon dioxide and water, is a natural process which takes place during the decay of all organic matter. If this process is controlled in a digester and arrested at an opportune time, then it is possible to obtain valuable intermediate products from which can be isolated good yields of pure chemicals. When applied in this specific manner the process is known as fermentation, or bioconversion.

The population of microorganisms which take part in these processes is quite large, and in some cases is quite varied, but they may be classified into two principal groups, i.e. the aerobics which require oxygen or can survive in its presence, and the anaerobics which live in the absence of oxygen and may be destroyed in its presence.

Microorganisms are also known to exist which will decompose inorganic materials and this raises the possibility of producing carbonaceous fuels by bioconversion of limestone, carbon dioxide, etc. Although a review of these possibilities does not strictly fall within the terms of reference of this study, it is mentioned here because it could, at some future date, yield fuels from practically unlimited sources of raw materials (91).

1. Aerobic Fermentation of Biomass

1.1 Industrial Alcohol

The production of industrial alcohol from starches and sugars by aerobic fermentation has been practiced for many years but this traditional method has been replaced to a very considerable extent by the production of synthetic ethanol from petroleum-derived ethylene which, until recently, has been more economical. In 1974, 75% (257 mm gal) of all the industrial alcohol produced in the U.S. came from this source. Apart from the more favourable economics it has been more logical to use petroleum as a source of alcohol rather than cereal grains and molasses, i.e. starch and sugars, because these materials have a more important use as a source of food for both humans and animals. However, the cost gap between these two methods will diminish as the supply of petroleum dwindles and the price increases, and, for these and other reasons, there will be a tendency to revert back to the fermentation technology.

The demand for ethanol has remained relatively stable during the past few years because its use has been restricted largely to chemical applications. However, ethanol is a very effective liquid fuel, especially for motor vehicles, and its use as even a partial replacement for gasoline would result in a greatly increased demand. It is unlikely that this demand could be entirely satisfied by using starches and sugars because they will be needed as foodstuffs. Hence there is an incentive to use wood and other cellulosic plants for the production of industrial ethanol, as these materials can be grown in areas which are not suitable for conventional farming and at a much lower cost.

1.2 Production of Ethanol from Wood by Acid Hydrolysis

Cellulose, like starch, can be hydrolysed to glucose and then fermented to ethanol. Cellulose differs from starch, however, in the manner in which the glucose units are joined together, and in its crystalline structure. This difference makes cellulose non-digestible by humans and all animals except ruminants, and it also makes it more difficult to hydrolyse to glucose either with mineral acids or with enzymes.

A large amount of research has been carried out on the hydrolysis of wood with mineral acids in order to maximize the yield of glucose and obtain a byproduct lignin with optimum properties for ultimate utilization. The resistance of the lignocellulose complex in the wood to hydrolysis requires the use of high temperatures and acid concentrations which cause decomposition of the resulting sugars. Thus the process must be interrupted before completion when the yield of sugar has reached its maximum value, i.e. about 50% of the weight of the cellulose. The fermentation of the resulting sugar solution to ethanol is readily accomplished in yields of 85-90%.

The process has been carried out commercially in several countries during war periods when there was a shortage of cereal grains and other foodstuffs. These plants (with the exception of those being operated in Russia) were forced to close when cereals and molasses became plentiful again because they could not compete with alcohol produced from these traditional raw materials. The current energy crisis, however, has revived interest in this process because of its excellent potential for supplying a liquid fuel, and because it does not consume raw materials which are becoming increasingly needed as food. The Katzen study, sponsored by the U.S. Forest Products Laboratory, estimated the cost of producing both methanol and ethanol from wood waste. They concluded that, under present conditions, the production of ethanol from wood waste was not competitive with the production of ethanol from either ethylene or grain, unless it could be combined with the production of methanol and other chemicals in a rather sophisticated chemical complex (Table 27), (75).

Table 27. Ethanol from Ethylene, Grain and Wood*

Feedstock	Investment (million US$)	Production Cost	Gross Profit	Net Profit	Selling Price
		(dollars per US gallon)			
25 million US gal/yr capacity					
Ethylene @ 11c/lb	20	0.67	0.24	0.12	0.91
Grain @ $3/bu	25	1.13	0.30	0.15	1.43
Wood waste @ $34/ODton	70	1.06	0.84	0.42	1.90
100 million US gal/yr capacity					
Ethylene @ 11c/lb	53	0.50	0.16	0.08	0.76
Grain @ $3/bu	66	1.03	0.20	0.10	1.23
Wood waste @ $34/ODton	185	0.87	0.55	0.28	1.42

* These estimates are based on a yield of 590 lb (267 kg) of glucose or 49 US gal. (185 litres) of 190° proof ethanol per ton of wood.

More recently, Wayman and his associates at the University of Toronto have been carrying out experiments on the production of ethanol, methanol, and other chemicals from aspen wood (90). Their tentative conclusion is that ethanol can be produced more economically than methanol from wood, and that relatively small plants, i.e. 60-120 t/d, may be economically viable. If this conclusion can be verified, the process may have application in the developing countries.

1.3 Production of Ethanol from Cellulose by Enzymatic Hydrolysis

The natural composition of wood has made it very resistant to attack by microorganisms. Pure cellulose on the other hand is more vulnerable and the U.S. Army Laboratories at Natick, N.J. have discovered an enzyme which will hydrolyse it to glucose, which can then be fermented to ethanol. The process, however, at its present stage has several limitations, e.g. the cellulose must be finely divided, the rate of reaction is relatively slow, and not all of the feedstock can be hydrolysed. With certain improvements it may ultimately have application in the production of ethanol from waste paper, garbage, etc., but the added energy costs of pulverizing these materials to a fine powder before they can be hydrolysed is a serious disadvantage which will be difficult to overcome.

