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Alternative Roles for Biomass in Coping with Greenhouse Warming

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Displacing fossil fuel with biomass grown sustainably and converted into useful energy with modern conversion technologies would greatly reduce the build-up of CO_2 in the atmosphere. This use of biomass for fossil fuel substitution would be far 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.

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 transformed 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 sequestra-

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tion 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 annual 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 US tree-planting program, involving up to 139 million hectares of economically marginal and environmentally sensitive croplands and pasturelands and understocked forestlands held by private owners other than the forest industry. Such an effort would have the potential for offsetting up to 56 percent of present US 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 Gt/yr. Projected normal demand growth is in the range 2–3 percent/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 percent of US fossil CO_2 emissions would be $27/tC and $48/tC (figure 1), respectively.[12] The annual cost of such a large-scale US 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-percent increase) and the cost of gasoline by 1.0 cent/liter (3.8 cents/US gallon), 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 90 percent of the CO_2 from the flue gases of coal-fired steam-electric plants with a chemical absorption process 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 coal integrated gasifier/combined cycle (CIG/CC) 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 substantial 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 1 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 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, used at efficiencies of the order of 10 percent—only about a fifth of the efficiency of typical stoves fueled with natural gas or liquid petroleum gas. Further, compared to the 34–36-percent efficiencies achieved with modern, large-scale, 400–600-megawatt coal-fired steam-electric plants, typical biomass–fired steam-electric power plants have efficiencies in the range 20–25 percent. The strong scale economies inherent in steam-electric power-generating technology dictate the choice of less costly alloys in boiler construction and thus lead 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 percent,[26,27] while refinery losses in making gasoline from petroleum are only about 10 percent.

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 3).

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

As noted above, 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 above-ground harvestable plant matter (including the tops and leaves); in some places (e.g. Ethiopia, Hawaii, 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 US croplands (over 10 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 a total potential US biomass energy supply of 29.3 EJ/yr (1 exajoule = 10^{18} joules) 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 4).[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 onsite needs, while still meeting all onsite 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 onsite needs.[30]

Existing forests also can often 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 US Congress estimated that net annual growth in US 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] 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 US commercial forestland could be doubled, to 800–1,600 million tonnes/yr, corresponding to an average productivity of 4–8 tonnes/ha/yr.[40]

The potential of using existing forests in the US 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 US that, for environmental and other reasons, is protected by law from exploitation and the 86 million hectares of other US 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 US. Less than the full potential is likely to be exploited. The 1989 ORNL study of the US 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 $17.8 \cdot 10^9$ cubic meters on 3,800 million hectares of global forests in 1970.[42] For comparison, the estimated global average annual wood harvests in the period 1985–87 were $3.26 \cdot 10^9$ 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

The production of 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 5).[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 2 and 3).

Electricity produced in steam-electric power plants would be more costly using biomass than using 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 US 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 gasifier/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 1a and table 2).

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 percent 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 alterative technologies are indicated in figure 1b. Here biomass-derived methanol and ethanol are considered as alternatives to gasoline and coal-derived methanol (table 7). 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 pre-industrial 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 pre-industrial level of CO_2, and the global mean temperature increases 0.1° C per decade to 2° C above the preindustrial level by 2100.[47] This scenario involves a strong emphasis on energy efficiency, a shift to renewables and to nuclear energy in the first half of the 21st century, and a reversal of deforestation.

Here we explore the possibilities 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 coproducing 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 8 and 9).

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 silviculture 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 UK and maize (corn) in the US have more than tripled since the mid-1940s. At present maize yields in the US average 7.5 tonnes/ha/yr of grain plus an equal quantity of residues (table 8). Moreover, the targeted annual productivity corresponds to a 0.4-percent efficiency for converting solar energy into recoverable biomass energy, while the practical maximum photosynthetic efficiency under field conditions is about 5 percent,[49] and 2.4 percent has already been attained for Napier grass under optimal field conditions.[50] These data suggest a large potential for long-term gain.

