COAL VERSUS BIOMASS ELECTRICITY GENERATION - COMPARING ENVIRONMENTAL IMPLICATIONS USING LIFE CYCLE ASSESSMENT

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ABSTRACT

A life cycle assessment (LCA) on coal-fired power systems has been conducted to assess the environmental effects on a cradle-to-grave basis. Three different designs were studied: 1) a plant that represents the average emissions from coal-fired power plants in the U.S. today, 2) a plant that meets the New Source Performance Standards (NSPS), and 3) an advanced plant incorporating a low emission boiler system (LEBS). The boundaries of the analysis include all material and energy streams from the following three subsystems: coal mining, transportation, and electricity generation. Upstream processes required for the operation of these main subsystems were also included. Finally, a sensitivity analysis was conducted to minimize the risk of imperfect data, to account for variations in data, and to cover alternate processing steps/routes. Ultimately, the resulting emissions, resource consumption, and energy requirements are compared to the results of the recently completed LCA for a biomass gasification combine-cycle power system. This allows us to quantify the environmental benefits and drawbacks of biomass power compared to the option that currently makes up the lion's share of generation technology in the U.S. today. This study sets the stage for future studies of coal and biomass cofiring plants. This paper details the methodology used in the coal study and compares the results with those obtained from the previous LCA of an advanced biomass power system.

Keywords: life cycle assessment, emissions, energy, electricity, biomass, coal-fired power plant, environment, carbon dioxide

INTRODUCTION

LCAs of two power generating options were conducted. The first was on a biomass gasification combined cycle power plant, using biomass from a dedicated feedstock supply system. To complement this work, the developed methodology was applied to three types of pulverized coal-fired power systems. Generally, an LCA is conducted on two competing processes. Such a comparative analysis highlights the environmental benefits and drawbacks of one process over the other and often similar parts of the competing processes are excluded. In order to obtain a complete picture of each individual system and to answer the question of how each system by itself will impact the environment a comparison was not performed in this initial work. Each individual assessment included all processes involved in electricity production for that power generation system. 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.

DETAILS OF THE COAL LCA

The coal LCA was a joint effort between the National Renewable Energy Laboratory (NREL) and the Federal Energy Technology Center (FETC) to examine the environmental status of current coal-fired power plants along with future coal technologies. Three cases were examined: 1) a plant that represents the average emissions and performance 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). Coal mining, transportation, and electricity generation are the three subsystems examined. All material and energy streams from these subsystems as well as from any upstream processes required for their operation were included in the analysis.

All three cases use the same type of coal (Illinois No. 6), and both surface and underground mining were examined. The coal is either surface mined via strip mining or mined by the underground technique of longwall mining. 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. Some of the specifics of this coal LCA study are outline below, however, for more details about the methodology and results refer to Spath and Mann (1998).

Average Plant

The coal power plant consists of the following main equipment/process steps: pulverized coal boiler, baghouse filter, and a conventional limestone flue gas clean-up system. The emissions for this case represent the average emissions from all U.S. coal-fired power plants in 1995. These were calculated by dividing the total coal-generated U.S. emissions of a particular pollutant on a weight basis (kg) by the total electricity generated (kWhr) from coal in the U.S. To maintain a mass balance around the power plant, a specific plant with emissions similar to the calculated averages and which is feeding the designated type of coal for this LCA was identified. The actual resource requirements, final emissions, and energy consumption from this specific plant were used in the study.

NSPS Plant

Emissions for this case are calculated based on flue gas clean-up removal efficiencies such that the power plant meets the New Source Performance Standards (NSPS), the Clean Air Act Amendment (CAAA), and other requirements like state or regional regulations. Table 1 indicates the standards of performance for new electric utility steam generating units using fossil fuels, otherwise know as the NSPS, taken from the Code of Federal Regulations (40 CFR 60.42a, 60.43a, and 60.44a). New plants built after 1978 are required to meet these standards. This case has the same process configuration as the average plant. The main difference between the NSPS plant and the average plant is in the flue gas clean-up removal efficiencies, achieved through design changes such as boiler modifications and more advanced clean-up technologies.