Recently Dr. G.T. Tsao of Purdue University has announced the discovery of a "proprietary" solvent which converts crystalline cellulose into amorphous cellulose and which yields a solid lignin byproduct that is essentially free of either cellulose or hemicellulose (45). Vegetation containing the lignocellulose/hemicellulose complex is subjected first to mild acid treatment to obtain a solution of hydrolysis products from hemicellulose as one phase and solid lignocellulose as the other phase. The hemicellulose hydrolyzate solution subsequently can be used for furfural manufacture, for conversion into fuels or single cell proteins by microorganisms that specialize in processing C5 sugars. It is claimed that the amorphous cellulose from this process is transformed by conventional cellulose enzymes into glucose at more than 90% yield in less than 24 hours.

The two Canadian processes for making cellulose more accessible to microorganisms by (a) exploding wood chips at a high temperature (Iotech Co.), or by pre-steaming (State Technology Ltd.) may also be of interest in this connection.

1.4 Production of Ethanol from Sugarcane

1.41 Economics

Cane sugar is an excellent raw material for the manufacture of ethanol and yields of about 50% based on the weight of dry sugar can be realized (15). The relative economics of producing alcohol from sugarcane, corn, and ethylene, has been studied by E.S. Lipinsky of the Battelle Columbus Laboratories (44). He concluded that ethanol produced from sugarcane could be competitive with ethanol from other sources if some credit is allowed for the fermentation residue which has a high protein content and is normally used as a cattle food.

Table 28. Cost of Ethanol from Sugarcane Juice

	$/gallon (US)
Sugarcane juice	0.81
Operating Costs	0.32
Annualized capital charge	0.22
Stillage byproduct credit	(0.19)
Net cost per gallon	1.16

This study is based on current economic conditions in the U.S. which will be subject to rapid change with increasing prices of petroleum.

1.42 Production of Ethanol from Sugarcane in Brazil

The concept of producing both a liquid and a solid fuel from a terrestrial plant with one of the highest productivities appears to have very interesting possibilities, especially in the developing countries. As already noted, this concept is now being exploited to advantage in Brazil, which is the second largest producer of sugarcane in the world and also has to import over 80% of its petroleum requirements.

Because of the availability of molasses Brazil has always produced substantial quantities of ethanol by fermentation of this byproduct of the sugarcane industry. The use of alcohol in gasoline has been legal since the 1930's but large-scale use did not take place until after

World War II. The Brazilian Government, through its national petroleum corporation, Petrobras, then agreed to purchase the growing quantities of ethanol produced from molasses and blend it with essentially all of the gasoline sold in Brazil. Since that time the alcohol content of Brazilian gasoline has ranged from 2-8% (77) and at this level no engine adjustments appear to have been necessary. More recently, the rapid increase in price of petroleum since 1974 has caused the Brazilian Government to embark on the second stage of its alcohol motor fuel program. This will involve a 20% increase in the alcohol content of gasoline, and will require an increase in ethanol production from the current level of 350 million gallons per year to 860 million gallons per year by 1981. The replacement of this percentage of imported gasoline with domestic alcohol will be of considerable help in reducing Brazil's foreign exchange problems.

1.5 Production of Ethanol from Cassava

As noted in the preceding chapter, cassava is being considered as a potential raw material for the production of ethanol in Brazil. The yield of alcohol from cassava is about 165-180 litres per ton which, on a weight basis, is much higher than that from sugarcane. However, since sugarcane has a much higher yield per hectare, the alcohol yield per hectare of sugarcane is also higher (40). The basic reason for considering cassava is that it is easy to grow and there are large areas of suitable land available. Sugarcane, on the other hand, can only be grown in a few parts of the country much of which is already under cultivation, so that a greatly expanded ethanol production will require other raw materials as well as sugarcane.

The cost of producing ethanol from cassava has been estimated by McCann and Saddler who have considered the possibility of growing it in Northern Australia as the raw material for the production of a variety of food products as well as ethanol (49). On the basis of their estimates ethanol could be produced at a cost of $0.65 per gallon at a minimum production level of 200,000 tonnes per year. This cost includes a 25% DCF return before tax and it therefore was concluded that it would be economically viable to produce ethanol from cassava for use in ethanol-gasoline blends.

1.6 Use of Ethanol as a Motor Fuel

Most of the advantages and disadvantages which pertain to the use of methanol as a motor fuel also apply to ethanol. It has a lower calorific value than gasoline, but since an ethanol engine ideally operates at a higher compression ratio and delivers 18% more power per litre than gasoline, the two factors effectively cancel one another. Ethanol may, however, give slightly better mileage because an alcohol engine can be tuned to run on a much leaner mixture than a gasoline engine. It also does have a marked advantage in eliminating the use of lead anti-knock compounds and in reducing the amount of hydrocarbon and oxide of nitrogen emissions.

From a toxicological point of view ethanol is considered to be much less toxic than methanol. Workers have been exposed to relatively high concentrations of ethanol fumes without any apparent serious long-term effects (54).

1.7 Constraints to the Production and Use of Alcohol as a Fuel

The distillation of fermented juices to produce liquors with a high ethanol content is an art that has been practiced for many generations. It is apparent that the skills and equipment required for this operation are not very difficult to obtain. It is also apparent that the process can be carried out on a relatively small scale as a cottage industry, although the labour and fuel required become proportionately larger as the scale becomes smaller.

