The Net CO_2 Emissions and Energy Balances of Biomass and Coal-Fired Power Systems

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To determine the environmental implications of producing electricity from biomass and coal, life cycle assessments (LCA) have been conducted on systems based on three power generation options: 1) a biomass-fired integrated gasification combined cycle (IGCC) system, 2) three coal-fired power plant technologies, and 3) a system cofiring waste biomass with coal. Each 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. Each study was conducted independently and can therefore stand alone. However, the resulting emissions, resource consumption, and energy requirements of each system can ultimately be compared. Although the studies conducted quantified resources consumed, as well as several air, water, and solid waste emissions, this paper will pay particular attention to net CO_2 emissions and energy balances. The biomass IGCC system emits only 4.5% of the CO_2 produced by the average coal power system. This is due to the absorption of CO_2 from the power plant by the growing biomass. Cofiring residue biomass at 5% and 15% by heat input reduces greenhouse gas emissions on a CO_2-equivalent basis from the average coal system by 6.7% and 22.4%, respectively, per unit of electricity produced. The life cycle energy balance of the coal systems is significantly lower than the biomass system because of the consumption of a non-renewable resource. Not counting the coal consumed by these systems, the net energy produced is still lower than from the biomass system because of energy used in processes related to flue gas clean-up. Cofiring biomass reduces total system energy consumption by 6.4% and 19.9% for the 5% and 15% cofiring cases, respectively.

1. INTRODUCTION

The march of advanced biomass power technologies toward commercialization has provided a more complete set of data for conducting economic analyses and writing operating procedures. These data can also be used to better define the environmental consequences of producing electricity from biomass. Life cycle assessment (LCA) is a systematic analytic method used to quantify the emissions, resource consumption, and energy use of a manufacturing process. LCAs were conducted on a biomass power system, and for comparison purposes, on three coal-fired technologies and a power plant cofiring biomass with coal. Even though the results of each LCA can be compared to highlight the environmental benefits and drawbacks of one process over the other, each study was conducted independently so that the total environmental picture of each process could be evaluated irrespective of any competing process. Material and energy balances were used to quantify the emissions, resource depletion, and energy consumption of all processes between transformation of raw materials into useful products and the final disposal of all products and by-products.

2. DESCRIPTION OF SYSTEMS STUDIED

2.1. LCA of a Biomass Gasification Combined Cycle Power Plant

An LCA on the production of electricity from biomass in a combined cycle system based on the Battelle/FERCO gasifier was completed in 1997. The overall system consists of the production of biomass (hybrid poplar) as a dedicated feedstock crop, its transportation to the power plant, and electricity generation. Upstream processes required for the operation of these sections are also included. The primary purpose of conducting this LCA was to answer many of the questions that are repeatedly raised about biomass power in regards to CO_2 and energy use, and to identify other environmental effects that might become important once such systems are further implemented. For details about the methodology and results for this biomass-to-electricity LCA refer to Mann and Spath (1997).

2.2. LCA of Coal-Fired Power Production

In order to examine the environmental aspects of current and future pulverized coal boiler systems, three systems were studied: 1) a plant that represents the average emissions and efficiency of currently operating coal-fired power plants in the U.S. (this tells us about the status quo), 2) a new coal-fired power plant that meets the New Source Performance Standards (NSPS), and 3) a highly advanced coal-fired power plant utilizing a low emission boiler system (LEBS). The overall systems consist of coal mining, transportation, and electricity generation. In keeping with the cradle-to-grave concept of LCA, upstream processes required for the operation of these three subsystems were also included in this study. All three cases use the same type of coal (Illinois No. 6), and both surface and underground mining were examined. The coal is transported via rail, truck, or a combination of rail and barge by one of four cases tested: average user by land, average user by river, farthest user, and mine mouth. The main modes of transportation were barge and train, although some diesel-fueled trucks were required for transporting items such as chemicals, catalysts, and ash. Major results will be presented here; for a more detailed description of the methodology and complete results, refer to Spath and Mann (1999).

2.3. LCA of a Plant Cofiring Biomass with Coal

An LCA was conducted on the production of electricity from a coal-fired power plant cofiring waste (primarily urban) biomass. The power plant is similar in design to the average case studied in the coal LCA, since currently operating coal-fired boilers can obtain the most benefit from cofiring biomass. Overall changes in emissions, resource consumption, and energy use were quantified for systems cofiring at rates of 5% and 15% by heat input, compared to a baseline system firing only coal. Cofiring was assumed to take place in the course of normal power plant operation. Thus, no construction or decommissioning of the plant is included in the assessment, although plant modifications required for cofiring were assessed.

3. MAJOR RESULTS

Although each LCA examined many different air, water, and solid waste emissions, plus numerous natural resources, only CO_2 and energy balance results will be presented here. Because of increasing concerns about the role of man-made gases on global climate change, special attention is directed toward CO_2. Quantifying CO_2 emissions from the power plant are not as much of a concern as looking at the net CO_2 produced by the entire life cycle system. This is especially obvious when biomass systems are being studied since CO_2 is absorbed during photosynthesis, greatly reducing CO_2 emissions per unit of energy produced. Similarly, the net amount of energy produced by the system is more important than the amount of energy that is produced by the power plant. Upstream processes such as feedstock production, transportation, and chemical manufacture consume significant quantities of energy, resulting in less energy produced by the system overall.