The land area targeted for biomass energy crops in 2050 is equivalent to 15 percent and 40 percent of the amount of land now in forests and croplands, 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 per year at the beginning of the next century, agreed to in the November 1989 Noordwijk 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 croplands 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 1,500 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 cropland 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 US, 30 million hectares of cropland 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 croplands 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 croplands have "wetness" problems—poor drainage, high water tables, or flooding; when used for ordinary agriculture these lands could potentially contribute to surface and ground water pollution[12]—problems that could be eased with the production of some types of energy crops as alternatives. Moreover, the amount of idle cropland 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 cropland.[54] There are also 60 million hectares now in pasture, range, and forest considered capable of supporting biomass production for energy.[27]

The needed 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 contributions from residues, energy crops, and existing forests (like the ORNL estimate of potential US 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 required 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 12 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 sixfold 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 croplands 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 disproportionate 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 "natural" condition. For example, some bird species require dead wood and the associated insect populations for survival. 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

* C_3 plants have the most common kind of carbon metabolism found in most temperate grasses and trees. C_4 plants—exemplified by many tropical grasses—use a slightly different mechanism for taking up carbon dioxide from the atmosphere. Wheat is a typical C_3 plant, whereas maize is a typical C_4 crop.

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 gasifier/gas turbine power-generating technologies designed originally for coal. While commercially ready coal gasifier/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 biomass gasifier/gas turbine demonstration plant in Sweden 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-megawatt 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 coproduction 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 US 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 7 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

Full exploitation of the biomass energy potential will probably require 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 cogeneration and power from renewable energy sources, like the 1978 Public Utility Regulatory Policies Act (PURPA) in the US, could be helpful in nurturing a biomass-based power industry. The expansion of biomass-based power generation in the US, from about 250 megawatts in 1980[68] to some 9,000 megawatts 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 a much more important role. Though carbon-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 products 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.

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 (1a) and to alternative strategies for substituting biomass for fossil fuels in liquid fuels production (1b). For each alternative the CO_2 emissions offset or displaced (in tC) per tonne of biomass (tB) is shown in parentheses on the graphs.

The 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 (\$27/tC) and **B** = the marginal cost (\$48/tC) of offsetting US CO_2 emissions 56 percent 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 net fossil-fuel CO_2 emissions displaced when biomass energy is substituted for fossil fuel energy 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 C/unit of energy output). The CO_2 emissions avoided are assumed to be 23 kg C/GJ of input coal (HHV basis) and 0.76 kg C/liter of gasoline displaced.

