U.S. CARBON OFFSET POTENTIAL USING BIOMASS ENERGY SYSTEMS

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Abstract. A previous analysis had assumed that about 20% of 1990 U.S. C emissions could be avoided by the substitution of biomass energy technologies for fossil energy technologies at some point in the future. Short-rotation woody crop (SRWC) plantations were found to be the dedicated feedstock supply system (DFSS) offering the greatest C emission reduction potential. High efficiency biomass to electricity systems were found to be the conversion technology offering the greatest C emission reduction potential. This paper evaluates what would be required in terms of rate of technology implementation and time period to reach the 20% reduction goal. On the feedstock supply side, new plantings would have to installed at an average a rate of 1×10^6 ha yr^{-1} while average yields would have to increase by 1.5% annually over the 35-year period. Such yield increases have been observed for high value agricultural crops with large government research support. On the generation side, it requires immediate adoption of available technologies with a net efficiency of 33% or higher (such as the Whole Tree Energy™ technology), installation of approximately 5000 MWe of new capacity each year, and rapid development and deployment of much higher efficiency technologies to result in an average of 42% efficiency by 2030. If these technology changes could be achieved at a linear rate, U.S. C emission reduction could progress at a rate of about 0.6 % yr^{-1} over the next 35 years.

1. Introduction

Biomass energy systems are comprised of a broad range of technologies that vary greatly in the feedstocks and conversion systems used, the efficiency with which biomass is converted to usable energy, and the cost of implementation and their C benefits. Of the two major options for large-scale use of biomass in the energy sector, electric power generation and liquid fuels for transportation, substitution of electric

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power generation from woody DFSS for coal-fired electric power was found to be about twice as effective in offsetting C emissions as the conversion of woody crops to ethanol for substitution of gasoline (Graham *et al.*, 1992; Wright *et al.*, 1991). To meet the goals for C emission reductions suggested by the Framework Convention on Climate Change held in June 1992 at the United Nations Conference on Environment and Developments, optimal strategies for C offset must be developed. Since biomass energy systems do require the use of land resources, it is extremely important to select and develop systems which obtain the maximum energy output and C emission reduction with the minimum use of land.

Conflicts between land uses are sure to occur as more and more people search for places to live, work, grow their crops, produce livestock, produce cellulosic resources, conserve wild areas for recreation and biological diversity, and designate areas for the sequestration of C. Finding ways to meet all of these needs will be an ever increasing challenge. An analysis by Marland and Marland (1992) has suggested that within a 50-year time horizon, establishment of woody DFSS on cropland results in a larger C offset than would reforestation when the land has the potential of producing greater than 4.0 MgC ha^{-1} yr^{-1} in a biomass energy system with an energy conversion efficiency of 33% or greater.

Our previous analysis of the C emission reduction potential of biomass energy systems suggested that a 20% reduction below 1990 levels could be achieved "in the future" by using woody DFSS to fuel efficient biomass electric power systems. This analysis establishes the target time as 2030 and evaluates the rate of change that is required in SRWC and biomass power systems to meet a 20% reduction goal by 2030. Factors considered include the probability of developing and building new, high-efficiency electric generation capacity, the possibility of achieving rapid SRWC yield increases while simultaneously expanding the feedstock production land base, and the contribution that soil C sequestration in SRWC systems could make to meeting the goal.

2. Estimation of C Offset Potential

Estimates of C offset potential in the United States require several assumptions about feedstock yields, land areas available, conversion efficiency, fuel substitution factors, and C inputs to producing the feedstock (Graham *et al.* 1992). The information requirements for calculating C offset potential can be broken down into four linked categories as follows:

Amount of feedstock as function of:
    (biomass yield/hectare, harvest and storage losses, number of hectares)
Amount of energy produced as a function of:
    (amount of feedstock, conversion efficiency)
Fossil fuel displaced as a function of:
    (energy produced, fuel substitution factors, fossil fuel C level)

Net C offset as a function of:
(fossil fuel displaced, C input to feedstock, C sequestration)

All of these assumptions should be tempered by environmental considerations. While the environmental benefits for soils and water quality offered by DFSS and the air quality benefits offered by advanced conversion system may be very positive, those attributes will have to be confirmed. Current and future regulations and societal concern about pollution potential could initially slow the implementation of biomass energy systems. Delaying implementation of advanced biomass energy systems could also have negative environmental risks. Developers of the technologies must be sensitive and responsive to local environmental issues, while pursuing implementation of the technology to assure that global environmental goals are met.

