A Life Cycle Comparison of Electricity from Biomass and Coal

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ABSTRACT

It has become widely accepted that biomass power offers opportunities for reduced environmental impacts compared to fossil fuel-based systems. Intuitively obvious are the facts that per kilowatt-hour of energy produced, biomass systems will emit less CO_2 and consume less non-renewable energy. To quantify the magnitude of these and other environmental benefits and drawbacks, life cycle assessments (LCA) on the production of electricity from biomass and coal systems have been performed. 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.

Results demonstrate significant differences between the biomass and coal systems. Per kWh of electricity produced, the amount of CO_2 emitted by the biomass system is only 4.5% of that emitted by the average coal power plant operating in the U.S. today. This is due to the absorption of CO_2 from the power plant by the growing biomass. 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. For each unit of energy consumed by the biomass system, almost 16 units of electricity are produced; the average coal system produces only 0.3 units of electricity per unit of energy consumed. Not counting the coal consumed, the net energy produced is still lower than that of the biomass system because of energy used in processes related to flue gas clean-up.

Introduction

The production of electricity generally results in several negative environmental effects. Biomass power has the potential to mitigate the emissions and resource consumption typically associated with coal-fired power production. The true impact of biomass power technologies, however, has not been well understood or quantified. LCA is an ideal tool for defining the emissions, resource consumption, and energy use of a manufacturing process. Studies were conducted on a biomass power system, and for comparison purposes, on three coal-fired technologies. 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.

The power plant life was set at 30 years and each study was conducted on a yearly basis. This includes the process steps associated with constructing the plant in the two years prior to start-up as well as decommissioning the plant in the latter part of year 30. The results of each study were averaged over the life of the plant so that a comparison between the different systems could be made. The functional unit, also known as the production amount that represents the basis for the analysis, was chosen to be the unit of energy produced. Thus the results are per kWh of net electricity produced by the power plant.

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). To better manage the data generated, the system was broken into three subsystems: coal mining, transportation, and electricity generation. 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 Coal Plant

The average coal power plant consists of the following main equipment/process steps: pulverized coal boiler, baghouse filter, conventional limestone flue gas clean-up (FGC) system, heat recovery steam generator, and steam turbine. 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. The capacity of this plant was 360 MW, with a feed rate of 3,272 Mg bone dry coal per year at 100% capacity.

NSPS Coal 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 gives 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, but is sized at 425 MW; the coal required at 100% capacity is 3,532 Mg/day on a bone-dry basis. 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)
NO_x	260 (0.60)
SO_x	258 (0.60)
particulates	13 (0.03)

LEBS Coal 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 Department of Energy sponsorship. The objective of the LEBS program is to develop technologies that result in lower emissions such that the NO_x and SO_x emissions are 1/6 of the NSPS and the particulate emissions are 1/3 of the NSPS. The DB Riley technology uses a low-NO_x system with advanced burners, air staging, and a wet ash slagging system. The copper oxide flue gas clean-up process uses a regenerable sorbent, removing both SO_2 and NO_x from the flue gas; sulfuric acid or sulfur, instead of a solid waste, is produced from the SO_2. The sorbent is regenerated using natural gas as the reducing agent. The capacity of the LEBS plant is 404 MW, with a coal requirement of 2,729 Mg/day (bone dry basis).

Coal Mining

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 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 were not found to be 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. Another important difference between the two mining techniques is that underground mining requires limestone which emits a large amount of particulates during its production. Therefore the particulate emissions in systems using this mining method will be higher. For example, the average yearly particulate emissions for the average system are 0.0092 g/kWh of net electricity produced for the surface mining case versus 0.93 g/kWh of net electricity produced for underground mining.

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. 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).