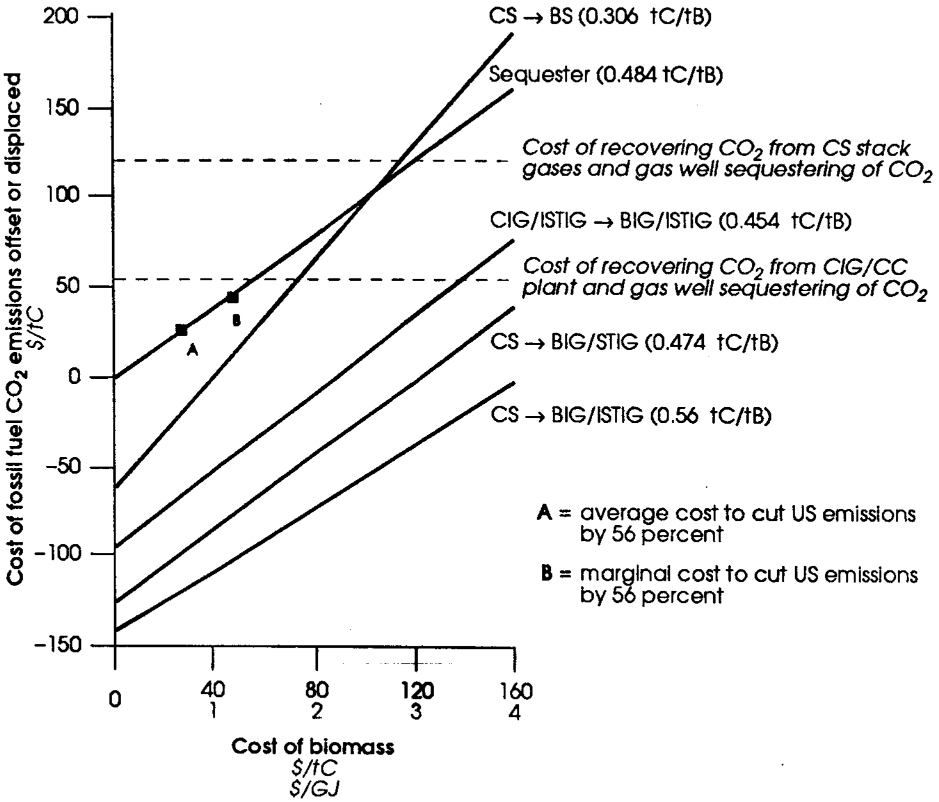

Figure 1a

Figure 1a:
see tables 2 and 6 for cost and performance estimates of alternative technologies

CS → BS: Substitute biomass-fired steam-electric power (BS) for coal-fired steam-electric power (CS)

CS → BIG/STIG: Substitute biomass-integrated gasifier (BIG)/steam injected gas turbine (STIG) power for coal-fired steam-electric power

CS → BIG/ISTIG: Substitute BIG/intercooled steam injected gas turbine (ISTIG) power for coal-fired steam-electric power

CIG/ISTIG → BIG/ISTIG: Substitute BIG/ISTIG power for coal-integrated gasifier/ISTIG power

CIG/CC: Coal integrated gasifier/combined cycle

Figure 1b:
see tables 3 and 7 for cost and performance estimates of alternative technologies

Gasoline → B/MeOH: Substitute methanol from biomass for gasoline @ 25 cents/liter (wholesale price projected for 2000 in the US)

C/MeOH → B/MeOH: Substitute methanol from biomass for methanol from coal

Gasoline → B/EthOH: Substitute ethanol from biomass for gasoline @ 25 cents/liter

