CARBON SEQUESTRATION VERSUS FOSSIL FUEL SUBSTITUTION: ALTERNATIVE ROLES FOR BIOMASS IN COPING WITH GREENHOUSE WARMING

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Abstract

Displacing fossil fuel with biomass grown sustainably and converted into useful energy with modern conversion technologies would be more effective in decreasing atmospheric CO_2 than sequestering carbon in trees. Some industrial restructuring would be required to bring about a major energy role for biomass. However, the prospect that electricity and liquid fuel from biomass could often be less costly than from coal and petroleum makes this strategy for coping with greenhouse warming inherently easier to implement than many alternatives.

Introduction

Since it was initially proposed,[1] there has been much discussion[2-17] of carbon (C) sequestration by forests as one strategy for offsetting CO_2 emissions to reduce greenhouse warming. While the substitution of biomass for fossil fuel has sometimes been mentioned,[1-9] there has been no systematic comparison of these alternative biomass strategies for coping with greenhouse warming.

In this paper it is shown that, while sequestering C in forests is a relatively low-cost strategy for offsetting CO_2 emissions from fossil fuel combustion, substantially greater benefits can be obtained by displacing fossil fuel with biomass grown sustainably and converted into useful energy using modern energy conversion technologies. Biomass substituted for coal can be as effective as C sequestration, per tonne of biomass, in reducing CO_2 emissions; however, fuel substitution can be carried out indefinitely, while C sequestration can be effective only until the forest reaches maturity. Also, far greater biomass resources can be committed to fossil fuel substitution at any given time than to C sequestration, because (i) producers will tend to seek biomass species with higher an-

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nual yields for energy applications, and (ii) biomass for energy can be obtained from sources other than new forests. Thus biomass can play a larger role in reducing greenhouse warming by displacing fossil fuel than by sequestering C. Moreover, biomass energy is potentially less costly than the displaced fossil fuel energy in a wide range of circumstances, so that the net cost of displacing CO_2 emissions would often be negative. Thus bioenergy strategies have "built-in" economic incentives that make them inherently easier to implement than many alternative strategies for coping with greenhouse warming.

Carbon Sequestration

The basic C sequestration proposal calls for planting trees in forest reserves that would be maintained in perpetuity. With this approach, C absorption would continue until the forest matures, which could be some 40 to 100 years, if trees of long rotation are selected. This is not a permanent solution, but it does allow time to develop alternative, zero-CO_2-emitting energy sources. The capacity of growing forests to absorb C from the atmosphere depends on various factors, but 2.7 tonnes of C per hectare per year (tC/ha/yr) is typical[18] of average values assumed in most C-sequestration studies; as biomass, on a dry-weight basis, is about half C, the corresponding biomass productivity would be about twice as large. However, Moulton and Richards have estimated that the *total* forest ecosystem sequestering rate (including roots and soil C) could average 5.3 tC/ha/yr for a U.S. tree-planting program. Such an effort, involving up to 139 million hectares of economically marginal and environmentally sensitive crop lands and pasture lands and understocked forestlands held by private owners other than the forest industry, would have the potential for offsetting up to 56% of present U.S. CO_2 emissions.[12]

Variations on the C sequestration proposal that permit a continuing absorption of C in forests beyond maturation involve cutting down the mature trees, replanting, and either putting the harvested wood into permanent storage ("pickling the trees") or stimulating the market demand for long-lived forest products by offering a "bounty" for harvesting trees for this purpose.[16] The requirements for tree harvesting, transport, and storage will make the "tree pickling" option much more costly than basic reforestation and thus much less interesting, at least until less costly options are exhausted. The market for long-lived forest products is likely to be able to offset only a small fraction of fossil CO_2 emissions; in the period 1985-87 global consumption of sawnwood and wood-based panels averaged only 600 million cubic meters/yr,[19] with a total C content of 0.13 gigatonne/year (Gt/yr). Projected normal demand growth is in the range of 2-3%/yr to the year 2000,[20] and offering a bounty is not likely to change demand growth much. Thus present and prospective sequestering rates in long-lived forest products are small compared to the rate of anthropogenic CO_2 emissions, some 5.9 Gt C/yr in 1985 (Table 1). Sequestering of C in trees will probably be considered primarily in the form of the basic sequestering option, rather than these variations.

The cost of offsetting CO_2 emissions by sequestering C in trees is directly related to the cost of growing biomass. According to Moulton and Richards, average and marginal unit costs for a tree-growing program offsetting 56% of U.S. fossil CO_2 emissions would be \$27/tC and \$48/tC (Figure 1), respectively.[12] The annual cost of such a large-scale U.S. effort, some \$19.5 billion, might be paid for by a carbon tax of \$15/tC on all fossil fuels consumed, the effect of which would be to increase the cost of coal-based electricity generation by 0.4 cents/kwh (a 7% increase) and the cost of gasoline by 1.0 cent/liter, according to our calculation. If the sequestering rate were half the value estimated by Moulton and Richards, the required tax would be twice as large.

These costs are modest relative to the costs presently estimated for recovering and sequestering CO_2 from fossil fuel power plants. Recovering with a chemical absorption process 90% of the CO_2 from the flue gases of coal-fired steam-electric plants and piping the recovered CO_2 to, and sequestering it in, abandoned natural gas wells has been estimated to cost about \$120/tC for the Netherlands.[21] An innovative approach applicable to integrated coal gasifier/combined cycle power plants leads to an estimated cost for CO_2 removal and sequestering of a little more than \$50/tC,[21,22] which is still more than the estimated cost of sequestering C in new forests.[12]

While the cost of offsetting CO_2 emissions by sequestering C in forests is low, it is usually positive, because there are typically no offsetting credits from ancillary benefits. Some alternative strategies for reducing CO_2 emissions have negative net costs because such benefits can exceed the gross costs – e.g. investments in improving energy efficiency that obviate more costly expenditures for energy supply.[23] It has been shown in detailed studies for Sweden[24] and the Netherlands,[25] for example, that major reductions of CO_2 emissions could be achieved in those countries at negative net cost by exploiting cost-effective opportunities for improving energy efficiency. To the extent that there are negative cost opportunities for reducing or offsetting CO_2 emissions, they warrant higher priority than growing trees for C sequestration.

Fossil Fuel Substitution

The major alternative to C sequestration as a strategy for using biomass in coping with greenhouse warming is to grow biomass sustainably for energy markets, with the amount grown equal to that burned in a given period. When biomass is used this way, there is no net atmospheric buildup of CO_2, because the CO_2 released in combustion is compensated for by that extracted from the atmosphere in photosynthesis. The potential for reducing CO_2 emissions through biomass substitution depends on the fossil fuel displaced and on the relative efficiencies of converting biomass and fossil fuel into useful energy.

Suppose first that the conversion efficiencies are equal. Then each GJ of biomass substituted for fossil fuel would reduce emissions by the C content of one GJ of fossil fuel displaced – 0.014 tC, 0.019-0.020 tC, and 0.023-0.025 tC, for natural gas, petroleum, and coal, respectively. Oven-dry biomass, with a heating value of about 20 gigajoules/tonne (GJ/tonne) and a C content of 0.5 tonnes/tonne, can sequester 0.5/20 = 0.025 tC per GJ of heating value. Thus substituting biomass for coal is essentially equivalent to C sequestration, while substituting biomass for petroleum or natural gas would be less effective than C sequestration, in terms of the impact on the atmosphere of producing a tonne of biomass.

In practice the efficiencies of making useful energy will not be the same for biomass and fossil fuels. It is customary to assign much lower efficiencies to biomass. Most biomass used for energy in the world today is in the form of fuelwood, crop residues, or dung for cooking in rural areas in developing countries, at efficiencies of the order of 10% – only about a fifth of the efficiency of typical stoves fueled with natural gas or liquid petroleum gas. Further, compared to the 34-36% efficiencies achieved with modern, large-scale, 400-600 MW coal-fired steam-electric plants, typical biomass-fired steam-electric power plants have efficiencies in the range of 20-25%. The strong scale economies inherent in steam-electric power-generating technology dictate the choice of less costly alloys in boiler construction and thus to the production of lower quality steam and to lower efficiencies at plant scales of tens of megawatts, which are typically needed for biomass applications because of the dispersed nature of the biomass resource. Moreover, if liquid fuels like methanol or ethanol are produced from biomass as alternatives to gasoline in transport applications, conversion losses amount to nearly 50%,[26,27] while refinery losses in making gasoline from petroleum are only about 10%.

This outlook changes, however, if consideration is given to modern conversion technologies and future energy needs. The technologies of choice for producing electricity from biomass at modest scales in the near term are likely to be integrated gasifier/gas turbine cycles, which would offer efficiencies higher than for coal steam-electric power generation, as well as lower capital costs.[28-30] Also, if synthetic liquid fuels from biomass are considered not as alternatives to petroleum-based liquid fuels but as alternatives to synfuels derived from coal[31] – the appropriate comparison for a world faced with the declining availability of secure petroleum supplies – then the conversion efficiencies are comparable for biomass and fossil fuel feedstocks (Table 5).

Thus if biomass is considered primarily as a substitute for coal using modern conversion technologies for producing either electricity or liquid synfuels, the effect on atmospheric CO_2 would be comparable to what could be achieved with C sequestration, per tonne of biomass produced (Figure 1).

Relative Potentials for Reducing Greenhouse Warming

Biomass can play a larger role in reducing global warming when used to displace fossil fuel than when used to sequester C. This is in part because, when biomass is substituted for fossil fuel, the use of a given piece of land is not limited to just the period till the forest matures, as is the case for the basic C sequestration proposal. Additionally, the market for biomass as a substitute for fossil fuel is much larger than that in the variant of the sequestration proposal in which C is stored in long-lived forest products.

