Greenhouse Gas Emission Impacts of Substituting Switchgrass for Coal in Electric Generation:

The Chariton Valley Biomass Project

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EXECUTIVE SUMMARY

The Chariton Valley Biomass Project has been initiated to develop the infrastructure necessary to create a market for switchgrass-fired electric generation in south central Iowa. The Center for Global and Regional Environmental Research has completed a study of the greenhouse gas emission impacts of switchgrass production and combustion as a substitute for coal as electric generation fuel. The proposed displacement of up to five percent of the coal-fired generation at the Ottumwa Generating station appears to provide a positive impact on greenhouse gas emissions. The current analysis indicates that co-firing five percent switchgrass with coal may reduce emissions of greenhouse gases (carbon dioxide equivalent emissions (CO_2-eq)) by as much as 509,000 tons per year. This reduction in emissions could lead to annual income for the project of over $2.5 million if a modest credit price of $4.96 per ton CO_2-eq is achieved. Success of the project could lead to the use of 200,000 tons of switchgrass planted over 50,000 acres. Stack testing conducted at the facility during a test-burn in late 2000 (at 2.5 percent co-fire rate) appeared to confirm decreases in carbon dioxide (CO_2), sulfur dioxide (SO_2) and particulate emissions at the power plant. It is hoped that this result can be improved during future testing programs as the facility approaches the full five percent co-fire rate and optimizes its co-firing operation.

The cultivation of perennial grassy crops such as switchgrass can provide many additional environmental benefits in the highly erodible soils of south central Iowa. Among the benefits are reductions in soil erosion and water contamination with sediment and agro-chemicals, and improvements in wildlife habitat. The value of these environmental benefits can be difficult to quantify in terms that financial markets can incorporate into pricing structures. The creation of emission trading programs for greenhouse gases and SO_2 offer an important step in the direction of providing direct financial reward to environmentally-beneficial operations such as the Chariton Valley Biomass Project.

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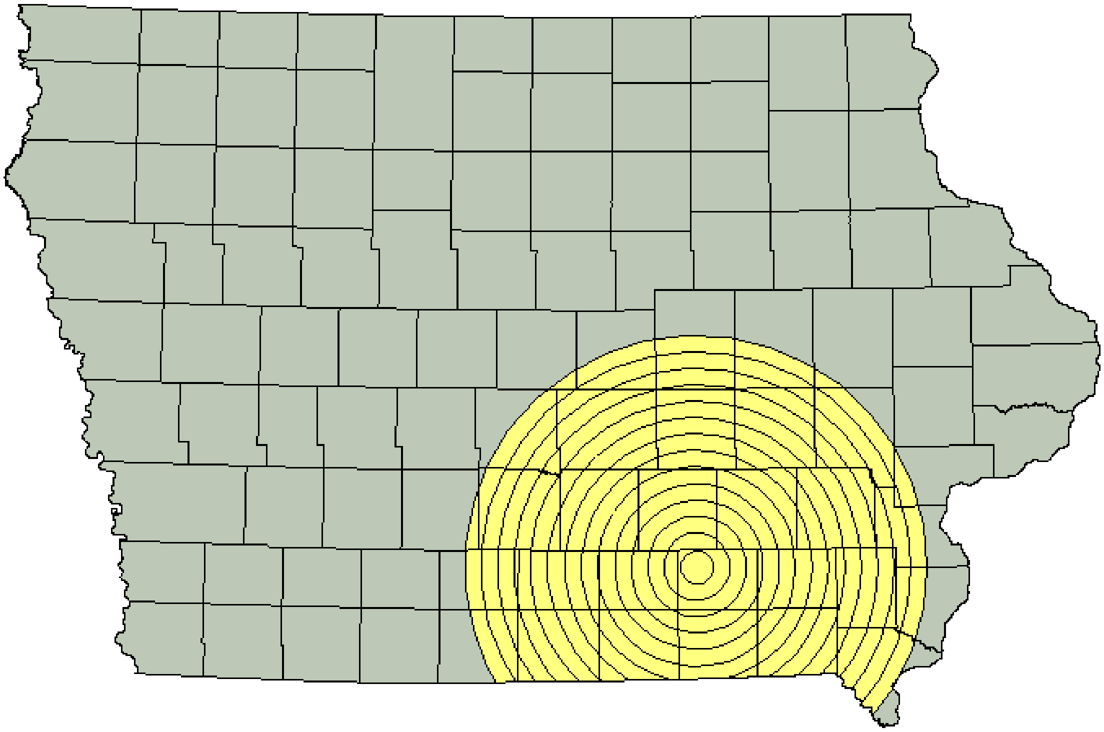
INTRODUCTION

