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BIOMASS AND HYDROGEN: AN ANSWER TO THE EUROPEAN LIQUID FUELS CRISIS IN THE 21ST CENTURY?

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January 1982

WP-82-3

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PREFACE

Recently IIASA's Energy Systems Program investigated opportunities for Western Europe to supply all the energy needed through large-scale solar technologies and local uses of renewables. Within that framework the uses of biomass take on a central role in supplying liquid fuels.

The primary objective of this paper is to assess the resource potential and production costs involved in the large-scale collection and transformation of biomass to methanol. The energy collectable from wastes, agricultural energy crops, and wood energy farms is discussed on the basis of climate conditions, expected yields, and delivery costs to plant on national and regional levels. Estimates account for collection, transport, and opportunity costs but neglect potential environmental costs due to harvesting as well as indirect costs such as for water, materials, fertilizer, or labor. In addition, two processing alternatives for obtaining methanol are examined. They involve thermal gasification and synthesis from biomass only or blending with hydrogen obtained from solar thermal conversion plants, the latter method appearing twice as effective with respect to biomass use. At last the author envisions elements of a transition to a biomass-to-methanol system for meeting Western Europe's demand for motor fuels in the longer term.

CONTENTS

INTRODUCTION

This study considers the eventual shift by the nations of Western Europe from fossil fuels to biomass to meet the demand for liquid fuels in the 21st century. The primary objective is to assess the resource potential and production costs involved with collecting biomass on a large scale and transforming it into methanol to meet the ground transportation needs for Western Europe. As such the study does not explicitly quantify the potential environmental costs of harvesting or the potentially large indirect costs to other sectors resulting from the systems needs for water, materials, fertilizer or labor. More sophisticated analysis will be needed to model the competing interactions of the demand for food, fiber and energy and their common materials inputs.

Both the cost and quantities of available biomass resources are estimated for three major categories: waste streams from agricultural and forest industries, agricultural energy farms, and silvicultural energy plantations. Within each category the total energy content of biomass is estimated as a function of climate conditions, expected yields and delivery costs to the plant door on national and regional levels. Three separate cost categories are constructed on a regional basis for each type of biomass feedstock. These estimates include not only collection and transport costs but also the opportunity costs of selling a given product in another market (e.g., wood chips to the pulp industry market).

In addition to estimating the delivered cost of biomass to the plant, two alternative processing routes to produce methanol are examined. The first uses thermal gasification and a methanol synthesis reaction of the original biomass feedstock, while the second adds available hydrogen* to increase the methanol yield of the biomass-to-methanol process twofold.

The flexibility of a hydrogen energy carrier suggests it could be used to stretch constrained biomass stocks in Central Europe to meet rising liquid demands if the cost of hydrogen-blended methanol is competitive with routes of processing biomass alone. It is assumed that all of the biomass is transformed to methanol or an intermediate methane gas even though it is recognized that the production of methanol may be insignificant during the transition from nonrenewable fuels such as oil and gas to renewable fuels derived from biomass or directly from the sun. Methanol is the assumed fuel of choice in the long run due to higher process efficiencies and greater flexibility in the feedstocks. Thus an important part of this paper is an investigation of the costs of producing methanol with or without available hydrogen to meet rising liquid fuel demands over time.

We find that an all out effort to collect biomass could yield 4700 terawatt-hours (TWh† or 10^9 kWh; roughly 380 million mtoe or 2.8 billion boe) in Europe (see Table 1 for the countries considered) of primary energy from waste streams and biomass plantations at an average cost of $(1977) 3.67/GJ ($22.5/boe). This would require the use of roughly 10% of the study area to be devoted to biomass production. Future land use conflicts and uncertainties in collection factors suggest that a more "practical" limit of 3100 TWh could be delivered using only 4.5% of the land area at an average cost of $3.10/GJ.

By using the expected evolution of capital costs for the methanol synthesis plants and the feedstock costs generated in the biomass survey, we find that the potential exists to harvest sufficient biomass to completely meet the equivalent of the 1975 European motor fuel demand of 1761 TWh (~140 million mtoe or 1.1 billion boe) (OECD 1977) at a cost of roughly $50/boe (1975 dollars), using current technology. Increases in process efficiency and decreases in capital costs could reduce this cost in half and increase methanol production to a level 1.3 times the 1975 demand.

For higher demand levels, a greater use of the biomass feedstocks would press the European stock to its limits both physically and ecologically. If 5% is considered to be a reasonable limit of European land devoted to biomass cultivation, the use of hydrogen blending will increase methanol production from slightly over today's demand level to roughly 3 times today's demand given the commercial development of hydrogen-biomass to methanol technology in the medium term. The tradeoff

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*Hydrogen is assumed to be available from STEC (solar thermal energy conversion) plants in the south of Europe.

†1TWh ≈ 0.8 million tons of oil equivalent (mtoe); 1 GJ = 0.163 boe.

Table 1. Europe of the 19.

South	Central	North
France	Austria	Denmark
Greece	Belgium	Finland
Italy	Federal Republic of Germany	Norway
Portugal	Ireland	Sweden
Spain	Luxemburg	
Turkey	Netherlands	
Yugoslavia	Switzerland	
	United Kingdom	

here is the severity of land use conflicts from biomass production that society is willing to tolerate vis-a-vis paying the higher fuel costs of producing methanol from hydrogen (see Methanol Synthesis section) at 1/2 to 1/3 of the biomass requirements to meet the same demand alone.

The analysis of a large-scale biomass-to-methanol system is organized along three major directions. Firstly the methodology and results of a biomas feestock inventory are presented. Secondly the characteristics of a biomass-to-methanol system are described. Finally, those considerations are combined to yield a range of methanol production costs and a comparison of the amount of methanol produced at these costs versus current and projected demands for ground transport liquids over the next fifty years. The energy demands, which were generated using the MEDEE-2 model, should serve as benchmarks to compare the biomass and biomass-with-hydrogen processes.

BIOMASS FEEDSTOCK INVENTORY

The feedstocks survey is divided into four main streams of potential biomass output: wastes, catch crops,* agricultural (nonwood) energy farms, and wooded energy farms. We begin with the waste streams since they are both the most abundant available and the most difficult feedstock to handle.

Waste streams are divided into four major groups: agricultural residues, forestry residues (mill and logging), municipal solid waste (urban refuse), and manure from animal and human sources. Each group will be treated separately since some wastes are more readily convertible to gases than other, densified, solids.

*Crops grown after the harvest but before the end of the growing season for fodder or energy purposes.

In each section the rationale for estimating the reasonably collectable waste is discussed in parallel to the development of supply costs per unit oven dry (metric) ton (ODT) in cheap, moderate, and expensive cost categories. To save time we have organized the estimates of available wastes into three regional groupings of nations shown in Table 1.

WASTES

Waste Estimation Overview

A few rules of thumb guide the estimation of potentially available waste streams. First 100% waste stream recovery is not only not possible but probably not desirable economically. The more realistic limit is probably 50% of the *collectable* waste stream defined in this paper.

Second, a premium in the form of a high inelasticity of demand for liquid fuels pushes most if not all the available biomass feedstocks into methanol production. Of course, in the transition years between the fossil and renewable energy systems this assumption is an oversimplification because biomass will be needed for heat production in remote areas where oil has become too dear. However, the demand for liquid fuels has fewer and more costly substitutes than the production of low-grade heat. Thus one generally assumes the optimal allocation of biomass resources to approach 100% towards the production of methanol.

Third, the assumed real-term price rise of final energy by 2 to 3 times the present value stimulates the development of a more efficient waste collection system in forestry and agriculture. For example, collection of straw waste goes from 0% in many countries (i.e., it is usually burned) to 30% with the evolution of whole-crop harvesting techniques.

Finally, the agricultural and forestry pattern of land use that characterized Europe in 1975 is assumed to prevail in the future, due to the general ignorance of the effects that the price of energy will have on patterns of agricultural use. With these 1975 production levels of crops and wood, it is relatively straight forward to estimate the maximum potential waste stream available.

Agricultural Waste

It is assumed that farmers in the 21st century will continue the increasing trend toward mechanization and piggy backing of harvesting operations in grain or cereal areas. The rapid developments in residue collection machinery suggests that not only straw residues but also green matter, tree clippings from vegetable and fruit trees, and nut shells may utlimately be collected. However, to be conservative we have concentrated on the potential for straw residue and leave the generation and collection of other residues to future research.

Straw Yield and Collection

Gross straw generation figures by country were taken from estimates of White (1979) for the European Communities and Pelizzi (1980) for the world. Both estimates assume a range of grain/straw ratio between .8 to 1.2. These ratios could change significantly towards the production of more straw if the value of energy residue approached the value of the grain, but the present differential between grain prices and straw value is at least a factor of 10 (per kcal of food energy vs. commercial energy). For convenience, no increases in grain yield per hectare are assumed, so that simple multiplication yields the following total straw residues by region (Table 2):

Table 2. 1975 gross straw generation (10^6 oven dry tons, ODT, metric).

	North	Central	South	Total
10^6 ODT	18	44.7	118	181
TWh (primary energy)	84.6	205.4 209.6	560	850

For such gross residues a range of collection factor from 0 to 100% have been suggested in the literature for specific regions. In some areas straw may be too valuable as a soil supplement or erosion retardent to justify more than 10% (Anderson 1977), while in other areas the straw generation is highly concentrated and readily available for bulk collection (White 1979). Unfortunately, a common thread to most of the feasibility studies is the emphasis on "readily available" straw rather than a look 30 to 40 years into the future to determine how much straw and in what soil regions can man afford to remove from fields or from its more traditional role of animal bedding in dry areas.

The 40% of recovery factor selected here is higher than some readily available estimates (Anderson 1977), but conservative in the long run and consistent with a recent FAO study (FAO 1980). The other 60% of the straw is thus available for traditional uses and returned to the ground or for the emerging market for straw as a wood or chemical feedstock, as is discussed later in the opportunity cost section. Using the 40% recovery factor gives 340 TWh of primary straw energy for the whole region of Europe at a medium cost. The factors that make up this cost are discussed below.