Moreover, when biomass is produced for energy markets, producers will seek to maximize the harvestable annual yield of biomass rather than the total amount of C that can be sequestered in a mature forest. This goal shift will probably lead producers to choose short-rotation woody or herbaceous crops instead of long-rotation forests. For long-rotation forests, achievable harvestable yields with present technology are about 4-8 dry tonnes/ha/yr in temperate regions and 10-12 tonnes/ha/yr in tropical areas, compared to yields for short-rotation tree crops of 9-12 tonnes/ha/yr in temperate and 20-30 tonnes/ha/yr in tropical regions.[9,32-35] Moreover, even higher yields are feasible with herbaceous crops. For example, the annual yield of sugar cane, averaged over 17 million hectares of cane harvested globally in 1987, was about 35 dry tonnes/ha/yr of aboveground harvestable plant matter (including the tops and leaves); in some countries (e.g. Ethiopia, Peru, Zimbabwe), the average yield is about twice the global average.[36] Moreover, herbaceous crops can often be grown at relatively high productivity on crop and pasture lands where the soil and climatic conditions are not especially favorable for growing trees. For example, switchgrass (*Panicum virgatum*), a perennial herbaceous crop, has been found to be relatively drought-resistant and to provide good erosion control, while offering good yields on marginal U.S. crop lands (over 10 dry tonnes/ha/yr) with relatively low levels of inputs.[37,38]

Biomass can also play a larger role in coping with greenhouse warming as a fossil fuel substitute than as a store for sequestering C because the land that can be used for energy production is not restricted to new lands for planting forests or alternative crops. In a study carried out for the Oak Ridge National Laboratory (ORNL), it was estimated that comparable contributions to total potential U.S. biomass supplies of 29.3 EJ/yr in the period beyond 2030 would come from those agricultural and forest residues that could be economically recovered in environmentally acceptable ways (8.9 EJ/yr), from growth in existing forests (9.5 EJ/yr), and from biomass energy crops (10.8 EJ/yr) (Table 2).[39]

While some biomass residues are often already being used for energy or other purposes, they could be used much more effectively with modern, energy-efficient conversion technologies. For example, in the cane sugar industry, bagasse (the residue left after crushing the cane to extract the sugar juice) is presently fully used in most parts of the sugar-producing world just to satisfy the steam and electricity requirements of sugar factories. But by employing energy-efficient steam-using equipment in the factory, by using biomass gasifier/gas turbines instead of inefficient steam turbines for electricity generation, and by using for fuel the tops and leaves of the cane plant (now often burned off just before the cane harvest) as well as the bagasse, it is feasible to increase electricity production from cane residues to more than 40-fold on-site needs, while still meeting all on-site steam requirements for sugar processing.[29] Similarly, using residues from kraft pulpmaking for gas turbine-based power generation in energy-efficient pulp mills can result in electricity production that is more than five times on-site needs.[30]

Existing forests can often also provide additional biomass for energy beyond that offered by logging residues. In many temperate zone forests, annual removals are much less than annual growth. For example, a 1980 study by the Office of Technology Assessment of the U.S. Congress estimated that net annual growth in U.S. commercial forests in the 1970s was some 400-800 million tonnes/yr, while annual harvests of "industrial roundwood" for lumber, plywood, pulp, and other forest products were only 180 million tonnes/yr.[40] When harvests are much less than growth, forest yields tend to be lower than what they might otherwise be. Moreover, much of the unharvested stock is often too low in quality for use in traditional forest products markets but is well suited for energy applications. Removal of the low-quality woodstock for energy purposes can simultaneously lead to enhanced yields of high quality wood.[40,41] The increased productivity of high quality wood in regrowth forests managed this way can help ease the pressures to exploit original-growth forests, thereby easing environmental concerns.

Existing forests can also be made more productive by full stocking with trees well suited to the sites. The Office of Technology Assessment estimated that with full stocking net annual growth of biomass on United States commercial forestland could be doubled, to 800-1600 million tonnes/yr, corresponding to an average productivity of 4-8 tonnes/ha/yr.[40]

The potential of using existing forests in the U.S. for bioenergy purposes can be estimated by assuming a biomass productivity of 6 tonnes/ha/yr on the 190 million hectares of commercial timberland (exclusive of the 14 million hectares of timberland in the U.S. that is protected by law from exploitation for environmental and other reasons and the 86 million hectares of other U.S. forest land). Potential biomass production on commercial timberland in excess of current removals (some 200 million tonnes/yr) would be 940 million tonnes/yr or 18.8 EJ/yr – equivalent in energy terms to current coal use in the U.S. Less than the full potential is likely to be exploited. The 1989 ORNL study of the U.S. bioenergy potential targeted recovering for energy about half this amount.[39]

At the global level the potential for utilizing wood from existing forests for energy is quite uncertain, owing to the paucity of data on the total productivity of the world's forests. However, Earl estimated that the annual increment of wood was 17.8×10^9 cubic meters on 3800 million hectares of global forests in 1970.[42] For comparison, the estimated global average annual wood harvests in the period 1985-87 were 3.26×10^9 cubic meters for industrial roundwood, fuelwood, and charcoal.[19] If the productivity of the world's forests today is close to Earl's estimate, some of the unused increment (having an energy content of 125 EJ/yr, equivalent to 1.27 times total world coal consumption in 1988[43]) could be recovered for energy purposes.

In practice the biomass sources used for energy will probably be a diverse mix of residues, increased production from existing forests, and wood or herbaceous crops planted for energy purposes on unforested land or understocked forested land. The appropriate mix will be determined by economics, water and land resources availability, and constraints posed by environmental and soil conservation considerations.

The Costs of Reducing Greenhouse Warming

Producing biomass for energy purposes is more costly than growing trees to sequester C because of the added costs of harvesting, processing, transport, drying, and storage. In the case of short-rotation wood crops, for example, the total cost paid for biomass at an energy conversion facility can be more than three times the cost of growing the biomass (Table 3).[44,45] However, revenues from the sale of energy produced from biomass can be taken as a credit against the cost of providing it. Here the estimated costs of reducing CO_2 emissions are presented for both power generation and liquid fuels production from biomass as alternatives to fossil fuels, using alternative technologies (Figure 1 and Tables 4 and 5).

Electricity produced from biomass in steam-electric power plants would be more costly than from coal, for biomass costing more than about $1/GJ when coal costs about $1.8/GJ, a typical expected lifecycle price for coal power plants that might be ordered in the U.S. today. The corresponding cost of fossil fuel CO_2 displacement by biomass with this technology would be greater than the cost of sequestering C in forests, except in special circumstances where biomass is available at very low cost (e.g. mill residues in the forest products industry).

In contrast, with biomass gasifer/gas turbine technologies, which are expected to be both less capital-intensive than coal steam-electric plants and to have comparable or greater efficiencies, electricity from biomass could be less costly than electricity from coal using biomass priced at more than double the coal price (Table 6). As there are likely to be substantial biomass supplies available at prices less than double the coal price, the corresponding cost of reducing CO_2 emissions would often be negative if biomass gasifier/gas turbine power were substituted for coal steam-electric power (Figure 1 and Table 4).

While the biomass versions of the gas turbine technologies considered here could be commercialized more quickly than the corresponding coal versions (because unproven sulfur removal technology is needed for coal but not for biomass), the latter might be commercialized eventually. If they were to become the norm for coal-based power generation, the biomass versions could still be competitive for biomass prices up to 20% more than the coal price, since the biomass plants would be less capital-intensive (Table 6).

The net costs of reducing CO_2 emissions through biomass substitution for fossil fuels in liquid fuels production with alternative technologies are indicated in Figure 1. Here biomass-derived methanol and ethanol are considered as alternatives to gasoline and coal-derived methanol (Table 11). As for electricity, there appear to be major opportunities for displacing fossil CO_2 emissions with biomass at negative cost. The indicated economics are especially promising for ethanol derived from lignocellulosic feedstocks (e.g. wood) using enzymatic hydrolysis.[27]

As neither the gas turbine technologies nor the alcohol technologies described here are yet commercially available, one cannot assign a high degree of precision to these cost estimates. However, the cost estimates should not be far off, at least for the biomass gasifier/gas turbine power technologies and for the biomass/methanol technologies, since there are no major technological hurdles that must be overcome in commercializing them.

The Potential for Biomass Energy in Coping with Greenhouse Warming

The global CO_2 emissions scenarios advanced by Working Group III of the Intergovernmental Panel on Climate Change (IPCC)[46] provide a useful context in which to examine the global prospects for displacing CO_2 emissions through substituting biomass for fossil fuel. Global emissions levels for three IPCC scenarios through the middle of the next century are presented in Table 1.

For the "business as usual" scenario (Scenario A), the IPCC Working Group I projects that the buildup of greenhouse gases would lead to an increase in the global average temperature at a rate of 0.3°C per decade, to 4°C above the preindustrial level by 2100.[47] For Scenario D, the most ambitious scenario considered by Working Group III for coping with greenhouse warming, CO_2-equivalent greenhouse gas emissions stabilize by 2100 at 560 ppm, double the preindustrial level of CO_2, and the global mean temperature increases 0.1°C per decade or 2°C above the preindustrial level by 2100.[47] This scenario involves a strong emphasis on energy efficiency, a shift to renewables and nuclear energy in the first half of the 21st century, and a reversal of deforestation.

Here we explore the prospects for reducing CO_2 emissions to the Scenario D levels through the use of biomass for energy. For this exercise we construct a new biomass energy-intensive Scenario D' with the same CO_2 emissions levels as Scenario D (Table 1). Our reference scenario is a variant of the IPCC Scenario B, which involves an emphasis on energy efficiency, natural gas as a low-C fossil fuel, a reversal of deforestation, and modest amounts of bioenergy. We choose this as a point of departure because energy efficiency is likely to be the most cost-effective strategy for reducing greenhouse emissions,[24,25] natural gas is widely seen as the fossil fuel of choice in the decades immediately ahead,[48] and a consensus is emerging that deforestation should be curbed, even though it might be difficult to achieve this goal. To avoid double-counting biomass in estimating the potential role of bioenergy, however, we construct for our reference scenario, Scenario B', a variant of Scenario B that involves no biomass for energy. In Scenario B' deforestation is assumed to be halted rather than reversed, and coal is substituted for the biomass used for energy in Scenario B (Table 1). If all the difference in emissions between Scenarios B' and D' were achieved with biomass substituting for coal, fossil CO_2 emissions amounting to 1.7 Gt C/yr by 2025 and 5.4 Gt C/yr by 2050 would have to be displaced (Table 1).