In the Chariton Valley Biomass Project significant amounts of southern Iowa farmland and Conservation Reserve Program (CRP) set-aside have been replanted, or are planned for replanting to switchgrass, which will be harvested and burned as a solid fuel in the Ottumwa Generating Station (OGS) operated by Alliant Energy. At maximum capacity of a 5 percent co-fire, nearly 50,000 acres of switchgrass will be required from southern Iowa (Figure 1). The switchgrass will be grown and harvested, transported to OGS and chopped into approximately inch-long segments for injection into the boiler. On-site modifications to accommodate the switchgrass operation include construction of new buildings to store switchgrass and house bulk material shredders and conveyors. The burners have been retrofit to allow switchgrass combustion.

Figure 1. 70-Mile Radius of Anticipated Switchgrass Production (5-mile increments)



The Center for Global and Regional Environmental Research (CGRER) has calculated potential reductions in greenhouse gas emissions by switching from 100 percent coal-fired generation to a mix of five percent switchgrass and 95 percent coal. The analysis quantifies emissions of the three primary greenhouse gases, carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). The net balances of emissions of these gases are quantified over an annual cycle of fuel production and consumption, and related to CO_2-equivalent (CO_2-eq) emissions by use of Intergovernmental Panel on Climate Change (IPCC) 100-year Global Warming Potentials (Table 1). In addition to the greenhouse gases, emissions of sulfur dioxide (SO_2) and nitrogen oxides (NO_x) are estimated at the point of combustion within the OGS facility in order to estimate potential compliance costs or benefits of switchgrass-fired generation with Acid Rain Program requirements under Title IV of the Clean Air Act.

Table 1. Global Warming Potentials (GWP) Relative to Carbon Dioxide

Greenhouse Gas	Symbol	GWP
Carbon Dioxide	CO_2	1
Methane	CH_4	23
Nitrous Oxide	N_2O	296

Source: IPCC, 2001

A Review of Potential Analysis Methodologies

A growing body of research related to bioenergy systems in indicative of the interest that greenhouse gas emission impacts, and greenhouse gas emissions accounting is receiving. The following critique of quantification techniques parallels an evolution of methods as traditional air quality compliance methods are adapted to meet the more complex accounting requirements of greenhouse gas emission balances. Advances in scientific knowledge regarding carbon cycling in the environment are also reflected. The analytical approaches range from the highly certain point-source measurement, to more uncertain, but infinitely more comprehensive life cycle approaches. In order to adapt to meet the needs of the emission trading community, an analysis technique must return emission estimates with reasonable certainty, reasonable breadth, and in a manner that can be reproduced in order to meet time and budget constraints that the emission trading business community will require.

Point-Source Approach

This most straightforward approach, characteristic of many command-and-control type regulatory programs, point-source measurement is employed widely by the U.S. Environmental Protection Agency (USEPA). In the point-source method the emissions from a single point (or few points) are directly measured on a continuous basis. Emissions from support activities outside of the major point of emission are ignored. The point-source approach has been adapted to monitor sulfur dioxide emissions for the Acid Rain emission trading program, where it relies upon direct physical measurement of point-source emissions, before and after a change, to determine reductions (USEPA, 2000). The method is valuable for its clear definition, accuracy, and ease of management, however it falls far short of accounting for the net balance of greenhouse gases from fossil fuel or bioenergy systems. This method is utilized for analysis of the acid rain-causing pollutants SO_2 and NO_x emissions from the Chariton Valley Biomass Project.