2. Anaerobic Fermentation

2.1 Historical Background

The formation of methane (i.e. natural gas) and carbon dioxide by the anaerobic digestion of animal and vegetable matter was first recognized and reported during the latter part of the 19th century. It is now believed that the process is part of the mechanism by which some of the large deposits of fossil fuels were formed in the earth's crust. The mixture of gases which is produced is highly combustible and has been commonly designated as "biogas". It consists essentially of about 2/3 methane and 1/3 carbon dioxide, but it also contains moisture and minor amounts of hydrogen, nitrogen, organic sulphides, and higher hydrocarbons. The crude gas may be used directly for heating and lighting applications but it cannot be piped any distance without first removing the moisture and the carbon dioxide.

During the past 50 years many cities in Europe and North America have built anaerobic digesters to treat their sewage and in many cases have used the gas as a source of fuel for this operation. Any excess gas, which is often the case during the summer months, is generally piped into the municipal gas system.

Apart from a few scattered instances the construction of small biogas plants by individual families was initiated in India in 1951 (84). The thrust for this development was the desire to convert cow dung into a cleaner, more convenient fuel rather than burning it directly. Progress was slow until the mid-seventies when the fuel crisis stimulated the Government to provide additional technical and financial support. In 1976 there were over 36,000 biogas units in operation in India and the Government has a target of 100,000 by 1978. Most of these units are on an individual family scale and are reported to produce only enough gas during part of the year for their immediate needs, which are mostly cooking (99.5%) with a small percentage used for lighting (0.5%). There are, however, a few larger units operated by cooperatives, government, or industry, in which part of the gas is used as a fuel for small engines to generate power or electricity.

The largest number of biogas installations is in China where more than 2,800,000 peasant families in the province of Szechuan were producing their own biogas by the beginning of August 1976 (82).

The Chinese design is of interest because it is constructed of brick and cement and has no moving parts. The digester has two compartments, one of which acts as a storage tank for the liquid slurry when it is forced from the digestion chamber by the formation of gas. The average capacity is about 10 m^3 and this is capable of generating 5 m^3 of gas per day which is sufficient to meet the lighting and cooking needs of 5 persons. The gas is also used for driving small internal combustion engines. The Chinese report that, under their conditions, there is a 90% reduction in pathogenic organisms due to the long retention time under unfavourabe growth conditions at the bottom of the tank.

In addition to these developments it is also reported (63) that there are 27,000 biogas installations in Korea, 7,500 in Taiwan, and much smaller numbers in Pakistan, Nepal, Bangladesh, the Philippines, Thailand, Indonesia and Japan. In some of these countries, where the availability of firewood is not a problem, the anaerobic digesters are used for sanitation and environmental control. Japan, for example, has carried out considerable work on the treatment of industrial and urban wastes as well as livestock wastes from the point of view of pollution control. It is the only country which has adopted a high temperature digestion, i.e. 53-54^{o}C in the thermophylic range. They claim that thermophylic digestion makes it possible to increase the digester loading by a factor of 2.5 and at the same time to reduce the retention time to 5-7 days. The use of these high temperatures, however, is a much more sophisticated operation which requires heat exchangers, insulation, and much better supervision. For this reason it does not appear to be suitable for any but the very large units.

In the industrialized countries there is also increased interest in anaerobic digestion, not only of sewage, but also of animal and vegetable wastes from the standpoint of recovering fuel, feed, and fertilizer values. Most of the work in the U.S. is being carried out on a pilot scale by universities or agricultural research organizations under the sponsorship of the Department of Energy.

2.2 Operating Parameters

Biological reactions are very sensitive to shocks such as rapid fluctuations in temperature, pH, rate of feed addition, etc., and are therefore much more difficult to operate on a steady basis than chemical reactions. This makes it rather difficult for a farmer to obtain a steady supply of fuel from his biogas unit which is subject to all the variables of the weather and to the lack of uniformity of the feed material. As an example, it is not practicable to heat the digester during the winter months since the energy required would amount to a large proportion of that produced. The only solution is to conserve as much heat as possible by adequate insulation.

A very considerable amount of research has been carried out on anaerobic fermentation, primarily to improve the yield of gas and to increase the rate of production (63). The optimum conditions will vary from one system to another, but for all systems they fall within certain limits as discussed below.

2.21 p^H Control

The anaerobic digestion of organic wastes is believed to take place in two stages, i.e. in the first stage the acid-forming microorganisms hydrolyse the carbohydrate and other complex organic compounds into acetic and other volatile fatty acids, hydrogen, and carbon dioxide. In the second stage the methane-forming microorganisms convert these three intermediate products into methane. The microorganisms involved in the first stage grow relatively quickly, i.e. 3-4 hours, whereas those responsible for the second stage may take 10 days or more to double in number. These stages must be kept in phase with one another because the build-up of excess acids from the first stage will inhibit the microorganisms which produce methane in the second stage. It is therefore essential to control the pH by not overloading the system or allowing the temperature to drop several degrees.

For the fermentation of manure the pH should be in the range of 7-8.5, the optimum being at 7.4. The output and quantity of the gas will be affected if the pH is varied from the required range. It is important to monitor the pH value of the solution and adjust it if necessary by the addition of sodium bicarbonate solution or slaked lime (45).

2.22 Solids Concentration

The maximum solids concentration should not exceed 8-10% because of the difficulty in stirring and obtaining adequate mixing at higher concentrations. The minimum solids content may be as low as 0.1-0.5% but at these levels there is a serious danger that the microorganisms will be washed out of the tank along with the sludge because of the high rates of liquid and solid throughput. The optimum concentration is therefore between about one and eight percent.