The emissions reduction needed by 2025 could probably be met by using for energy various industrial and agricultural residues, which are prime candidates for initial bioenergy systems. Detailed assessments indicate attractive economics in the sugar cane industries for co-producing electricity plus sugar or alcohol,[29] and in the kraft pulp industry for electricity plus pulp.[30] There are many other residues that could probably also be exploited (Tables 14 and 15).

For 2050, we assume that one-third of the targeted fossil CO_2 emissions reduction is achieved by displacing coal with residues, and two-thirds by displacing coal with biomass crops, both woody and herbaceous, grown on 600 million hectares, at an average productivity of 12 dry tonnes/ha/yr.

While much higher than the productivity of natural forests, the assumed productivity is consistent with what has been achieved to date with experimental trials and demonstrations and with limited commercial plantation experience (see earlier discussion). Considering that the era of modern scientific silvaculture began only around 1970 in both temperate and tropical zones[9] and that the growing of herbaceous crops for energy purposes is even more embryonic, at least this average productivity could plausibly be achieved on a large scale by the second quarter of the next century. For comparison, average productivities of wheat in the U.K. and maize in the U.S. have more than tripled since the mid-1940s. At present maize yields in the U.S. average 7.5 tonnes/ha/yr of grain plus an equal quantity of residues (Table 15). Moreover, the targeted annual productivity corresponds to a 0.4% efficiency for converting solar energy into recoverable biomass energy, while the practical maximum photosynthetic efficiency under field conditions is about 5%,[49] and 2.4% has been attained for Napier grass, under optimal field conditions,[50] suggesting a large potential for long-term gain.

The land area targeted for biomass energy crops in 2050 is equivalent to 15% and 40% of the amount of land now in forests and crop lands, respectively.[19] It is also equivalent to what would be in new forests by 2050 if the ambitious goal for net forest growth of 12 million hectares at the beginning of the next century, agreed to in the November 1989 Nordwijk Declaration,[51] were realized.

Houghton has estimated that 500 million hectares of land in Africa, Asia, and Latin America could be available for reforestation.[3] His criteria for availability were that the land (i) had supported forests in the past, and (ii) was now unused for crop lands or settlements. He estimated that an additional 365 million hectares of land in the fallow cycle of shifting cultivation might also be targeted for reforestation. Independently, Grainger has estimated that some 758 million hectares of degraded lands are available for reforestation.[52] Moreover, some of the world's 1500 million hectares of tropical grasslands might be used for biomass energy crops (e.g. growing perennial grasses). At present about 750 million hectares of these grasslands are burned off each year,[53] and some of this land may be amenable to different management practices if benefits were to accrue to the local populace. While the various estimates of available land are quite uncertain, they suggest that large areas may be available for energy crops in tropical areas.

Considerable land might also be available for energy crops in industrialized countries. In the European Community over 15 million hectares of crop land would have to be taken out of production if agricultural surpluses and Community expenditures on agricultural subsidies were to be brought under control.[34]

In the U.S., 30 million hectares of crop land were idled in 1988 to reduce production or conserve land.[6] The land available for biomass production could be considerably greater than this. About 43 million hectares of crop lands have erosion rates exceeding the maximum rate consistent with sustainable production;[12] shifting this land from annual food crops to various perennial energy crops could greatly reduce erosion. An additional 43 million hectares of crop land have "wetness" problems – poor drainage, high water tables, or flooding; when used for ordinary agriculture these lands could potentially contribute to surface- and groundwater pollution[12] – problems that could be eased with the production of some types of energy crops as alternatives. Moreover, the amount of idle crop land might increase substantially. A 1987 report of the New Farm and Forest Products Task Force estimated that over the next quarter century new crops will be needed for some 60 million hectares of existing crop land.[54] There are also 60 million hectares now in pasture, range, and forest considered capable of supporting biomass production for energy.[27]

The contribution of biomass from energy crops could be reduced either by greater use of biomass residues or by the extraction, with improved management, of additional biomass from existing forests. If the global emissions reduction of Scenario D' in the middle of the next century were achieved with equal shares from residues, energy crops, and existing forests (like the ORNL estimate of potential U.S. biomass supplies[39]), existing forests would contribute for energy an amount of biomass equivalent to about half of the annual increment[42] in excess of current removals,[19] and thus the assumed contribution from energy crops would be half as large. However, because of the uncertainties in forest statistics worldwide, we have not included in Scenario D' a contribution from wood from existing forests.

We conclude that the CO_2 emissions levels of Scenario D could plausibly be achieved without exploiting low-C energy supplies other than natural gas and biomass. It might be feasible to reduce emissions further by exploiting other renewable energy technologies for which the prospects are auspicious,[27,55] as recognized implicitly by Working Group III in formulating Scenario D.

Toward Sustainable Biomass Production

If biomass is to play a major role in the energy economy, strategies for sustaining high yields over large areas and long periods are needed. The experience of sustaining high sugar cane yields over centuries in the Caribbean and in countries like Brazil suggests that this will be feasible, but good management practices and new research are required to achieve this wider goal.

Achieving sustainable production and maintaining biological diversity may require polycultural strategies (e.g. mixed species in various alternative planting configurations) for biomass production in many areas. Biomass energy systems can usually accommodate a variety of feedstocks. At present, however, monocultures are favored for energy crops, in large part because management techniques in use today tend to be adapted from monocultural systems for agriculture. Polycultural management techniques warrant high priority in energy crop research and development.

While net biomass energy yields for short rotation tree crops are typically twelve times energy inputs,[56] it is desirable, both economically and environmentally, to try to reduce energy inputs. For example, the nutrient status of afforested lands might be maintained by recycling nutrients and by choosing suitable mixed species and clones.[57,58] The promise of such strategies is suggested by 10-year trials in Hawaii, where yields of 25 dry tonnes/ha/yr have been achieved without N-fertilizer when *Eucalyptus* is interplanted with N_2-fixing *Albizia* trees.[59]

Research can lead not only to improvements in present techniques for producing energy crops but also to new approaches. For example, long-term experiments in Sweden have shown that: (i) in most forests trees grow at rates far below their natural potential, (ii) nutrient availability is usually the most important limiting factor, and (iii) optimizing nutrient availability can result in four- to six-fold increases in yield. Under nutrient-optimized conditions all tree species investigated have behaved similarly to C_3 crop plants, with about the same total biomass yield per unit of light intercepted by the leaves during the growing season.[60] Growing trees under nutrient-optimized conditions thus could make it possible to achieve high yields with existing species and clones, thus facilitating the incorporation of pest resistance and other desirable characteristics, and the maintenance of a diverse landscape mosaic. To the extent that crop lands and wastelands would be converted to energy crops this way, it may be feasible not only to maintain but to improve biological diversity. An additional advantage of pursuing non-nutrient-limited production strategies is that the trees thus produced shift a percentage of their increased overall yield from roots to above-ground production – again similarly to the experience with agricultural crops.[35]

Nutrient-induced yield increases can be achieved without nutrient leaching when good forest management is practiced. But achieving sustainable high yields this way requires implementing techniques being developed for matching nutrient applications to the time-varying need for nutrients.[60,61]

Achieving high levels of biological diversity will also require maintaining some of the land in biomass-producing regions in a "natural" condition. For example, some bird species require for survival dead wood and the associated insect populations. Experience in Swedish forests suggests that maintaining a relatively modest fraction of forest area in such natural reserves is adequate to maintain a high level of bird species diversity.[62] Research is needed to understand how best to achieve desirable levels of biological diversity under the wide range of conditions under which biomass might be grown for energy.

While major expansions are needed for research efforts relating to sustainable biomass production, there is time for the needed research and extensive trials, because major bioenergy industries can be launched in the decades immediately ahead using as feedstocks primarily residues from the agricultural and forest products industries.

Developments Needed in Biomass Energy Conversion Technology

Research and development (R&D) are needed on converting biomass efficiently and cost-effectively into modern energy carriers, if biomass is to play a major role in the global energy economy.

While there has been relatively little R&D on biomass energy conversion, there has been considerable effort aimed at "modernizing coal" through thermochemical conversion, for both electricity and fluid fuels applications. Some of this coal conversion technology can be adapted to biomass.

For the near term the prospects are auspicious for commercializing biomass gasifer/gas turbine power-generating technologies designed originally for coal. While commercially ready coal gasifer/gas turbine technologies cannot provide electricity at lower cost than existing coal steam-electric power systems, simplified versions under development offer the potential for substantially lower cost.[63,64] Such simplified technologies could probably be commercialized more quickly for biomass than for coal, because biomass contains negligible sulfur, the cost-effective removal of which is the major technological hurdle that must be overcome before these technologies can be commercialized for coal.[28-30] Recently, a Finnish/Swedish consortium announced plans to build a demonstration plant in Sweden with such technology and have it running in two to three years.[65]

For the longer term, power generation R&D should focus on technologies well matched to the characteristics of biomass. Gasifiers should be designed to exploit the fact that biomass is much more reactive and thus easier to gasify than coal. Power-generating technologies other than gas turbines should also be developed—e.g. advanced fuel cells for applications at smaller scales than the 5-100 MW scales for which gas turbines are well suited.

Methanol can be derived from biomass using thermochemical conversion technology like that used for coal. While methanol is likely to be less costly from biomass than from coal in small-scale plants,[66] methanol can be produced from coal in plants of much larger capacity, giving rise to scale economies that cannot practically be exploited with biomass, owing to the dispersed nature of the biomass resource. Alternative liquid fuel technologies designed to exploit the unique characteristics of biomass—e.g. technologies based on biological processes—might be able to compensate for this scale disadvantage.

Fuel ethanol is produced from sugar cane via fermentation on a large scale in Brazil. Though with present technology this ethanol is not competitive at the pre-August 1990 world oil price, the co-production of electricity from cane residues using gasifier/gas turbine power generating technologies at alcohol distilleries could make the ethanol competitive even at this low oil price.[29] For temperate climates, the production of ethanol from low-cost lignocellulosic feedstocks (e.g. wood) via enzymatic hydrolysis techniques is promising. Analyses carried out at the U.S. Solar Energy Research Institute (SERI) suggest that, with emphasis on R&D, ethanol produced this way could be competitive with gasoline from petroleum by the turn of the century for biomass costing less than $3/GJ (Table 11 and Figure 1).[27]

Finally, R&D on the growing, harvesting, and preparation of biomass feedstocks should be coordinated with the R&D on biomass conversion.[67] It may often be possible to substantially reduce costs for costly items (e.g. biomass drying), as well as overall costs, by taking a systems approach to development.

