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A life cycle assessment of biomass cofiring in a coal-fired power plant

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Abstract The generation of electricity, and the consumption of energy in general, often result in adverse effects on the environment. Coal-fired power plants generate over half of the electricity used in the U.S., and therefore play a significant role in any discussion of energy and the environment. By cofiring biomass, currently operating coal plants have an opportunity to reduce the impact they have, but to what degree, and with what trade-offs? A life cycle assessment has been conducted on a coal-fired power system that cofires wood residue. The assessment was conducted in a cradle-to-grave manner to cover all processes necessary for the operation of the power plant, including raw material extraction, feed preparation, transportation, and waste disposal and recycling. Cofiring was found to significantly reduce the environmental footprint of the average coal-fired power plant. At rates of 5% and 15% by heat input, cofiring reduces greenhouse gas emissions on a CO_2-equivalent basis by 5.4% and 18.2%, respectively. Emissions of SO_2, NO_x, non-methane hydrocarbons, particulates, and carbon monoxide are also reduced with cofiring. Additionally, total system energy consumption is lowered by 3.5% and 12.4% for the 5% and 15% cofiring cases, respectively. Finally, resource consumption and solid waste generation were found to be much less for systems that cofire.

Abbreviations *DOE* U.S. Department of Energy · *EPA* U.S. Environmental Protection Agency · *EPRI* Electric Power Research Institute · *GWP* global warming potential · *LCA* life cycle assessment · *LHV* lower heating value · *Tg* teragrams (10^{12} g)

Introduction

The United States currently obtains greater than 55% of its electricity from coal, and coal-fired power plants consume 87% of all U.S. coal produced (U.S. DOE 1998). There is no question that coal contributes enormously to the high standard of living made possible by easy access to electricity. However, along with its benefits, the chemical make-up of coal and the older technologies used at most operating coal-fired power plants create significant environmental impacts. Coal mining can result in the destruction of land that is strip mined, the production of overburden waste and slag heaps, mine fires, and the occasional collapse of underground mines. At the power plant, sulfur dioxide, nitrogen oxides, and particulate matter are released into the air; coal-fired power plants are responsible for 93.4% and 80.2% of power production SO_2 and NO_x emissions, respectively. Additionally, because coal is a fossil fuel, its use results in the production of CO_2. In the U.S., coal is responsible for 35.8% of all CO_2 emissions, and 73.5% of the CO_2 from power plants (U.S. DOE 1998). On the disposal side, the relatively high ash content of coal results in large quantities of solid waste, of which less than half is reclaimed for use in asphalt, wallboard, cement, and structural fill production.

In an effort to reduce the environmental impacts associated with electricity production, owners and operators of coal-fired power plants have considered adding biomass to their fuel mix. Biomass, either grown specifically to produce energy or that which is recovered from a residue stream, reduces the net greenhouse gases produced per unit of electricity generated. Additionally, because of its low sulfur content relative to coal, biomass can reduce power plant SO_2 emissions. Biomass also contains less ash than coal, thus decreasing the amount of solid waste generated. Likewise, because biomass is more volatile than coal and usually contains lower amounts of fuel-bound nitrogen, cofiring may result in lower NO_x emissions. Other impacts associated with producing and using coal, such as mining emissions and particulates generated during limestone production for flue gas scrubbing, will also be reduced.

For power plant managers, the decision to cofire will not typically be driven by environmental concerns but by economic interests. The environmental benefits, however, may provide economic incentives because of regulatory policy, electric industry deregulation, and fuel supply issues (EPRI 1997a). The regulations on sulfur emissions, for example, may make biomass cofiring more economic than installing pollution control technology, or may increase the number of SO_2 trading credits available to the power plant owner. Additionally, consumers may choose companies that include a green component in their portfolio, and with a capital cost of U.S.$50–250/kW, biomass cofiring is an attractive and inexpensive near-term renewable option. The federal and some state governments may also choose to require a certain level of renewable

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energy to be used in electricity production, a requirement known as a renewable portfolio standard. Finally, certain conditions may exist where residue biomass is cheaper than low-sulfur, high-quality coal.

In order to quantify the magnitude of the benefits offered by cofiring, an LCA was used to evaluate systems that cofire wood residue at 5% and 15% by heat input, compared with a baseline system firing only coal. More detail on the analysis techniques can be found in Mann and Spath (2000). The methodology used in this study is consistent with that described by the ISO 14000 series of standards, particularly that which covers inventory analysis. In conducting a life cycle inventory, energy and raw material requirements, emissions, effluents, and solid waste are quantified for each process, from resource extraction to final product use and disposal. Because the systems being compared are sufficiently similar and the goals of this study are largely satisfied by the inventory step, a less-is-better approach has been taken with regard to the impact assessment portion of this LCA. That is, for each emission, unit of energy consumed, and resource used, an improvement is said to have been made if the cofiring system has a smaller environmental impact than the coal-only system.

The software program chosen to conduct this analysis is Tools for Environmental Analysis and Management (TEAM), by Ecobalance, Inc. This program has two primary functions: (1) it provides a database of common processes such as extraction of raw materials and manufacture of large market chemicals, and (2) it propagates the calculations through each process block in order to add up the total environmental emissions emitted by the system. A check on the reliability of the data within the TEAM database was conducted during our LCA of biomass gasification combined cycle (Mann and Spath 1997). Additionally, this program is well regarded in the LCA community for its depth and accuracy. Processes that were not available in the database were constructed manually using data obtained from the literature and from research conducted on cofiring systems.