Costs of Straw Collection and Delivery to Plant

The system costs of collecting straw and delivery to a processing plant were derived from a number of studies (Inman

1977, Alich 1977, White 1979, Harris 1980). The costs of physical collection come from the Stanford Research Institute (SRI) work using whole-crop harvesters to give a range from $7.00 to 21.50/ton (Alich 1977) of straw. This estimate is confirmed by Mitre and FAO studies (Inman 1977 and FAO 1980).

Transport costs were estimated as a function of distance and the different levels of tractor and truck availability in each region. Densification machinery was used for distances greater than 50 km in the expensive categories and was estimated to cost roughly $10/ton (Reed 1978).

Opportunity Costs of Straw

The use of straw for energy may have to compete with new processes that convert straw to pulp, chemicals, or newspaper stock besides competing with the traditional use of straw as bedding for livestock (White 1979). Accordingly, we have included an opportunity cost of between $20-30/ton for the medium cost category and $40-50/ton for the expensive cost category to reflect possible competition from other users. The opportunity cost in the medium category represents the current market for wood pulp and/or mill wastes (Gibson 1978). The expensive category includes an additional premium to model unspecified environmental costs that could arise as collection factors approach 60%. The total costs by category are summarized in Table 3 along with the range of delivery costs estimated by the SRI for three different areas in the United States.

Table 3. Straw waste delivery costs projected for the short term ($/GJ in 1977 constant dollars).

Europe study estimates:	Cheap[a]	Medium[b]	Expensive[b]
North	0.92	2.30	5.03
Central	0.78	3.1	6.2
South	1.2	3.4	6.7
FAO estimate[c] (Pelizzi 1980)	0.94	1.52	
United States SRI estimate (Alich 1977)		1.1-2.05[a]	

Note: Assumptions for Europe include opportunity costs of $20-30/ton and $40-50/ton in the medium and high-cost categories, respectively. For further explanation see text.

[a]Distance of 30 km to plant is assumed.

[b]Distance of 50 km transport to plant for medium and high-cost straw is assumed in this study.

[c]1.52 is today's price, and 0.94 is the projected medium-term cost.

The SRI and FAO studies assume no opportunity costs which partially account for the higher prices estimated here. The other reasons for the gap include the longer transport distance and the higher collection factors in the expensive category and the overall higher transport costs in Europe assumed here.

Forestry Wastes

Mill Wastes

Current national production levels of timber products serve as the basis for the following projections of potentially available wastes. A percentage of wastes that can be utilized from this stream is derived by making assumptions about the future production levels and the extent to which demand premiums for liquid fuel cause a shift from biomass now used for secondary wood products and onsite fuel towards its use as an energy feedstock for methanol. In terms of production it is assumed that modern forestry management practices will raise the overall production of wood by a factor of 1.2 in the northern and central regions of Europe and 1.5 in the south in the next fifty to 100 years. These estimates are corraborated by forest studies in the European countries, which project at least a doubling of forest yield using known forestry practice (White 1979).

The cost of collecting mill wastes has been estimated by a number of sources (Inman 1977, Alich 1977, Harris 1980) to range from \$2.85/ton (.16/GJ) to \$22/ton (1.6/GJ). Our estimates are considerably over these values because we assume a premium will have to be paid to bid wood for energy away from the pulp, plywood, and particle board industries in order to yield any substantial fraction of biomass wastes relative to the industries throughput of the products. The mangitude of these premiums relative to the collection and transport costs for wood is shown for the medium cost category by region (Table 4):

Table 4. Mill residues - in 1977 constant dollars per oven dry ton (\$/ODT).

Cost category	Handling, collection, & transport	Resource premium	Total \$/ODT	\$/GJ
Medium	15	20	35	2.18
High	30	40	70	4.36
Present alternative uses[a]				
Wood chips			32	
Sawdust			5	
Bark			6	

[a]1977 U.S. prices for these products.

Given these cost assumptions a "typical" wood process industry mass flow was constructed using data from Howlett and Gamache (1977). Below (Table 5) the typical proportions of wood products and chips from an input log of 100 kg are shown in the first column. The second column shows what percentage of each category was used for energy purposes (usually heat) in 1975. The final column shows what amounts of wood are assumed to be used for energy feedstocks in the 21st century.

Table 5. Wood processing streams, present and future.

	1975 Split (kg)		2030 Split (kg)		
	Product	Local Heat	Product	Local Heat	Energy Feedstock
Wood products	32	0	32	0	0
Mill residues; pulp, sawmill shavings etc.	27	11	20	8	10
Process wastes	8	22	10	10	10
Total	67	33	62	18	20

Ratio of feedstock-to-wood products = .62.

SOURCE: The 1975 split is adopted from Howlett and Gamache (1977).

This chart shows that the energy feedstock could come from either the streams now used for heat products, or uncollected waste. The extent and nature of this energy substitution will depend on the development of demand for wood products and, probably, the "substitutability" of solar heat for traditional biomass-to-heat processes.

On a gross productivity basis these assumptions lead to the use of roughly 8% of the annual growth of the forest that is collected as mill waste while 50% continues to serve the wood products industry. This translates to .62 times the total board output produced in each country to be available for energy feedstocks. This estimate is at the lower end of the range of Mitre estimates when one takes the 40% collection factor x Mitre's residual coefficient of 1.5 - 2 m^3 waste/m^3 of production (Howlett and Gamache 1977). The total potentially available wastes in m^3 and TWh as projected for the medium cost category for each region in 2030 are displayed in Appendix 1.

Logging Wastes

Logging wastes are defined as that part of the *above ground* biomass currently left in the forest after harvesting. Improved logging methods could retrieve between 30-70% of the branches and diseased trees now left to rot (White 1979). Readily available or collectable wastes have been estimated as a function of tons/ha or tons/m^3 of 1975 output. The range of logging residual generators used in the SRI and Mitre studies is 90-110 tons/ha harvested (Alich 1977, Howlett and Gamache 1977). This means roughly 30% of the total forest growth is left in the woods. If one assumes a 30-year harvesting cycle and 40% availability this translates to roughly 0.25 tons waste/m^3 output wood. Mitre's estimate of 4-17 ODT/1000 ft^3 (.14-.57 tons waste/m^3 output) corraborates this estimate over a wide range of forest types. The value of .25 tons/m^3 or 1.2 MWh/m^3 is thus applied to the 1975 production levels taken from FAO statistics for 1978 (FAO 1980) to yield the logging wastes available (Appendix 1).

The costs of collecting these residues are shown in Table 6. Note how higher collection percentages are assumed for each price

Table 6. Costs of central region logging wastes projected for 2030 (1977 constant dollars).

Logging Residue Costs	Cheap $/ton	Medium $/ton	Expensive $/ton	Reference Cost $/ton
Collection	10	20	30	10 (Gibson 1978)
Transport	7	15	40	15 (Harris 1979)
Environmental penalty/resource premium	-	10	20	
Total ($/ton)	17	45	90	48 (Howlett and Gamache 1977)
Total ($/GJ)	1.06	2.8[a]	4.8[a]	
Collection factor (%)	20	40	80	
Yield (tons/ha/yr)	.5	1[a]	2	
or in terms of 1975 output (MWh/m^3)	.7	1.4	2.8	
Yield (TWh)	38	76	152	

Other estimates:	$/GJ
Howlett and Gamach (1977)	2.59
Gibbson (1978)	1.08
Alich (1977)	1.34-2.2

[a]Roughly 6% of the annual growth of the trees on 50% of the Central European forest land.

rise by category. For reference also other estimates are given of the cost of delivering logging residues to a site 50 km from the forest.

Once again, the high resource premiums or environmental costs result from the possibility of intermarket competition and in this case potentially adverse effects of nutrient depletion in the long run.

Municipal Wastes

Data for the energy content/ton of solid wastes for the U.K., F.R.G., Netherlands, France, and Switzerland were taken from Paul (1978). For the rest of the central and northern nations we assumed 300 kg/capita waste at an energy content of 3.8 TWh/ton taken from Pimentel (1978). The remaining southern countries use 180 kg/capita from an unpublished estimate for Spain (J.A. Torralbo, Centro de los Estudios Energia, personal communication, 1979).

Since waste collection networks are strongly correlated with population density different collection factors were assumed for areas or cities with populations over or under 100,000 in 2030 (Table 7). Implicitly a zero collection factor is assumed for those living in rural areas.

Table 7. Population distribution 2030: projections based on UN Housing Statistics (1974).

Urban areas	Towns greater than 100,000	Towns less than 100,000	Overall collection factor
North .85 of which	.68	.17	
Collection factor	.9	.7	
	.61	.12	.73
Central .85 of which	.595	.21	
Collection factor	.85	.7	
	.51	.14	.65
South .75	.48	.27	
Collection factor	.75	.5	
	.36	.14	.50

Using the collection factor and the population of each region in 2050 gives the available waste shown in Table 8.

Since little information was available on costs for municipal waste collection, $20/ton was estimated as incremental cost of taking the garbage to the plant instead of a landfill or

Table 8. Municipal waste generation projected for 2050.

	2050 Population (10^6)	kg/cap	Collection factor	10^6 tons collected	TWh energy
North	24.2	237	.73	4.2	15.3
Central	184.2	335	.65	40.2	144
South	387	188	.5	36.4	130

incineration plant. Sorting costs at the plant were assumed to vary from $10-40/ton depending on the region. No attempt has been made to reduce these costs by means of a credit for the savings that are incurred by eliminating the need for landfill space or municipal waste incineration.

These estimates lead to an overall cost of delivered waste as energy feedstock of $2.88/GJ in the north, $3.14/GJ in the central region and $4.32/GJ in the south of Europe. For reference, the costs of collection, transport, and disposal of municipal solid wastes in the U.S. without any landfill credits are estimated to range from $6-24/ton or $2.0-8.0/GJ (Arthur D. Little 1979).