Industrial Infrastructure Issues

Fully exploiting the biomass energy potential will probably require evolving industries quite different from those that now provide energy, because biomass energy systems would be different from the energy systems now in place—they would be rural-based, relatively labor-intensive, variable from region to region, and more decentralized. Structurally, these industries would have characteristics of today's agricultural and forest products industries, as well as of today's energy industries. Public policy changes may well be needed to facilitate their orderly development.

While articulation of the needed policies is beyond the scope of the present analysis, these changes could probably be brought about by creatively using familiar policy instruments. For example, general policies promoting co-generation and power from renewable energy sources, like the 1978 Public Utility Regulatory Policies Act (PURPA) in the U.S., could be helpful in nurturing a biomass-based power industry. The expansion of biomass-based power generation in the U.S., from about 250 MW in 1980[68] to some 9,000 MW in 1990[27] was due in large part to the influence of this Act. Likewise, policies aimed at removing agricultural subsidies and simultaneously providing interim incentives to farmers to shift production to biomass for energy[34] could be quite helpful in nurturing bioenergy industrial development.

Conclusion

Biomass strategies are attracting considerable attention as options for coping with greenhouse warming. While, to date, emphasis has been on planting trees to sequester carbon, the growing of biomass for energy provided by modern energy conversion systems would enable biomass to play much wider roles. Though C-sequestering strategies will be important where the produced biomass cannot be practically harvested for energy (e.g. in areas remote from energy markets or on steep slopes) or where the creation of new forest reserves is deemed desirable for environmental or economic reasons, biomass energy strategies will usually be preferred. Moreover, since biomass energy will often be less costly than fossil fuel energy, biomass energy strategies will be inherently easier to implement than many other proposed strategies for coping with greenhouse warming.

The techniques and technologies for growing biomass and converting it into modern energy carriers must be more fully developed, and new industrial infrastructures must be evolved in order to realize the full potential for bioenergy. Despite such challenges, bioenergy industries could be launched in the decades immediately ahead, starting off using residues from agriculture and forest product industries. Initially, biomass could be converted into modern energy carriers using technologies developed for coal that could be adapted to biomass with little incremental effort. If at the same time the R&D needed on the sustainable production and conversion of biomass is given high priority, and if policies are adopted to nurture the development of bioenergy industries, these industries will be able to innovate and diversify as they grow and mature.

Methodology for the Calculations Presented in the Figures and Tables

The calculations presented in the following figures and tables were carried out on a self-consistent basis. All costs are presented in 1989 dollars. Where costs were originally presented in the dollars of other years, they were converted to 1989$ using the US GNP deflator. Fuel energy is presented in terms of the higher heating value (HHV).

For electricity production, the costs are evaluated assuming a 6.1% real discount rate [the value recommeneded by the Electric Power Research Institute (EPRI) for evaluating utility investments], an insurance rate of 0.5% per year, and a 30-year system life. In Tables 7-9, *two values are shown* (in the form A/B) for the fixed capital charges and busbar costs: A, with a property tax rate of 1.5% of the initial capital cost per year and a 38% corporate income tax rate, and existing tax preferences [corresponding to an annual capital charge rate of 0.1030 for fossil fuel systems and 0.1007 for renewable and nuclear systems (EPRI, Technical Assessment Guide, Palo Alto, CA, 1986)]; and B, with zero corporate income and property taxes [corresponding to an annual capital charge rate of 0.0784]. The latter capital charge rate is used when evaluating the cost of CO_2 emissions offsets.

The schedule of fixed capital expenditures during construction of power plants is assumed either to reflect average experience, or, if relevant experience is not available, equal annual payments are asumed for an idealized plant construction period, as recommended by the EPRI. For the latter case, interest charges during construction, as a fraction of the fixed overnight construction cost is given by:

$$IDC = [(1 + i)^g/g]/CRF(i,g) - 1,$$

where

$$i = \text{discount rate},$$
$$g = \text{idealized construction period, in years},$$
$$CRF(i,g) = i/[1 - (1 + i)^{-g}].$$

Biomass fuel costs were evaluated using a 5% real discount rate, while a 10% real discount rate was used for evaluating the costs of liquid synthetic fuels production.

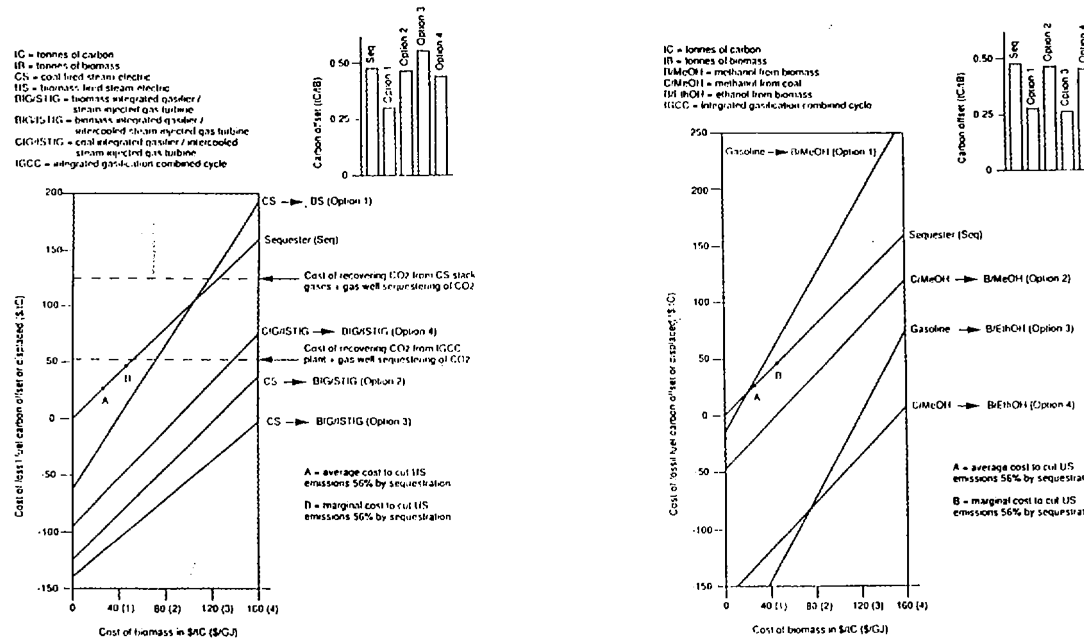

Figure 1. Alternative ways to use biomass to cope with greenhouse warming. Sequestering carbon in forests is compared to alternative strategies for substituting biomass for coal in power generation (left) and to alternative strategies for substituting biomass for fossil fuels in liquid fuels production (right).

The top histograms show the CO_2 emissions reduction (in tonnes C/dry tonne of produced biomass) for sequestering and for four alternative options in which biomass is substituted for fossil fuels. The lower graphs show the cost of fossil CO_2 emissions offset or displaced (in \$/tonne C) versus the cost of biomass for these alternative strategies. On the lines labeled "sequester," A = the average cost and B = the marginal cost of offsetting US CO_2 emissions 56% through tree-planting on 139 million hectares, at an average total forest ecosystem sequestering rate of 5.3 tonnes C/ha/yr, as estimated by Moulton and Richards (see text). The cost of fossil fuel displaced is $(C_b - C_f)/E_f$, where C_b (C_f) is the unit cost of the energy output from the biomass (fossil fuel) system, and E_f is the CO_2 emission rate of the fossil fuel displaced (in tonnes of C per unit of energy output). The carbon dioxide emissions avoided are assumed to be 23 kg C/GJ of input coal (HHV basis) and 0.76 kg C/liter of gasoline displaced.

On the left (see Tables 4, and 6-9 for cost and performance estimates of alternative technologies):
- Option 1: Substitute biomass-fired steam-electric power for coal-fired steam-electric power.
- Option 2: Substitute biomass-integrated gasifier/STIG power for coal-fired steam-electric power.
- Option 3: Substitute biomass-integrated gasifier/ISTIG power for coal-fired steam-electric power.
- Option 4: Substitute biomass-integrated gasifier/ISTIG power for coal-integrated gasifier/ISTIG power.

On the right (see Tables 5 and 10-11 for cost and performance estimates of alternative technologies):
- Option 1: Substitute methanol from biomass for gasoline @ 25 cents/liter (wholesale price projected for 2000 in the US).
- Option 2: Substitute methanol from biomass for methanol from coal.
- Option 3: Substitute ethanol from biomass for gasoline @ 25 cents/liter.
- Option 4: Substitute ethanol from biomass for methanol from coal.