C/MeOH → B/EthOH: Substitute ethanol from biomass for methanol from coal

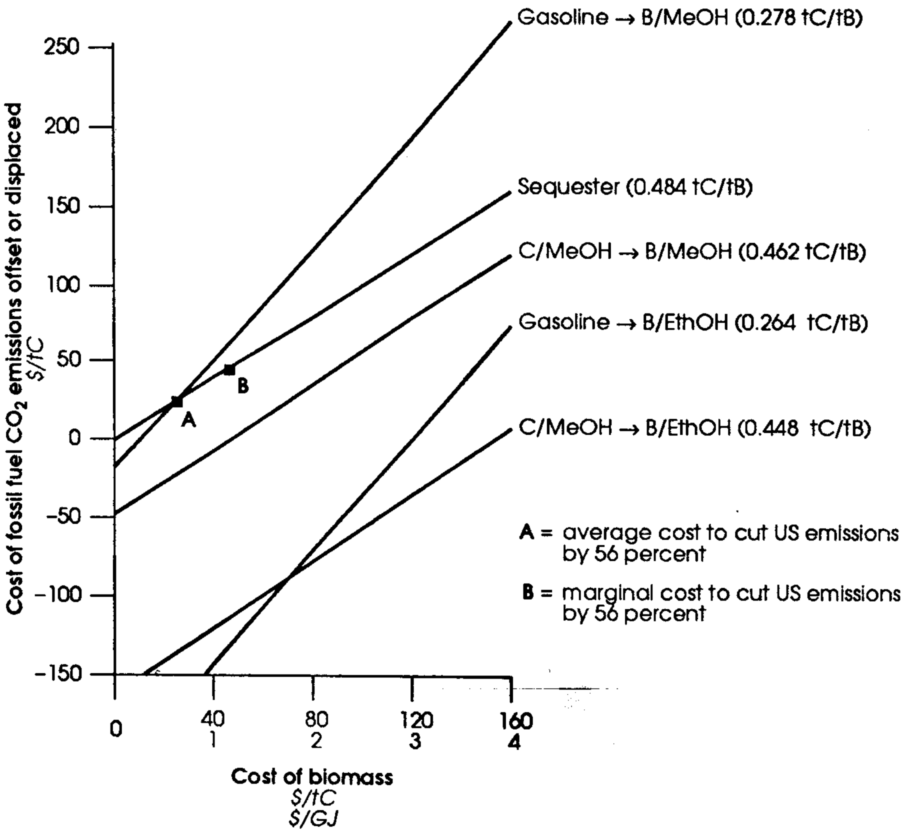

Figure 1b

METHODOLOGY FOR THE CALCULATIONS PRESENTED IN THE FIGURES AND TABLES

The calculations presented in the 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 dollars 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-percent real discount rate (the value recommended by the Electric Power Research Institute [EPRI] for evaluating utility investments), an insurance rate of 0.5 percent per year, and a 30-year system life. The corresponding annual capital charge rate is 0.0784. Corporate income and property taxes are neglected.

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 assumed for an idealized plant construction period, as recommended by EPRI. For the latter case, interest charges during construction, as a fraction of the fixed overnight construction cost, are given by:

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

where

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

The costs of producing biomass fuels were evaluated using a 5-percent real discount rate, while a 10-percent real discount rate was used for evaluating the costs of liquid synthetic fuels production.

Table 1: Alternative global CO_2 emission 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 9).

g. The contribution of deforestation to global emissions in 1985 assumed by Working Group III 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 J.T. Houghton, G.J. Jenkins, and J.J. Ephraums, eds., *Climate Change: the IPCC Scientific Assessment*, (Cambridge UK: Cambridge University Press, 1990)).

Table 2: When 1 tonne of biomass (B)[a] displaces coal (C)[b] in power generation using steam turbine (S) and steam-integrated gas turbines (STIG and ISTIG) with integrated gasifiers (IG)[c]

COST OF ELECTRICITY PRODUCTION WITH ALTERNATIVE TECHNOLOGIES
for details see table 6

	Heat rate *MJ/kWh*	**Busbar cost** *cents/kWh*
Coal option		
CS = 2 x 500 MW Steam-electric plant with AFBC[d]	10.55	5.09
CIG/ISTIG = 109 MW CIG/ISTIG plant	8.55	3.50
Biomass option[a]		
BS = 27.6 MW steam-electric plant	15.36	$3.60 + 1.536 \cdot P_b$
BIG/STIG = 2 x 51.5 MW BIG/STIG plant	9.92	$2.06 + 0.992 \cdot P_b$
BIG/ISTIG = 111 MW BIG/ISTIG plant	8.39	$1.65 + 0.839 \cdot P_b$

IMPACTS OF SHIFT

Technology shift	**Coal energy displaced** *GJ*	**CO_2 emissions displaced** *tonnes C/tonne B*	**Net cost of displacing CO_2** *\$/tonne C*
CS → BS	13.31	0.306	$-61.44 + 63.33 \cdot P_b$
CS → BIG/STIG	20.61	0.474	$-124.88 + 40.89 \cdot P_b$
CS → BIG/ISTIG	24.37	0.560	$-141.89 + 34.61 \cdot P_b$
CIG/ISTIG → BIG/ISTIG	19.75	0.454	$-94.13 + 42.69 \cdot P_b$

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 biomass 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 1a for graphical presentation.

d. Atmospheric fluidized bed combustors. See table 6.