2.23 Organic Loading Rate (Time)

As indicated above a uniform loading rate is essential to maintain a stable equilibrium between the two reactions taking place in the fermenter. The time required to hydrolyse various components in the feed varies greatly so that increasing the rate of loading will increase the rate of production of the gas (due to the larger amount of materials which hydrolyse easily) but will decrease the yield of gas per unit weight of organic material. As an example, results obtained in pilot plant experiments showed that increasing the loading from 1.17 to 5.29 kg dry solids/m^3 of tank volume per day increased the total volume of gas from 0.22 to 0.47 m^3/m^3/day, but reduced the volume of gas produced per unit weight of organic matter from 0.22 to 0.09 m^3/kg/day (79). The normal loading rate is about 0.8 kg/m^3/day as dry solids. Thus the efficiency of anaerobic digestion is a function of the volatile solids added and the volume of the digester.

2.24 Nutrient Levels

Living microorganisms require carbon, nitrogen and phosphorous (C/N/P) and the concentration of these elements must be maintained in the approximate ratio of 200:5:1 in order to obtain optimum growth. Small amounts of potassium are also needed but the ratio is not critical and there is usually sufficient potassium in the feed to maintain an adequate supply. Cadmium and some of the other heavy elements are quite toxic to microorganisms but they are often eliminated by precipitation with hydrogen sulphide which is normally formed in the digester by reduction of sulphates. Ordinary inorganic salts are not toxic at low concentrations but the individual cation level should normally not exceed 1000-2000 ppm.

From the point of view of nutrient concentration cattle dung is almost a perfect substrate. However, if too much straw or other agricultural residues are used in the feed, it may be necessary to add supplemental nitrogen and/or phosphorous in the form of leguminous plants and/or human and animal wastes.

2.25 Temperature

Anaerobic fermentation may be carried out with either of two main groups of microorganisms, i.e. the mesophylic group, which reach their optimum growth rate at 35-37°C, and the thermophylic group which are optimum at 55-65°C. As mentioned earlier it is often difficult to maintain even the lower level of either of these two optimum temperatures, and the thermophylic system so far appears to be completely impractical.

2.3 The Economics of Biogas Units

The conventional practice of burning dried animal dung in an open fire is very inefficient as only about 5-11% of the heat is used effectively, the remainder being dispersed as an acrid smoke which is injurous to the eyes. In contrast to this it has been estimated that 50% of the energy available in the original cow dung can be converted into biogas and, if this biogas is burnt in a specifically designed cooker, a conversion efficiency of 60% can be obtained (25). The overall recovery is therefore 30%. If a conventional cooker is used the conversion efficiency is only 35% and the overall recovery will be reduced to 21% which is still about twice the amount of heat available from burning dung in a open fire (64). A comparison of the relative efficiency of biogas with other fuels, mostly from Shelat and Karia (79), is shown in Table 29.

Table 29. Relative Fuel Value of Biogas and Other Major Fuels

Fuels	Fuel Heating Value	
Coal (town) gas	4,000-4,445	Kcal/m^3
Biogas	4,800-6,225	"
Methane gas	7,965-9,500	"
Acetylene gas	13,335-14,225	"
Propane gas	19,460-23,115	"
Butane gas	25,780-30,225	"
Animal dung	2,127	Kcal/kg
Soft coke	6,200-6,600	"
Coal	7,550	"
Charcoal	6,950-7,750	"
Fire wood	3,885-4,700	"
Kerosene	10,800	"
Furnace oil	10,800	"
Ethanol	7,120	"
Methanol	5,340	"
Electricity	860	Kcal/kwh

A number of studies have been carried out on the economics of operating biogas plants on an individual family scale (55, 85). Swaminathan (85) has used three different criteria for estimating the value of the biogas, i.e.:

(a) The cost of a thermal equivalent of kerosene.
(b) The cost of generating 1 cu. ft. of biogas.
(c) The cost of the quantity of kerosene which is thermally equivalent to the quantity of dung required to produce 1 cu. ft. of biogas.

His calculations indicate that for a small 2.83 m^3/day unit the value of the biogas produced, i.e. 0.0186 rupees (R), is somewhat less than the sum of the value of the raw material and the cost of production (0.009 R plus 0.0155 R = 0.0245 R). This calculation, however, does not make any allowance for the value of the sludge as a fertilizer which should be considerably more than 0.0059 R, the difference between the value of the biogas and the total cost of production. In another calculation Swaminathan (85) has estimated that the increase in fertilizer value obtained by not burning any of the dung as a fuel is considerably greater than the total cost of producing the biogas. He therefore concluded that, from an individual farmer's point of view, the cow dung biogas plant is an economically viable proposition.

2.4 Advantages of Anaerobic Fermentation of Animal and Vegetable Wastes

(a) Biogas is a very convenient fuel with a high overall efficiency as shown in Table 29.

(b) The use of biogas provides a much cleaner, healthier, environment in the home and reduces the incidence of eye diseases caused by the smoke from the traditional burning of solid wastes.

(c) The fertilizer value of the waste, which is lost if the fuel is burned, is retained with the possible exception of a loss of about 10% of the nitrogen if the residual sludge is dried. This results in a substantial saving in foreign exchange.

(d) Anaerobic fermentation is superior to composting because it permits the recovery of 50% of the fuel value. This results in a saving in forest land through less dependence on firewood, estimated to be 0.3 acre for each 100 cu. ft/day (2.83 m^3/day) biogas plant.

(e) The process can be operated on almost any type of organic waste with solid contents up to 10%, and even on soluble materials. Using direct combustion techniques it is not generally practicable to recover heat from wet fuels if the moisture content cannot be reduced below 60-70% (48).