2.1 FEEDSTOCK POTENTIAL

The amount of land that might be economically available in the United States for production of energy crops is estimated to range between 14 and 28 × 10^6 ha (Wright *et al.*, 1991). The higher amount of 28 × 10^6 ha equals about 17.5% of the cropland in the United States that is considered capable of growing energy crops (Graham, 1993).

The land currently in the Conservation Reserve Program (CRP) has been hypothesized to be the land most likely to be first used for energy crop production. However, most of that land lies in the Great Plains, which is not very productive nor is it an area of high electricity demand. Furthermore even in regions of the country quite suitable for energy crops production, the CRP land tends to be the least productive and profitable cropland. The best cases where there may be a match between CRP land and wood energy crop requirements will be on croplands with moderate wetness. Tree crops such as poplars, sycamores, and silver maple, which have high moisture requirements, may perform very well on such lands if weed control problems can be resolved.

Fifteen years of research by U.S. DOE on the development of economically-viable, woody DFSS has demonstrated the need for relatively good quality land to attain high yields. Cost-supply analyses, constrained by current agricultural policies, indicate that the land most likely to be converted to dedicated feedstock production will be the better quality cropland, especially if it is located close to an energy conversion facility (Graham *et al.*, 1993).

The amount of feedstock which can be grown depends on the location, type and amount of land which can be converted to feedstock production as well as the plant material selected. The range of yields indicated in Figure 1 is primarily a function of site quality and genetic makeup of the plants. The high experimental and commercial yields in the Pacific Northwest can be attributed to the availability of selected clonal plant materials, favorable climate, and the establishment of both experimental and commercial plantings on fertile soils. The rest of the country does not have the

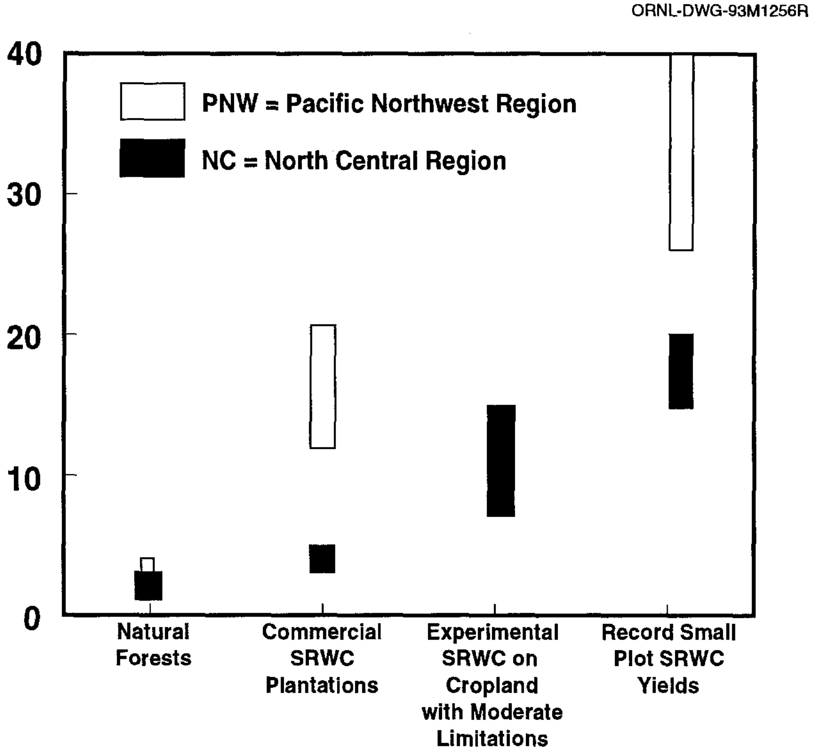

Figure 1. Mean biomass yield at harvest (Mg dry biomass/ha/year).

favorable climatic conditions of the Pacific Northwest, nor the commercial availability of select clonal plant material. Commercial yields are unlikely to ever equal the record yields shown in Figure 1 due to climatic variations, less than perfect management techniques, and environmental considerations. Achievement of larger plot yields on a commercial basis should be entirely possible if improved plant materials and technology transfer programs are widely available.