Table 1. Alternative Global CO_2 Emissions Scenarios[a-f] (10^9 tonnes of C/year)

	Commercial Energy					Deforestation[g]			Cement		Total			
	A	B	B′	D	D′	A	B=D	B′=D′	A	B=B′=D=D′	A	B	B′	D=D′
Year														
1985	5.1	5.1	5.1	5.1	5.1	0.7	0.7	0.7	0.1	0.1	5.9	5.9	5.9	5.9
2000	6.5	5.6	5.6	5.7	5.4	1.0	-0.2	0.0	0.2	0.2	7.7	5.5	5.8	5.6
2025	9.9	6.6	6.6	5.4	4.9	1.4	-0.5	0.0	0.2	0.2	11.5	6.4	6.8	5.1
2050	13.5	7.6	8.1	3.0	2.7	1.4	-0.3	0.0	0.3	0.2	15.2	7.5	8.3	2.9

[a] *Scenarios A, B, and D, developed by Working Group III of the Intergovernmental Panel on Climate Change (Table 8, Appendix, in Intergovernmental Panel on Climate Change, "Formulation of Response Strategies," Report prepared for IPCC by Working Group III, June 1990) are for the averages of the high and low economic growth variants of the scenarios developed by this Working Group. Due to rounding, totals do not always equal the sums of the components.*

[b] *Scenario A, the "Business as Usual" scenario: the energy supply is coal-intensive; only modest increases in energy efficiency are achieved; deforestation continues until the tropical forests are depleted.*

[c] *Scenario B: the supply mix shifts toward low-C fuels, notably natural gas; there are large increases in energy efficiency; deforestation is reversed.*

[d] *Scenario D: the measures of Scenario B are complemented by a shift to renewables and nuclear power in the first half of the next century, to the extent that emissions remain stable near the 2.9 Gt C/yr level after 2050.*

[e] *Scenario B′, developed by the authors (see text): like Scenario B, except deforestation is halted, not reversed, and, in 2050, 23.3 EJ/yr of coal, with a CO_2 emission rate of 0.5 Gt C/yr, is substituted for the 23.3 EJ/yr of biomass energy in Scenario B.*

[f] *Scenario D′, developed by the authors (see text): the same total emissions as Scenario D; the difference in emissions between Scenarios B′ and D′ (1.7 Gt C/yr in 2025 and 5.4 Gt C/yr in 2050) is achieved entirely by substituting biomass for fossil fuel (Table 1b).*

[g] *The contribution of deforestation to global emissions in 1985 assumed by Working Group III (Intergovernmental Panel on Climate Change, "Formulation of Response Strategies," Report prepared for IPCC by Working Group III, June 1990) in the construction of its scenarios is lower than many other estimates. In its report assessing the scientific aspects of greenhouse warming, Working Group I assigned to deforestation a value of 1.6 ± 1.0 Gt C/yr for the 1980s (Chapter i, in Climate Change: the IPCC Scientific Assessment, J.T. Houghton, G.J. Jenkins, and J.J. Ephraums, eds., Cambridge University Press, Cambridge, 1990).*

Table 2. Potential Biomass Supplies for Energy in the US, as Estimated by the Oak Ridge National Laboratory[a]

Feedstock	Net Raw Biomass Resource[b,c] (EJ/year)	Cost[c] ($/GJ) Current	Target
Residues			
Logging Residues	0.8	> 3	< 2
Urban Wood Wastes and Land Clearing	1.2	2	2
Forest Manufacturing Residues	2.1	1	<1
Environmentally Collectible Agricultural Residues	2.0	1-2	1
Municipal Solid Waste and Industrial Food Waste	2.4	2-3	< 1.5
Animal Wastes	0.5	< 4	3.5
Subtotal	8.9		
Biomass from Existing Forest			
Commercial Forest Wood	4.5	< 2	< 2
Improved Forest Management	4.5		< 2
Shift 25% of Wood Industry to Energy	0.5	2	2
Subtotal	9.5		
Biomass from Energy Crops			
Agricultural Oil Seed	0.3		
Wood Energy Crops	3.2	3	2
Herbaceous Energy Crops			
Lignocellulosics	5.5	4	2
New Energy Oil Seed	0.4		
Aquatic Energy Crops			
Micro-Algae	0.3		
Macro-Algae	1.1	3.5	2
Subtotal	10.8		
Total	29.3[b]		

[a] Source: Table 2.4-3, page 85, in W. Fulkerson et al., Energy Technology R&D: What Could Make a Difference? A Study by the Staff of the Oak Ridge National Laboratory, vol. 2, Supply Technology, ORNL-6541/V2/P2, December 1989.

[b] These are biomass supplies net of estimated losses in production and handling, before conversion to fluid fuels or electricity.

Table 3. Delivered Cost of Wood Chips from Populus *Plantation Systems ($/ODT)*

Production Cost[a,b,c]	
Establishment[d]	5.27
Land rent[e]	6.43
Maintenance[f]	
Insecticides/Fungicides	0.93
Fertilizer	1.07
Management	2.64
Land Taxes	0.96
SUBTOTAL	17.30
Harvesting[g,h]	
Harvester, Tractor	4.58
Baler	3.87
SUBTOTAL	8.45
Transport[g]	
Loader/Unloader	4.46
Tractor/Trailer[i]	5.15
SUBTOTAL	9.61
Chipper/Conveyor[g]	3.15
Storage/Drying[g]	
Storage[j]	6.77
Drying[k]	11.08
SUBTOTAL	17.85
TOTAL	56.36 ($2.90/GJ[l])

[a] For short-rotation populus on good-quality agricultural land. Based on the use of a production model incorporating findings from the US DOE Short-Rotation Woody-Crop Program (C.H. Strauss and L.L. Wright, "Woody Biomass Production Costs in the United States: An Economic Summary of Commercial Populus Plantation Systems," Solar Energy, 45(2), pp. 105-110, 1990).

[b] The levelized production cost is given by:

$$[CRF(i,N)*E + i*L + M]/\{i*Y_t/[(1+i)^t - 1]\},$$

where

i = discount rate = 0.05
N = plantation life = 12 years (two rotations)
$CRF(i,N)$ = capital recovery factor = $i/[1 - (1+i)^{-N}]$ = 0.1128
t = rotation period = 6 years
L = land price = \$1800/ha
E = plantation establishment cost = \$654/ha
M = annualized maintenance cost = \$78.5/ha/yr
Y_t = yield at harvest = 95 ODT/ha

[c] While the average annual yield is 95/6 = 15.8 t/ha/yr, the levelized yield used in the economic analysis is:

$$i*Y_t/[(1+i)^t - 1] = 0.1470*95 = 14.0 \text{ tonnes/ha/yr}.$$

<u>*Notes to Table 3*</u>*, cont.*

[d] *The establishment cost includes mowing/brushing, plowing, herbicides, liming, fertilization, planting.*

[e] *The land rent (i*L) is for a land price of $1800/ha (typical for a good corn production site).*

[f] *The maintenance costs include (i) insecticides, fungicides applied every other year beginning in year 2 @ a cost of $26/ha/application, corresponding to an annual levelized cost of $13/ha/yr; (ii) fertilizers applied every other year beginning in year 3 @ a cost of $37/application, corresponding to an annual levelized cost of $15/yr); (iii) management @ $37/ha/yr, and (iv) land taxes @ 0.75% of the land price per year or $13.5/ha/yr.*

[g] *<u>Source</u>: C.H. Strauss, S.C. Grado, P.R. Blankenhorn, and T.W. Bowersox, "Economic Valuations of Multiple Rotation SRIC Biomass Plantations," <u>Solar Energy</u>, 41(2), pp. 207-214 (1988).*

[h] *For a harvesting strategy in which trees are cut, crushed, field-dried, and baled before loading and transport to the storage/conversion site. [It has been found that for bolts of crushed wood averaging 10 cm in diameter, moisture contents (wet basis) have dropped from 50% to 20-30% after 6 days in the field (P.E. Barnett, "Evaluation of Roll Splitting as an Alternative to Chipping Woody Biomass," in <u>Biomass Energy Research Conference</u>, University of Florida, Gainsville, March 12-14, 1985. Crushing tree-length stems with diameters up to 18 cm at a rate of 14 m/minute requires only modest amounts of energy--some 0.88 kWh/tonne (C. Ashmore, "Preliminary Analysis of Roll Crushing of Hybrid Poplar Using the FERIC Roll Crusher," unpublished, 1985).]*

[i] *Round-trip truck transport costs for a conversion facility located 40 km from the harvesting site.*

[j] *For 6 months of storage, with the wood covered by heavy polyethylene film.*

[k] *Drying with unheated, forced-air system, based on a study by Frea (W.J. Frea, "Economic Analysis of Systems to Pre-Dry Forest Residues for Industrial Boiler Fuel," <u>Energy from Biomass and Wastes VIII</u>, D.L. Klass, ed., Institute of Gas Technology, 1984).*

[l] *Poplar has a heating value of 19.38 GJ/tonne (HHV basis).*

Table 4. When 1 Tonne of Wood[a] Displaces Coal[b] in Power Generation:[c]

Technology Shift:	Coal Energy Displaced (GJ)	CO_2 Emissions Displaced (tonnes C/tonne wood)	Cost of Displaced CO_2 ($ per tonne C)
Option 1 CS-->BS	13.31	0.306	$- \$61.44 + 63.33*P_b$
Option 2 CS-->BIG/STIG	20.61	0.474	$- 124.88 + 40.89*P_b$
Option 3 CS-->BIG/ISTIG	24.37	0.560	$- 141.89 + 34.61*P_b$
Option 4 CIG/ISTIG-->BIG/ISTIG	19.75	0.454	$- 94.13 + 42.69*P_b$

Biomass-Based Electricity Production with Alternative Technologies[a]

	Heat Rate (MJ/kWh)	Busbar Cost (cents/kWh)
BS = 27.6 MW Steam-Electric Plant[d]	15.36	$3.60 + 1.536*P_b$
BIG/STIG = 2 x 51.5 MW BIG/STIG Plant[d]	9.92	$2.06 + 0.992*P_b$
BIG/ISTIG = 111 MW BIG/ISTIG Plant[d]	8.39	$1.65 + 0.839*P_b$

Coal-Based Electricity Production with Alternative Technologies[b]

	Heat Rate (MJ/kWh)	Busbar Cost (cents/kWh)
CS = 2 x 500 MW Steam-Electric Plant w/AFBC[d]	10.55	5.09
CIG/ISTIG = 109 MW CIG/ISTIG Plant[d]	8.55	3.50

[a] Here biomass is poplar with HHV (LHV) = 19.38 (18.17) GJ/dry tonne, containing 25 kg C/GJ (HHV basis). P_b is the wood price, in $/GJ.

[b] For Illinois #6 coal with HHV (LHV) = 29.6 (28.5) GJ/dry tonne, a C content of 23 kg/GJ (HHV basis), and for delivered coal costing $1.83/GJ (West North Central Region, US).

[c] See Figure 1 for graphical presentation.

[d] See Table 6.