Manure

Livestock Manure

Considerable work has been done on estimating the total amounts of dry solids available from livestock manure on a country-by-country level (White et al. 1979). However, due to the roughly 80-95% moisture content of manure and its diffuse distribution in most of Europe a number of limiting factors or caveats must be considered when estimating the amount of waste collectable in 50 years time.

First, the wet nature of the biomass suggests that it would be more efficient to use a fermentation process to transform it to an intermediate product, methane gas, rather than use it as a direct feedstock to the gasification process. As such we have used the estimates of White et al. for the m^3 of medium BTU gas/head of livestock which was transformed to the national level using livestock statistics (White et al. 1979). In countries outside the EC we have used his methodology as well as FAO livestock counts (Pelizzi 1980) to generate similar figures. To be conservative no increase in the 1975 population of cattle, pigs, and poultry was assumed.

Second, the cost and efficiency of generating gas from manure is highly dependent on the size of the herd at the plant site. Most systems in the U.S. are designed from herds of 10,000-25,000 cattle but EC statistics show that the majority of farmers have herds under 100 cattle (White et al. 1979).

Thus it appears that the collection factor or the proportion of waste that actually could be used in Europe might be considerably lower than those assumed for the United States. On the other hand, the trend within the EC is towards larger herd sizes and greater concentration. Given all these factors, an optimistic outlook was decided on to give the following collection factors: cattle 50%, pigs 40%, and poultry 50-70%. To reach these factors one must assume a gradual evolution of European livestock practices toward larger herds and densities. This may be too optimistic but is obtainable *if* Europe follows the U.S. pattern of increasing mechnization and housing of livestock. However, the effect of these collection assumptions is small (±2%) in comparison to the other waste streams available in Europe. The gas that could be generated from the European livestock manure is shown in Table 9.

The costs of collecting and processing manure may depend primarily on herd size, since current estimates indicate that a minimum of 1000 pig or 100 cattle are needed to produce methane at appropriate economies of scale (Klass 1978). However, recent

Table 9. Livestock-manure-to-gas yields and totals, near-term potential.

	10^6 cattle	Gas yield (GJ/head/h)[b]	Collection factor	Primary Energy (TWh)
North				
Cattle	5.93	6.5	.50	5.2
Pigs	11.9	1.1	.40	1.4
Hens	430	.116	.76[a]	8.1
				14.0
Central				
Cattle	12.83	6.5	.50	11.5
Pigs	47.36	1.1	.6	8.7
Hens	184.5	.116	.4	2.3
				22.5
South				
Cattle	95.8	6.5	.4	69.2
Pigs	24.45	1.1	.6	4.5
Hens	158.14	.116	.4	2.0
				75.7
Europe Grand Total				112.9

[a]Collection factor is higher in the north than in the other regions since almost all poultry in the north is housed due to colder weather.
[b]The yields given assume availability of low-temperature solar collectors to provide the process heat for the anaerobic digestion process. This increases the net yield of gas by a factor of 1.3/head.

network analysis in the U.S. shows that even small systems have an attractive rate of return (Hull, 1979). The range of estimates for finished gas products varies according to the size of the herd considered and assumptions about the capital recovery factor and the level of credits for the fertilizer produced as a byproduct of digestion. In Table 10 the range of estimates in the literature is contrasted to the present study assumption.

Table 10. Estimates of biogas capital costs (1977 constant dollars).

Reference	Capital cost (10^6 $)	Capacity (kWh/yr)	$/GJ	Herd Size	Comments
Klass 1978	10.8	4.09×10^8	4.87	25,000	cattle feedlot
Hull 1979	.03[a]	9×10^5	1.17	400	dairy (no feedstock cost)
			1.52	400	dairy ($10/ton of manure cost)
Alich 1977			6.6		$10/ton of manure cost
			5.6		no feedstock cost
			2.6		optimistic (with byproduct credit)
Study estimate		1.62×10^8	3.2-9.8 (cheap) (expensive)	1,000	cattle feedlot

[a]includes equipment only, no capital or design cost, etc.

Human Wastes

As in the case of livestock waste, the bulky nature and high moisture content of human wastes suggests to process these wastes via anaerobic digestion in large holding facilities.

Fortunately, industrial societies have evolved towards an increasingly centralized system of human waste collection and disposal. The following assumes that this trend spreads to the south over the next century and thus enables society to achieve relatively high collection factors in *urban areas*: 80% in the north, 65% in the central region, and 45% in the south.

An estimate of the amount of human waste generated by region was obtained by multiplying the above 2030 population estimates by Pimentel's per-capita estimate of 61 kg/yr of dry organic matter produced (Pimentel 1978). From this value we assume a 30% conversion efficiency to methane or 784 kcal/ton of organic matter. Coupling these yields to the collection factors above gives the estimates of available methane from wastes in the year 2030 shown in Table 11.

Table 11. Energy in human wastes projected for 2030.

	Population (10^6)	ODT[b] (10^6)	Gas yield/ ODT[c]	Collection factor	Gas output[a] (TWh)
North	24	1.47	1.8 MWh	.7	1.9
Central	184	11.04	1.8 MWh	.6	12.1
South	387	23.85	1.8 MWh	.45	19.3
Total					33.3

[a]Population x ODT x (gas yield/ODT) x CF = TWh (gas).
[b]ODT oven dry ton.
[c]30% process efficiency.

Costs of Municipal Sewage

Estimating the cost of gas from a municipal sewage facility is very difficult due to the issue of "waste" credits. For example, how much would a city planner be willing to pay a system that reduces the need for city landfills and cuts the hauling costs in half? That theoretical price is certainly high in areas where environmental regulations have forbidden the disposal of wastes within city limits or beyond (c.f. New York). In addition, since very few of these plants have actually been built even a conventional cost analysis using capital recovery factors is difficult.

The only definite figure we found in literature was a plant that cost 4 million dollars and had an output of 152 GWh of gas (U.S. DOE, 1980). Using a capital recovery factor of .15 and assuming no incremental feedstock costs gives an energy cost of $1.08/GJ. This compares to the estimates for the northern, central, and southern regions of 4.0, 5.0 and 7.2 $/GJ, respectively. This discrepancy is largely due to the much larger operation and maintenance and collection costs expected in many countries, particularly the south, where building an infrastructure for collecting manure will involve considerable expenses.

Waste Estimation Summary

Figure 1 combines all the cost yield data into one supply curve for the study region as a function of delivered energy price. Table 12 gives a more disaggregated look by region of the wastes estimated at the medium cost. In general, straw wastes and forestry residues are the least expensive categories followed by municipal solids, and the higher-quality gas from animal and human manure. Forest wastes provide roughly 50% of all wastes ranging at the upper limit on feedstock costs estimated at $7.00/GJ ($43/barrel). The average cost for 1912 TWh of all types of waste that could be supplied at this price is $2.89/GJ. How this cost compares to the cost of raising biomass specifically for feedstock use will be discussed in the next three sections on the biomass resource potential.

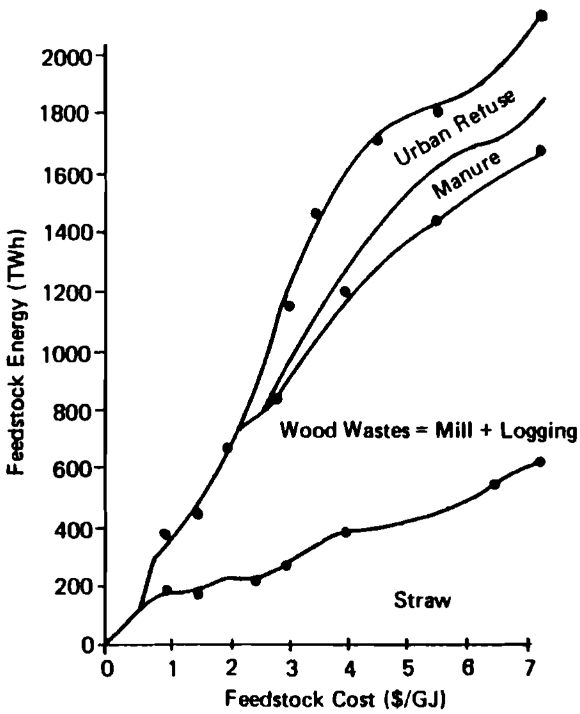

Figure 1. Estimated waste feedstocks vs. delivered cost to plant.
Note: Data points are estimated by interpolation of cost ranges and should not be seen as exact point estimates.

Table 12. Energy from biomass in Europe: Projected medium-cost waste streams (TWh) in 2030.

	Primary Energy (TWh)			CH_4 gas from manure (TWh)	
	Agri-cultural wastes	Forest wastes	Municipal solid wastes	Human	Livestock
North	33	370	15	1.9	14.3
Central	84	178	144	14.2	22.5
South	224	297	130	17.2	75.7
Total	341	845	289	33.3	112.5

Grand total: 1621 TWh

ENERGY FARMING

Catch Crops

Catch crops are defined as crops grown after the harvest but before the end of the growing season for fodder or energy purposes. The recent EC biomass study (White 1979) found grains to be the most attractive crops to use for this piggy-back technique. Estimates of the available yield for a growing season of 4 to 8 weeks were based on data on sugar beet yield from the EC statistics.

We have adopted these yield figures for EC countries and extended this treatment to the other European countries. To account for precipitation and lesser soil quality the yield in southern countries is assumed to be lower by 40%.

The EC study estimates the potential for catch crops by assuming that 100% of the total grain area and 50% of the vegetable area could be used for energy purposes. We use a more conservative progression of 10 to 30% of the total grain area for the possible planting of catch crops, such as fodder beet, fodder radish, or kale in the north, or grain sorghum in the south.

For the cheap, moderate, and expensive cost categories by region we ignore the vegetable area in order to be conservative. The above crop use fractions are largely arbitrary and designed only to show the potential for maximizing the utility of agricultural lands as energy prices rise.