Table 1: New Source Performance Standards for Fossil-Fueled Power Plants

	g/GJ heat input, HHV (lb/MMBtu)
NOx	215 - 344 (0.50 - 0.80) (a)
SOx	258 (0.60)
particulates	13 (0.03)

(a) Allowable emissions depend on the type of coal.

LEBS Plant

Emissions for this case are those forecasted from a future plant utilizing a Low Emission Boiler System (LEBS). LEBS is projected to have significantly higher thermal efficiency, better performance, and a lower cost of electricity than current coal-fired power plants. The technology being considered in this assessment is by the developer, DB Riley Inc and is being developed under the Department of Energy's sponsorship. The objective of the LEBS program is to develop technologies that result in lower emissions such that the NOx and SOx emissions are 1/6 of the NSPS and the particulate emissions are 1/3 of the NSPS. The DB Riley technology uses a low-NOx system with advanced burners, air staging, and a wet ash slagging system. The copper oxide flue gas clean-up process utilizes a regenerable sorbent, removing both SO_2 and NOx from the flue gas and producing sulfuric acid or sulfur as a by-product instead of producing a solid waste. The sorbent is regenerated using natural gas as the reducing agent.

Coal Mining

The resources, environmental emissions, and energy use associated with the excavation of coal were included in this LCA. The processes studied include raw material extraction, equipment manufacture, coal mining, all necessary transportation of chemicals, etc., and any upstream processes. The resources, energy, and emissions associated with the mining equipment are based on the types of machinery used for each coal excavation process, the fuel requirements, and the lifetime of the machinery.

Overall, the environmental impacts from surface and underground mining are not significantly different in any of the three power plant cases examined. The main difference between these two mining techniques is that the surface mining subsystem results in a higher amount of airborne ammonia emissions due to the production of ammonium nitrate explosives which are used at the mine. For example, the average yearly airborne ammonia emissions for the average case are 0.099 g/kWh of net electricity produced for surface mining versus 0.00022 g/kWh of net electricity produced for underground mining. Because the resources, emissions, and energy usage are similar for both mining techniques the results presented in this paper will be stated for surface mining only.

Transportation

Three forms of transportation were considered for the coal-to-electricity system: barges, trains, and trucks. Data indicate that coal transport by trucks is relatively small, and therefore is assumed to be zero in this analysis. However, some amount of truck transport was considered for transporting other items such as chemicals, wastes, etc. The area where Illinois No. 6 coal is mined is landlocked, so some coal transport by railcar is required even when considering barges as the primary means of transport. Also, some of the coal which travels by barge is later transferred to railcar for overland shipment to its final destination. Thus, the following four transportation cases were examined: (1) average user by land: railcar = 483 km, (2) average user by river: railcar = 48 km plus barge = 435 km, (3) farthest user: railcar = 1,538 km plus barge = 504 km, and (4) mine mouth: minimal truck transport. The results presented in this paper are based on the average user by river transport case.

The trucks, trains, and barges use diesel fuel, light fuel oil, and heavy fuel oil, respectively. The resources, energy, and emissions related to extracting crude oil, distilling it, producing a usable transportation fuel, and distributing it to refueling stations plus the emissions produced during combustion of the fuel were included in the total inventory. The material requirements for each of the various modes of transportation were used in determining the resources, energy, and emissions associated with vehicle production and decommissioning.

DETAILS OF THE BIOMASS LCA

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 biomass used in this LCA was hybrid poplar. Twenty air, twenty-five water, and seven solid emissions, plus seventeen natural resources and six types of energy were quantified for the system. In keeping with the cradle-to-grave concept of LCA, the energy and material flows of all processes necessary to operate the power plant are included in the assessment. The overall system consists of the production of biomass 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).