The system boundaries for this life cycle assessment include all operations required for the power plant to cofire biomass and coal. These include surface coal mining, construction material production, manufacturing of cofiring-related equipment, coal and biomass transportation, grid electricity production used in upstream processes, and the avoided operations of biomass mulching and landfilling. Avoided operations are those processes that would have taken place if the biomass had not been cofired with coal at the power plant. The emissions, resource consumption, and energy use that would have occurred if these operations had taken place are subtracted from the total inventory of the cofiring system.

System description

Cofiring biomass with coal is not likely to result in capacity additions, but will instead take place in currently operating coal-fired power plants. Cofiring has successfully been tested in all boiler types, including pulverized coal boilers, cyclone boilers, stoker boilers, and bubbling and circulating fluidized bed boilers. The majority of current U.S. coal plants use pulverized coal boilers, and it is this type that can handle higher percentages of biomass cofiring. A detailed discussion of cofiring costs and projected growths can be found in the Technology Characterizations prepared by EPRI and the Department of Energy (EPRI/DOE, 1997).

Table 1 lists the major specifications for the plant operation with and without cofiring. The no cofiring case represents a plant with the average emissions and efficiency of coal-fired power plants currently operating in the U.S. (Spath and Mann 1999). Plant capacity is diminished slightly in the cofiring cases because of the efficiency losses that result from the biomass having a lower energy density and higher moisture content than coal. Based on data from various cofiring tests (EPRI 1997a; EPRI/DOE 1997; Gold and Tillman 1993; Hughes 1997; NRBP 1996; Tillman and Prinzing 1994; Tillman et al. 1997; Tillman et al. 1998) efficiency losses of 0.5 and 0.9 percentage points were assumed for the 5% and 15% cofiring cases, respectively.

The power plant, particularly the fuel handling, storage, and feeding systems, will require modest modifications in order to cofire biomass. An automated feeding system to supply biomass to the boiler is needed to allow continuous cofiring over a period of 24 h. Additionally, equipment to receive and process the biomass is needed, but a biomass dryer may or may not be necessary depending on the boiler configuration and the acceptable level of derating. The amount of biomass that is required for 5% cofiring is probably small enough to be added to the coal feed conveyor, mitigating the need for a separate feed conveyor and feed port. However, the volume of biomass required at the 15% cofiring level will necessitate a separate feeding system, including a biomass injection port into the boiler. Equipment production, including acquisition of raw materials, was included in this LCA.

Table 1. Coal-fired power plant data

Design parameter	No cofiring	15% cofiring	5% cofiring
Plant capacity (MW)	360	350	354
Average operating capacity factor (%)	60	60	60
Coal feed rate at 100% operating capacity (Mg/day) (as-received basis)	3,872	3,291	3,679
Biomass feed rate at 100% operating capacity (Mg/day) (as-received basis – 50% moisture)	0	1,498	499
Power plant efficiency (%)	32	31.1	31.5

Power plant feedstock

The power plant is assumed to use Illinois No. 6 coal, excavated using surface mining from mines located in central Illinois. This coal has a heat of combustion of 28,661 kJ/kg (LHV, bone-dry basis), and is fired at 15.4 wt% moisture. The biomass used in this study is assumed to be wood residue, the nature of which varies greatly. Generally however, sources of biomass considered to be feasible for the type of cofiring projects examined here include clean urban waste wood, mill residue, biomass generated during timber stand improvements, some construction and demolition (C/D) residues, and industrial wood residues. The availability of such materials for power generation depends heavily upon location and the price that the operator is willing to pay. Wiltsee (1998) describes the amount of biomass residue available, plus the primary use and disposal methods, in 30 U.S. metropolitan areas. The U.S. Environmental Protection Agency (EPA) reports that 9,834,000 Mg of wood, excluding C/D waste, and 25,400,000 Mg of yard trimmings, were generated in the municipal waste stream in 1996. This represents 5.2% and 13.4% of the total amount of waste generated annually in the United States. Approximately 4.5% of the wood and 38.6% of the yard trimmings are recovered for further processing and use (U.S. EPA 1998a). Thus, it is felt that significant quantities are still available for energy generation. The composition of biomass for cofiring, shown in Table 2, was based on data from various wood cofiring tests conducted by the Electric Power Research Institute (EPRI) and the U.S. Department of Energy (DOE).

Avoided operations

Because the biomass used at the power plant is not grown for the purpose of cofiring, a credit is not taken for the absorption of CO_2 during the growth cycle (see Mann and Spath 1997). Rather, the emissions, resource consumption, and energy use that would have occurred during the normal routes of biomass disposal are avoided, and credited in the life cycle inventory. Using data from Wiltsee (1998), it was assumed that 46% of the cofired biomass would have been landfilled and 54% would have been mulched or converted to other short-lived products. In the case of mulch, it is likely that most decomposition occurs under aerobic conditions, although decomposition at the interior and bottom of mulch piles will be anaerobic. Additionally, chipping and mulching wood increase the surface area subject to degradation by both microorganisms and air oxidation. Pier and Kelly (1997) found that 20% of the gas coming from sawdust piles was methane; therefore, of the total carbon in the biomass, 13.9% ends up as methane. For this assessment, all of the mulch disposed of through normal routes was assumed to decompose, with 10% of the carbon going to methane and 90% to CO_2. To take into account differences in pile heights and decomposition conditions, the sensitivity analysis tested additional cases of 0%, 5%, and 15% conversion of the carbon to methane.