The net yield level of 11.2 dry Mg ha^{-1} yr^{-1} selected as representative of current DFSS technology assumes careful matching between land types and species or varieties, successful use of best available technology for weed control, and no unexpected disease or pest problems. Achieving such yields with most woody crops appears to require that water be available to the trees most of the year. Previously cropped bottomlands subject to flooding once or twice per year could be very suitable for trees but limiting for annual crops. There are over 40×10^6 ha of relatively good cropland in this category in the United States. Nearly half of that land is in the north central region of the United States, but all parts of the United States contain such lands. There would seem to be a reasonably good potential that suitable lands for woody DFSS will also be economically available.

Figure 2 shows the relationship which exists between average net yield assumptions and available land base in the calculation of total exajoules (EJ or 1 × 10^{18} J) of feedstocks which can be produced. Calculation of EJ is obtained by multiplying total net Mg of feedstock produced by the average energy content of the feedstock. Total net Mg equals (annual yield ha^{-1} minus harvest and handling losses) × number of hectares). Harvest and handling losses can vary considerably among feedstocks and handling systems. They may be as small as 5% or less for trees harvested and hauled in whole form and dried under cover, but as large as 17 to 20% for trees chipped in the field and stored under open conditions for 6 months or more. The curves in Figure 2 (originally developed for another paper) assumed an average of energy content of 18.5 Gj Mg^{-1} derived from averaging the higher heating energy values of woody and herbaceous crops. The set of curves allows an approximate reference to the hectares and average net yields required to produce a given level of primary energy. These curves clearly show the importance of achieving high average yields of DFSS, under any assumptions about land availability.

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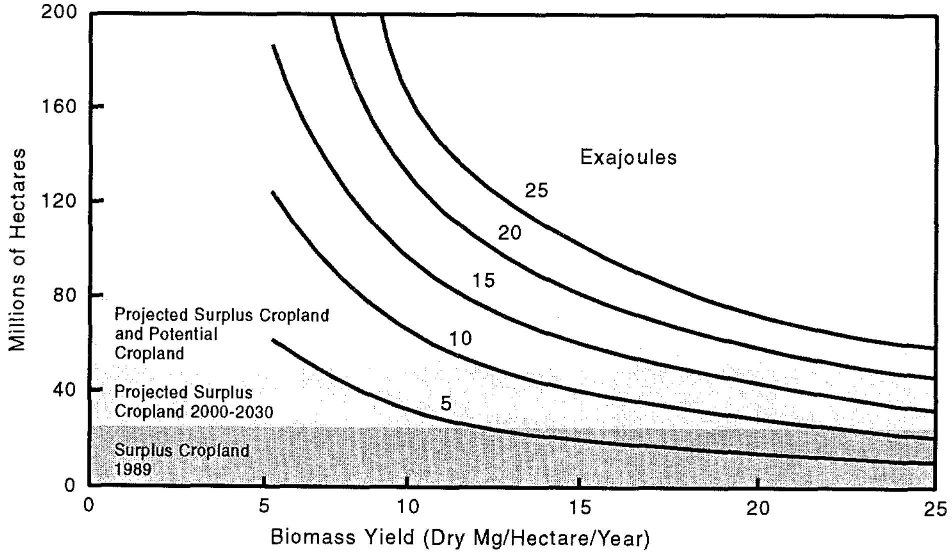

Figure 2. Potential primary energy production as a function of biomass yield and number of hectares.