COMPARISON OF COAL AND BIOMASS SYSTEM RESULTS

Energy

The energy use within the system was tracked so that the net energy production could be assessed. Several types of efficiencies can be defined to study the energy budget of the biomass and coal systems. First, the power plant efficiency, defined in the traditional sense as the energy delivered to the grid divided by the energy in the feedstock to the power plant (coal and natural gas in the LEBS case or biomass). Four other types of efficiencies can be defined as follows:

Table 2: Energy Efficiency Definitions

Life cycle efficiency (%) (a)	External energy efficiency (%) (b)	Net energy ratio (c)	External energy ratio (d)
$=\frac{Eg-Eu-Ec-En}{Ec+En+Eb}$	$=\frac{Eg-Eu}{Ec+En+Eb}$	$=\frac{Eg}{Eff}$	$=\frac{Eg}{Eff-Ec-En}$

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 case only)
Eb = energy contained in the biomass fed to the power plant (biomass case only)
Eff = fossil fuel energy consumed within the system (e)

(a) Includes the energy consumed by all of the processes.
(b) Excludes the heating value of the coal and natural gas feedstock from the life cycle efficiency formula.
(c) Illustrates how much energy is produced for each unit of fossil fuel energy consumed.
(d) Excludes the energy of the coal and natural gas to the power plant.
(e) Includes the coal and natural gas fed to the power plant since these resources are consumed within the boundaries of the system.

Table 3 contains the resulting efficiencies and energy ratios for each coal case and the biomass case.

Table 3: Efficiencies and Energy Ratio Results

Case	Power plant efficiency (%)	Life cycle efficiency (%)	External energy efficiency (%)	Net energy ratio	External energy ratio
Average	32	-76	24	0.29	5.0
NSPS	35	-73	27	0.31	5.1
LEBS	42	-66	36	0.38	6.7
Biomass	37	35	35	15.6	15.6

(a) Efficiencies are on a higher heating value basis.

(b) Biomass LCA numbers for life cycle efficiency and external energy efficiency are the same since by definition renewables are not considered to be consumed within the boundaries of the system. The same is true for the net energy ratio and external energy ratio numbers.

In regards to the coal LCA, for the average and NSPS cases the majority of the total energy requirement comes from limestone production whereas for the LEBS case the majority of the total energy is required for natural gas production. As stated up above, the LEBS plant uses natural gas to regenerate the sorbent in the flue gas clean-up process. Limestone production accounts for 38% and 40% of the system energy consumption for the average and NSPS cases, respectively, and for the LEBS case natural gas production accounts for 55% of the system energy consumption. For the biomass LCA, feedstock production accounts for 77% of the system energy consumption.

Resources

Fossil fuels, metals, and minerals are used in all of the processes steps required to convert coal or biomass to electricity. Table 4 shows the majority of resources used for each coal and biomass case studied. For all three coal cases, coal is used at the highest rate. For the average and NSPS cases, limestone and oil account for the majority of the remaining resources consumed. For the LEBS case, natural gas and oil account for the majority of the remaining resources consumed. For the biomass LCA, oil, iron, and coal account for 94% by weight of the resources consumed. As expected, the majority of the fossil fuels are consumed by farming operations in feedstock production.

Table 4: Resource Consumption

	Average		NSPS		LEBS		Biomass	
	% by wt (a)	g/kWh (b)	***% by wt (a)***	g/kWh (b)	***% by wt (a)***	g/kWh (b)	***% by wt (a)***	g/kWh (b)
Coal	***80.4***	474.44	***78.0***	433.84	***97.3***	352.49	***11.6***	0.78
Limestone	***17.4***	102.84	***19.7***	109.49	***0.0***	0.04	***1.1***	0.07
Oil	***1.9***	11.48	***2.0***	11.32	***1.3***	4.88	***65.0***	4.37
Natural gas	***0.2***	1.25	***0.2***	1.26	***1.3***	4.53	***3.6***	0.24
Iron ore	***0.0***	0.11	***0.0***	0.11	***0.0***	0.095	***8.6***	0.58
Iron scrap	***0.0***	0.12	***0.0***	0.12	***0.0***	0.10	***9.0***	0.60

(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) Resource consumption per kWh of net electricity produced averaged over the life of the system.