The delivered costs for these crops were extrapolated from the cost data in White (1979). These growth and harvesting costs ranged from $.67-1.67/GJ. We assume that both the cultivation and transport costs would be significantly higher in the south than in the other two regions. The results by region for yield and land use suggested by these costs are shown in Table 13 below.

Table 13. Energy from catch crops in 2030

	Delivered[b] cost $/GJ	Land available 10^6 ha	Total cropland %	Yield[a] tons/ha	Primary TWh
South	2.85	14	15	3	210
Central	2.04	6.1	36	5.5[a]	175
North	2.04	2.1	23	4.5	58
Total					443

[a] 5.5 tons/ha equals the EC average estimated in White (1979).
[b] 1977 constant dollars.

Land Potential

The amount of land available for energy farming will be dependent on energy prices as well as local cultural practices and resource constraints. Rather than try and estimate a specific amount of "substitutable" or marginal arable land in each region suitable for energy farming, the total land available is varied parametrically with respect to the expected price for the feedstock product. These variations are encompassed within three price categories, low, medium, and high-cost feedstock. Of course, the price of the feedstock is also contingent on the costs of production and the available soil and water resources.

The bar charts below (Figure 2) give the relative magnitudes of marginal farmland, pasture, and forest availability for energy purposes in the medium-price category, and land with the potential to be used as energy farms. By inspection most of the heavily-forested land lies in Scandinavia while a significant portion of European farmland lies in southern regions, particularly Turkey.

In the south, where arable land is scarce, 1 to 2% of the crop area is assumed to be available for energy farming. While there is a significant amount of land in the south potentially amenable to energy farming at even these low fractions of total farming land, the competing demand to produce food or fiber on all arable land will continue to be significant. Inadequate rainfall may also be a constraint for energy crops in this region although proper crop selection may solve this problem (Muriani, 1978).

Much of the land in the south previously classified as arable is now considered rough grazing land (see for instance, the World Agricultural Atlas 1969). This land may or may not be reclaimed for energy crop use, and its use will also depend on the future economic climate, such as in the case of Greece and Turkey. Thus, in order to capture the uncertainty in land suitability in the cost categories, we vary the amount of land considered available from 8 to 25% of the present pasture land.

In contrast to the unproven feasibility of using southern soils for high-yield agriculture, the northern and central regions have large areas of fertile soil that are capable of supporting fodder beets and other high mass-yield crops. To exploit this range of possibilities we allocate 2-8% of the marginal agricultural land and 10-22% of the pasture land to agricultural energy crops.

The resulting magnitudes of land available for agricultural energy crops can be contrasted to the land available from forests. Estimates of available forest land were derived by assuming that 6-10% of national commercial forest land might eventually be available for silviculture. These estimates, which also vary with respect to the relative prices for fiber and energy, are discussed at greater length in the silviculture section.

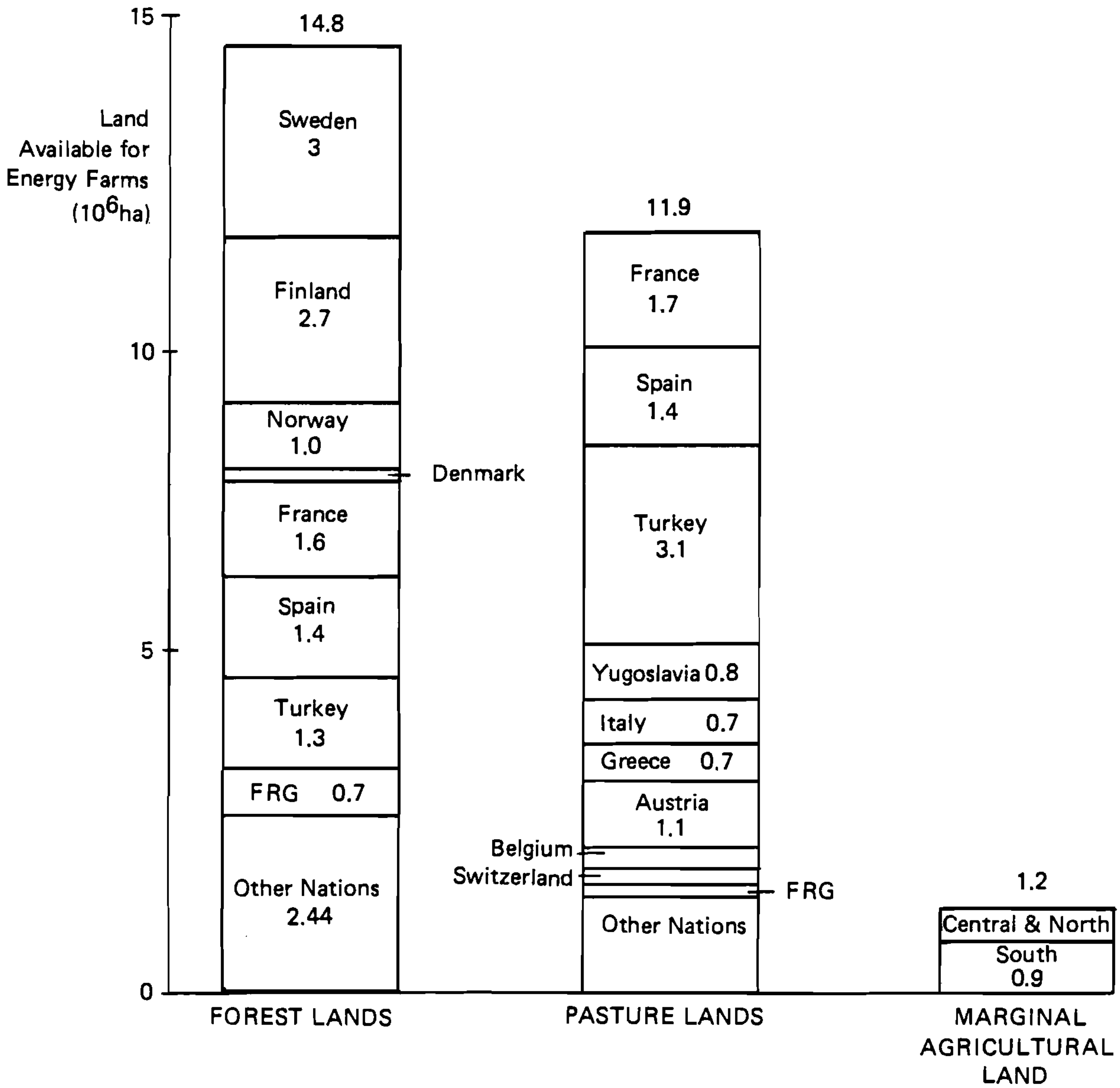

Figure 2. National potentials of marginal farmland, pasture, and forests for energy production, medium-cost range, in the year 2030.

The absolute magnitude of the land available in each country and the expected energy yields are discussed in the following sections on energy farming for agricultural and forest energy crops.

Agricultural Energy Farms

Agricultural energy farms (i.e. marginal farmland as well as pastures) are for our purposes defined as the large-scale cultivation of non-woody vegetable material that is used to maximize energy yields and not digestible cellulose content. Fodder beet, sorghums, kale, and lucerne are all cadidates due to their fast growth in variable climates. Such farm crops in the future might either displace marginal crops and/or marginal farmland, pasture lands, or "waste lands" where a lack of water but not nutrients had precipitated an earlier abandonment.

Since yields as high as 20 ODT/ha have been contemplated by the designers of these crop systems (Harris 1979), the land must be both arable and well prepared prior to production. During cultivation the crop must be well managed with irrigation and fertilizer supplements. A minimum of 20 inches rain is usually required in most plantation schemes.

The problem of where to find enough suitable land for these new crops is much discussed but probably overrated. The European Communities list over 34 million ha of agricultural land as marginal, 25% of the total agricultural land, and 8% of the total land. Possibly even more land could be freed if the price supports for milk were removed and thus the need for roughly 20% of the land in Europe now classified as pasture. The vinyards and related subsidies could be still another potential source of land although the soil characteristics and precipitation patterns might not be suitable for this concept. Thus, while there may be little land available in the next five years the steady growth of energy prices and the ongoing rapid structural change in European agriculture could free up sufficient land to implement the energy farm concept.

Yields

Crops suitable for energy farms are the topic of intense research in and out of the EC. New Zealand researchers favor the fodder beet and lucerne (Harris 1979) but sorghum and green winter crops may be more suitable in cold climates. Yield estimates (e.g., Harris 1979) vary from 22 tons/ha for fodder beet to only 7.9 tons/ha for lupins. Our yield assumptions lie in the middle of this range with 12 tons/ha in the short run and 15 tons/ha for maximum potential at medium cost.

Before coupling the yield assumptions to biomass availability, one must examine the economies of producing and harvesting these crops with high moisture content. Since the New Zealand study has the most comprehensive treatment of the costs involved in cultivating and transporting it has been chosen as the main source of the estimates discussed below.

The costs of establishing and maintaining a large-scale energy farm constitute the major portion of the cost of energy feedstocks during the early years of initial market penetration. Harris (1979) estimates that establishment and maintenance (including periodic fertilizer application) for agricultural energy platations can cost up to \$20/ton of crop/ha. Harvesting and transportation costs are lower than these costs. The final costs of energy farming, i.e., the opportunity costs of raising energy rather than food, is highly variable and/or controversial, and as such could either exceed or fall below the previous three cost categories (building, harvesting, and transport).

Essentially we have taken the findings of the New Zealand study and modified them to coincide with the cost category for Central Europe, New Zealand's climate analogue. Below these estimates are contrasted with the New Zealand findings (Table 13). Beneath the cost components are the yield and availability assumptions that synthesize an estimate of the available primary energy (TWh) for each price.

Table 13. Cost estimates of agricultural energy crops in Central Europe and New Zealand (\$/ton).