Unlike mulch, decomposition in landfills occurs under mostly anaerobic conditions, resulting in a gas that can be approximated as a mixture of 50% CO_2 and 50% CH_4 (Barlaz 1998; Bingemer and Crutzen 1987; McBean et al. 1995; U.S. EPA 1998b). Because lignin is resistant to microbial degradation under anaerobic conditions (Bingemer and Crutzen 1987; Ham et al. 1993; Micales and Skog 1997; Tong et al. 1990), only non-lignin compounds (e.g., cellulose, hemicellulose, acetate, etc.) were assumed to be subject to decomposition in the landfill. The question of the extent to which these compounds decompose is difficult to answer, however. In key laboratory experiments on the decomposition of components of the municipal solid waste stream, Barlaz et al. (1989) found that 71% of the cellulose and 77% of the hemicellulose would degrade. However, lignin, in addition to being resistant to microbial attack, can retard the decomposition of closely-associated cellulose and hemicellulose (Young and Frazer 1987). Because the lignin content of dry softwood and hardwood is approximately 28.5% and 27.0%, respectively, the extent of decomposition of wood in landfills will be less than that of the waste stream as a whole. Barlaz (1998) reports that for branches 55.6% of the non-lignin components decompose. In shorter experiments, Eleazer et al. (1997) report that 48% of the cellulose and 41% of the hemicellulose in branches decomposed. It is important to note, however, that branches have significantly higher lignin contents ($\sim$33%) than the wood that is assumed for the power plant; therefore, the extent of decomposition of residue wood will be higher. To take into account the full lifetime in which landfilled wood will contribute to climate change, the cellulose and hemicellulose fractions of the biomass were assumed to be 50% degraded, while the lignin was assumed to remain intact. Approximately 34.7% of the carbon in the landfilled biomass, then, is assumed to decompose, while the remainder is assumed to be indefinitely stored.

Two processes combine to reduce the total amount of methane that is actually released from the landfill. First, microbes in the surface soil oxidize approximately 10% of the methane to CO_2 (Bogner 1992). Secondly, to comply with air regulations, a fraction of the gas produced at U.S. landfills is collected and burned. Regulations for landfill gas are aimed at reducing non-methane organic compounds, but indirectly result in a reduction in methane emissions. Approximately 5% of all current and projected

Table 2. Biomass analysis

	Carbon	Oxygen	Hydrogen	Nitrogen	Sulfur	Chlorine	Ash
Weight%, dry basis	50.62	41.40	5.76	0.25	0.03	0.00	1.94
Moisture, as received: 50 wt%							
Lower heating value: 18,295 kJ/kg (7,873 Btu/lb)							

landfills are required to collect and process the gas (McGuigam 1998). Because such requirements fall only on landfills greater than a certain size [2.5 Tg and 2.5 million m^3, producing more than 50 Mg non-methane organic compounds per year (Federal Register 1996)], collection of gas at 5% of sites results in a 39% reduction in the total amount of methane emitted from U.S. landfills (Meadows et al. 1997). The U.S. EPA (1998b) states that by the year 2000 54% of landfill methane will be generated at landfills with recovery systems, with an average collection efficiency of 75%. This results in a 40.5% reduction in methane generated in landfills. Although the Federal Register and U.S. EPA numbers were similar, the more conservative reduction estimate of 40.5% was assumed in this analysis.

Figure 1 summarizes the assumptions regarding the fate of the carbon in the biomass if it is not used for cofiring. Because energy is the lowest value product possible from wood residues, it is assumed that no wood that would have been used in durable products such as fiber board or playground equipment is used for cofiring. Therefore, semi-permanent sequestration of carbon in these products is not an issue for the system being studied. As shown in Fig. 1, the total CO_2 and methane avoided per 100 kg of biomass are 111.7 kg and 6.5 kg, respectively.

The emissions, resource consumption, and energy use were tracked for all steps required to transport coal, biomass, and necessary chemicals and materials. Included in the calculations are the extraction of raw materials (crude oil, metal ore, etc.), production and decommissioning of transportation equipment, production and distribution of transportation fuel, combustion of the fuel, and unloading and loading the materials transported. The trains and barges use light fuel oil and heavy fuel oil, respectively. For the LCA we assume that the coal required by the power plant is transported 48 km (30 miles) by rail and 435 km (270 miles) by barge. Details of the transportation system are given in Spath and Mann (1999). Transportation of the biomass is by truck and rail, over an average distance of 80.5 km (50 miles), based on that considered to be the economic haul distance for biomass residue to a power facility. The actual distance will be case specific (NRBP 1996). The ratio of biomass transported by truck to that transported by rail will vary depending on the facilities and infrastructure available; for this study, the breakdown was set at 40% by truck and 60% by rail. This ratio was determined based on discussions with the plant manager at Burlington Electric's McNeil Station, which currently generates 50 MW of biomass-derived power and is the site of the demonstration of the Battelle/FERCO biomass gasifier. Results from the LCA conducted on a biomass-fired power plant (Mann and Spath 1997) showed that there is little difference in the environmental impacts from various modes of transportation compared with the total emissions and resource consumption of the entire system.