Air, Water, and Solid Wastes

In terms of total air emissions, CO_2 is emitted in the greatest quantity for all cases examined for both the coal and biomass LCA. For the coal cases, CO_2 accounts for 98-99 wt% of the total air emissions. The following are the total CO_2 emissions for the average, NSPS, and LEBS case: 1,022 g/kWh, 941 g/kWh, and 741 g/kWh of net electricity produced. The majority of the CO_2 is emitted from the power plant subsystem during operation of the coal-fired plant. For the biomass case, CO_2 accounts for 67 wt% of the total air emissions at a rate of 46 g/kWh of net electricity produced. The feedstock production subsystem is responsible for greater than half of all net CO_2 emissions from the use of fossil fuels in the farming operations. Because carbon dioxide emitted from the power plant is recycled back to the biomass as it grows, biomass power systems have the ability to reduce the overall amount of CO_2 added to the atmosphere. Figures 1 and 2 show the CO_2 emissions for the coal and biomass system, respectively.

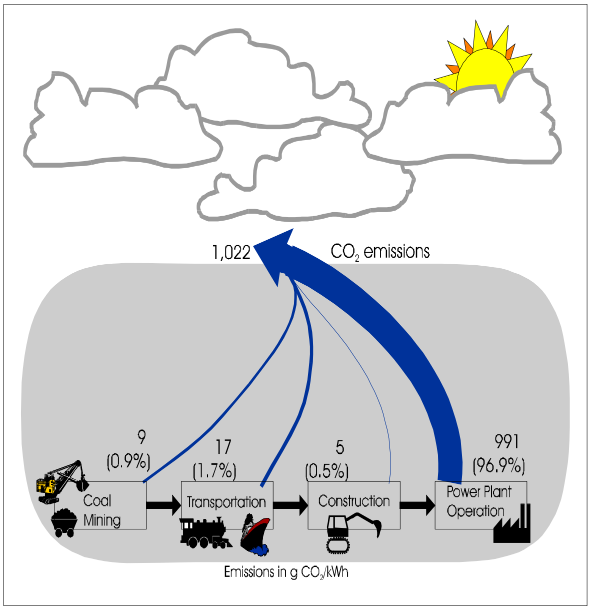

Figure 1. Coal LCA CO_2 Results

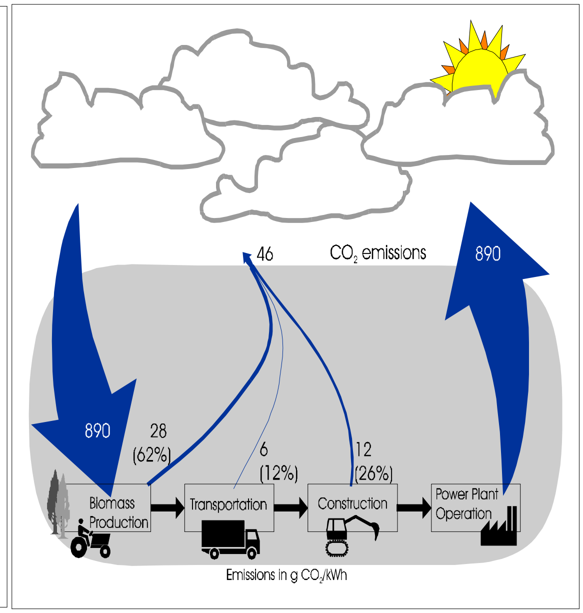

Figure 2. Biomass LCA CO_2 Results

The following table contains the next highest air emissions from the three coal cases and the biomass case studied:

Table 5: Air Emissions

	Average		NSPS		LEBS		Biomass	
	% by wt (a)	g/kWh (b)	***% by wt (a)***	g/kWh (b)	***% by wt (a)***	g/kWh (b)	***% by wt (a)***	g/kWh (b)
Particulates	44.3	9.21	61.0	9.78	4.4	0.11	0.2	0.042
SOx	32.2	6.70	15.7	2.53	28.0	0.72	1.3	0.30
NOx	16.1	3.35	14.6	2.34	21.3	0.54	3.0	0.69
CH_4	4.4	0.91	5.2	0.84	27.9	0.75	0.0	0.0051
CO	1.3	0.27	1.5	0.25	7.5	0.19	0.4	0.083
NMHCs (c)	1.0	0.21	1.3	0.20	7.5	0.19	2.6	0.60
Isoprene (d)	0.0	0.0	0.0	0.0	0.0	0.0	92.3	21.17

(a) Percent of total air emissions *excluding* CO_2 emissions. Not all resources consumed by the system are shown; therefore the numbers do not add up to 100%.
(b) Air emissions per kWh of net electricity produced averaged over the life of the system.
(c) NMHCs = non-methane hydrocarbons including volatile organic compounds (VOCs).
(d) Isoprene is the compound used to model biogenic emissions from the trees.