	New Zealand[a]		Central Europe		
			Cheap	Medium	Expensive
Harvesting/ maintenance	24		20	30	30
Transport	8		10	10	15
Opportunity cost	8		10	20	30
(\$/ton)	40		40	60	75
(\$/GJ)	2.2		2.2	3.2	4.3
Land available (10^6 ha)			2.78	5.4	6.64
Yield (tons/ha)	-	near term	10	12	15
	-	maximum	15	18	20
Total (TWh)			228	486	637

[a]Adapted from Harris (1979).

The dramatic rise in opportunity costs can be interpreted as a growing demand for European agricultural (food) exports or a shrinkage of the available land due to environmental and/or urban area encroachment.

The problem of available land may be worse in the southern region, particularly in Turkey and Spain. Turkey's population is projected to double in 35 years which will create significant pressure to cultivate more grains to feed the people. To account for these factors we have doubled the opportunity costs for agricultural crops in the southern region. This yields a delivered price of roughly 1.5 times the cost of the central region crops for the south.

A summary of the estimated availability and projected yields in the medium-cost pasture land and tilled land category (\$2.2-3/GJ) is shown below by region (Tables 14 and 15).

Table 14. Estimates of available pasture land for energy.

Region	Land million ha	Total Pasture %	Fraction total land %	Near-term yield TWh
North	.017	11	-	1
Central	3.5	15	4.5	245
South	8.43	12	2.8	350
Total near-term	11.9	12	2.7	596

Table 15. Estimates of available tilled land for energy.

Region	Land 10^6 ha	Total agric. %	Total land %	Near-term yield TWh
North	.14	1.5	-	8
Central	.35	1.8	-	26
South	.89	1	-	50
Total	1.38	1.2	.3	84

The actual rate of penetration for agricultural energy crops into the market will depend on government policy in two areas: food price subsidies and farm equipment research and development. Continued use of subsidies to support marginal farming in Europe will not only use up land suitable for agricultural energy farms but also discourage innovation in harvesting techniques necessary to the energy farming concept. Fortunately, rather substantial R&D programs to develop whole-crop harvesting and transportation techniques are being pursued in Sweden, the F.R.G., France, and Denmark. These programs also have spillover benefits into the field of wood energy farms, discussed below in the next section.

Wood Energy Farms

Wood has a high energy density relative to other biomass that makes it an attractive feedstock candidate for a range of thermochemical processes from direct combustion to gasification. As a result, the design and characteristics of wood energy farms or silvicultural biomass plantations have been extensively surveyed in the literature (Inman 1977, Harris 1979, Salo 1979).

Since plans have already been drawn up for silvicultural plantations, we have relied on two design studies in the United States and New Zealand (Salo 1979, Harris 1980), for the majority of the cost data presented here. In addition the yield data presented in these two reports is used because of the wide range of unverifiable experimental yields from 8-48 tons (ODT)/ ha/yr for various plant layouts.

The Basic Concept

With silvicultural plantations one seeks to maximize the yield of biomass per hectare; this is achieved by taking advantage of the explosive growth of trees from the ages of 1 to 6 rather than waiting for 20-30 years for cutting. During this period trees, like all species, are most susceptible to environmental threats and are thus usually protected with extensive irrigation; at the same time fertilizer treatment is used to maximize yield. A discussion of the environmental effects of this shift in harvesting cycles and fertilizer regime is reserved for the final section of this paper.

For the last 200 years the size of Europe's forest has been gradually shrinking, principally as a result of population pressure and industrialization. However, reforestation programs in the last twenty years have reversed the degradation of the forest stock in most Western European countries. For the purpose of estimate we assume the total commercial forest area to remain roughly constant over the next 50 years.

Coupled to reforestation programs is the gradual diffusion of modern forest management techniques to the south from the F.R.G. and Sweden. Forestry experts feel that it should be fairly easy to double the yield of existing forests in the next century. (Forests in the F.R.G. yield twice as much lumber per hectare than in France.) This improved efficiency might certainly help free some prime forestry land for energy plantation use. Alternatively, energy plantations could also be used to help recondition the soils of disafforested land and bring marginal forest land to productive use.

Available Forest Land

From the earlier bar charts (in Figure 2) it was apparent that almost 50% of the potential forest land for energy production was located in the northern region. A significant potential also exists in the south although lower rainfall and lower soil quality may reduce the yields as discussed below.

We have assumed that under favorable circumstances and a sustainable demand for feedstocks up to 10% of the forest land could be used for energy plantations (Table 16). This land could either come from today's commercial forests or disafforested lands as mentioned above. The actual deployment of the concept will depend on the development of a market for energy feedstocks from biomass, the yield per dollar invested per hectare, and the development of cost-effective delivery systems.

Table 16. Potentially available forests for energy production.

Region	Land 10^6ha	Total commercial forest %	Total land %
North	6.9	11	6
Central	1.54	10	1.5
South	6.9	11	2.5
Total	14.34	10	3.3

Yields

Energy farms require significant investments in irrigation and fertilizer application to reach the yields desired. The U.S. study by Salo et al. (1979) uses trickle irrigation to obtain a medium yield of 20 tons/ha in an area with at least 500 mm of annual precipitation. Under this plan year-old seedlings of sycamore and European elder will be planted in 1981 at the American prototype energy farm. In conjunction 170 kg of nitrogen and 76 kg of phosphate will be required per hectare per year. Whether these amounts will be enough fertilizer capacity to supply numerous such silvicultural plantations in Europe remains to be seen.

In contrast, the New Zealand energy farm study requires no irrigation and less-intensive application of fertilizer to cultivate a yield of 11.2 tons/ha for pinus radiata (Harris 1979). This type of plantation might be more suitable in areas with scanty precipitation, such as in the southern regions. Growing costs are estimated to be \$14.8/ton including fertilizer and preparation, which is roughly equivalent to the estimates of growing cost for the Mitre farm (\$14/ton; see Salo et al. 1979).

In the present study it is assumed that both of these plans could be adopted on a large scale in the central and northern regions of Europe and in France. Unfortunately, a large portion of the forests in Turkey and Greece may not be suitable to these plantations because of low rainfall. A possible candidate for energy feedstocks in this area then is the sturdy eucalyptus for which yields as high as 30 tons/ha have been claimed (Muriani 1978). We adopt a goal of 1/3 of that maximum or roughly

10 tons/ha of eucalyptus of the cheap category, and 1/2 of the maximum or 15 tons/ha for the medium and high-cost cases. This yield is corraborated in Slesser and Lewis' survey of biomass yields in semiarid areas (1979).

The most uncertain components of this cost are the fertilizer and transport costs discussed below. These fertilizer costs could either rise or fall dramatically, depending on future break-throughs in biomchemical research and the cost of hydrogen for fertilizer production.

Since fertilizer and irrigation costs compose 30% to 50% of the operating and maintenance costs in the studies by Harris (1979) and Salo et al. (1979), respectively, the evolution of future prices for water and fertilizer from natural gas will be particularly important. We have varied the costs by factors of 2, 4, and 6 to capture the growing demand for fertilizers that may not be met by future supplies.

The choice of transportation systems is conditioned by the distance of the wood energy farm to the processing plant and the desired yield/ha. More modest schemes like that described in the New Zealand study use traditional logging equipment to recover up to 12 tons/ha/yr of stemwood and bark in untended forests. The Mitre scheme in contrast harvests one section of forest every six years in the winter with advanced feller chippers attached to trailing wagons that haul the whole tree without roots to the plant. Due to the uncertainties in costs however, both plans estimate the cost of conventional logging techniques to be roughly $2,500 per hectare for a transportation distance of 30 km. Beyond 30 km, mobile densification equipment would probably be cost effective. This total cost includes fuel, maintenance, and annualized capital cost for the harvesting system.

In the present study, transportation costs are varied from $5-15/ton of hauled wood due to the uncertainties in plant lay-outs, future fuel costs, and transport distance to the nearest gasification plant. These costs fall within the range of those quoted in the Mitre and New Zealand studies.

To illustrate how the principal components of an energy farm come together, a sample calculation of costs is shown for the south (Table 17). These costs are considerably higher than they would be in the north, which is due to a lack of capital for irrigation systems and fertilizers and the lower yields expected.

Estimates of the costs and yields for the central and northern regions were made using the same methodology (Appendix 3). The overall results of these assumptions for medium costs of $3-4/GJ are illustrated in Table 18.

BIOMASS RESOURCE POTENTIAL AND COST SUMMARY

The maximum amounts of collectable biomass feedstocks for the realistic and maximum long term are shown in Table 19. A more disaggregated breakdown by type of feedstock is given in Figure 3. The results imply an allout effort to collect biomass

Table 17. Sample calculation of delivered costs for a southern wood energy farm ($/ODT; in 1977 constant dollars).

	Delivered costs ($/ODT)			Reference cost
	Cheap	Moderate	Expensive	
Preparation and Maintenance	20	30	30	14 (1)
Harvesting, Chipping	15	15	20	18 (2)
Fertilizer[a]	5	10	15	3 (1)
Irrigation[b]	5	10	20	4.2 (1)
Transportation	5	10	15	5-15 (2)
Opportunity Cost	-	8	15[c]	3-12 (2)
Total $/ton	50	83	115	
$/GJ	2.68	4.46	6.18	
(1) Mitre estimate (Salo et al. 1979) 2.04[e]				
(2) New Zealand estimate (Harris 1979) 4.32[f]				
Commercial forest used[d] at this price	4%	12%	20%	
10^6ha	2.8	6.4	10.8	
Yield assumed/ha ODT	12.5	15	16	20 (1)
Total primary energy at this price (TWh)	140	526	898	

[a]Assumes a 2x, 4x, 6x, price rise for fertilizers that is ultimately limited by the production price of hydrogen or the discovery of cheap biological nitrogen fixers for all climate zones.
[b]The price of scarce water in the south is assumed to be at least twice the cost of water in the southeastern United States.
[c]Implies that today's rapidly increasing demand for wood products is not diminished by the microfiche revolution or substitution by plastics in the future.
[d]There are 54 x 10^6ha of commercial forest in this region and 71.6 million of total forest listed by the FAO (Pelizzi 1980).
[e]Includes a $4/ton return to investor but no opportunity cost for the land.
[f]Includes 50km of transport and an opportunity cost of $10/ton or $120/ha.