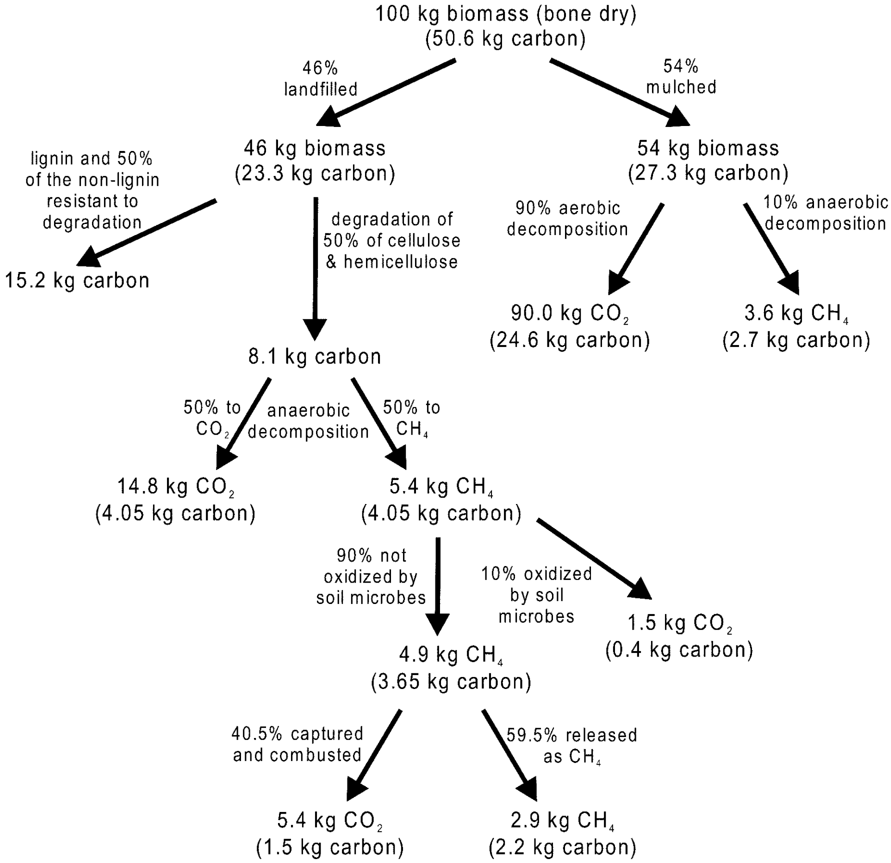

Fig. 1. Avoided fate of biomass

Table 3. Air emissions

	15% cofiring		5% cofiring		No cofiring Emissions (g/kWh)
	Emissions (g/kWh)	% change from no cofiring	Emissions (g/kWh)	% change from no cofiring	
Carbon dioxide	954	−6	1,003	−2	1,018
Carbon monoxide	0.2	−5	0.3	−1	0.3
Non-methane hydrocarbons	0.2	−11	0.2	−4	0.2
Methane	−5.0	−652	−1.0	−214	0.9
Nitrogen oxides (NO_x)	3.1	−8	3.3	−2	3.3
Nitrous oxide (N_2O)	0.0	−19	0.0	−6	0.0
Particulates	8.1	−12	8.9	−3	9.2
Sulfur oxides (as SO_2)	5.9	−12	6.5	−3	6.7

Results

Air emissions

The air emissions that combine to account for 99.9 wt% of those tracked in this analysis are shown in Table 3. Although the amount of N_2O being emitted from this system is very low, it has been included in this table because it is a powerful greenhouse gas. The vast majority of air emissions from the power plant are reduced through the practice of cofiring. The rates of reduction of some emissions are lower than the rate of cofiring because of the loss in power plant efficiency and because some emissions occur in producing and using the biomass. It is important to recognize that an average reduction in air emissions does not by itself, imply a similar reduction in the associated health and environmental impacts. As shown below, however, the typical power plant pollutants that are believed to have the most serious environmental and health consequences are substantially reduced.

The amount of SO_2 produced decreases because of the lower sulfur content of the biomass feed compared with coal. Smaller quantities of sulfur in the feed also result in a reduction in the amount of lime and limestone required for flue gas cleanup. Because the majority of the system particulates are due to the production of these absorbants, overall system particulate emissions are reduced with cofiring. Actual reductions in both SO_2 and particulates will depend on the quantity of sulfur in the coal being used and the amount of scrubbing that is practiced. Particulate emissions from the plant stack are not expected to be greatly affected with cofiring (NRBP 1996). In this analysis, reductions in NO_x were assumed to be due solely to the lower amount of fuel-bound nitrogen in the biomass. This assumption was made to reflect the fact that site-specific details on boiler configuration and downstream NO_x reduction technology are not known. It is likely, however, that in real cofiring situations, higher fuel volatility will cause NO_x emissions to be even lower than assumed here (Tillman 2000). During many of the cofiring tests conducted by EPRI, a measurable reduction in NO_x beyond a dilution effect was observed (EPRI 1997a; EPRI 1997b; Hughes 1997). Using the equation presented in Tillman (2000), power plant NO_x may be reduced by as much as 26.4% and 9.8% for 15% and 5% cofiring rates, respectively.

Methane emissions become negative for the systems employing cofiring because of the avoided decomposition emissions. The methane released during surface mining operations is also reduced, but at a rate slightly lower than the rate of cofiring because of efficiency losses. In the 15% cofiring case, a 13% reduction in coal mine methane is realized. However, relative to the amount of mulch and landfill methane avoided, the impact of this reduction is small, equating to less than 2% of the methane that would have been released had the biomass been allowed to decompose.

Greenhouse gas emissions

Coal-fired power plants essentially have three opportunities to reduce their greenhouse gas emissions: efficiency improvements, CO_2 removal and sequestration, and biomass cofiring. Because existing plants cannot easily take advantage of new technologies that offer higher conversion efficiencies, and installation of CO_2 capture equipment is costly and impractical, biomass cofiring offers the most economical means of reducing the net amount of greenhouse gases they produce. Quantifying CO_2 emissions from the power plant itself is not as much of a concern as looking at the net emissions of the greenhouse gases produced by the entire system. Although CO_2 receives the most attention for its potential contribution to climate change, two other greenhouse gases, methane and N_2O, are also produced by these systems. The capacity of methane to contribute to the warming of the atmosphere, a measure known as the global warming potential (GWP), is 21 times that of CO_2, while the capacity of N_2O is 310 times that of CO_2 (Houghton et al. 1995). Thus, the GWP of a system can be normalized to CO_2-equivalence to describe its overall effect on global climate change.