In all three coal cases the power plant produces most of the SO_x, NO_x, and CO while most of the methane comes from the mining operations. For the average and NSPS case, the majority of the particulates come from the production of limestone (89% of the total particulate emissions for both cases). For the LEBS case, the majority of the particulates are emitted by the power plant during normal operation (47% of the total particulate emissions) and the second major source of particulates is copper oxide production (22% of the total particulate emissions). For all three cases, the NMHC emissions are evenly distributed among the mining, transportation, and power plant subsystems. However, for the LEBS case 36% of the total NMHC emissions are emitted during natural gas production.

For the biomass LCA, significant air emissions were found to come from all three subsystems, but primarily from feedstock production and the power plant. Particulate emissions, although not found to be released in significant quantities overall, are greater than six times higher during the two years of plant construction than during normal operation. NMHC emissions, primarily from operating the power plant, represent only 0.9% of all air emissions including CO_2. The majority of air emissions produced in the feedstock production section are typical of those from diesel-fueled farm equipment. However, the total amount of these emissions is small in comparison to air emissions from the power plant.

For all three coal cases, the majority of the water emissions from the system occurred in the mining and power plant subsystems. The water emissions were evenly distributed between these two subsystems. For the biomass LCA, emissions to water occurred mostly in the feedstock production system. Note that for each system examined the power plant produces a significant amount of water which is treated prior to discharge and thus this stream is not considered a waste stream. In general, though, for both the coal and the biomass LCA the total amount of water pollutants was found to be small compared to other emissions.

The majority of the solid waste in the coal average and NSPS cases comes from the power plant in the form of flue gas clean-up waste that must be landfilled (76-77% of the total waste). The flue gas clean-up process for the LEBS case utilizes a regenerable sorbent, therefore, the majority of the waste from this system is non-hazardous solid waste which comes from the mining operations. For the biomass LCA, non-hazardous solid waste was produced, but in small quantities.

SENSITIVITY ANALYSIS

A sensitivity analysis was conducted on many of the variables in each analysis. For the coal LCA, the following variables had the largest effect on resource consumption, emissions, and energy usage: reducing the power plant construction materials, changing the power plant operating capacity factor, increasing the transportation distance to the farthest user case, and decreasing the transportation distance to the mine mouth case. Changing the power plant efficiency or changing the coal transport distance are the only variables that had a noticeable effect on the efficiency and energy ratio results.

For the biomass LCA, the amount of carbon that is sequestered by the soil at the plantation most strongly affects the net amount of CO_2 released. Apart from this impact, biomass yield had the largest effect on the amount of resource consumption, net emissions, and energy use for the system. Two other variables that had noticeable effects when increased or decreased were the fossil fuel usage at the plantation and the power plant efficiency. However, for all sensitivity cases studied the life cycle efficiency is not significantly less than the power plant efficiency and the net energy ratio does not drop below 11.

CONCLUSIONS/FUTURE WORK

LCAs on separate biomass- and coal-fired power plants were conducted to quantify the cradle-to-grave emissions, resource consumption, and energy use. The results of the two analyses are being compared in order to begin to answer the question of how biomass power plants measure up environmentally against fossil-based systems. For both the coal and biomass systems, CO_2 is the air emission that is emitted in the greatest quantity. When comparing the CO_2 emissions on a life cycle basis, the biomass system produces significantly less carbon dioxide because the CO_2 emitted from the power plant is recycled back to the biomass as it grows. Overall, the biomass system emits only 46 g/kWh of net electricity produced versus 741 - 1,022 g/kWh for the three coal cases. The energy results show that the biomass system produces a significantly higher amount of electricity per unit of fossil energy consumption than the coal system. The net energy ratio for the biomass system is 16 compared to 0.3- 0.4 for the three coal cases. The next power generation option that will be examined is co-firing of biomass in a coal-fired boiler. To complement this work, an assessment of a natural gas-fired IGCC plant will also be conducted.

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