(f) The equipment required for anaerobic digestion is relatively simple and can be made from readily available materials as the process is operated at ambient temperature and pressure.

(g) A medium or high BTU gas may be obtained depending on the transportation and end use requirements.

(h) The process has a favourable environmental impact because it reduces smoke and improves sanitation in the villages.

2.5 Disadvantages of Anaerobic Fermentation of Animal and Vegetable Wastes

(a) The principal disadvantage of the biogas process is the relatively slow rate of anaerobic fermentation as compared with thermal methods of gasification. The time required for fermentation can be reduced from 100 days to approximately 7 days by increasing the temperature from 35°C to 54°C, thus changing the bacterial type from mesophylic to thermophylic. This improved rate of digestion may be quite important in large scale units because of the large amount of heat expended in maintaining the digester at this higher temperature.

(b) The process may destroy most but not all of the pathogenic organisms which may be present and some type of post-treatment of the sludge is desirable or necessary to remove this potential hazard. Of course this hazard is also present with the original material.

(c) Biogas, when mixed with air in certain proportions, forms an explosive mixture which could be quite dangerous.

(d) A scum normally forms on the surface of the slurry in the digester and this has to be disturbed at regular intervals to maintain biological activity.

2.6 Potential of Anaerobic Fermentation of Animal and Vegetable Wastes

It is apparent that anaerobic fermentation of animal and vegetable wastes to produce biogas has considerable potential which is only being utilized to a minimum extent at the present time. An approximate estimate of the quantity of fuel and fertilizer which could be recovered from all of the available human and animal wastes in the South Gujarat Region of India* is shown in Table 30 (79).

* According to the 1971 census this region has a total human population of 3,367,370 and a total animal population of 1,775,216.

Table 30. Potentialities of Biogas Plants (Per Annum)

	Case I When only installed plants in the region are considered	Case II When available yield from both the cattle and human wastes of the region are considered
1. Biogas	4.93 million m^3	366.0 million m^3
2. Kerosene equivalent of available gas	3.20 million litres	238.0 million litres
3. Electrical energy equivalent of available gas	26.0 million Kwh	2136.0 million kwh
4. Manure	40,000 tonnes	2.10 million tonnes
5. Nitrogen content in the manure	600.0 tonnes	31,500.0 tonnes

These estimates indicate that less than 1.5% of the total human and animal waste available is being utilized for the production of biogas. Some of the reasons which have been given for the slow adoption of biogas plants are as follows:

(a) High installation costs.
(b) Low productivity during winter months when the fuel is needed most.
(c) Corrosion of gas holder.
(d) Necessity of owning cattle.
(e) Lack of suitable extension and maintenance service.
(f) Lack of land in the village for disposal of the slurry.
(g) Social prejudice against acceptance of dung - night soil gas plants.
(h) Lack of alternative sources of fuel for villagers who do not own any cattle.

"It is of interest to note that biogas plants have been developed in the developing countries, and that scientists in the industrialized states have only become aware of the potential for such systems during the past decade - largely as a consequence of the so-called "environmental crisis" (25).

Anaerobic fermentation of aquatic plants (85-95% m.c.) and wet agricultural wastes appears to be a most appropriate technology for the processing of biomass into fuel, fertilizer and feed. Waterweeds thrive on sewage, they clean the water effectively and grow rapidly in the process. Thus they may serve a dual role of improving the environment and providing a significant source of energy.

An economic assessment of the production of biogas from water hyacinth has been carried out by Lecuyer and Martin (43). Water hyacinths were selected as a feedstock because of their prolific growth rate and because they are floating plants which can be easily harvested. The biogas was upgraded from 5340 Kcal/m^3 to 8900 Kcal/m^3 (pipeline quality) by absorption of the carbon dioxide in hot potassium carbonate solution. It was concluded that the process is ecologically sound, technically feasible, and almost economically viable at current prices for natural gas. It was suggested that if any reasonable value could be assigned to the residue the process would be economically feasible at the present time. The only serious objections to this process are the large amounts of land and water required.

E. Novel Unproven Concepts

This project has only been concerned with technologies which are either known or have been proven at least at the pilot stage. There are, however, a number of new unproven concepts which should at least be mentioned because of their possible future application.

1. Biophotolysis

It is known that a certain type of filamentous blue-green alga, Anabena azolla, which lives in the cavities of azolla leaves, is capable of using solar energy to fix nitrogen from the air. The nitrogenous compounds which are thus formed are absorbed and utilized by the azolla as part of its growth nutrients. More recently it has been discovered that the alga may also be used to release hydrogen from water (57). This is the first reported photosynthetic system for producing hydrogen directly from water (biophotolysis) and appears to be a promising biological method for producing hydrogen on a large scale. The U.S. Dept. of Energy is currently sponsoring projects to prove the potential of the process by demonstrating photolysis on a sustained basis. The economics of this system will also be analysed.

Hydrogen is a very valuable fuel so that its production directly from water by photosynthesis would have a very great potential. However, this process is still at the exploratory stage and it may take several years of experimental work before it will be possible to assess its practicability. It does not appear therefore to have application in the developing countries at the present time, but it is suggested that progress in this field be ckecked at regular intervals in order to take advantage of any developments that may occur.

2. Plant Crops as a Source of Hydrocarbon Fuels

Plants rich in hydrocarbon-like materials can be harvested and will yield approximately 10±5% of "oil". Experiments with a Brazilian plant of the milkweed family (Euphorbia tirucalli) indicate an output of 16 tonnes of oil production per hectare. Tapping of some trees will yield latex which can be processed into liquid motor fuels raising the prospect of establishing "gasoline tree plantations" (59).