The Zero-Net Approach

Given the nature of carbon cycling within a bioenergy system, the point-source strategy is clearly insufficient for capturing the full greenhouse gas benefits of such an application. Recognizing this insufficiency, the Intergovernmental Panel on Climate Change (IPCC) presented guidance for bioenergy system benefit accounting that allows crediting for carbon uptake during the growing season (IPCC, 1995). This method offsets the carbon dioxide emissions from the bioenergy fuel by crediting the carbon cycle for plant material that is combusted, resulting in a net-zero emission of carbon. While valid, the zero-net method still neglects the carbon storage benefits of field residue, root systems and soil, which therefore results in under-crediting the benefits of the bioenergy crop. The zero-net method also introduces apparent error in its assumption that all carbon in the plant material is released as CO_2 during combustion. IPCC guidance on combustion of solid fuels indicates that as much as 5 percent of the fuel carbon is emitted as carbon monoxide or remains fixed in solid wastes from the operation. Additionally, the contributions of other greenhouse gas emissions (CH_4 and N_2O), though relatively small, are missed completely.

Life Cycle Analyses

Numerous researchers have focused upon the life cycle implications for greenhouse gas emissions from bioenergy systems. Turhollow and Perlack, in 1991, performed a limited life cycle analysis of three potential energy crops; hybrid poplar, sorghum, and switchgrass. Their analysis estimated energy consumption for plowing, planting, harvesting and hauling the crop, and energy consumed during the production of fertilizers and herbicides. It was estimated that hybrid poplar cultivation for bioenergy purposes caused net emission of 1.30 kilograms of carbon per gigajoule (kg C/GJ). Sorghum production led to emission of 1.84 kg C/GJ, and switchgrass production led to emission of 1.93 kg C/GJ. The authors ignored the carbon released from combustion of the energy crop, relying upon the closed-loop biomass (zero-net) assumption for carbon recycling. Importantly, the authors also ignored direct greenhouse gas emissions due to cultivation of the soil (CO_2), application of nitrogen fertilizer (N_2O), and the benefits of carbon sequestered into the soil, and did not provide credit for offsetting emissions from fossil fuel consumption that would otherwise occur.

Ellington, Mbo and El-Sayad (1993), published a description of the life cycle greenhouse gas implications of biomass-derived methanol for vehicle consumption. The authors sought to describe the renewable methanol fuel cycle by applying the following program:

"(1) Define the complete system and identify and quantify all sources of GHG emissions, including mobile and stationary sources.

(2) Define the discrete periods of the system's entire life cycle.

(3) Execute material and energy balances to quantify all operating GHG emissions for each period and for each "invested" quantity."

Here the invested quantity is the amount of energy that went into producing subcomponents of equipment, i.e. the energy in steel production for the steel contained in the tractors or other equipment used to process the methanol. The contribution to overall energy balances of the invested quantity was found to be insignificant when compared to total energy consumption within the system. Importantly, the figures for invested energy were developed by using high degrees of averaging and parameterization from national statistics, thus leading to high uncertainty in the resulting estimates. As in the study by Turhollow and Perlack, the authors established estimated fuel consumption for vehicles and equipment needed to plant, harvest, haul, convert, and consume the bioenergy product. The study found that for every 1 unit energy of methanol produced, 2.4 units of energy input are required. The study also continued to ignore the impact of soil carbon sequestration upon greenhouse gas balances, and did not attempt to quantify the greenhouse gas emission benefit of replacing existing fossil fuel consumption.

In 1996, Schlamadinger and Marland published a study of full fuel cycle carbon balances for bioenergy crops, with forestry a particular focus. While called a 'full fuel cycle' the focus of this research was primarily upon the final disposition of forest products into either short-term or long-term uses. Short-term uses, such as in the pulp and paper industry lead to rapid turnover of much of the carbon stock as the product is quickly used, discarded, and decays, returning CO_2 to the atmosphere. The study does however add the important factor of soil carbon sequestration, estimated at 18 metric tons C per hectare, and accounts for the benefit derived from offsetting fossil fuel combustion. The study does not account for emissions that occur from energy consumption during the planting, management, harvest and transport of the bioenergy crop, nor does it attempt to include additional greenhouse gases such as methane and nitrous oxide.