2.2 ENERGY PRODUCTION POTENTIAL

Electric power generation from biomass is a conversion technology which is already in commercial use. These technologies use solid fuel, not liquid or gaseous fuel. The feedstock for nearly all of this existing power generation is wood, mostly wood wastes and residues already in the hands of wood products industries, especially the pulp and paper industry. (A liquid intermediate product, namely "black liquor," is a significant fraction of the fuel actually fed to boilers in the pulp and paper industry. Even in this case the original feedstock in the pulp/paper process is wood in the solid form, usually chips of 2.5 or 5.0 cm, top size.) The technologies now used commercially for electric power generation from wood or other biomass fuels are traveling grate stoker boilers, Hydrograte™ boilers and fluidized-bed combustion (FBC) boilers. All three accept fuel in the form of chipped wood (or other solid biomass residue) and burn the fuel mostly on or in a bed at the bottom of a boiler, which generates steam that is converted to electric power in a steam turbine/generator unit. All three of these boiler technologies continuously move the unburned fuel (i.e., ash) out of the boiler: the traveling grate via slow continuous moving of the floor, the Hydrograte™ via vibration of water-cooled tubes that constitute the grate, and the FBC via separation of ash from the sand that forms most of the mass in the bed, a bed fluidized by air blown in from underneath.

The existing power generation from biomass fuel is generally characterized by relatively small unit size (in the 10- to 50-MWe range, mostly less than 30 MWe) and low efficiency (on the order of 20% net efficiency on a higher heating value basis, or a heat rate of 17,000 Btu or 17,918 J per kWh). The low efficiency is the result of economic decisions reflecting the small unit size and the low cost of fuel that is often readily available waste material. The largest (about 50 or 60 MWe) and most efficient have efficiencies closer to 25%. These plants fire wood fuel that is often about 50% moisture, by weight on a wet basis. The high moisture content contributes to a low boiler efficiency, in the 65 to 70% range, compared to the 84 to 89% boiler efficiency expected of a 200 MWe coal-fired boiler. (Johnston *et al.*, 1991).

Future wood-fired, and other biomass-fired, power plants are expected to be higher in efficiency. The higher efficiencies will result from (1) market forces, assuming that biomass wastes and residues will be less readily available and cost more in the future; (2) successful research and development efforts; and (3) selection of larger unit sizes (on the order of 100 MWe or larger, perhaps even to 400 MWe). With very advanced technologies, such as fuel cell processes, net thermal efficiencies may reach 50% or higher (higher heating value basis) within the next two to four decades. High temperature, modified Rankine cycles (steam turbines with direct combustion) may provide an opportunity to achieve relatively high efficiencies now with biomass fuels. Steps are being taken to optimize efficiency of biomass conversion by (1) using the existing higher efficiency steam cycles to cofire coal with wood and (2) planning for a demonstration plant using Whole Tree Energy™ technology.

The Electric Power Research Institute (EPRI) is cosponsoring case studies of the co-firing option and has sponsored an assessment (Johnston *et al.*, 1991) and field tests (Ostlie *et al.*, 1993) of the Whole Tree Energy^{TM} option. Both of these options are capable of net thermal efficiencies, on a higher heating value basis, above 30%. [In fact, both are anticipated to convert wood to electric power with a heat rate of about 10,000 Btu (10,540 GJ)/kWh, i.e., about 34% net thermal efficiency.]

Co-firing of wood with coal has been done in the United States in a few commercial operations for several decades (Ostlie, personal communication) and more recently in some experimental conditions. Under these operational or test conditions only a small fraction of the heat input to the boiler, usually 5% or less, is from wood. Because the combustion environment is determined by the primary fuel (coal), which is not a high moisture fuel, the combustion occurs with a relatively small loss of heat rate (about 10%). The larger size of the coal-fired units (i.e., 200 to 500 MWe) allows the steam cycle to achieve economies of scale and, therefore, higher performance at acceptable cost, giving net efficiencies in the 34% range typical of large, efficient coal-fired units. The case studies being cosponsored by EPRI (with the Tennessee Valley Authority and the U.S. Department of Energy) are investigating co-firing at higher percentages where the heat contributed by the wood is in the 10% to 15% range. By moving from the conventional pulverized-coal boilers (tiny particles burning in suspension) or cyclone-fired boilers (larger coal particles burning in a molten slag of coal ash in rotation flow on the wall of a cylindrical barrel) to the new fluidized-bed combustion (FBC) boilers, utilities could cofire wood in higher percentages, say up to 50%. However, there are as yet very few FBC boilers in utility service.