The GWP of the 15%, 5%, and no cofiring cases is 849.3 g CO_2-eq/kWh, 1,002.9 g CO_2-eq/kWh, and 1,038.9 g CO_2-eq/kWh, respectively. Cofiring biomass at 15% thus reduces the GWP of the coal-fired power plant by 18.2%. A 5.4% reduction is obtained by cofiring at 5%. The reduction in the GWP of the cofiring systems is higher than the rate of cofiring because the GWP of the methane and CO_2 that would have been produced during decomposition is greater than the greenhouse gases produced in supplying and combusting the biomass plus the value of the carbon sequestered in the landfill. For all systems, the majority (>89%) of the CO_2 emissions, which make up greater than 98% of all air emissions, come from combustion of the coal. In the 15% cofiring case, operations related to flue-gas cleanup (the production, transportation, and use of limestone and lime), coal transportation, and coal mining account for 20%, 15%, and 8% of the non-coal CO_2 (i.e., the CO_2 not produced during coal combustion at the power plant), respectively.

In determining the net greenhouse gas emissions balance for this system, it is important to recognize that not all of the emissions and avoided emissions will occur at the same time. While CO_2 will be emitted at the power plant as soon as biomass is fired, the release of CO_2 and methane from mulch, and particularly from landfills, will be delayed. Because it is exposed to the elements, the time frame for complete decomposition of mulch would likely be on the order of just a few years, and is reported to occur at a rate of 10% per year (Harmon et al. 1996). In landfills, non-lignin species of wood are estimated to have half-lives on the order of 20–40 years, although faster rates have also been reported (Micales and Skog 1997).

System energy balance

The energy use within each process block was calculated so that the net energy consumption of the system could be determined. Energy is used either in consuming a material that has a fuel value or by consuming a material for which energy was used in its manufacture. When a fuel is consumed, either for energy generation or because it is the feedstock to a process, the heating value of that fuel (LHV basis) is subtracted from the net energy balance of the system. This reflects the fact that the fuel had a potential energy that was consumed by the system. In the case of a renewable energy resource such as biomass grown for energy uses, its heating value is not subtracted from the net energy of the system because it is both consumed and produced by the system. For the current case, the net energy is reduced by the heating value of the coal and the energy consumed in upstream processes (e.g., transportation, mining, etc.). The biomass residue, though, cannot be considered a traditional renewable fuel since it is not grown within the boundaries of the system. However, landfilling or mulching wood that has an energy value would result in a loss of potential energy from the system. By using this fuel, therefore, loss of this energy is avoided. Thus, the only energy that is consumed when biomass residue is used at the power plant is the fossil energy required to deliver it and prepare it for combustion. Additionally, the energy that might be generated from landfill gas is considered to be lost if the biomass is cofired.

In addition to power plant efficiency, two other measures for assessing energy use can be defined:

$$\text{Net energy ratio} = \frac{E_g}{E_{ff}}$$

$$\text{External energy ratio} = \frac{E_g}{E_{ff} - E_c}$$

where: E_g=electric energy delivered to the utility grid, E_{ff}=fossil fuel energy consumed within the system, including that in the coal fed to the power plant, E_c=energy contained in the coal fed to the power plant.

The net energy ratio measures the total amount of energy produced by the system for every unit of energy consumed by the system. The external energy ratio differs from the net energy ratio in that the energy contained in the coal fed to the power plant is not subtracted from the net energy of the system. This provides a better means of measuring the amount of energy that is consumed in upstream operations. The net energy ratios of the 15%, 5%, and no cofiring cases are 0.35, 0.32, and 0.31, respectively. The respective external energy ratios are 5.60, 5.21, and 5.06. An increase in either of these ratios reflects an increase in overall system efficiency.

While power plant efficiency decreases with increasing cofiring levels, the total system energy efficiency increases. Two factors are responsible for this. First, as less coal is burned at the power plant because of cofiring, less energy is consumed by the system overall. Secondly, less upstream energy is required to produce and deliver biomass fuel to the power plant than to produce and deliver coal. While both feedstocks must be transported, coal must also be mined and cleaned. Additionally, a significant amount of energy is consumed in producing limestone and lime for SO_2 emissions control. Because of the lower sulfur content of biomass, lower quantities of the absorbants are required in the cofiring scenario than when firing coal alone. Figure 2 shows the activities that consume the majority of each system's total energy, excluding the coal

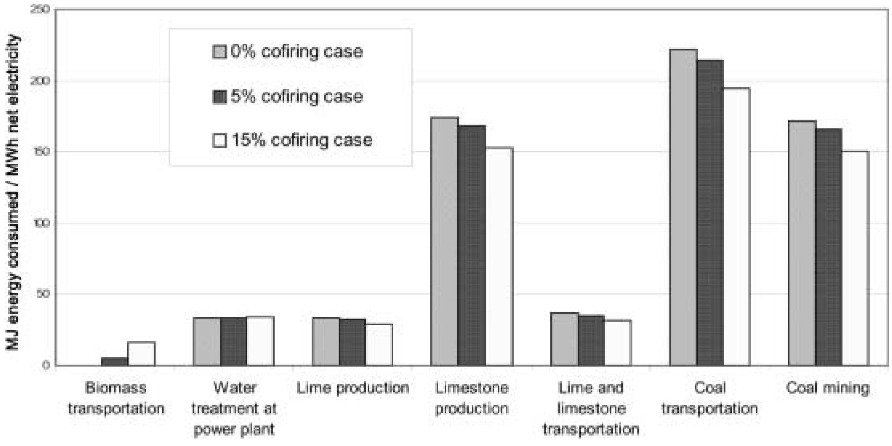

Fig. 2. Non-coal system energy consumption

Table 4. Non-renewable natural resource consumption

	15% cofiring			5% cofiring			No cofiring	
	% by wt[a]	g/kWh	% change[b]	% by wt[a]	g/kWh	% change[b]	% by wt[a]	g/kWh
Coal	80	395	−13	80	436	−4	80	452
Limestone	18	90	−12	18	99	−3	18	103
Oil	2	10	−10	2	11	−3	2	11
Natural gas	0.2	1.1	−12	0.2	1.2	−4	0.2	1.2