3.1. CO_2 Emissions

Figures 1 and 2 illustrate the major sources and amounts of CO_2 emissions for the biomass IGCC and average coal systems. In terms of total air emissions, CO_2 is emitted in the greatest quantity from all systems examined. Net CO_2 emissions from the biomass IGCC system account for approximately 67% by weight of all air emissions. From the coal systems, CO_2 accounts for 98-99% of the total air emissions. However, note that in the case of the biomass IGCC system, because carbon dioxide emitted from the power plant is recycled back to the biomass as it grows, net emissions from this system are only 4.5% of those from the average coal system. Net CO_2 emissions for the NSPS and LEBS coal cases are 941 g/kWh, and 741 g/kWh of net electricity produced, respectively.

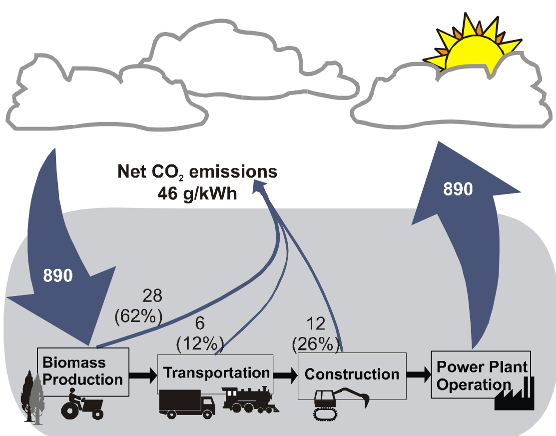

Figure 1: Biomass Power System
95% carbon closure

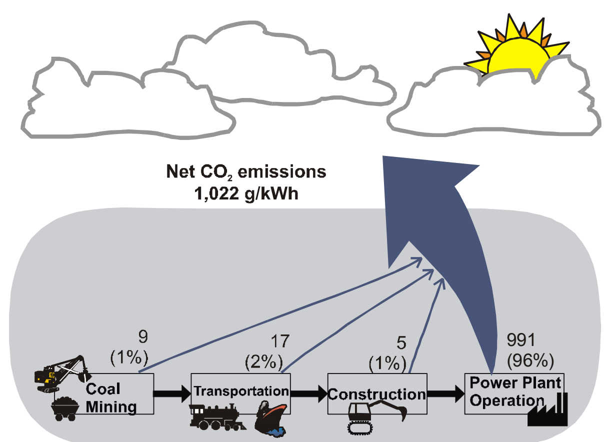

Figure 2: Average Coal Power System
0% carbon closure

The carbon closure of a system can be defined to describe the net amount of CO_2 (as carbon) released from the system in relation to the total amount of carbon circulating through the system. Referring to Figure 1, the carbon closre of the biomass IGCC system is:

$$(1-\frac{net}{Ctotal})*100 = (1-\frac{46}{46-890})*100 = 95\%$$

In addition to CO_2, two other greenhouse gases, methane and N_2O, are produced by these systems. The capacity of methane and N_2O to contribute to the warming of the atmosphere, a measure known as the global warming potential (GWP) of a gas, is 21 and 310 times higher than 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 warming. Because biomass is diverted from landfills for the cofiring cases, methane and CO_2 that normally would be produced at the landfill are avoided. These avoided emissions are taken as a credit against the emissions from the cofiring systems. Therefore, the reduction in the GWP of the cofiring systems is higher than the rate of cofiring on an energy input basis. The 15% cofiring case reduces the GWP of the no cofiring case by 22% on a per kWh basis. A 7% reduction is obtained by cofiring at 5%. Table 1 shows the carbon closures, net GWP on a CO_2-equivalence basis, and net CO_2 emissions, for all of the systems studied. Because no CO_2 is removed from the atmosphere by the coal systems, their carbon closures will always be zero. The carbon closure of the biomass IGCC system could be higher than 95% if the soil on which the biomass is grown is able to permanently sequester carbon.

Table 1: Carbon Closure, Global Warming Potential, and Net CO_2 Emissions

	Biomass IGCC	Average coal	NSPS coal	LEBS coal	15% cofiring	5% cofiring	0% cofiring
Carbon closure	95.1%	0%	0%	0%	15.1%	5.1%	0%
Net GWP (g CO_2 equivalent / kWh)	49	1042	960	757	816	981	1,052
Net CO_2 (g/kWh)	46	1,022	941	741	927	1,004	1,031

3.2. Energy Production and Consumption

Given that the systems being studied exist for the purpose of producing electricity, the net energy balance was examined carefully. Energy is consumed in two ways: 1) in upstream processes that create an intermediate feedstock (e.g., fertilizer or limestone) or effect an operation (e.g., transportation), and 2) by destroying a material that has the potential to be converted to energy (e.g., natural gas). The net energy of the system is the energy produced as electricity by the power plant less the energy consumed throughout the system. In the case of the coal-fired systems, because coal is a non-renewable resource, it is said to be consumed by the process; thus, its energy content is subtracted from the energy produced by the plant. Biomass, on the other hand, is both created and consumed within the boundaries of the system, and so its energy is not subtracted from the net. In addition to the standard power plant efficiency, which is the energy delivered to the grid divided by the energy in the feedstock to the power plant, four other measures of efficiency were defined in Table 2.