Table 5. When 1 Tonne of Wood[a] Displaces Fossil Fuel-Based Liquid Fuels:[b]

Technology Shift:	Fossil Fuel Displaced (GJ)	CO_2 Emissions Displaced (tonnes C/tonne wood)	Cost of Displaced CO_2 ($ per tonne C)
Option 1 G-->B/MeOH	14.0	0.278	- $17.7 + 69.8*$P_b$
Option 2 C/MeOH-->B/MeOH	20.1	0.462	- $47.7 + 42.0*$P_b$
Option 3 G-->B/EthOH	13.2	0.264	- $214.1 + 72.1*$P_b$
Option 4 C/MeOH-->B/EthOH	19.5	0.448	- $161.8 + 42.5*$P_b$

Alcohol from Wood with Alternative Technologies[a]

	Efficiency (%, HHV)	Production Cost (cts/l, gasoline-equiv.)[c]
B/MeOH = MeOH from biomass[d] (IGT fluidized bed gasifier)	57.7	23.85 + 5.32*P_b
B/EthOH = EthOH from biomass[e] (enzymatic hydrolysis of wood)	53.5	8.90 + 5.49*P_b
Fossil Fuel-Based Liquid Fuels		
G = Gasoline from petroleum, 2000[f]	90.0	25.2
C/MeOH = MeOH from coal,[g] (Texaco, entrained-flow gasifier)	55.7	29.9

[a] Here biomass is poplar with HHV (LHV) = 19.38 (18.17) GJ/dry tonne, containing 25 kg C/GJ (HHV basis). P_b is the wood price, in $/GJ.

[b] See Figure 2 for graphical presentation.

[c] Assuming 1 GJ of alcohol is equivalent to 1.2 GJ of gasoline, so that 1 liter of MeOH (EthOH) is worth 0.59 liters (0.80 liters) of gasoline.

[d] From Table 11 the cost is (14.07 + 3.14*P_b)/0.59 cents/liter.

[e] From Table 11 the cost is (7.12 + 4.39*P_b)/0.80 cents/liter.

[f] The US wholesale gasoline price, as projected for 2000 by the US Dept. of Energy [Energy Information Administration, Annual Energy Outlook 1990 with Projections to 2010, DOE/EIA-0383(90)].

[g] For coal costing $1.58/GJ, the cost per liter is (12.48 + 3.25*1.58)/0.59 (Table 11).

Table 6. Busbar Costs for Alternative Power Technologies[a] (in 1989 cents/kWh)

	CS[d]	BS[e]	CIG/STIG[f]	BIG/STIG[g]	CIG/ISTIG[f]	BIG/ISTIG[g]
Fuel[a]	$1.055*P_c$	$1.536*P_b$	$1.011*P_c$	$0.992*P_b$	$0.855*P_c$	$0.839*P_b$
Variable O&M	0.72	0.50	-0.16	0.10	- 0.13	0.09
Fixed O&M	0.32	0.80	0.86	0.62	0.73	0.52
Capital	2.12	2.30	1.68	1.34	1.34	1.04
Total	3.16 + $1.055*P_c$	3.60 + $1.536*P_b$	2.38 + $1.011*P_c$	2.06 + $0.992*P_b$	1.94 + $0.855*P_c$	1.65 + $0.839*P_b$
Example:						
P_c = $1.8/GJ[b]	5.1		4.2		3.5	
P_b = $2.9/GJ[c]		8.1		4.9		4.1

[a] P_c = biomass price, and P_b = biomass price, in $/GJ (HHV basis); O&M = operation and maintenance cost. The capital charges presented here are for the case with zero corporate income and property taxes.

[b] The levelized price of coal, 2000-2030, delivered to utilities in the West/North Central United States, as projected by the US Dept. of Energy.

[c] The delivered cost of wood chips from short rotation populus tree crops, including the costs of 40 km transport, drying, and 6-months storage (Table 3).

[d] CS = a subcritical, coal-fired steam-electric plant (two 500 MW units) with atmospheric fluidized bed combustors, a 10.55 MJ/kWh heat rate, an installed capital cost of $1610/kW, and a 68% capacity factor. See Table 7.

[e] BS = a 27.6 MW biomass-fired steam-electric plant, having a 15.36 MJ/kWh heat rate, an installed capital cost of $1925/kW, and a 75% capacity factor. See Table 8.

[f] CIG/STIG = a coal-integrated gasifier/steam-injected gas turbine and CIG/ISTIG = a coal-integrated gasifier/intercooled steam-injected gas turbine. Both systems use an air-blown, pressurized, fixed-bed gasifier with hot-gas cleanup. The CIG/STIG plant consists of two 50.5 MW units; its heat rate is 10.11 MJ/kWh; its installed capital cost, $1410/kW. The CIG/ISTIG plant consists of one 109.1 MW unit; its heat rate is 8.55 MJ/kWh; its installed capital cost, $1120/kW. The capacity factor is assumed to be 75%. See Tables 9 and 10.

[g] BIG/STIG = a biomass-integrated gasifier/steam-injected gas turbine and BIG/ISTIG = a biomass-integrated gasifier/intercooled steam-injected gas turbine. The cost/performance characteristics of these systems are based on the corresponding coal designs (note f), without the hot-gas sulfur removal technology, which is not needed for biomass. A BIG/STIG plant consists of two 51.5 MW units; its heat rate is 9.92 MJ/kWh; its installed cost, $1120/kW. A BIG/ISTIG plant consists of one 111.2 MW unit; its heat rate is 8.39 MJ/kWh; its installed cost, $875/kW. The capacity factor is assumed to be 75%. See Tables 9 and 10.

Table 7. Electricity Cost for New US Coal-Fired Steam-Electric Plants w/AFBC (cents/kWh)

Coal[b]	1.93
Variable O&M	0.72
Fixed O&M	0.32
Capital[c]	2.79/2.12
Total	5.76/5.09

[a] Assuming EPRI estimates for heat rate (10.55 MJ/kWh), overnight construction cost ($1169/kW), other capital ($81/kW), and O&M costs. East or West Central US siting, for a subcritical plant (two 500 MW units) with atmospheric fluidized bed combustors (Electric Power Research Institute, Technical Assessment Guide, Palo Alto, CA, 1986).

[b] For a 30-year levelized coal price of $1.83/GJ, appropriate for the West/North Central region of the US, 2000-2030, as projected by the US Dept. of Energy.

[c] Following a US Department of Energy analysis of steam-electric power plants [Energy Information Administration, Annual Outlook for US Electric Power: Projections Through 2010, DOE/EIA-0474(90), June 14, 1990], it is assumed that the average capacity factor is 68% and that construction profile for these plants is:

Year before plant begins operating	Annual expenditure as % of overnight construction cost
8	4.0
7	14.0
6	33.0
5	34.0
4	11.0
3	3.0
2	1.0

so that interest during during construction adds 31% to the overnight construction cost.

Table 8. Cost of Electricity from Biomass-Fired Steam-Electric Plant[a] (cents/kWh)

Fuel[b]	$1.536 * P_b$
Variable O&M	0.50
Fixed O&M	0.80
Capital	2.95/2.30
Busbar Cost	$1.536 * P_b$ + (4.25/3.60)

[a] Based on an EPRI design for a 24 MW condensing/extraction cogeneration plant producing 20,430 kg/hour (45,000 lb/hour) of steam at 11.2 bar (165 psia) for process (Electric Power Research Institute, Technical Assessment Guide, Palo Alto, CA, 1986). Here it is assumed that this steam is instead condensed, thus producing an additional 3.6 MW of electric power.

[b] For a heat rate of 15..6 MJ/kWh [corresponding to steam conditions of 86 bar (1265 psia) and 510 °C (950 °F) at the turbine inlet and a turbine efficiency of 80%]. Here P_b is the price of biomass, in $ per GJ.

[c] Assuming EPRI values for the overnight construction cost ($1693/kW), other capital ($127/kW), and idealized construction period (3 years).

[d] Assuming a 75% capacity factor and equal annual capital expenditures during the construction period.

Table 9. Estimated Busbar Cost for IG/STIG and IG/ISTIG Power Plants Fueled with Coal and Biomass (in cents/kWh)

	CIG/STIG[a]	BIG/STIG[b]	CIG/ISTIG[a]	BIG/ISTIG[b]
Fuel[a]	$1.011*P_c$	$0.992*P_b$	$0.855*P_c$	$0.839*P_b$
Operating Labor[b]	0.30	0.20	0.28	0.19
Maintenance[c]	0.42	0.32	0.33	0.24
Administrative costs[d]	0.14	0.10	0.12	0.09
Water requirements[e]	0.028	0.028	0.026	0.026
Catalysts and binder[f]	0.018	-	0.016	-
Solids disposal[g]	0.071	0.069	0.060	0.059
H_2SO_4 byproduct credit[h]	- 0.273	-	- 0.231	-
Capital[i]	2.21/1.68	1.72/1.34	1.76/1.34	1.34/1.04
Totals	2.91/2.38 + $1.011*P_c$	2.44/2.06 + $0.992*P_b$	2.36/1.94 + $0.855*P_c$	1.95/1.65 + $0.839*P_b$

a Here P_c and P_b are the prices for delivered coal and biomass feedstocsk, respectively, in \$/GJ. Heat rates for CIG/STIG (@ 101.0 MW_e) and CIG/ISTIG (@ 109.1 MW_e) are 10.11 MJ/kWh and 8.55 MJ/kWh, respectively (J.C. Corman, "System Analysis of Simplified IGCC Plants," General Electric Company, Schenectady, NY, Report on Department of Energy Contract No. DE-AC21-80ET14928, September 1986). The output and performance of the biomass versions of these systems are estimated by starting with the coal systems and modifying them to account for the major differences arising from operation on biomass. The biomass gasification efficiency is assumed to be the same as the coal gasification efficiency. One difference is that only about 40% as much high pressure steam is needed to gasify a GJ of biomass as a GJ of coal, and the steam not needed for gasification can be injected into the turbine. However, this is not likely to have a significant effect on overall performance, since the injection of high-pressure steam into the combustor gives rise to approximately the same mass flow through the turbine and would require the same steam heating in the combustor as injection into the gasifier. An important difference, however, is that some low-pressure steam needed for the sulfur recovery unit with coal is not needed in the biomass systems. Here it is assumed that this low-pressure steam is injected into the turbine to increase power output and efficiency. As a result, the output and heat rate of the BIG/STIG are 103.0 MW_e and 9.92 MJ/kWh, while the corresponding quantities for BIG/ISTIG are 111.2 MW_e and 8.39 MJ/kWh, respectively.

b The coal-based systems required 3 operators for the gasification system, 4 for the hot-gas cleanup, and 3 for the power plant. At \$22.55 per hour, operating labor costs for the coal systems are \$1.977 million per year. Because hot-gas desulfurization is not needed for the biomass systems, it is assumed that 7 operators are needed for the biomass systems--four less because hot gas desulfurization is not needed and one more because of increased fuel handling requirements. Thus annual operating labor costs would be \$1.384 million.

c Annual maintenance costs (40% labor and 60% materials) are estimated to be

Notes for Table 9, cont.