It is reported that palm oil can be used for diesel fuel without further processing. There is much land in the tropics unsuitable for other crops on which the African oil palm (Elaeis guineensis) can be grown. The breeding of more productive plants and improvements in management and oil extraction is expected to make the price of palm oil competitive with diesel fuel derived from petroleum (1).

Yellow Pines sprayed with "Paraquat", a pesticide, have produced dense rosin which at times accounts for a high proportion of the dry weight of the trunk. Indications are that the rosin can be processed into liquid and gaseous fuels (89).

3. Methanol from Lignin

Wood contains approximately 70-75% cellulose and other carbohydrates, the remainder consisting essentially of lignin. Apart from some relatively small uses most of the lignin produced as a byproduct of pulping operations is now wasted or burned as a fuel. There is also the possibility that considerable quantities of lignin will be made available as the residue from wood hydrolysis plants if this route is selected to provide additional quantities of ethanol. Wayman (90), has suggested the use of lignin as a source of methanol and has calculated that one ton of poplar wood is capable of providing 60 gallons of ethanol and 20 gallons of methanol. This represents an energy recovery of about 45% in the form of liquid,highly efficient fuels which could be used as a replacement for gasoline.

4. High Octane Gasoline from Methanol

The Mobil Process converts methanol and ethanol directly into high octane gasoline using a proprietary zeolate catalyst. This process, similar to the Fischer Tropsch process in which a one-carbon fragment is built up into a range of aliphatic, olefinic and aromatic hydrocarbons, has been developed by the Mobil Oil Company on a cost-sharing basis with the U.S. Department of Energy. 2.37 gallons of methanol or 1.5 gallons of ethanol are required to make one gallon of gasoline plus some liquefied petroleum gas. Conversion operations are estimated to cost $0.50 per gallon in a plant with an output of 10,000 barrels per day of gasoline. Capital cost is estimated U.S. $28,000,000 (45).

This process may be of considerable importance in producing fuels for aircraft where minimum weight is essential, but for automobiles the alcohols may be preferred because of their higher efficiency, i.e. 42% as compared with 25% for gasoline, and because of the costs and energy losses involved in converting alcohol to gasoline.

5. Catalytic Gasification with Alkaline Carbonate

The pyrolysis of wood and sodium carbonate mixture in a 13:1 ratio will result in the production of light hydrocarbons, principally methane. Relatively little is known about the process and its potential remains to be evaluated (47).

6. Steam Reforming

Steam reforming could be used to convert the various hydrocarbons produced in pyrolysis/gasification processes to synthesis gas (47).

7. Hydrogenation

Hydrogenation, also referred to as liquefaction or carboxylolysis, is a reduction reaction in which carbon monoxide reacts with cellulosic material at 250-350^{o}C and pressures of 70-350 atmospheres. The resulting liquid fuel is similar to No. 6 Residual, but has a lower heating value. This process is currently being tested in a pilot plant in Albany, Oregon (47).

8. Hydrogasification

In this process part of the biomass is first converted to hydrogen by gasification and the resultant gas is shifted to increase the hydrogen content. The hydrogen-rich gas then reacts with the remaining biomass at a high temperature and pressure to yield a product gas with high methane content which is then upgraded to pipeline quality synthetic natural gas (SNG). The hydrogasification reaction is highly exothermic, permitting biomass of high moisture content to be treated without the addition of extra heat (47).

9. Fuel Cells

Fuel cells generate electricity from methane or hydrogen and have very few moving parts. Conversion into electricity occurs at an efficiency of 40%, and 40% of the energy content of the gas is converted into heat. Indications are thus that fuel cells can recover in the form of electricity and heat up to 80% of the energy content of the gas used. The fuel cell-gas powerplant appears to be an efficient combination for decentralized energy generation on the user's premises (74).

A platinum catalyst fuel cell for methanol and another fuel cell have been developed that give more than 30,000 hours of continuous operation on methanol using tungsten carbide and charcoal as electrodes and sulphuric acid as elecrolyte. Although hydrogen is somewhat simpler to use in a fuel cell, methanol can be stored and shipped more easily than hydrogen (47).

Chapter IV

Conclusions and Recommendations

Since the 1973 oil crisis world-wide interest in biomass as a source of fuel has mushroomed and activity in this field has increased enormously. But factual information is still scarce and unreliable. Agreement is even lacking on how to measure firewood, the world's most widely used fuel.

In comparison with the sophisticated technologies developed to gather, process and use fossil fuels, progress in the management of renewable energy sources, except for water power, has been meagre. The technique of burning wood and dung has changed little for thousands of years. The world's poorest people still cook their meals on stoves which waste 96% of the heating value of the fuel.

The prospect of economic gains has stimulated extensive research into the management of commercial fuels such as coal, oil, gas and water power. No similar motivation exists for improving management, harvesting and utilization of biomass. Non-commercial fuels are either gathered free of charge over a wide expanse of the country or are purchased from small entrepreneurs. Unless the government or donor agencies provide and organize research, the people have to depend entirely on their own meagre resources. Some important improvements have been achieved here and there but little information has spread beyond the immediate neighbourhood and many promising developments have been abandoned for lack of funds or management know-how.

Research into energy production from biomass in industrialized countries has limited relevance to major population centers in the developing world and hardly any to the problems of the rural population. In the industrial world energy is used in huge concentrations, per capita consumption is large, equipment is capital intensive and complex. Technologies thus developed are difficult to adapt to the needs for energy of the rural people.

Biomass as the source of energy has many advantages for the villager of the developing world, and enhanced self reliance is one of the most important ones.