Table 3: When 1 tonne of biomass (B)[a] is converted to methanol (MeOH) or ethanol (EthOH) to displace fossil-fuel–based gasoline (G) or methanol[b]

COST OF LIQUID FUELS PRODUCTION WITH ALTERNATIVE TECHNOLOGIES
for details see table 7

	Efficiency *percent HHV*	**Production cost** *cents/liter gasoline equivalent*[c]
Fossil fuel option		
G = Gasoline from petroleum, 2000	90.0	25.2[d]
C/MeOH = methanol from coal *Texaco, entrained-flow gasifier*	55.7	29.9[e]
Biomass option		
B/MeOH = methanol from biomass *IGT fluidized bed gasifier*	57.7	$23.85 + 5.32 \cdot P_b$[f]
B/EthOH = ethanol from biomass *enzymatic hydrolysis of wood*	53.5	$8.90 + 5.49 \cdot P_b$[g]

IMPACTS OF SHIFT

Technology shift	**Fossil fuel displaced** *GJ*	**CO_2 emissions displaced** *tonnes C/tonne wood*	**Cost of displaced CO_2** *\$/tonne C*
G → B/MeOH	14.0	0.278	$-17.7 + 69.8 \cdot P_b$
C/MeOH → B/MeOH	20.1	0.462	$-47.7 + 42.0 \cdot P_b$
G → B/EthOH	13.2	0.264	$-214.1 + 72.1 \cdot P_b$
C/MeOH → B/EthOH	19.5	0.448	$-161.8 + 42.5 \cdot P_b$

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 biomass price, in \$/GJ.

b. See figure 1b 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. The US wholesale gasoline price, as projected for 2000 by the US Department. of Energy (Energy Information Administration, *Annual Energy Outlook 1990 with Projections to 2010*, DOE/EIA-0383(90)).

e. For coal costing \$1.58/GJ, the cost per liter is $(12.48 + 3.25 \cdot 1.58)/0.59$ (table 7).

f. From table 7 the cost is $(14.07 + 3.14 \cdot P_b)/0.59$ cents/liter.

g. From table 7 the cost is $(7.12 + 4.39 \cdot P_b)/0.80$ cents/liter.

Table 4: Potential biomass supplies for energy in the US, as estimated by the Oak Ridge National Laboratory[a]

Feedstock	**Net raw biomass resource**[b] *EJ/year*	**Cost** *$/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 forests			
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		

a. Source: 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, table 2.4-3, p.85.

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

Table 5: Delivered cost of wood chips from *populus* plantation systems ($/oven-dry tonne)

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 (1990), pp.105–110).

b. The levelized production cost is given by:

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

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 = $1,800/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:

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

Table 5 *continued*

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

e. The land rent (*i·L*) is for a land price of $1,800/ha (typical for a good corn production site).

f. The maintenance costs include (i) insecticides and fungicides applied every other year beginning in year 2 at 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 at a cost of $37/application, corresponding to an annual levelized cost of $15/yr); (iii) management at $37/ha/yr, and (iv) land taxes at 0.75 percent of the land price per year or $13.5/ha/yr.

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

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 centimeters in diameter, moisture contents (wet basis) have dropped from 50 percent to 20–30 percent after six days in the field (P.E. Barnett, "Evaluation of Roll Splitting as an Alternative to Chipping Woody Biomass," in *Biomass Energy Research Conference*, University of Florida, Gainesville, 12–14 March 1985. Crushing tree-length stems with diameters up to 18 centimeters at a rate of 14 meters per 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 kilometers from the harvesting site.

j. For six 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," in D.L. Klass, ed., *Energy from Biomass and Wastes VIII*, Institute of Gas Technology, 1984).

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

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	$1.055 \cdot P_c$	$1.536 \cdot P_b$	$1.011 \cdot P_c$	$0.992 \cdot P_b$	$0.855 \cdot P_c$	$0.839 \cdot P_b$
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	$3.16 + 1.055 \cdot P_c$	$3.60 + 1.536 \cdot P_b$	$2.38 + 1.011 \cdot P_c$	$2.06 + 0.992 \cdot P_b$	$1.94 + 0.855 \cdot P_c$	$1.65 + 0.839 \cdot P_b$
Examples:						
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 = coal price, and P_b = biomass price, in $/GJ (HHV basis); O&M = operation and maintenance cost.