$2.812 million for CIG/STIG (including $0.634 million for chemical hot-gas cleanup) and $2.342 million for CIG/ISTIG (including $0.591 million for chemical hot-gas cleanup). The corresponding values for BIG/STIG and BIG/ISTIG, without chemical hot gas cleanup, are $2.178 million and $1.751 million, respectively.

[d] *Annual administrative costs, assumed to be 30% of O&M labor, are $0.930 million for CIG/STIG, $0.874 million for CIG/ISTIG, $0.677 million for BIG/STIG, and $0.625 million for BIG/ISTIG.*

[e] *Raw water costs are $0.189 million per year for all systems.*

[f] *Annual catalysts and binder costs $0.121 million ($0.113 million) for CIG/STIG (CIG/ISTIG) and zero for BIG/GT systems.*

[g] *Annual costs for solids disposal are $0.469 million ($0.428 million) for CIG/STIG (CIG/ISTIG) and are assumed to be the same for the corresponding BIG/GT systems.*

[h] *Annual H_2SO_4 byproduct credits are $1.815 million for CIG/STIG, $1.659 million for CIG/ISTIG, and zero for BIG/GT systems.*

[i] *For the unit capital costs given in Table 10 and an assumed 75% capacity factor.*

Table 10. Estimated Installed Capital Cost (in $/kW) for IG/STIG and IG/ISTIG Power Plants Fueled with Coal and Biomass

	CIG/STIG[a]	BIG/STIG[b]	CIG/ISTIG[a]	BIG/ISTIG[b]
I. Process Capital Cost				
Fuel Handling	44.4	44.4	41.2	41.2
Blast Air System	15.1	15.1	10.8	10.8
Gasification Plant	180.5	180.5	93.3	93.3
Raw Gas Physical Clean-up	9.9	9.9	8.6	8.6
Raw Gas Chemical Clean-up	197.4	0.0	169.3	0.0
Gas turbine/HRSG	330.4	330.4	287.7	287.7
Balance of Plant				
Mechanical	45.1	45.1	37.0	37.0
Electrical	72.9	72.9	54.3	54.3
Civil	73.5	73.5	68.1	68.1
SUBTOTAL	969.2	771.8	770.3	601.0
II. Total Plant Cost				
Process Plant Cost	969.2	771.8	770.3	601.0
Engineering Home Office (10%)	96.9	77.2	77.0	60.1
Process Contingency (6.2%)	60.1	47.9	47.8	37.3
Project Contingency (17.4%)	168.6	134.3	134.0	104.6
SUBTOTAL	1294.8	1031.2	1029.1	803.0
III. Total Plant Investment				
Total Plant Cost	1294.8	1031.2	1029.1	803.0
AFDC (3.05%, 2 yr construction)	39.5	31.5	31.4	24.5
SUBTOTAL	1334.3	1062.7	1060.5	827.5
IV. Total Capital Requirement				
Total Plant Investment	1334.4	1062.7	1060.5	827.5
Preproduction Costs (2.8%)	36.3	28.9	28.8	22.5
Inventory Capital (2.8%)	36.3	28.9	28.8	22.5
Initial Chemicals, Catalysts	2.8	0.0	2.6	0.0
Land	1.5	1.5	1.5	1.5
TOTAL	1411	1122	1122	874

[a] The CIG/STIG plant consists of two 50.5 MW_e STIG units, each coupled to a Lurgi Mark IV dry-ash, air-blown, fixed bed gasifier. The CIG/ISTIG plant consists of a single 109.1 MW_e ISTIG unit, coupled to a Lurgi Mark IV single dry-ash, air-blown, Lurgi Mark IV fixed bed gasifier. Costs were estimated according to the rules set forth in the EPRI Technical Assessment Guide [J.C. Corman, "System Analysis of Simplified IGCC Plants," General Electric Company, Schenectady, NY, Report on Department of Energy Contract No. DE-AC21-80ET14928, September 1986].

[b] The biomass versions of these plants have outputs of 103.0 MW_e and 111.2 MW_e for BIG/STIG and BIG/ISTIG, respectively (see note a, Table 9). It is assumed that BIG/STIG (BIG/ISTIG) costs are the same as CIG/STIG (CIG/ISTIG) costs, except that the raw gas chemical clean-up phase required for coal would not be needed for biomass, because of its negligible sulfur content.

Table 11. Costs for Alcohol Production from Coal and Biomass Feedstocks[a]

	C/MeOH[b]	B/MeOH[c]	B/EthOH[d]
Annual Production (10^9 liters)	2.103	0.384	0.261
Onstream Time (hours/yr)	8000	8000	8000
Fixed Capital Investment ($\$10^9$)	1.436	0.265	0.098
Working Capital ($\$10^6$)	53.1	13.0	–[e]
Production Cost (cents/liter)			
Fixed Investment	9.321	9.420	5.13
Working Capital	0.253	0.338	–[e]
Wood	–	$3.14*P_b$	$4.39*P_b$
Coal	$3.25*P_c$	–	–
O&M	2.905	4.309	1.99
Total	$12.48 + 3.25*P_c$	$14.07 + 3.14*P_b$	$7.12 + 4.39*P_b$
Total Cost (cents/liter, gasoline-equiv.)[f]	$21.15 + 5.51*P_c$	$23.85 + 5.32*P_b$	$8.90 + 5.49*P_b$
Example: P_c = \$1.6/GJ[g], P_b = \$2.3/GJ[h]	30.0	36.1	21.5

[a] For an annual capital charge rate on fixed (working) capital of 0.1365 (0.10), based on a 10% real discount rate, a 15-year plant life, and an insurance cost of 0.5% of the fixed capital cost per year.

[b] C/MeOH = methanol from coal, with a Texaco pressurized, entrained-flow, oxygen-blown coal gasifier plus methanol synthesis plant. The conversion efficiency, coal-to-methanol, is 55.7% (HHV basis). See Table 12.

[c] B/MeOH = methanol from biomass, with a pressurized, steam/oxygen-blown, fluidized bed biomass gasifier being developed by the Institute of Gas Technology plus methanol synthesis plant. The conversion efficiency, biomass-to-methanol, is 57.7% (HHV basis). See Table 12.

[d] B/EthOH = ethanol from biomass. Performance and cost projections are US Dept. of Energy estimates of what could be achieved by 2000 with an intensive research, development, and demonstration effort targetting enzymatic hydrolysis technology applied to lignocellulosic feedstocks. The conversion efficiency, wood-to-ethanol, is 53.5% (HHV basis). See Table 13.

[e] Included with the fixed capital cost.

[f] Assuming that in gasoline engines modified for alcohol use, 1 GJ of alcohol is worth 1.2 GJ of gasoline (LHV basis), so that 1 liter of MeOH (EthOH) is worth 0.59 (0.80) liters of gasoline.

[g] For a plant in the Midwest US burning Illinois No. 6 coal.

[h] As in Table 6, except that for alcohol production biomass drying is not necessary.

Table 12. Costs for Methanol Production Using Coal and Biomass Feedstocks

	Methanol from Coal[a,c]	Methanol from Biomass[b,d]
Annual Production (billion liters)	2.103	0.384
Onstream Time (hours/year)	8000	8000
Fxd Invstmnt[e] (billion $)	1.436	0.265
Working Capital (million $)	53.1	13.0
Production Cost (cents/liter)		
Fixed Investment[f]	9.321	9.420
Working Capital[f]	0.253	0.338
Wood[g]	-	$3.14*P_b$
Coal[h]	$3.25*P_c$	-
Slfr Byprdt Crdt	- 0.451[c]	-
Slag Disposal	0.115	-
Ctlsts & Chmcls	0.563	0.479
Electricity	-	0.817
Steam	-	- 0.366
Water	0.084	0.113
Fuel	-	0.282
Operating Labor	0.220	0.253
Maintenance	1.292	1.492
Direct Overhead	0.099	0.113
Gnrl Plnt Ovrhd.	0.983	1.126
TOTAL	12.48 + $3.25*P_c$	14.07 + $3.14*P_b$
CO_2 Emission Rate[i] (tonnes C/GJ)	0.0412	-

[a] US Dept. of Energy, "Assessment of Costs and Benefits of Flexible and Alternative Fuel Use in the US Transportation Sector. Technical Report Three: Methanol Production and Transportation Cost," August 1989, based on a study prepared for the DOE's Office of Policy, Planning, and Analysis, by Chem Systems, Inc. Cost estimates are drawn from reports published by the Electric Power Research Institute and other sources. It is assumed that the methanol plant is located at the coal mine mouth in Illinois.

[b] Chem Systems, Inc., "Assessment of Cost of Production of Methanol from Biomass," report to the Solar Energy Research Institute, December 1989.

Notes for Table 12, cont.

[c] Based on the use of a Texaco pressurized, entrained-flow, oxygen-blown coal gasifier, producing a gas consisting primarily of hydrogen and carbon monoxide.

[d] Based on the use of a pressurized, steam/oxygen-blown, fluidized bed biomass gasifier being developed by the Institute of Gas Technology.

[e] The overnight construction cost is $1,290 million for the MeOH-from-coal plant and $238 million for the MeOH-from-biomass plant. With a 3-year construction program with 30% of the cost paid at the end of the 1st yr, 50% at the end of the 2nd, and 20% at startup, the total installed cost becomes $1,436 million for the MeOH-from-coal plant and $265 million for the MeOH-from-biomass plant, assuming a 10% discount rate.

[f] For an annual capital charge rate on fixed (working) capital of 0.1365 (0.10), based on a 10% real discount rate, a 15-year plant life, and an insurance cost of 0.5% of the fixed capital cost per year.