Fuel is available locally, conversion equipment is inexpensive and rather simple to operate, and the size of the unit can be scaled to local requirements, thereby keeping the cost of distribution to a minimum.

Some conversion processes such as biodigestion of human, animal and agricultural wastes also reduce pollution and health hazards.

Cost comparisons of commercial energy with heat from biomass are difficult. Firewood may be purchased at the village market, or it may be gathered free of charge but at the expense of arduous labor, which is scarce at planting and harvesting time.

Political decisions determine the availability and cost of commercial energy to the rural population. Enormous sums, usually from outside the country, must be invested to generate and distribute electrical energy, and most villagers can buy it only if the price is subsidized. It is reported that 85% of Indian villagers cannot afford to buy electricity. The World Bank plans to loan $15 billion over the next 10 years to bring electricity within the reach of 300 million more people and it is hoped that 50% of these will be able to buy some. It is quicker and requires less capital to bring liquid or gaseous fossil fuels to the villagers, but future shortages appear inevitable and it is doubtful whether any will be available to the poorer countries after 1985. Such supplies would have to come from more costly sources such as arctic and offshore wells, oilshale and oilsand processing. It is predicted that costs in real terms will increase by 50% by the year 2000 and 100% by 2020.

A. Makhijani (48) points out that those who have the least, also use it with the least efficiency. The useful work from energy input averages less than 5% in the villages compared with 20% overall efficiency for commercial energy.

The technology of growing, harvesting and converting biomass for energy production is yet in its infancy and prospects are good that systematic research will quickly bring significant improvements.

Donors, both bilateral and multilateral, have recently become much more interested to assist developing countries with their energy problems. Several divisions of IDRC have supported or plan to support energy research as an outcome of their involvement in a wide range of other investigations.*

The variety of biomass fuels available, the wide range of energy consumption patterns, and the socially conditioned response to these alternatives indicate that IDRC's pattern of promoting local research and exchange of information by establishing networks of researchers could effectively increase the availability of energy from biomass.

We recommended that IDRC be prepared to support specific research at selected institutions in Asia, Africa and Latin America which could lead to increased availability of energy from biomass and to its more effective use. The following major areas are proposed for consideration.

1.) Research to increase energy available from wood

(a) Improved techniques for the inventorying of tree biomass and to estimate biomass increment.

*SSHR division arranged a meeting in Sri Lanka on the Social and Economic Evolution of Biogas Technology (Nov. 7, 1976, File: 3-A-76-4158). The same division authorized a "Rural Energy Studies in Fiji" (Feb. 17, 1977, File: 3-A-76-0186). Present energy use, projected needs, alternative energy sources, evaluation of comparative social and economic costs, assessment of biogas production, health implications of biogas production, etc. are investigated. On October 14, 1977 (File: 3-P-77-0076) SSHR initiated studies in 5 Asian countries to foster research capability in different environments and to develop a methodology to evaluate the social and economic value of biogas plants. The Health Sciences division has contracted for a study of power sources for the pumping of water, and in another project connected with waste water management the possibility of biodigestion of algae and other aquatic plants is being investigated. AFNS division is interested in a study of improving the efficiency of wood-burning cooking stoves.

(b) Research into management and harvesting techniques of tree biomass for fuel which are compatible with the multipurpose uses of trees. Coppicing, lopping and pollarding techniques and the systematic harvesting of firewood from fruit and fodder trees and windbreaks are some examples.

(c) Ascertain the effect of energy tree plantations on the quality of the soil and develop management techniques to protect and enhance soil productivity.

(d) Research into the development of more efficient wood-burning stoves which can be made locally from readily available materials at a cost that most villagers can afford. Ancillary research which does not fall strictly within our present terms of reference is also recommended, that is the investigation of more efficient cooking utensils and less energy-demanding food preparation methods which are culturally acceptable. The Chinese practice of using soya bean curds instead of boiling the beans, the frying of food rather than boiling, and super-pasteurization of milk to eliminate the need for cooling, are some examples.

2.) Energy from aquatic biomass

Aquatic plants account for 1/3 of the annual growth of all phytomass (73), and some of the most productive vegetation known to man is in this category. Biodigestion of aquatic plants for fuel, feed and fertilizer utilizes a hitherto neglected resource, while reducing the serious environmental hazards of clogged waterways and excessive evaporation of scarce water. Moisture contents in excess of 90% in these plants do not handicap the anaerobic digestion process.

Interest in the use of aquatic plants for energy is of recent origin in industrialized countries, and as far as we could ascertain very little work has been done in the developing world in spite of an emerging concensus that there is great potential for this source of energy. We are recommending that IDRC support:

(a) Research into biodigestion techniques including biodigester design and operation. The principle of anaerobic digestion has been known for a long time but better understanding is needed and this could quickly bring significant improvements.

(b) Studies of inventory methods and of the productivity of aquatic plants.

(c) Development of harvesting techniques for aquatic biomass.

(d) Research into processing of digester slurry for feed and fertilizer.

3.) Plants as a source of hydrocarbons

Hitherto unused plants have been identified as potentially large producers of latex which can be used as feedstock for a range of hydrocarbons. Indications are that some of these plants have multiple uses, may respond readily to breeding for enhanced specific capabilities, and may thrive on otherwise unproductive land.

4.) Evaluation of promising techniques of lignocellulose conversion into sugars and the pyrolysis of lignocellulosic materials into gaseous and liquid fuels

In industrial and developing countries alike claims have been made recently of successful breakthroughs in the rapid and near-complete enzymatic digestion of lignocellulosic materials into sugars. The aim is to produce alcohol from the sugars by fermentation.