Co-firing offers a low-capital-cost option for introducing wood firing into utility power systems. The boiler, turbine/generator and balance of plant already exist. From the perspective of the public looking for a low-cost way to achieve the benefits of being CO_2-neutral by using a renewable fuel rather than a fossil fuel, co-firing may seem to be an obvious choice. However, from the perspective of a utility already operating existing capacity on coal, the wood co-firing does not add any new capacity (i.e., no additional MWe). Furthermore, the only economic benefits accompanying the additional cost of adding wood handling, wood drying (required in the case of co-firing above about 4 to 7% heat input in a pulverized-coal unit), and wood firing are the benefits of avoided pollution control (most likely SO_2 control), avoided CO_2 emissions, and the unlikely benefits of finding adequate wood supplies costing less than the coal. In the absence of taxes or limits on CO_2 emissions the benefits may be small, and, therefore, the economic incentive to co-fire wood may also be small or even negative.

Whole-Tree-Energy^{TM} is a patented technology for dedicated wood firing (100% wood fuel) in new or converted boilers. The EPRI-sponsored evaluation (Johnston *et al.*, 1991) indicated this technology could be a low-cost way to produce electricity from wood, with an estimated cost of electricity at $0.046/kWh compared to $0.062/kWh for new state-of-the-art combustion of 50% moisture wood chips and $0.057/kWh for new coal-fired plants with scrubbers for SO_2 removal from the flue gas. (The plant sizes used in that evaluation were 100 MWe for the whole-tree and woodchip cases and 200

MWe for the coal.) The cost advantage of the Whole-Tree Energy^{TM} power plant is expected from several features of the technology: (1) no chipping cost and harvesting operations that are free of any delays or timing constraints possibly imposed by the chipping operation; (2) handling and stacking wood in its natural form for drying; (3) improved boiler efficiency, combustion rate, and combustion completeness due to use of dried wood; (4) combustion similar to a gas-fired boiler, above a bed of whole trees that produce the fuel gas as they are heated and volatilized; (5) an efficient steam cycle using high pressure, high temperature superheat and reheated steam; (6) stack gas cleaned and cooled by a condensing heat exchanger that transfers heat to the air used to dry the trees and also scrubs particulates from the flue gas; and (7) elimination of many items that add to the cost of coal-fired plants, such as the SO_2 scrubber, coal bunkers, coal pulverizers and related starters, controls and electrical wiring, structural steel and foundations.

As suggested above, several features of Whole Tree Energy^{TM} are different from currently existing biomass power systems. Wood is handled its natural whole tree form until just before combustion. After harvest and transport to the power plant site, the whole trees are piled in a tall stack (such as a circular pattern some 120 m in diameter and 30 to 50 m high) inside a tent-like structure. The trees are dried from their typical 40 to 50% moisture down to less than 25% moisture by warm air (waste heat that would otherwise go up the smoke stack). After being dried, trees are removed from the stack and randomly dropped onto an open-topped conveyer channel which moves in intermittent steps to the boiler. Near the boiler, the trees are batch-sawed into load sections of a length close to that of the boiler wall (perhaps about 8 to 10 m). The wood is pushed into a 2-stage sealed door and ram system, dropped into the boiler, and burned in a 3-stage combustion process. The combustion process takes advantage of the relatively low moisture content of the dried wood to perform complete combustion with relatively low overall excess air (10 to 15%). This brings about high-temperature combustion in air with low levels of NO emissions. Above the deep bed of whole trees, the boiler is very much like one built for firing natural gas. Much of the release of the energy in the fuel emerges as heat above the bed, as the gaseous fuel released by volatilization of the wood burns in the tall (25 to 35 m) space above the fuel bed (bed depth of about 4 or 5 m). Fully implemented, the Whole-Tree-Energy^{TM} concept also encompasses innovations in the growing, harvesting, and transportation of the feedstock. While the system can use wood from overage, declining forest stands and residue from existing logging operations, the optimum environmental benefits of the system will be derived from the use of DFSS.

2.3 FOSSIL C DISPLACEMENT

The amount of raw energy levels of biomass and coal required to produce a kilowatt hour of electricity from coal or biomass is the same if the conversion efficiencies are the same. A simplifying assumption made in our analysis is that the conversion efficiencies of new biomass energy systems will be similar to those of the coal systems being displaced. The conversion efficiency for most modern coal-burning facilities averages about 33% but can be much higher. Process conversion efficiencies for converting coal to energy are anticipated to greatly improve in the future (Starr *et al.*, 1992). Improvements in coal conversion technologies will be applicable to biomass.