[g] Here P_b is the price of biomass, in $/GJ, and the wood conversion efficiency is 57.7% (HHV basis).

[h] Here P_c is the price of coal, in $/GJ, and the coal conversion efficiency is 55.7% (HHV basis).

[i] Dry Illinois #6 coal (68% C) has a heating value of 29.6 GJ/tonne and a CO2 emission rate of 0.0229 tonnes C/GJ.

Table 13. Projected Cost for Ethanol Production in 2000 from Lignocellulosic Feedstocks[a]

Annual Production[b] (billion liters)	0.261
Onstream Time (hours/year)	8000
Installed Capital Cost (billion $)	0.098
Production Cost (cents/liter)	
Capital[c]	5.13
Wood[d]	$4.39*P_b$
O&M	1.99
Total	$7.12 + 4.39*P_b$

[a] Performance and cost projections for 2000 are what is estimated could be achieved with an intensive research, development, and demonstration effort targetting enzymatic hydrolysis technology and lignocellulosic feedstocks, according to a 1990 Department of Energy Interlaboratory White Paper (Office of Policy Planning and Analysis, US Dept. of Energy, "The Potential of Renewable Energy," SERI/TP-260-3674, March 1990).

[b] For a wood handling capacity of 2110 dry tonnes/day, a 91% average capacity factory, and an ethanol yield of 450 liters of ethanol (@ 23.5 MJ/liter, higher heating value) per tonne of dry wood feedstock. For wood with a higher heating value of 19.75 GJ/tonne, this corresponds to a conversion efficiency of 53.5%.

[c] Assuming a 10% real discount rate and a 15-year plant life, the capital recovery factor is 0.1315. Including an insurance cost of 0.5% of the initial capital cost per year brings the total annual capital charge rate (neglecting taxes) to 0.1365.

[d] Here P_b is the price of biomass, in $/GJ.

Table 14. Scenario for CO_2 Emissions Reduction via Biomass Energy Use[a] (Gt C/yr)

2025	Electricity and alcohol from sugar cane[b]	0.7
	Electricity from kraft pulp industry residues[c]	0.2
	Energy from other residues[d]	0.8
	Total	1.7
2050	Electricity and alcohol from sugar cane	0.7
	Electricity from kraft pulp industry residues	0.2
	Energy from other residues	0.9
	Energy from biomass energy crops[e]	3.6
	Total	5.4

[a] A scenario for reducing global CO_2 emissions from the Scenario B' level to the Scenario D' level (Table 1) through bioenergy use only.

[b] Assuming that sugar cane production grows at the historical rate of 3%/year, from 968 million tonnes of cane (tc) in 1987 to 2976 million tonnes in 2025 and that electricity is coproduced in excess of onsite needs @ 885 kWh/tc with BIG/ISTIG technology or the equivalent (using for both plant energy and excess electricity 2.85 GJ of bagasse and 5.0 GJ of the cane tops and leaves per tc). Assuming this displaces electricity that would otherwise be produced from coal, CO_2 emissions would be reduced 0.640 Gt C in 2025. Also assuming that in 2025 45% of the cane is used to produce ethanol, at a rate of 70 liters/tc, and that this alcohol displaces gasoline, CO_2 emissions would be further reduced by 0.058 Gt C/yr in 2025 (J.M. Ogden, R.H. Williams, and M.E. Fulmer, "Cogeneration Applications of Biomass Gasifier/Gas Turbine Technologies in the Cane Sugar and Alcohol Industries: Getting Started with Bioenergy Strategies for Reducing Greenhouse Gas Emissions," Proceedings of the Conference on Energy and Environment in the 21st Century, MIT Press, Cambridge, MA, 1990)

[c] Assuming that chemical pulp production grows to 2025 at the rates projected to 2000 by the Food and Agricultural Organization (FAO), so that global production increases at an average rate of 3.1%/yr, from 105 million tonnes in 1988 to 330 million tonnes in 2025. It is further assumed that electricity is coproduced at a rate of 2544 kWh/tonne of pulp (tp) in excess of onsite needs with BIG/ISTIG technology or the equivalent (using for both plant energy and excess electricity 7.0, 25.3, and 8.4 GJ/tp of hog fuel, black liquor, and forest residues, respectively). Assuming the produced electricity displaces electricity that would otherwise be produced from coal, CO_2 emissions in 2025 would be reduced by 0.204 Gt C (E.D. Larson, "Biomass-Gasifier/Gas Turbine Applications in the Pulp and Paper Industry: an Initial Strategy for Reducing Electric Utility CO_2 Emissions," Proceedings of the Ninth EPRI Conference on Coal Gasification Power Plants, Palo Alto, CA, 17-19 October, 1990).

[d] Since residues from other major forest product and agriculural industries are large compared to those from the sugar cane and kraft pulp industries (Table 15), it is assumed that comparable emissions reductions could be achieved through use of some of these residues for energy.

[e] Assuming that biomass is produced on 600 million hectares at an average productivity of 12 dry tonnes/ha/yr and that the produced biomass displaces coal and thus CO_2 emissions at an average rate of 3.6 Gt C/yr.

Table 15. Selected Global Residue Production Rates (EJ/year)

Forest Product Industries[a]	
Kraft Pulp[b]	
Hogfuel	0.7
Black Liquor	2.7
Forest Residues	0.8
Subtotal	4.2
Sawnwood and Wood Panels[c]	
Mill Residues	3.6
Forest Residues	6.2
Subtotal	9.8
Agricultural Industries[a]	
Sugar Cane[f]	7.6
Wheat[g]	12.9
Rice[g]	10.6
Maize[g]	7.3
Barley[g]	3.8
Subtotal	42.2
Total	56.2

[a] *Assuming higher heating values of 20 GJ and 15 GJ per dry tonne of woody and agricultural residues, respectively.*

[b] *Assuming hog fuel, black liquor, and logging residues (which excludes roots, stumps, branches, needles, and leaves) of 7.0 GJ, 25.3 GJ, and 8.0 GJ per tonne of pulp, respectively (characteristic of the kraft pulp industry in the US Southeast), for the 1988 global chemical pulpwood production of 105 million tonnes (E.D. Larson, "Biomass-Gasifier/Gas Turbine Applications in the Pulp and Paper Industry: an Initial Strategy for Reducing Electric Utility CO_2 Emissions," Proceedings of the Ninth EPRI Conference on Coal Gasification Power Plants, Palo Alto, CA, 17-19 October, 1990).*

[c] *Assuming mill (note d) and forest (note e) residues of 0.30 tonnes and 0.52 tonnes per cubic meter of sawnwood/wood panel products, respectively (characteric of the US forest products industry in 1976), for the 1985-87 world sawnwood/wood panels production rate of 600 million cubic meters (World Resources Institute, World Resources 1990-91, Oxford University Press, New York, 1990).*

[d] *Primary and secondary mill residues of the US forest products industry not used by the pulp industry in 1976 amounted to 34.7 million dry tonnes (Office of Technology Assessment, Energy from Biological Processes, vol. III, Appendices, Part A: Energy from Wood, September 1980), while US sawnwood and wood panels production amounted to 115.4 3 million cubic meters (FAO, 1978 Yearbook of Forest Products, United Nations, Rome, 1980). Thus 34.7/115.4 = 0.30 tonnes of mill residues were produced for each cubic meter of sawnwood and woodpanels produced.*

Notes to Table 15, cont.

[e] US forest residues totalled 76.4 million tonnes in 1976 (Office of Technology Assessment, Energy from Biological Processes, vol.III--Appendices, Part A: Energy from Wood, September 1980). Assuming each of the 40 million tonnes of pulp produced in the US in 1976 (FAO, 1978 Yearbook of Forest Products, United Nations, Rome, 1980) was associated with 0.42 tonnes of forest residues (E.D. Larson, "Biomass-Gasifier/Gas Turbine Applications in the Pulp and Paper Industry: an Initial Strategy for Reducing Electric Utility CO_2 Emissions," Proceedings of the Ninth EPRI Conference on Coal Gasification Power Plants, Palo Alto, CA, 17-19 October, 1990), the residues associated with sawnwood/woodpanels production in 1976 amounted to 59.6 million tonnes. Thus some 59.6/115.3 = 0.52 tonnes of forest residues were associated with each cubic meter of sawnwood and wood panels production.

[f] Assuming bagasse amounting to 2.8 GJ and recoverable cane tops and leaves amounting to 5.0 GJ per (wet) tonne of harvested stem (J.M. Ogden, R.H. Williams, and M.E. Fulmer, "Cogeneration Applications of Biomass Gasifier/Gas Turbine Technologies in the Cane Sugar and Alcohol Industries: Getting Started with Bioenergy Strategies for Reducing Greenhouse Gas Emissions," Proceedings of the Conference on Energy and Environment in the 21st Century, MIT Press, Cambridge, MA, 1990), for the 1987 cane production rate of 968 million tonnes worldwide (Food and Agriculture Organization of the United Nations, FAO Production Yearbook, vol. 41, 1987).

[g] Global grain production rates, 1986 (US Dept. of Commerce, Statistical Abstract of the United States 1990, US Government Printing Office, Washington, DC, 1990) and associated residue production rates, assuming residue production coefficients characteristic of US grain production in the period 1975-77 (note h) were:

Grain	1986 Production (million tonnes)	Residue Coefficient	Residue Production (million tonnes)
Wheat	538	1.6	861
Rice	473	1.5	710
Maize	485	1.0	485
Barley	182	1.4	255

[h] Selected US grain production rates, 1975-77 (US Dept. of Agriculture, Agricultural Statistics 1978, US GPO, Washington, DC, 1978) and grain residue production rates (Office of Technology Assessment, Energy from Biological Processes, vol. II, Technical and Environmental Analyses, September 1980), along with the corresponding residue coefficients, were:

Grain	Annual Production (ave., 1975-77) (million tonnes)	Residue Production (ave., 1975-77) (million tonnes)	Residue Coeficient
Wheat	57.2	90.7	1.6
Rice	5.2	7.8	1.5
Maize	155.6	155.3	1.0
Barley	8.5	12.1	1.4

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