[a] Percent of total resource consumption. Not all resources consumed by the system are shown; therefore the numbers do not add up to 100%

[b] Percent of reduction due to cofiring, based on the amount consumed in each case per kWh produced

used by the power plant. The total amount of energy consumed in the no cofiring case is 11.5 MJ/kWh; cofiring reduces total system energy consumption by 3.5% and 12.4% for the 5% and 15% cofiring cases, respectively.

Resource consumption

Fossil fuels, metals, and minerals are all used in the process steps required to convert coal or biomass to electricity. Table 4 shows the resources used in the most significant quantities for each case. Coal is consumed at the highest rate, accounting for nearly 80% of all non-renewable resources.

Solid waste

The waste resulting from operation of the various systems needed to cofire biomass with coal can be grouped into three main categories: (1) flue gas cleanup waste, (2) boiler ash, and (3) miscellaneous non-hazardous process waste. Additionally, due to cofiring, there is an avoided waste in the form of the biomass that was not disposed of in the landfill; this waste is measured as a credit in the cofiring cases. In the no cofiring case, the biomass not used at the power plant was not counted as a penalty, since biomass disposal is outside of the legitimate boundary of current coal-fired power plants. The amounts of both flue gas cleanup waste and boiler ash are reduced through cofiring. Boiler ash is reduced because of the lower ash content of biomass (0.1 g/kJ) compared with coal (0.3 g/kJ). The lower lime and limestone requirements result in less flue gas cleanup waste. The production of limestone and lime used in flue gas cleanup is responsible for 90% of the miscellaneous non-hazardous waste, with the remaining 10% from surface mining operations. Including the biomass as an avoided solid waste, the 15% and 5% cofiring cases reduce the amount of system waste landfilled by 85.6% and 27.6%, respectively.

Trace metals

The amount of trace metals in biomass will be dependent upon its source. Clean, untreated wood, such as that assumed in this study, will likely have lower concentrations of trace metals than those that are typical of coal (EPRI 1997a). Among others, these include arsenic, beryllium, cadmium, mercury, and lead. The amount released will be in direct proportion to the difference in the concentrations between the coal and the wood, although differences in wood and coal ash concentrations may affect the partitioning of some metals between gaseous emissions and solid waste. Case-specific studies will be required for actual cofiring operations once the source of the biomass has been identified.

Water emissions

As with the coal cases studied in Spath and Mann (1999), water emissions were low compared with other emissions. The majority of the water emissions are from the mining and power plant subsystems. Cofiring results in a net reduction because of avoided mining operations and because less water contamination occurs in sections of the system related to biomass procurement. Additionally, it is likely that contamination of groundwater from landfill leachate will be reduced because of the reduction in disposal of organic material. The magnitude of this reduction, however, is difficult to quantify, as groundwater contamination from landfills is highly site-specific, and the allocation of the contamination to different materials in the landfill is unknown.

Sensitivity analysis

An important component of any LCA is the sensitivity analysis. The impact of different assumptions on the results can be measured by varying parameters and observing the subsequent changes. The extensive sensitivity analyses conducted for the coal LCA (Spath and Mann 1999) make a study of many of the variables in the cofiring system redundant. For example, the conclusions drawn by varying feedstock transportation distance, operating capacity, power plant efficiency, and the amount of materials recycled will be the same for this and the previous study. Two important parameters, however, could be identified for the cofiring situation that were not applicable to the previous study: the rate of cofiring, and the fate of biomass in avoided operations.

Sensitivity of results to cofiring rate

Figure 3 shows the net CO_2 emissions and GWP per kWh of electricity produced, for various rates of cofiring. The lines cross early as the rate of cofiring increases because the avoided landfill methane becomes more important than the CO_2 released by the power plant; as more biomass is used to cofire, less is allowed to decompose to methane and CO_2. Because these avoided emissions are subtracted from the net emissions of the system, and because methane has a GWP 21 times that of CO_2, the GWP of the system is actually less than the net CO_2 emissions at cofiring rates greater than about 3%. The percentage reduction in CO_2 emissions and GWP from the no cofiring case because of cofiring is shown in Fig. 4. These results are not linear because of the efficiency loss with cofiring. Within the range of cofiring rates shown on Fig. 4, for every 1% increase in cofiring rate (by energy input), there is approximately a 1.0–1.3% drop in the GWP of the system. Therefore, the reduction in system GWP is at least as great as the rate of cofiring, and increases with increasing cofiring rates. An interesting result is that the efficiency losses increase the magnitude of this positive impact, because at higher cofiring rates more biomass must be used per unit of coal avoided to produce the same amount of electricity.