Another comparison that is often made when wood replaces coal as a feedstock is the relative tonnage of wood and coal that is required. Since wood is delivered with a much higher moisture content than coal and has a slightly lower energy content per unit of dry weight (compared to sub-bituminous coal), much greater tonnage of delivered feedstock will be necessary to produce the same amount of electricity. Delivery and storage of the feedstocks will have sociological and environmental impacts that may contribute to limiting the amount of biomass energy that can be used for a given facility, especially those located near urban centers. On the positive side, however, a greater number of smaller energy production facilities scattered throughout the rural sections of the United States could have very positive economic impacts with positive environmental attributes as well.

2.4 NET C OFFSET

The greatest C benefit of biomass energy systems can be attributed to the effect gained by leaving fossil C fuels in the ground. This benefit is cumulative with time. However, DFSS also provides a significant amount of C sequestration both in the soil and in the average standing stock of biomass materials. As average yields increase, the amount of standing C ha^{-1} was estimated to increase from 16.8 to 27.7 Mg. This represents the maximum C sink offered by the standing trees which is attained by the end of the first rotation on any given hectare. The value of that C sink must be divided by the number of years over which the analysis is conducted in order to add the value to the cumulative C offset gained by fossil energy substitution. If divided by a value of 35 years (1996 to 2030), the annualized value of carbon sequestration in the trees varies from 0.48 to 0.80 Mg C ha^{-1} yr^{-1}.

The C increment that might be occurring in the soil also offers an additional C sink. It cannot be assumed, however, that soil C will always be incremented on DFSS sites. Conversion of pastureland, moist bottomlands, and peat soils to DFSS may in fact result in an initial loss of soil C. Both above and belowground C losses would occur if forested land were converted to woody crop plantations. It is not recommended that forests be cleared for energy plantations. After a recent evaluation of published literature, Ranney *et al.*, (1991) concluded that changes in soil C levels may range between a loss of 5 Mg to a gain of 10 Mg C ha^{-1} before reaching equilibrium.

Some recent experimental information (Hansen, 1993) suggests that soil C values increase at an average rate of about 1.24 Mg C yr^{-1} over the first 18 to 20 years of an unharvested hybrid poplar stand established on land previously managed for row crops. This was determined by comparisons between soil C contents of soil in the stand and the adjacent land in row crops. The comparisons showed that soil C increments were occurring below 30 cm depth and that soil surface levels of C were similar to that on row crop land.

The experimental data are inadequate to predict the period of time over which these increases will continue, and the extent to which harvesting at 6- to 12-year intervals would affect the rate of C turnover. Given the unknowns, our calculations are based on a conservative assumption that the soil C is likely to increase at about 1.0 Mg C ha^{-1} yr^{-1} over the first 12 years of the plantation after which an equilibrium is assumed to occur. To simplify the calculations, an average soil C increment of 0.3 Mg C ha^{-1} yr^{-1} was used over the 35-year period of our calculations (1995–2030).

If the C sequestration assumptions made above are added to the C offsets achieved by fossil fuel substitution, then the total C offset per hectare increases from 6.0 Mg C ha^{-1} yr^{-1} to 9.7 Mg C ha^{-1} yr^{-1} by 2030. It should be noted that the C offset values have already been reduced by the C emissions which result from woody crop plantation management activities (Graham *et al.*, 1992).

2.5 CONVERTING POTENTIALS TO REALITY

Taking advantage of the global C benefits offered by biomass energy systems will be complex because it requires changing attitudes, habits, and institutions in the agricultural, energy, and environmental sectors of society. However the interest is becoming stronger, new policies are being initiated, and the utilities are looking seriously at both co-firing and the opportunities offered by new technologies. Discussion on the pros and cons of C taxes and incentives can be found almost daily in the news. Analyses by utilities are indicating that biomass energy and reforestation will be among the lower cost options available for meeting reduced emission requirements while meeting energy needs.