Biomass Power Production

The system studied is built around the concept of power generation in a biomass integrated gasification combined cycle (IGCC) plant. This technology improves the efficiency of the conventional steam cycle by adding a gas turbine, which generates electricity from the combustion of the gasifier fuel gas. Steam is raised in a heat recovery steam generator and passed through a standard steam turbine. Although the capital cost of this system is higher than that of the conventional steam boiler/steam turbine, the higher efficiency results in a lower cost of electricity.

The gasifier examined is low pressure and indirectly heated, like that developed at Battelle Columbus Laboratories specifically for biomass gasification. Future Energy Resources Corporation now owns the rights to this technology and is participating in its demonstration at the existing McNeil power plant in Burlington, Vermont. This system is called indirectly heated because the heat necessary for the endothermic gasification reactions is supplied by sand circulating between the char combustor and the gasification vessel. The IGCC plant studied was sized at 113 MW, and requires 1,334 bone dry Mg/day at 100% capacity.

Feedstock Production

The biomass used in the IGCC plant was assumed to be supplied from an energy plantation as hybrid poplar wood chips grown on seven-year rotations at a rate of 13.4 dry Mg/ha/year (6 dry t/acre/year). Hybrid poplar requires less fertilization than most traditional row crops such as corn, but field trials indicate that nitrogen, phosphorus, and potassium fertilizers will be necessary. In the base case, nitrogen fertilizer, as a 50/50 mixture of urea and ammonium nitrate, was assumed to be applied at a rate of 100 kg/ha nitrate in year four of the seven year rotation. Phosphorus was assumed to be applied as triple superphosphate, at a rate of 22.4 kg/ha as P in year one of the seven year rotation. Also in the first year, potassium, or potash fertilizer, was applied as K_2O at a rate of 39.2 kg/ha as K. Potassium and potash fertilizers were not required in subsequent years.

From experience gained in hybrid poplar field trials, herbicide application has been found to be necessary for the proper growth and survival of young trees. For the LCA, both a pre-emergent herbicide (Oust™ by DuPont) and a post-emergent herbicide (Roundup™ by Monsanto), were assumed to be used. The application rate of each is 36.5 cm^3 of active ingredient per hectare in the first and second years of each crop rotation. These herbicides will be applied before planting and during crop establishment; no herbicide applications are expected to be required once canopy closure occurs. The use of pesticides to control insects and small mammals on hybrid poplar plantations is expected to be unpredictable and sporadic, if at all. For the study conducted, use of pesticides was assumed to be zero. Transportation of farm chemicals was assumed to be 60% by rail and 40% by truck over a distance of 640 km.

All water required by the biomass as it grows was assumed to be supplied by rainfall. Therefore, the resources consumed do not include water use at the plantation. Also, emissions and energy use do not reflect any irrigation practices should they be used. However, the emissions and energy use for each operation required to plant, grow, and harvest biomass were included in the LCA.

The soil on which hybrid poplar is grown has the potential to sequester carbon such that the total amount of atmospheric carbon that is absorbed by the biomass is more than that contained in the biomass to the power plant. Because the actual amount sequestered will be highly site specific, and given that the values in the literature vary so widely and are based on a small number of field trials, it is impossible to say what constitutes a representative value. Therefore, a range of values was incorporated into the sensitivity analysis, with the base case assumption that there will be no net soil carbon gain or loss.

Major Results

Although each LCA examined many different air, water, and solid waste emissions, plus numerous natural resources, only major results will be presented here. Except for the discussion of total system energy balance, results are given per kWh of net electricity production.

Air Emissions

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.

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.