As a fall-out from the intensive research into the gasification and liquefaction of coal there have been recent claims, mostly by U.S. institutions, of spectacular improvements in the conversion by pyrolysis of wood, agricultural byproducts and garbage into liquid and gaseous fuels. Capital and operating costs of several of these installations, where published, indicate that they could be adapted for use in villages of the developing world and that this could bring about a much more efficient use of biomass.

Systems which have been developed recently on a laboratory or pilot-plant scale and appear to merit careful evaluation for possible future use in the developing world are:

(a) Lignin conversion into methanol.
(b) Catalytic gasification of lignocellulosic materials with alkaline carbonates.
(c) Steam reforming, hydrogenation, and hydrogasification of lignocellulosic materials.

Only a few organizations exist in North America and Europe which could carry out the evaluation of these systems, and the terms of reference for a costly appraisal of this kind would have to be drafted with extreme care.

Our study of the state of the art of producing energy from biomass has convinced us that there are many opportunities, ranging from the improvement of simple wood-burning stoves to gasification processes of wet lignocellulosic biomass, where IDRC could support vitally needed research. Unless donors will lend a hand, the high price of being poor will continue to climb.

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Appendix 1.

DEFINITIONS

In order to avoid any confusion regarding combustion terminology the following definitions have been used throughout this Report.

Calorie - is the quantity of heat required to raise the temperature of 1 gram of water through 1 degree centigrade.

Calorific Value - is the number of heat units liberated per unit quantity of fuel, e.g. BTU/lb or K.cal/Kg. It assumes that all of the heat generated is available to the load, i.e. the purpose for which it is intended.

System Efficiency - is the efficiency of conversion of the calorific value of the fuel into heat which can do work, i.e. the efficiency with which heat is transferred to the load. It may also be referred to as output capacity and is expressed mathematically as

$$\frac{\text{Input Fuel} - \text{Losses}}{\text{Input Fuel}}$$

Effective Calorific Value - is the calorific value times the efficiency with which the heat is transferred to the load.

Heating Value-is the calorific value less the heat required to vapourize the water in the fuel. It does not take into account other losses in transferring the heat to the system, e.g. radiation.

Appendix 2.

ABBREVIATIONS, EQUIVALENTS, AND CONVERSION FACTORS

Length

cm	=	centimetre	=	0.394 inches
m	=	metre	=	3.281 feet
			=	1.094 yards
Km	=	kilometre	=	0.621 miles

Area

m^2	=	square metre	=	10.764 $ft.^2$
			=	1.196 $yd.^2$
ha	=	hectare	=	10,000 m^2
			=	2.471 acres
Km^2	=	square kilometre	=	100 ha
			=	0.386 mi^2

Volume or Capacity

m^3	=	cubic metre	=	1 X 10^6cc (cubic centimetres)
			=	35.316 ft^3
			=	1.308 yd^3
			=	1,000 l
			=	220 imperial gallons
			=	264 U.S. gallons
			=	(about) 740 Kg wood
			=	(about) 0.435 CE wood
l	=	litre	=	0.220 imp. gal
			=	0.264 U.S. gal
bbl	=	barrel (oil)	=	34.97 imp. gal
			=	42 U.S. gal
			=	(about) 315 lb. oil
			=	(about) 1.47 X 10^6 Kcal oil
			=	(about) 5.84 X 10^6 Btu oil
		cunit	=	100 ft^3 solid wood
			=	2.832 m^3
		cord	=	128 ft^3 stacked wood
			=	(about) 2.12 m^3 solid wood

Volume or Capacity (Cont'd)

mcf = thousands of cubic feet

Mass or Weight

g	=	gram	=	0.035 oz (ounces)
Kg	=	kilogram	=	1,000 g
			=	2.205 lb (pounds)
t	=	tonne	=	1,000 Kg
			=	1.102 short tons (of 2,000 lb)
			=	(about) 1.35 m^3 wood
DTE	=	dry tonne equivalent		
ODT	=	oven dry tonne		
		mole	=	the weight of a substance equal numerically to its molecular weight

Energy

j	=	joule	=	0.239 cal (calorie)
			=	1 watt/second
Btu	=	British thermal unit	=	1,056 j
				0.252 Kcal
Kcal	=	Kilocalorie	=	1,000 cal
			=	4,186 j
			=	3.968 Btu
		quad	=	1×10^{18} j
			=	1×10^{15} Btu
			=	25.2×10^{13} Kcal
CE	=	coal equivalent	=	energy equivalent of 1 tonne of coal
			=	(about) 6.9×10^6 Kcal
			=	(about) 2.3 m^3 dry wood
			=	(about) 5.6 barrels oil
			=	(about) 8,000 Kwh
KgCE	=	Kilogram coal equivalent	=	energy equivalent of 1 Kg of coal
			=	0.001 CE
Kwh	=	Kilowatt hour	=	3.6 mj (megajoules)
hp	=	horsepower	=	0.746 kw (kilowatts)

Temperature

^oC =	degree centigrade, or degree Celsius	=	5/9 (^{o} Far -32)

Ratios

m^3/ha =	cubic metres per hectare	=	14.291 ft^3/ac
tonnes/ha =	tonnes per hectare	=	0.446 short tons/ac
t/d =	tonnes per day		
Kcal/m^3 =	kilocalories per cubic metre	=	0.112 Btu/ft^3
Kcal/Kg =	kilocalories per kilogram	=	1.802 Btu/lb

Multiples

m or Kilo =	1 thousand	(e.g. kilowatt)
mm or mega =	1 million	(e.g. megawatt)
giga =	1 billion	(e.g. gigawatt)