Sensitivity of results to avoided fate of biomass

Because they are subtracted from the net emissions, higher or lower avoided methane and CO_2 emissions from landfill and mulch decomposition will affect the GWP of the entire cofiring system. While the assumptions in Fig. 1 were chosen to be conservative and are based on published data, variance is likely. This will be the case for not only the average system represented here, but especially for plant-specific situations. The amounts of methane and CO_2 that are avoided by cofiring biomass are dependent on several factors:

1. The split between how much of the biomass goes to the landfill and how much goes to mulch
2. The extent of degradation of biomass in landfills
3. The amount of landfill gas that is captured and combusted
4. The conditions under which the mulch will decompose (anaerobic or aerobic)

Several combinations of reasonable but less likely values (from the base-case) of each of these factors were tested for the 15% cofiring case in order to quantify the range of possible GWP results. The cases tested are shown in Table 5.

The first factor, disposal method, was varied to represent cases where all of the biomass is either landfilled or mulched. The second factor, extent of degradation of biomass in landfills, was varied between zero and 70% decomposition of the non-lignin components. Decomposition in landfills will be dependent on the design and location of the landfill, as higher moisture contents increase degradation. Newer landfills are generally covered to prevent rain from leaking in, although maintenance is only mandated for 30 years past the closure of the landfill (Federal Register 1991). Additionally, the subsistence moisture level required by methanogenic bacteria is very low and occurs even in the driest of landfills (McBean et al. 1995), although hydrolysis and fermentation reactions that precede methane generation will require water (Pauss et al. 1987). While zero decomposition is highly unlikely, especially over the long term, this would represent a worst-case

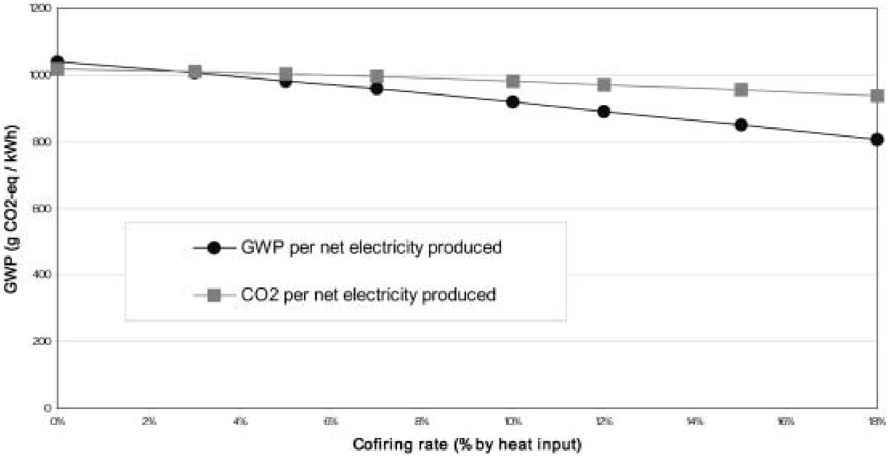

Fig. 3. The effect of cofiring rate on CO_2 emissions and GWP

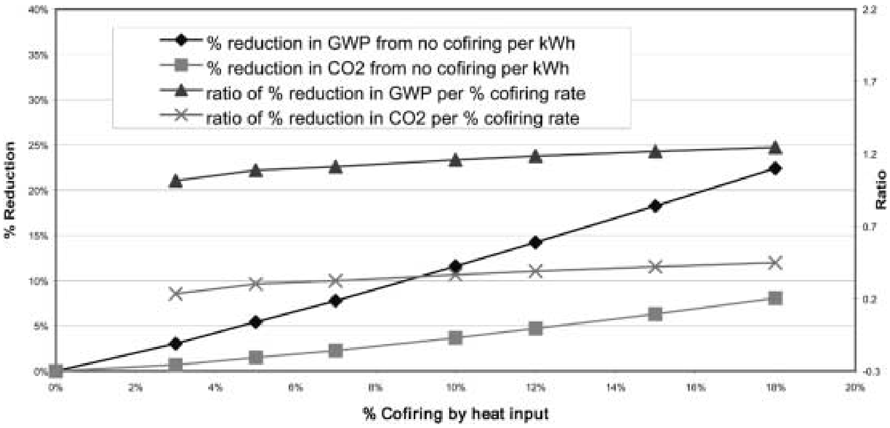

Fig. 4. Rate of reduction of CO_2 and GWP with cofiring

scenario for avoiding carbon emissions at the coal-fired power plant. The choice of 70% was made based on laboratory studies by Barlaz et al. (1989). Although theoretically possible, this high value is improbable for wood decomposition in modern landfills.

For the third factor, the percentage of landfill methane converted through collection and combustion was varied between zero and 75%, with 75% representing the maximum efficiency of collection systems. Landfill gas capture and combustion is only technically feasible for the period where a significant quantity of gas is being produced. Since wood decomposes more slowly than other organic materials in landfills, methane and CO_2 generation from wood may occur long after the more readily decomposable materials are consumed. While methanogenesis can last for as long as 40 years (Augenstein and Pacey 1991), methane production high enough for commercial collection occurs within the 5–20-year range (Suflita et al. 1992). If the collection system is shut down before decomposition of the biomass is complete, the methane that is produced from the wood will not be combusted, making the avoided greenhouse gases higher for the cofiring plant. Additionally, although this study represents average situations for both the power plant and the wood stream, cases will exist where the biomass would have been disposed of in landfills that are not required to collect their gases. Conversely, landfills that are required to collect their gas, or find that it is economically viable to do so, are expected to increase in number. Climate change discussions are likely to make this even more probable.

Because site-specific conditions will dictate the situations under which biomass is normally disposed of and the extent to which it decomposes, it is difficult to say which of the above cases represents the "average" or most likely scenario for cofiring. The base case was chosen to represent a conservative yet possible situation. Results of the sensitivity analysis on the avoided fate of the biomass are shown in Fig. 5. The relative standard deviation of the GWP for all cases tested is 10%, demonstrating that cofiring has a high probability of reducing the net greenhouse gas emissions of coal-fired power systems.