b. The levelized price of coal, 2000–2030, delivered to utilities in the west/north central United States, as projected by the US Department of Energy.

c. The delivered cost of wood chips from short rotation *populus* tree crops, including the costs of 40 kilometers transport, drying, and 6 months storage (table 5).

d. CS = a subcritical, coal-fired steam-electric plant (two 500-megawatt units) with atmospheric fluidized bed combustors, a 10.55 MJ/kWh heat rate, an installed capital cost of $1,610/kW. Based on an EPRI design (*Technical Assessment Guide* (Palo Alto, California: Electric Power Research Institute, 1986)), except that the construction period (eight years) and capacity factor (68 percent) are based on actual experience (Energy Information Administration, Annual Outlook for US Electrical Power: Projections through 2010, DOE/E1A-0474(90), 14 June 1990). Interest during an eight-year period of construction adds 31 percent to "overnight" construction costs.

e. BS = a 27.6-megawatt biomass-fired steam-electric plant, having a 15.36 MJ/kWh heat rate, an installed capital cost of $1,925/kW (*Technical Assessment Guide*). The capacity factor is assumed to be 75 percent.

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-megawatt units; its heat rate is 10.11 MJ/kWh; its installed capital cost, $1,410/kW. The CIG/ISTIG plant consists of one 109.1 MW unit; its heat rate is 8.55 MJ/kWh; its installed capital cost, $1,120/kW. The capacity factor is assumed to be 75 percent. See tables A-1 and A-2.

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 percent. See tables A-1 and A-2.

Table 7: Costs for alcohol production from coal and biomass feedstocks[a]

	C/MeOH[b]	B/MeOH[c]	B/EthOH[d]
Annual production			
10^9 liters per year	2.103	0.384	0.261[e]
Onstream time *hours per year*	8,000	8,000	8,000
Fixed capital investment *$\$10^9$*	1.436[f]	0.265[f]	0.098
Working capital *$\$10^6$*	53.1	13.0	–[g]
Production cost *cents/liter*			
Fixed investment[h]	9.321	9.420	5.13
Working capital[h]	0.253	0.338	–[g]
Wood[i]	–	$3.14 \cdot P_b$	$4.39 \cdot P_b$
Coal[j]	$3.25 \cdot P_c$	–	–
O&M	2.905	4.309	1.99
Total	$12.48 + 3.25 \cdot P_c$	$14.07 + 3.14 \cdot P_b$	$7.12 + 4.39 \cdot P_b$
Total cost *cents/liter, gasoline-equivalent*[k]	$21.15 + 5.51 \cdot P_c$	$23.85 + 5.32 \cdot P_b$	$8.90 + 5.49 \cdot P_b$
Examples (costs in cents/liter, gasoline-equivalent): P_c = \$1.6/GJ[l], P_b = \$2.3/GJ[m]	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-percent real discount rate, a 15-year plant life, and an insurance cost of 0.5 percent 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 percent (HHV basis). US Department 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.

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 percent (HHV basis). Chem Systems, Inc., "Assessment of Cost of Production of Methanol from Biomass," report to the Solar Energy Research Institute, December 1989.

d. B/EthOH = ethanol from biomass. Performance and cost projections are US Department of Energy estimates of what could be achieved by 2000 with an intensive research, development, and demonstration effort targeting enzymatic hydrolysis technology applied to lignocellulosic feedstocks. The conversion efficiency, wood-to-ethanol, is 53.5 percent (HHV basis) for wood with a higher heating value of 19.75 GJ/tonne. Office of Policy Planning and Analysis, US Department of Energy, "The Potential of Renewable Energy," SERI/TP-260-3674, March 1990.

e. For a wood handling capacity of 1,740 dry tonnes/day, a 91-percent average capacity factor, and an ethanol yield of 450 liters of ethanol (@ 23.5 MJ/liter, higher heating value) per tonne of dry wood feedstock.

Table 7 *continued*

f. 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 three-year construction program with 30 percent of the cost paid at the end of the first year, 50 percent at the end of the 2nd, and 20 percent 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-percent discount rate.

g. Included with the fixed capital cost.