Table 18. Wooded energy farms: long and short term potential.

	Land use	Potential (TWh)		Power density (W/m^2)	
Region	10^6ha	Short-term	Long-term	Short-term	Long-term
South	6.4	320	500	.6	.85
Central	1.54	95	142	.72	1.07
North	6.9	500	720	.83	1.2

Table 19. Biomass sources at realistic and maximum long-term potentials (1977 constant dollars).

	Realistic Potential (average cost=$3.10/GJ=$19.3/boe			Maximum Potential (average cost=$3.67/GJ=$22.45/boe)		
Source	Land $10^3 km^2$	% Current Streams	Energy TWh	Land $10^3 km^2$	% Current Streams	Energy TWh
Wastes	-	28	1313	-	40	1621
Catch crops	-	10	341	-	14	443
Pastures	119	13	595	-	21	1140
Marginal farm-land	14	1	84	-	3.5	345
Energy forests	125	8	750	148	10	1332
Totals	258	5.5[a]	3105	386	9.2[a]	4879
(Million mtoe/yr)			(250)			(420)

[a]Percentage of total land area.

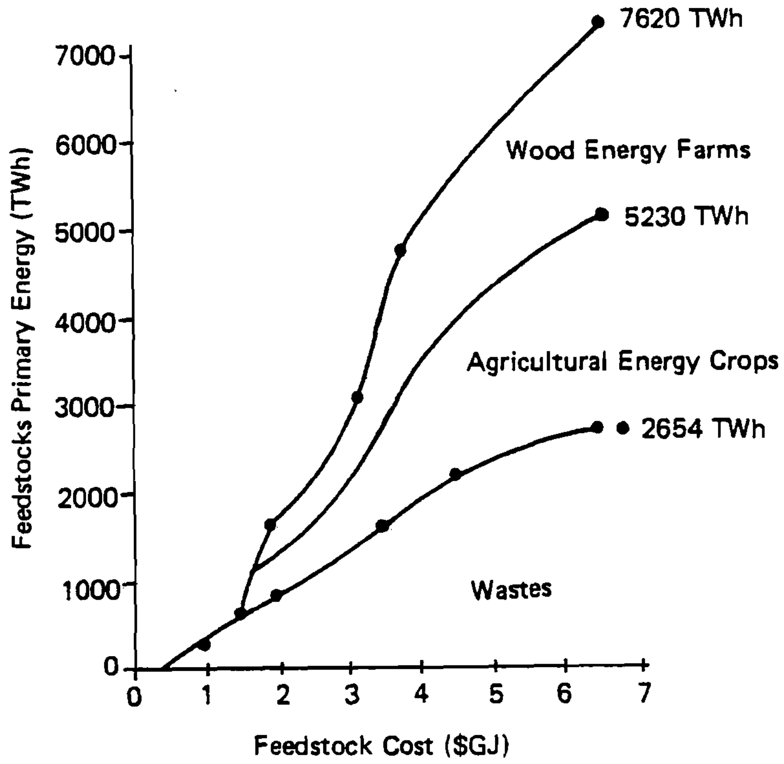

Figure 3. Composition of feedstock vs. cost.

for liquid fuels in all 19 countries. Given the likelihood that some of these projects will fall short of the yields projected or the possibility that some governments opt for different solutions to the liquids problem (conservation, electric cars, etc.), Table 19 also shows the "practical" or realizable biomass collection potential in the 21st century.

The judgment of what is "practical" is of course highly uncertain but represents at least a first-cut attempt to be conservative. If Europe is pressed for both *food* and energy in the 21st century this might limit the land use to roughly 5 or 6% of the total surface area, which is roughly equivalent to the area now devoted to agriculture. The reduction from "maximum" to practical biomass limits also stems from the uncertainty in collection factors particularly in the manure and urban waste category.

The composition or expected penetration of the different biomass types is shown in Figure 3 versus price. Note that at the maximum level of biomass collection of roughly 4700 TWh (rounded down from 4879) agricultural energy crops, forest energy farms, and waste stream contribute roughly equal shares.

A synthesis of the entire cost estimation effort for biomass streams is shown in Table 20. The overall biomass resource has been grouped into three cost categories for convenience, but in reality the costs are not discrete but continuous as was shown in Figure 3.

Table 20. Biomass resource categories by cost (1977 constant dollars).

	Resource Average (TWh)	Cost Range ($/GJ)	Average Cost ($/GJ)	Marginal Cost ($/GJ)
Cheap	1675	0.8-3.1	1.8[a]	3.2
Moderate	3057	3.11-5.19	3.67	5.2
Expensive[b]	2850	5.2-10.4	6.25	10.5

[a]equivalent to $32/ton dry wood or $11/boe;
[b]Costs of the expensive category may be underestimated due to the uncertainties in evaluating environmental costs.

METHANOL SYNTHESIS FROM GASIFICATION

Interest in gasification of biomass feedstocks to produce liquids began as a counter strategy to the rather complicated and expensive plants proposed for coal gasification. The design of these biomass gasification plants is now in the prototype stage with several governments giving it the highest priority in their overall biomass program (Frank 1980; Harris 1979). Most of these plants produce gas but recently there has been renewed interest in methanol synthesis from the gas stream. Indeed the governments of the United States and New Zealand are now funding the construction of two biomass-to-methanol plants schedule to be completed in the mid-1980s (Frank 1980).

In this section the basic chemistry, capital costs, and process efficiencies of converting biomass to methanol are defined. Projection of capital costs reductions and efficiencies are derived from work by Marchetti (1979a) and others. Finally, using the capital costs and the feedstock costs derived in the previous section, this section lays out and discusses at length estimates of the range of methanol costs to meet changing automotive fuels demands.

Basic Chemistry

The basic concept of gasification is to break the cellulose (C-H) bonds of woods into gaseous form and then create the conditions necessary to synthesize methanol under pressure. During the process the H-C ratio must be increased from 1.7 to slightly over 4 either by the addition of hydrogen or the subtraction of carbon in the form of CO_2. The basic chemistry is shown below.

Gasification	$C_6H_{12}O_6$ (cellulose) $\xrightarrow[600°C]{heat}$ $CO + H_2O$	(1)
Water shift reaction	$CO + H_2O \longrightarrow CO_2 + H_2$ CO_2 removed by water	(2)
Methanol synthesis	$CO + H_2 \longrightarrow$ pressure + catalyst $\longrightarrow CH_3OH$	(3)

with the ratio of $H_2/(2CO+3CO_2)$ to be greater than 1.

Reaction (2) is necessary only if no hydrogen is available from outside sources to increase the H-to-C ratio. Thus, two major benefits are derived if sufficient hydrogen is available:

- The capital costs typical of the water shift reaction are largely removed in the case of the synthesis process; the saving is perhaps 30% of the capital cost

- A higher percentage of the carbon in the gas stream is synthesized to methanol resulting in an increased yield of methanol per unit biomass by a factor of 2.3 (Osler 1978).

These methanol-from-wood gasification processes have the additional advantage of combining the endothermic requirements of biomass gasification with the exothermic heat releases during methanol synthesis and thus offer an opportunity for biomass drying or heat recovery cycles. Theoretical calculations by Antal indicate the heat requirements of the gasification process would be surprisingly small in comparison to coal gasification (Antal 1978).

Thus, on the surface it seems that hybrid schemes combining biomass with hydrogen yield a lower process cost and thus cheaper methanol. However, the *costs* of producing hydrogen are high and could overwhelm the favorable economies resulting from this process. Moreover the optimal design of the biomass gasification plant and the mix of hydrogen will depend on the price of biomass feedstock in relation to the cost of hydrogen. These uncertainties are reflected in the capital costs and efficiencies of the prototype designs surveyed below.

Capital Costs

Biomass gasification plants as such have not been proven commercially although the water shift and methanol synthesis steps are in use today. The major uncertainties stem from the actual gasifier design. The problem is to design reactors that reach high temperatures (800-1000°C) quickly in order to avoid the material and energy losses that occur in the phase changes of pyrolysis. Use of fine feedstock particles reduces residue but adds to processing costs. For example, power densities of 100 W/cm^2 can achieve fast gasification (milliseconds) at 85% efficiency but at a high cost.

For the purposes of the study we consider only conventional gasification designs since flash gasification still has to be proven commercially. Leading contenders appear to be the purox process (Osler 1978), the Lurgi process with entrained flames, and the Winkler process with fluidized bed combustion. All these designs are autothermal, i.e., the biomass provides the heat for the reaction. The efficiencies and capital costs for these processes are shown below (Table 21).

Table 21. Methanol processing costs without feedstock costs (in constant 1977 dollars).

Stand alone Biomass	Process efficiency	Process costs ($/GJ)	Capital costs ($/kW)	Reference
Purox	45	4.16	621	Osler 1978
Unspecified	51	3.8	363	Harris 1979
Fixed bed	55	[3.24][a]	593	Rooker 1980
Mitre design	47	-	568	Inman 1977
With hydrogen (Purox)	60	3.32	445	Osler 1978

[a]A .15 capital recovery factor was assumed along with O&M costs equivalent to 10% of the capital cost since a process cost was not given in the reference.

In order to arrive at delivered methanol costs, one must add the feedstock costs derived earlier and use some method of annualization to account for the capital costs involved in setting up the feedstock delivery system and/or the hydrogen delivery system. Of course, the feedstock costs will also be a function of the supply required to meet the liquid fuels demand.

Evolution of Process Costs over Time

A preliminary estimate of the evolution of the cost of methanol processing plants is attempted below (Tables 22 and 23). This analysis is admittedly optimistic towards the end of the time period, but the uncertainty in technological evolution over time makes this guess as good as any other.