Table 5. Biomass fate sensitivity cases (*bold type* denotes base case values)

Case	Fraction of biomass landfilled	Fraction of non-lignin degraded	Fraction of landfill gas combusted	Fraction of mulch to methane
Base case	**0.46**	**0.5**	**0.405**	**0.1**
A	1	0	N/A	N/A
B	1	0.3	0.75	N/A
C	1	0.3	0	N/A
D	1	**0.5**	0.75	N/A
E	1	**0.5**	**0.405**	N/A
F	1	**0.5**	0	N/A
G	1	0.7	**0.405**	N/A
H	1	0.7	0	N/A
I	**0.46**	0	N/A	**0.1**
J	**0.46**	**0.5**	0	**0.1**
K	**0.46**	**0.5**	**0.405**	0
L	**0.46**	**0.5**	0.75	**0.1**
M	**0.46**	**0.5**	0	0.15
N	**0.46**	**0.5**	**0.405**	0.15
O	0	N/A	N/A	0
P	0	N/A	N/A	0.05
Q	0	N/A	N/A	**0.1**
R	0	N/A	N/A	0.15

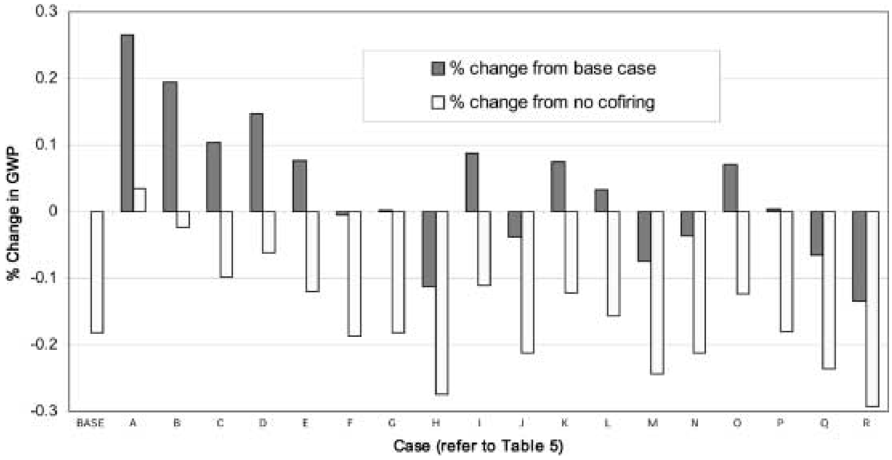

Fig. 5. Sensitivity to avoided fate of biomass

The largest increase in GWP from the base case is shown as Case A, and represents the situation where all of the biomass carbon is permanently sequestered in the landfill (i.e., zero avoided decomposition emissions). While this is a highly improbable scenario, it is interesting to note that it results in a GWP that is only 3% higher than that of the no-cofiring case. In fact, if all of the biomass is landfilled, cofiring will result in a net reduction in greenhouse gases if at least 8% of the carbon in the biomass decomposes, assuming all other parameters shown in Fig. 1 remain the same. This value is well below that used in the base case (35%), and demonstrates that, for almost all disposal scenarios, cofiring reduces the GWP of coal-fired power plants.

Where 70% of the non-lignin species in the wood decompose at the landfill and no landfill gas combustion occurs (Case H), a GWP reduction of 28% from the no-cofiring case can be realized. This scenario is improbable because in dry, modern landfills, wood is not likely to degrade to this extent. Other cases, however, are more probable and highlight realistic opportunities for significant reductions in GWP. The situation where the landfill is not required to collect and combust its gas (Case J) results in 21% and 4% decreases from the no-cofiring case and 15% cofiring base case, respectively.

When all of the biomass is disposed of as mulch and degrades such that 10% of the carbon ends up as methane (Case Q), a 24% reduction from the no cofiring case GWP is seen. Even allowing only 5% of the carbon to go to methane (Case P) results in an 18% reduction. Cases M, N, and R, which examine greater degrees of anaerobic decomposition of mulch because of larger piles and/or greater pile moisture, all result in larger reductions in GWP than those predicted in the 15% cofiring base case.

Situations where the reduction in GWP is not as great as in the base case include those where more of the landfill gas is combusted or less of the biomass carbon ends up as methane. For example, if all biomass is landfilled at a site that treats 75% of its gas (Case D), the GWP of the coal-only plant is reduced by only 6%, instead of the 18% predicted in the base case. Another example is the case where the portion of the biomass that ends up as mulch is decomposed under only aerobic conditions (Case O). This case results in a 12% reduction in GWP. These reductions, however, should be recognized as considerable, especially given the relatively low capital and operating costs of cofiring.

Conclusions

Cofiring can lead to significant reductions in the environmental impacts of coal-based electricity production. The amounts of nearly all air emissions are reduced by feeding even small amounts of biomass into the boiler. Additionally, because of avoided decomposition emissions, net greenhouse gas emissions are reduced at rates greater than the rate at which wood is added. The net energy balance of the system is improved because of a reduction in the amount of coal that is burned and because, on an energy-equivalent basis, procuring biomass residue for the power plant consumes less energy than mining and transporting coal. Consumption of nonrenewable resources is cut substantially from those levels required when firing coal alone. Finally, solid waste emissions are reduced not only at the plant in the forms of boiler ash and flue gas cleanup waste, but also because landfilling of available biomass resources is avoided. While existing coal-fired power plants will incur some capital expenses to cofire biomass, the environmental benefits are significant and may be justified by emissions restrictions and consumer desire for cleaner power.

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