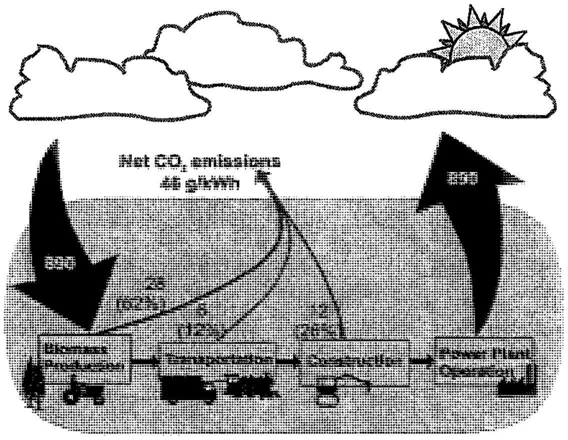


Figure 1: Biomass Power System
95% carbon closure

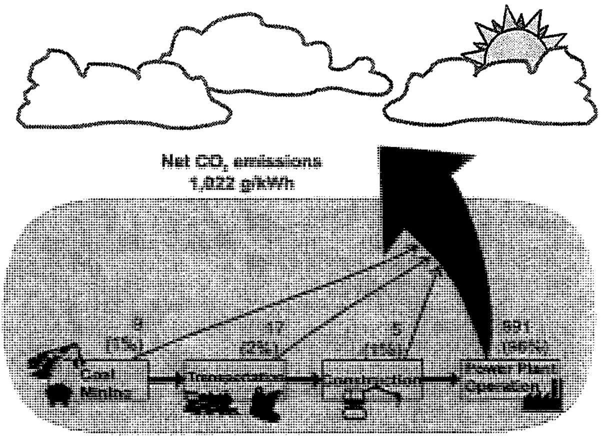


Figure 2: Average Coal Power System
0% carbon closure

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 closure of the biomass IGCC system is:

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

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.

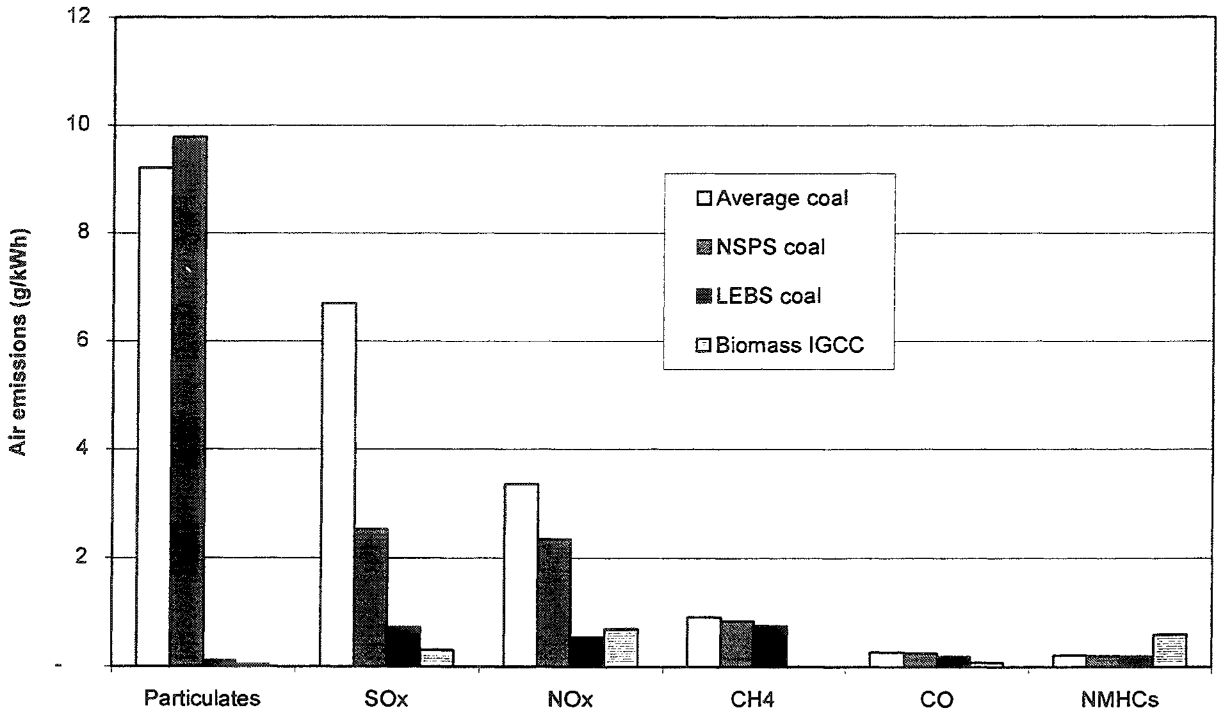
In addition to CO_2, two other greenhouse gases, methane and N_2O, are produced by these systems. The capacity of methane and N_2O to contribute to the warming of the atmosphere, a measure known as the global warming potential (GWP) of a gas, is 21 and 310 times higher than CO_2 (Houghton, *et al*, 1995). Thus, the GWP of a system can be normalized to CO_2-equivalence to basis, and net CO_2 emissions, for each of the systems studied. Because the majority of the air emissions are CO_2, the methane and N_2O do not significantly add to the global warming potential of the system.