Table 22. Biomass-to-methanol processing without hydrogen.

	1990	2000	2015	2030
Capital cost $/kW output	870	726	580	435
Efficiency %	45	50	55	55

For reference: 1975 oil refining costs are 50-100/kW.

Table 23. Processing of biomass and hydrogen to methanol.

		1990	2000	2015	2030
Capital cost $/kW		675	540	432	324
Efficiency %		55	60	66	70
Hydrogen	low	5.5	8.3	11.08	11.08
cost $/GJ	high	11.9	16.6	22.16	22.16

For reference: 2000 coal refining cost is estimated at 525 $/kW.

Estimates of the capital costs of biomass-to-methanol plants designed in the United States and New Zealand were taken for the year 2000 (Harris 1979; Osler 1978; Rooker 1980). Capital costs of plants built before then are assumed to be 25% higher due to cost overruns. The evolution of these costs over time are projected to decline and approach twice the cost of refining crude oil for gasoline ($100/kW)) if hydrogen is available. Reduction in biomass alone costs are limited to 1.5 times the hydrogen process cost or $300/kW.

Process efficiencies are projected to asymptotically approach 60% by 2030 for the gasification process involving biomass alone and 80% for biomass processing with hydrogen blending. The rate of these process efficiency increases is taken from work by Marchetti (1979a) on historical trends in the chemical industry.

For the sake of simplicity, the analysis assumes only two demand levels for Europe in the 21st century. The high demand is 3.5 times the 1975 demand for gasoline in ground transport while the low demand is 1.75 times that demand. These demands are based on a run of the MEDEE-2 model at IIASA in which passenger kilometers/capita triple over the 100 year time set (Khan and Hölzl 1982). These demands are reduced by 20% to account for the superior combustion efficiency of methanol versus gasoline. Thus 1 TWh of methanol replaces 1.2 TWh of gasoline demand in this analysis (Paul 1978).

Below the cost of meeting different demand levels over time for methanol are discussed. The projected costs of methanol are synthesized from previous estimates of feedstock costs, capital costs, as well as estimates of the range of costs to produce hydrogen from solar plants taken from Caputo (1980).

MEETING THE LONG-TERM DEMANDS FOR METHANOL

The Transition to Methanol Fuels

The first demonstration methanol synthesis plants are projected to come on line between 1982 and 1985, and commercial plants to follow in 1990. Buildup constraints in the model are assumed to limit the installed capacity of biogas gasification plants to 32 GW, or roughly 50 plants spread over 19 countries by the year 2000. These plants require 300 TWh of biomass feedstock per year supplied mainly from forest and agricultural wastes in the northern or central regions. At this time, plants for biomass-hydrogen combination plants might be in construction stage but no commercial plants are expected. The resulting methanol production of 150 TWh is projected to substitute for 6% of the low liquid demand in 2000 (10% of 1975 demand).*

During the next thirty years the frequency of cost reductions in hydrogen production could determine whether the biogas gasification plants will gradually shift to hydrogen blending or not. In any case, since the construction of hydrogen-blending plant will lag ten to fifteen years behind the biomass-alone plants, the aforementioned cost reductions may not materialize until after 2015.

In 2030 the cost of generating hydrogen is assumed to remain high but continued pressure from the rising price of oil and other liquid substitutes encourage the mobilization of biomass feedstock collection schemes up to the practical biomass availability limit stipulated in the above biomass resource summary. This would enable methanol to substitute for 70% of the medium European liquid fuels demand, i.e., 1707 TWh or roughly 1 billion boe/yr, at a cost of roughly $40/barrel.

If one follows the predicted advances in hydrogen generation technology (Marchetti, 1979b) one might project hydrogen costs from solar of 50 mills/kW via thermochemical cracking in 2030. With this available hydrogen it is possible to meet the same demand (1707 TWh) with 40% of the above biomass requirements, albeit at a methanol cost 1.5 to 2 times higher than that of the straight biomass option. However, this would "free" 1600 TWh of wood for other uses, such as backup for local heat, or electricity generation, etc.

Beyond 2030 - Meeting the Low Demand with Biomass

To meet the projected (low) demand of 2800 TWh of methanol in 2030 would require roughly 5200 TWh of biomass collection per year under the assumption of a 50% conversion efficiency in the medium term. Improvements in process efficiency could bring this feedstock requirement slightly below the maximum available estimate given (Table 19). The estimated cost of methanol at this demand is $50/boe with 60% of this cost (in 2030) derived from the feedstock cost.

Of course, the above estimate of maximum feedstocks implies full utilization of every available biomass option. In reality, some of these biomass utilization concepts are likely to prove difficult to implement or may not be cost effective from different

*Demand levels are taken from a study of Western European energy futures (Messenger 1981).

national energy perspectives. As such, the cost of the biomass feedstocks at the margin may be considerably higher than estimated.

Indeed the cost of methanol could be increased by up to \$20/boe if only biomass is available to meet the low demand due to land conflicts or low yields. Of course, the alternative to using more expensive biomass is to use hydrogen blending.

To meet the same demand using hydrogen would require only 1765 TWh of biomass (65% of the practical limit). The cost of methanol from this process beyond 2030 is projected to range from \$60 to \$100 per boe.

Beyond 2030 - Meeting the High Demand with Biomass

To produce enough methanol to meet a demand level of 5020 TWh in 2050 that is three and a half times today's gasoline demand will almost certainly require hydrogen blending to be feasible. Use of biomass alone would require the collection of twice the estimated maximum amount of feedstocks available in Europe. This would mean dramatic changes in land use and potentially sharp conflicts with the timber and agriculture industries.

The use of the hydrogen-blending process would reduce the biomass feedstock required to meet the high demand to 2462 TWh (feedstock) which is below the practical limit (Table 19). At this time, the system is also projected to be cost competitive with the biomass-alone system. If cheap hydrogen is available at 40 mills/kWh from solar systems or coal the projected cost of methanol is \$50/boe in comparison with the biomass-alone system cost of \$60/boe (see Figure 4). If hydrogen is more expensive the system may also be cost competitive with the biomass-alone systems due to the great uncertainty in estimating the environmental damage and foregone opportunities in timber and agricultural activities involved.

Methanol Cost Summary

The range of methanol costs for each processing route over time (2000-2060) is shown in Figure 5. The chart suggests that the biomass-with-hydrogen blending process could become cost competitive by 2030. This is a reasonable projection mainly because of the improved process efficiency (80%) and the lower capital costs (35% lower than in the case of the biomass-alone process) projected for the hydrogen blending process vis a vis the straight biomass gasification process.

To simplify the analysis, mean cost projections are also constructed for a constant liquids demand over time in Figure 5. In reality the costs of methanol from biomass alone will be lower during the assumed years of the transition since feedstock cost will be cheaper at lower levels of feestock demand. However, as the demands for liquids and thus biomass increase over time the hydrogen-blending option is expected to become more and more

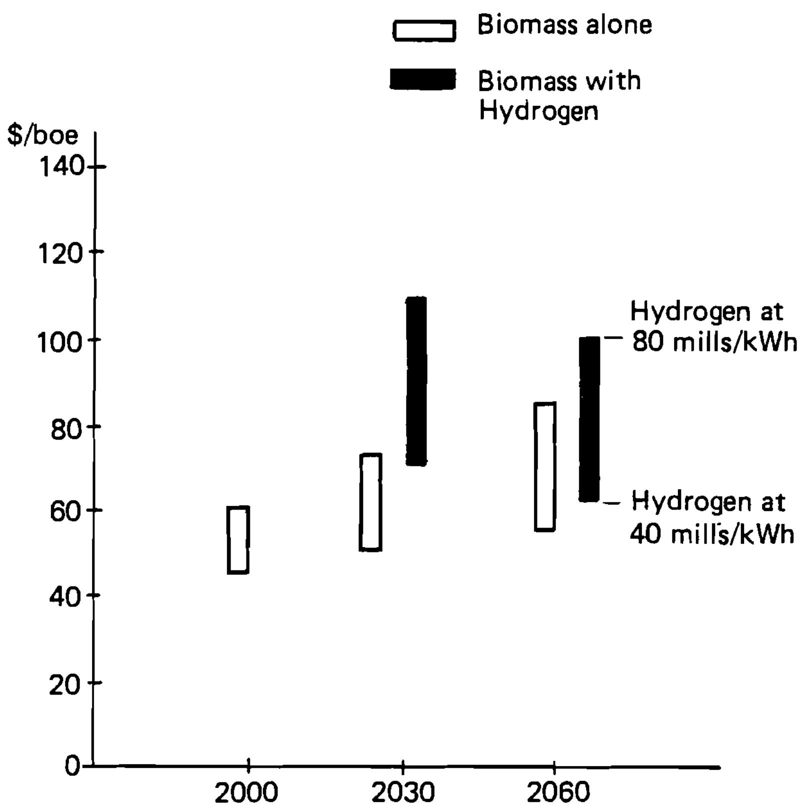

Figure 4. Methanol generation costs (1977 constant dollars).

Table 24. Methanol generation (low demand).