Table 2: Measures of Net Energy Production

Life cycle efficiency (%) (a)	External energy efficiency (%) (b)	Net energy ratio (c)	External energy ratio (d)
$=\frac{Eg-Eu-Ec-En}{Ec+En}$	$=\frac{Eg-Eu}{Ec+En}$	$=\frac{Eg}{Eff}$	$=\frac{Eg}{Eff-Ec-En}$
where: Eg = electric energy delivered to the utility grid Eu = energy consumed by all upstream processes required to operate power plant Ec = energy contained in the coal fed to the power plant En = energy contained in the natural gas fed to the power plant (LEBS system only) Eff = fossil fuel energy consumed within the system (e)			

The net energy ratio describes the amount of energy produced per unit of energy consumed. Although this is a more accurate and rigorous measure of the net energy balance of the system, the external measures are useful because they expose the rate of energy consumption by upstream operations. Table 3 gives the energy efficiency and ratio results for all systems studied.

Table 3: Energy Results

	Biomass IGCC	Average coal	NSPS coal	LEBS coal	15% cofiring	5% cofiring	0% cofiring
Power plant efficiency	37%	32%	35%	42%	31.1%	31.5%	32%
Life cycle efficiency	35%	-76%	-73%	-66%	-60%	-70%	-74%
External energy efficiency	35%	24%	27%	36%	25.5%	25.4%	25.6%
Net energy ratio	15.6	0.29	0.31	0.38	0.34	0.31	0.30
External energy ratio	15.6	5.0	5.1	6.7	5.6	5.1	5.0

Because the energy contained in the coal is greater than the energy delivered as electricity, the life cycle efficiencies of the coal systems are negative. Another way to view this is that because a non-renewable resource is expended, the coal systems consume more energy than they produce. The net energy ratio likewise indicates that only about one-third of every unit of energy into the coal-fired systems is obtained as electricity. Cofiring at 5% and 15% reduces the net energy consumption of the average coal system by 6.4% and 19.8%, respectively. This is due almost exclusively to the reduction in coal consumption. The biomass IGCC system results demonstrate that far more energy is produced than is consumed, because the process is based on a renewable resource.

The external energy efficiency and external energy ratio indicate that upstream processes are large consumers of energy in the coal systems. In fact, the operations related to flue gas clean-up and those associated with coal transportation, account for between 3.8% and 4.2% of the total system energy consumption, and between 67.4% and 70.5% of the non-coal energy. Processes involved in the gas clean-up operations include the production, transport, and use of limestone and lime in the average and NSPS systems, and the production, distribution, and combustion of natural gas in the LEBS system. These operations consume between 35.3% and 38.5% of the non-coal energy, and between 2.0% and 2.4% of the total energy of the systems. Transportation of the coal uses similar amounts: between 30.1% and 32.2% of non-coal, and 1.8% of total system energy.

4. CONCLUSIONS

The net CO_2 emissions of the biomass system are significantly lower than any of the coal systems because of the uptake of CO_2 during biomass growth. Biomass IGCC can obtain carbon closures of 95% or greater, depending on the amount of carbon that is sequestered in the soil. Coal power systems, because they do not remove from the atmosphere any of the CO_2 they produce, have carbon closures of zero. Cofiring biomass offers the opportunity to reduce the net GWP of coal-fired systems. The reduction in GWP is higher than the rate of cofiring (on a heat-input basis) because of the avoided landfill methane. Net GWP reductions are 7% and 22% when cofiring biomass at 5% and 15% by heat input. Therefore, cofiring waste biomass helps coal-fired power plants reduce greenhouse gas emissions in two ways: 1) the well-known cycling of carbon between the power plant and growing biomass, and 2) avoiding emissions that would have been produced at the landfill if the biomass were not used at the power plant.

The net energy balance of the biomass IGCC system shows that 16 units of energy are produced for every unit of energy consumed. Because of the use of a non-renewable resource, the coal systems consume more energy than they produce. Cofiring biomass with coal reduces net energy consumption by 20% and 6.4% for the 15% and 5% cofiring cases; however, the net energy balance is still negative.

REFERENCES

Houghton, J.T., L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg, K. Maskell, eds. (1996). Climate Change 1995 - The Science of Climate Change. Published for the Intergovernmental Panel on Climate Change. Cambridge University Press (New York).

Mann, M.K., P.L. Spath (1997). Life Cycle Assessment of a Biomass Gasification Combined-Cycle System. NREL/TP-430-23076. National Renewable Energy Laboratory (Golden, CO).

Spath, P.L., M.K. Mann (1999) Life Cycle Assessment of Coal-fired Power Production. NREL/TP-570-25119. National Renewable Energy Laboratory (Golden, CO).