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

i. Here P_b is the price of biomass in $/GJ.

j. Here P_c is the price of coal in $/GJ.

k. 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.

l. For a plant in the midwest US burning Illinois #6 coal.

m. As in table 5, except that for alcohol production, undried biomass is purchased.

Table 8: Selected global residue production rates (EJ/year)

Forest product industries[a]	
Kraft pulp[b]	
Hog fuel	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 exclude 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," in *Proceedings of the Ninth EPRI Conference on Coal Gasification Power Plants*, Palo Alto, California, 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 (characteristic 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* (New York: Oxford University Press, 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.

e. US forest residues totalled 76.4 million tonnes in 1976 (Office of Technology Assessment, op. cit.) 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, op. cit.), the residues associated with US sawnwood/woodpanels production in 1976 amounted to 76.4 – 40·0.42 = 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.

Table 8 *continued*

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," in *Proceedings of the Conference on Energy and Environment in the 21st Century*, (Cambridge, Massachusetts: MIT Press, 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 Department of Commerce, *Statistical Abstract of the United States 1990*, (Washington DC: US Government Printing Office, 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 Department of Agriculture, *Agricultural Statistics 1978*, (Washington DC: US Government Printing Office, 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	1986 production (average, 1975–77) *million tonnes*	Residue production (average, 1975–77) *million tonnes*	Residue coefficient
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

Table 9: 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 percent per year, from 968 million tonnes of cane (tc) in 1987 to 2,976 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 forty-five percent 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 per year 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," in *Proceedings of the Conference on Energy and Environment in the 21st Century*, (Cambridge, Massachusetts: MIT Press, 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 percent per year, 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 per 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," in *Proceedings of the Ninth EPRI Conference on Coal Gasification Power Plants*, Palo Alto, California, 17–19 October 1990).

d. Since residues from other major forest product and agricultural industries are large compared to those from the sugar cane and kraft pulp industries (table 8), 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 per year.

Table A-1: 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]	$1.011 \cdot P_c$	$0.992 \cdot P_b$	$0.855 \cdot P_c$	$0.839 \cdot P_b$
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]	1.68	1.34	1.34	1.04
Totals	2.38 $+1.011 \cdot P_c$	2.06 $+0.992 \cdot P_b$	1.94 $+0.855 \cdot P_c$	1.65 $+0.839 \cdot P_b$

a. Here P_c and P_b are the prices for delivered coal and biomass feedstocks, respectively, in $/GJ. Heat rates for CIG/STIG (@ 101.0 MWe) and CIG/ISTIG (@ 109.1 MWe) 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. 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 MWe and 9.92 MJ/kWh, while the corresponding quantities for BIG/ISTIG are 111.2 MWe and 8.39 MJ/kWh, respectively.

b. The coal-based systems required three operators for the gasification system, four for the hot-gas cleanup, and three 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 seven operators are needed for the biomass systems—four fewer 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 percent labor and 60 percent materials) are estimated to be $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 percent 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 A-2, assuming a 75-percent capacity factor.

Table A-2: 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]
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/ Heat recovery steam generator	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*
Miscellaneous costs[c]	437.7	348.7	347.8	271.5
Initial chemicals, catalysts	2.8	0.0	2.6	0.0
Land	1.5	1.5	1.5	1.5
TOTAL CAPITAL REQUIREMENT	*1411*	*1122*	*1122*	*874*

a. The CIG/STIG plant consists of two 50.5-MWe 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-MWe 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 MWe and 111.2 MWe for BIG/STIG and BIG/ISTIG, respectively (see note a, table A-1). 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.

c. Engineering home office, 10 percent of process capital cost; process contingency, 6.2 percent; project contingency, 17.4 percent. These plus process capital cost make the total plant cost: to this is added 3.05-percent of total plant cost for interest charges during two years of construction to get the total plant investment. Preproduction costs and inventory capital each add 2.8-percent of total plant investment.

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