	2000	2030	2060
Methanol Produced (TWh)	150	1707	2613
% of Low Liquids Demand	10	60	100
Principal Constraint	Plant buildup	Biomass, Delivery, Infra-structure, Hydrogen cost	Land use conflicts, Hydrogen cost

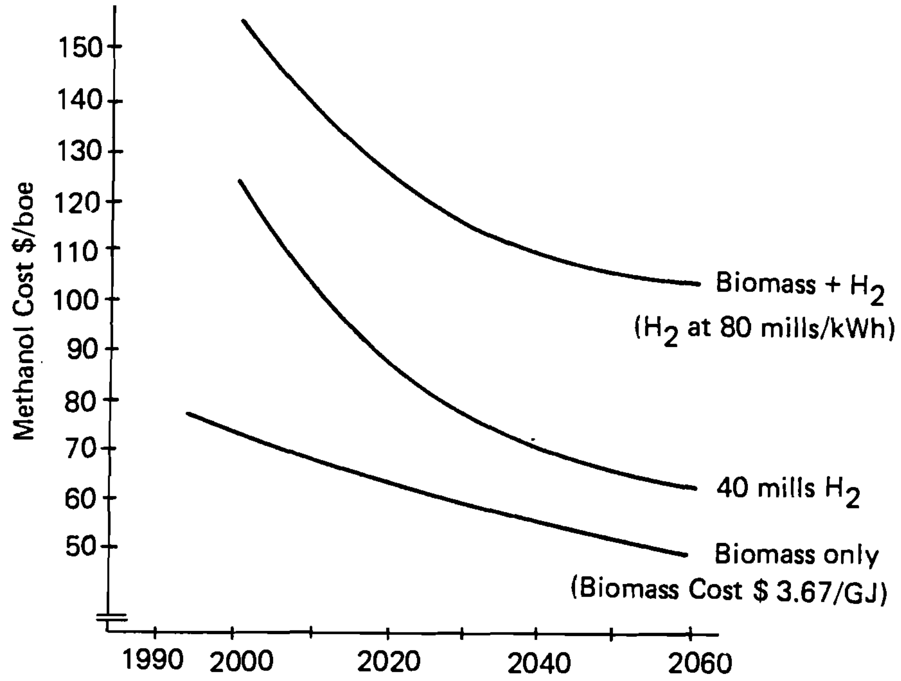

Figure 5. Methanol cost trajectory (1977 constant dollars).
Note: Methanol production assumed for all years
= 2 x 1975 automotive fuels demand
= 2 billion boe/year.

attractive as land use conflicts become increasingly severe for each additional unit of biomass required.

If the assumptions are optimistic or the cost of hydrogen from solar systems remains prohibitively high, the resulting pressure to harvest more biomass or mine more coal may raise the delivered cost of methanol considerably above these projections. On the other hand, technological progress over 100 years may indeed render these estimates far too conservative. As such these estimates may have uncertainties as high as ± 50% in either direction.

SUMMARY

Over the next fifty years a concerted effort to set up the necessary infrastructure to collect biomass feedstocks could yield 4700 TWh of primary energy at a delivered plant cost of $3.67/GJ ($22.5/boe). This amount of energy is equivalent to 80% of Western Europe's oil imports for 1975. An effort of this magnitude would require extensive exploitation of both agricultural and forest energy farms that would require using 10% of the surface area of Europe, a considerable share considering agricultural lands today account for only 15% of the area.

Competition with other food products and land use constraints suggest a more reasonable upper limit of biomass extraction of 3100 TWh might prevail in the mid term with a corresponding cost of delivery of \$3.10/GJ. Of course costs of feedstock will vary across regions and as a function of local demand but this analysis suggests the range should be limited to \$1.5/GJ and \$10/GJ. Using pilot designs and projected process efficiencies to convert this biomass to methanol, this analysis suggests this reasonable level of feedstock harvesting would meet the automotive demand for liquid fuels of 1.1 billion barrels of oil in Western Europe.

Of course feedstock costs will be subject to increasing marginal costs of extraction above a certain optimum. Costs will be considerably more expensive if European fuel demand increases markedly above 1975 levels. At demand levels roughly 50% above today's level, this analysis suggests a strong pressure to use hydrogen to stretch these carbon resources would emerge near the beginning of the 21st century. Using hydrogen in the methanol synthesis process effectively doubles the yield of biomass and would enable the maximum level of biomass harvesting postulated above to meet even the highest projections of fuel demand for 2030, three times today's consumption or 3.4 billion boe/yr.

The crucial variable in the penetration of hydrogen into the synthesis process will be its production cost. This analysis estimates the minimum cost of generating hydrogen at 30 mills/kWh from electrolysis, whereas the actual cost of "solar hydrogen" in the 21st century may range from 20 to 80 mills/kWh in the Mediterranean climate zones (Caputo, 1980). Dramatic breakthrough in hydrogen production technology (e.g. thermochemical splitting at high temperature) and blending methods could conceivably bring the cost of producing methanol from biomass down to \$40/boe using the lowest cost biomass feedstock available (\$6/boe or \$15/ton). However this must be considered an absolute limit since even the existence of "free carbon resources" and cheap refinery costs approaching those of today's oil industry would yield a methanol production cost of at least \$25/boe.

Towards the Transition to a Biomass to Methanol System

The results of this study suggest considerably more support should be devoted to planning and building the first generation of biomass plants in the 1980's. This effort is necessary not only to hasten the introduction of commercial plants and place a lid on oil prices but also to stimulate a market demand for biomass feedstocks. This in turn would provide the necessary profit incentives to begin development of the infrastructure necessary to build and operate a large-scale biomass transport and delivery system.

With such an all-out effort to mobilize biomass resources and commercialize gasification designs, up to 15% of the 1975 gasoline demand in Europe could be displaced by methanol in the year 2000. Ultimately, from 1.5 to 1.7 times this demand could be met by biomass alone. However, without the necessary government investment in commercialization efforts in at least one country per geographic region, the fruition of the scenarios discussed here may be set back for decades, if not permanently. It is hoped that the potential for fuels from biomass outlined here may serve as a catalyst to stimulate the necessary government support.

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APPENDIX 1

Forestry Wastes Generation (TWh), Medium-Cost Category, Country Summary

	Mill Wastes			Logging Waste
	1975 Production $10^6 m^3$	2030 Production[a,c] $10^6 m^3$	Milling Waste TWh[b]	1975 Production[d] TWh
Sweden	57.8	46.0	115.2	80.9
Norway	9.7	7.7	19.4	13.6
Denmark	1.6	1.28	3.2	2.2
Finland	40.2	32.0	80.4	56.0
Sub	109.3	87.0	218.2	152.7
Switzerland	3.8	3.04	7.6	5.3
FRG	28.6	22.8	57.2	40.0
Belgium and Luxemburg	2.7	2.16	5.4	3.8
Netherlands	.96	.77	1.9	1.3
Austria	11.3	9.04	22.6	15.8
U.K.	3.4	2.7	6.8	9.5
Ireland	.5	.4	1.0	.7
Sub	51.26	41	102.5	76.4
France	27.4	21.0	54.8	38
Italy	7.0	5.6	14.0	9.8
Spain	11.5	9.2	23.0	16.1
Portugal	2.9	2.3	5.8	4.1
Greece	7.8	6.2	15.6	10.9
Turkey	14.0	11.2	28.0	19.6
Yugoslavia	16.8	13.4	33.6	23.5
Sub	87.4	70	174.8	122.0
Total	248	198	495	345

Grand total = 840

[a] 1.25 production increase (2030/1975) x.62 ratio of feedstocks to collectable wastes (see p.8).
[b] 2.5 MWh/m^3 of waste.
[c] 1.5 production increase x.52 ratio of feedstock to collectable wastes for southern Europe.
[d] .25 tons (= 1.2 MWh) waste/m^3 of lumber harvested (see text).

APPENDIX 2

Biomass (TWh), Country Summary

	Straw	Forest Residues	Urban Wastes	Manure (Human Life-stock)	Catch Corps	Agric. Energy Farms	Biomass Farms	Total
North								
Sweden	12	196	6.1	3.6	24	18.5	300	560
Norway	2	35	2.6	2.2	2	5	139	188
Denmark	14	5	3.5	8.0	21	16.5	50	120
Finland	5	136	2.2	2.2	11	16	236	404
Sub	33	372	15	16	58	56	725	1275
Central								
Switzerland	2.2	13	4	1.3	3	8	9	40.5
F.R.G.	42.4	97	57	11.8	85	140	67	500.2
Belgium and Luxemburg	3.8	9	8	2.6	7	21	7	58.4
Netherlands	2.3	3	12	3.9	6	20	3	50.2
Austria	6.7	38	5	3.2	24	47	33	156.9
U.K.	2.4	16	54	10.4	45	180	21	350.4
Ireland	2.8	2	4	2.5	5	70	4	90.3
Sub	84.2	178	144	36	175	486	144	1247
South								
France	72	93	43	32	61	164	133	598
Italy	28	24	28	17.7	30	99	55	281.7
Spain	32	39	21	7.2	35	128	127	289.2
Portugal	3	26	4	2.4	9	37	31.5	114.9
Greece	8	10	3	2.5	10	62	22	117.5
Turkey	42	57	21	21.4	50	156	76.5	423.9
Yugoslavia	39	48	10	9.8	24	84	69	283.8
Sub	244	297	130	93	210	730	526	2210
Total	341	847	289	145	443	1272	1395	4732

APPENDIX 3

Wood Energy Farms, Costs and Yields in the Central and Northern Regions

	Cheap	Moderate	Expensive
North			
Cost ($/ton)	35	60	105
Yields (ton/ha)	15	20	18
Land-energy farms (10^6ha)	3.4	6.9	12.3
% of forest land	5	10	18
Total primary energy (TWh)	267	725	1155
Central			
Costs ($/ton)	40	60	100
Yield (tons/ha)	15	18	16
Land-energy farms (10^6ha)	.77	1.54	3.08
% of forest land	5	10	20
Total primary energy (TWh)	60	144	256

In 1977 constant dollars.

APPENDIX 4

Energy Density Assumptions

Form	Energy	
Pelletized wood	= 20.5 GJ/ton (metric)	
Dry wood	= 18 GJ/ton	1 m^3 wood = 0.78
Forest wastes	= 16 GJ/ton	(25% moisture)
Agr. wastes (straw)	= 14.4 GJ/ton	
Densified straw	= 17.5 GJ/ton	
Municipal solid waste	= 13.7 GJ/ton	
Human waste	= 784 kcal/kg (implies 20% conversion efficiency) = 3.2 GJ/ton of dry organic matter	
Methanol	= 20 GJ/ton = 1.5 MJ/liter	