Table 2: Global Warming Potential, and Net CO_2 Emissions

	Biomass IGCC	Average coal	NSPS coal	LEBS coal
Net CO_2 (g/kWh)	46	1,022	941	741
Net GWP (g CO_2 equivalent /kWh)	49	1,042	960	757

Figure 3 shows the major air emissions from these systems, excluding CO_2. Isoprene, the compound used to model biogenic emissions from the biomass as it grows, is also emitted at a rate of 21 g/kWh from the biomass IGCC system. It's extremely important to remember when studying these results, that the magnitude of different emissions cannot be compared to infer an environmental impact.

Figure 3: Air Emissions Excluding CO2



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 cases, the majority of the particulates come from the production of limestone (89% of the total particulate emissions for both cases). Although the overall amount of particulates are considerably less for the LEBS system, the bulk of the particulates are emitted by the power plant during normal operation (47% of the total particulate emissions); the second predominant source of particulates is copper oxide production (22% of the total particulate emissions). For all three coal cases, the NMHC emissions are evenly distributed among the mining, transportation, and power plant subsystems. However, for the LEBS system it should be noted that 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 when examining the emissions on a yearly basis. 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.

Energy

The energy use within each system was tracked so that the net energy production could be assessed. Upstream processes such as feedstock production, transportation, and chemical manufacture consume significant quantities of primary energy, resulting in less net energy produced by the system overall. 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 shown in Table 3. Energy results are shown in Table 4.

Table 3: Energy Efficiency Definitions

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

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.

The net energy ratio is a more accurate and rigorous measure of the net energy yield from the system than the external energy ratio because it accounts for all of the fossil energy inputs. However, the external measures are useful because they indicate the amount of energy consumption by upstream operations.

Table 4: Efficiencies and Energy Ratio Results

Case	Power plant efficiency (%)	Life cycle efficiency (%) (b)	External energy efficiency (%) (b)	Net energy ratio (b)	External energy ratio (b)
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.

Regarding the coal LCA energy results, the large difference between the life cycle efficiency and the external energy efficiency is due solely to the energy contained in the coal used at the power plants. Additionally, the external energy efficiency and external energy ratio indicate that upstream processes are large consumers of energy. In fact, operations related to flue gas clean-up and 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. 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 5 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 5: 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.

Sensitivity Analysis

A sensitivity analysis was used to identify those parameters that most influence the major results of the study. For the coal cases, finding ways to reduce the amount of coal being consumed, by increasing the power plant efficiency, for example, most greatly reduces emissions, resource consumption, and energy use. Changing the coal transportation distance had the second largest effect on the 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 were 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 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. Biomass IGCC systems 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. The net energy balance of the biomass IGCC system shows that 16 units of energy are produced for every unit of fossil energy consumed. Because of the use of a non-renewable resource, the coal systems consume more energy than they produce. The biomass system generally emits fewer air emissions and consumes far fewer resources than the coal systems.

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