One set of assumptions which achieves the theoretical goal of reducing U.S. fossil fuel emissions by 20% includes; (1) a land base of 28 × 10^6 ha, (2) average delivered biomass yields of 18.5 Mg ha^{-1} yr^{-1}, and (3) average conversion efficiencies of 42%. Table 1 shows that to bring those assumptions to reality by 2030, the United States would need to be planting about 1 × 10^6 ha per year and building or retrofitting 5000 MWe of biomass electric capacity per year. Additionally DFSS commercial yields would have to improve by 1.5% per year, and conversion facilities would have to improve efficiencies by 0.7% per year. Since installed capacity and established plantations will be difficult to improve, the implication is that by the time 2030 approaches, some new capacity will have to be capable of 50% or better conversion efficiency and some plantations will have to achieve yields higher than 18.5 Mg ha^{-1} yr^{-1}. The important question is, are these rates of change conceivable?

There are several coal and wood conversion technologies under development and in the demonstration phase which have the potential of achieving net efficiencies of 34 to 41% (Starr *et al.*, 1992). Modern commercial coal stations have efficiencies of 34%

Table 1. Annual rate of technology change required for meeting C offset goals

	1996	2010	2030	Annual rate of change
C offset Goals[1]	<1%	~10%	~20%	~0.6%
MWe	4,500	72,000	170,000	~5000MWe
Capacity factor	80%	80%	80%	
Conversion efficiency	33%	37%	42%	~0.7%
DFSS Mg ha^{-1} yr^{-1}	11	14	18.5	~1.5%
DFSS ha	1.5×10^6	18×10^6	28×10^6	$\sim 1 \times 10^6$

[1] Carbon offset as a percent of 1990 total U.S. fossil fuel C emissions of 1310×10^6 Mg (Marland, personal communication); utility C emissions from electric power production in 1989 equaled 478×10^6 Mg.

or higher, and they offer the opportunity for wood co-firing at the same efficiency. The Whole Tree Energy™ technology offers a new, wood-specific, steam-cycle technology that has 33 to 40% efficiency potential and which is now ready for a commercial-scale trial with little, if any, additional research. The developer of this technology believes that high temperature steam cycles could improve in efficiency up to 50% (Ostlie, personal communication). Gasification systems are also expected to achieve efficiencies in the range of 50% (DOE, 1992). Fossil-fuel efficiency improvements beyond 50% are anticipated to come from developments of the fuel cell. The molten carbonate fuel cell, which is the current focus of development, can directly replace the combustion turbine in an integrated cycle. All of these advanced systems have somewhat higher capital costs, but continuing development and environmental externalities are anticipated to make them competitive with use of coal as the feedstock (Starr *et al.*, 1992). They will likely be even more competitive if wood is used as part or all of the feedstock.

While the Whole Tree Energy™ technology could improve biomass energy efficiencies from 25 to ~40% now, it is expected that several decades will be required for a significant transition from today's conventional electricity generation systems to those of >50% efficiency. The history of energy fuel transitions (wood-coal-oil) shows that in a peacetime commercial environment almost a half century is required to significantly shift fuel patterns (Starr *et al.*, 1992). It has taken 30 years to get 50,000 MWe of gas turbine equipment installed by the U.S. electric industry. Catalytic cracking, commercially introduced in 1942, took about 20 years before it was generally used in refineries. Molten carbonate fuel cell technology is just now being tested with 200 kW size units. Starr *et al.*, (1992) suggest that it would take 35 to 50 years to get 75,000 to 125,000 MWe of fuel cell equipment installed. These types of projections suggest that installment of up to 170,000 MWe of new capacity with efficiencies ranging from 35 to 55% would be pushing the limits of feasibility, but it might be possible. It will also be very expensive. The fuel cell development and deployment is anticipated to require \$80 to \$150 billion and the IGCC is projected to require \$110 to \$175 billion (Starr *et al.*, 1992). However advanced steam cycle technologies may be available first and at costs of less than \$80 billion.

To complete the transition to high efficiency biomass energy systems, supplies of dedicated biomass feedstocks must be assured. Thus, in addition to an industrial transition, the United States must solve the challenges of introducing a new crop on large amounts of land. Soybeans provide the closest analogy to what would be required for energy crops. Prior to the 1920s soybeans were essentially an unknown crop. Between 1924 and 1979, the planted area increased from 0.18 to 28.58 × 10^6 ha (Specht and Williams, 1984). The increase in planted area and average yields was rather steady over that period of time. Yield improvements increased at an average annual rate of 1.9% from 1924 to 1980, with about 50 to 85% of that attributed to genetic improvements and the rest to agronomic practices. While soybeans represent a major "new crop" success, several other crop introductions have resulted in failure (Jaycor, 1985). The reasons for these successes and failures should be studied carefully.

The expectation of an average yield improvement change on the order of 1.5% yr^{-1} is possible based on experience with major agricultural crops (Table 2). Over a 30-year period, sorghum has been observed to increase yields at an average of 7% yr^{-1} though current increases are in the range of 1.5 to 2.0% yr^{-1}. Both corn hybrids and soybeans have shown commercial yield increases of close to 2% yr^{-1} over a 50+ year time frame. In all three of these cases, major yield increases were seen all at once with the introduction of greatly improved genetic materials. Adoption by farmers was very quick and average yields were able to rise quickly. Cotton and wheat yields have risen more slowly and have likely reached a plateau where further yield increases are anticipated to be very slow. Evans (1980) has suggested that average increases for yield potential have been in the range of 0.5 to 1.0% for many different crops.

Table 2. Rate of average yield improvements of major agricultural crops

Crop	No. of yr	Annual yield income	No. of Ha increase	Expected annual increase
Sorghum[1]	30	7.0%	0.5 × 10^6	1.5-2%
Corn hybrids[2]	50	1.9%	—	1.4%
Soybeans[3]	56	1.9%	28 × 10^6	<1.9%
Cotton[4]	30	0.7%	—	<0.7%
Wheat[5]	20	0.7%	—	<0.7%

[1] Miller and Kebede, 1984.
[2] Duvick, 1984.
[3] Specht and Williams, 1984.
[4] Meredith, Jr. and Robert Bridge, 1984.
[5] Schmidt, 1984.

With the availability of clonal propagation techniques it is entirely possible that large initial advances in yield potential of woody crops can be achieved. Gains achieved through breeding and genetic transformation can be quickly captured by the propagation of large numbers of copies of the genotypes. The potential of such advances has been demonstrated by work with hybrid poplars (Heilman and Stettler, 1990). It will be very important from an environmental and risk reduction standpoint that woody crops not be limited to a few genotypes. Thus, genetic advances will need to be made in several species simultaneously. Once initial advances in genetic improvement are realized through clonal technology, it may be very difficult to maintain the rate of yield improvements seen in annual agricultural crops. The breeding cycles of trees are much slower and yield improvement per breeding cycle is not generally very high. Average commercial yield increases of 1.5% yr^{-1} represent an optimistic, but not impossible, view of what could be achieved.

If both the woody crop yield improvements and the conversion technology improvements do occur as speculated, then approximately 10×10^{18} J of biomass energy could be produced by 2030 without emitting additional C into the atmosphere (Table 3). If substituted for coal-based electric power generation, about 272×10^6 Mg of C would be offset. If utility emissions of C increase by 2% yr^{-1} over the next 35 years then current levels would be doubled. Thus 1989 emissions 478×10^6 Mg C would increase to 956×10^6 Mg C . The level of emission reduction achievable by biomass energy would thus only offset about one-third of utility C emissions in 2030.

Table 3. Electricity production with DFSS and C offsets

	1996	2010	2030
Energy (J $\times 10^{18}$)	0.3	5	10
Electricity (TWh)	32	500	1200
C offset per hectare (MgC ha^{-1} yr^{-1})	5.2	6.6	8.6
C sequestered per hectare (MgC ha^{-1} yr^{-1})	0.78	0.89	1.1
Total C offset (Mg)	10.9×10^6	136×10^6	272×10^6
Percent reduction[1]	—	10%	21%

[1] Artificially assumes C sequestion is evenly spread over the 35-year period.

The rates of technology advances required are very optimistic but potentially achievable. However, the rates of genetic improvement required in the woody crops have only been achieved in agricultural crops receiving substantial research and technology transfer support. Similarly, the technology advances required to produce conversion systems with greater than 40% conversion efficiency will require a significant research effort. It may require the levels of support now devoted to developing "clean coal" technologies. A very strong commitment by government and industry working together will clearly be required.

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