Mann and Spath of the National Renewable Energy Laboratory, completed a 1997 life cycle analysis of a wood gasification system for electricity production. The analysis was developed for a hypothetical biomass-fired power plant to be constructed in the Midwestern United States. Like Ellington, et al, the researchers employed estimates of internalized energy consumption embodied within such items as steel, cement, aluminum, and rubber. Energy consumption, type of energy consumed (liquid, gas, solid) and resulting emissions were obtained using an extensive life cycle database system called, Data for Environmental Analysis and Management (DEAM). While providing valuable insight, the nature of the immense data summaries would indicate that uncertainty increases as reliance upon such data increases. For example, energy and related emissions for cast aluminum parts rely upon data from a single casting facility (Mann and Spath, Appendix B, 1997) that may or may not have contributed aluminum to the project, but is used to develop emission estimates for all aluminum used by the project. Energy and emissions from production of steel, whether virgin or recycled, whether galvanized or stainless, are all derived from the same data source, which is representative of the 1975-1980 period. Thus an apparent high degree of averaging and parameterization within the data underlying the life cycle model may lead to significant uncertainties surrounding the net benefit estimate when these outer layers of the life cycle are included in the total analysis.

Analysis of the Chariton Valley Biomass Project

This report utilizes the Incremental Life Cycle Analysis (ILCA), a greenhouse gas emission accounting approach that is specifically tailored to support trading of emission reduction credits (Ney, 2001). A narrowly focused approach such as the point-source approach, provides the simplest means to estimate emission reductions and to measure end results. However, given the ubiquitous nature of greenhouse gases throughout the environment and in human systems, particularly CO_2, such a narrow approach fails the critical test of accounting for the full scope of emission and emission reductions impacts upon the environment. Similarly, the zero-net approach is a useful tool for general planning activities, but it fails to capture the significant contributions of soil carbon sequestration, and over-estimates biomass-generated CO_2 emissions by as much as five percent by assuming that all biomass carbon is released as CO_2. The zero-net approach also fails to capture the potentially significant emissions from farming operations and does not allow for a multi-gas analysis. On the other end of the scale, full-scope life cycle analyses offer comprehensive accounting of emissions and emission reductions, but the lack of certainty in estimates and lack of measurability of end results, as well as time and expense considerations, render this approach inadequate for supporting emission trading activities. The ILCA methodology employed for the Chariton Valley Biomass Project utilizes a life cycle framework, but limits the scope of the analysis to focus on those aspects of the life cycle that most directly affect the balance of emissions and reductions, and are reasonably measurable.

Defining the Life Cycles

The first step in the process of quantifying net greenhouse gas emissions from each fuel is to describe the full fuel cycles. Figure 2 presents a schematic of the coal production and utilization cycle. The figure demonstrates the complexity inherent in analyzing fuel life cycles. In the central diagonal, from upper left to lower right, are the primary activities of the coal life cycle. Many of these activities release emissions of greenhouse gases directly, with indirect emissions arising from the energy consumed in performing the task (Table 2). The shaded elements above and below the central activities are largely exterior to the coal life cycle itself, forming a significant chain of activity that extends throughout the world economy.

The coal combusted at OGS must be mined, cleaned and refined, then transported to rail loading points. The coal is then transported via rail from the Utah-Wyoming area to the south-central Iowa power plant. Once at the plant, the coal is further prepared for combustion in the power plant boilers. Finally, after combustion, the waste ash is removed from the boiler or fly ash collection devices, and shipped to a landfill or for incorporation into cement products. Table 2 provides a summary of the primary direct and indirect emission sources, and the greenhouse gases emitted by each activity.

Figure 2. Elements of the Coal Production and Utilization Cycle Considered in the Analysis of Greenhouse Gas Emissions

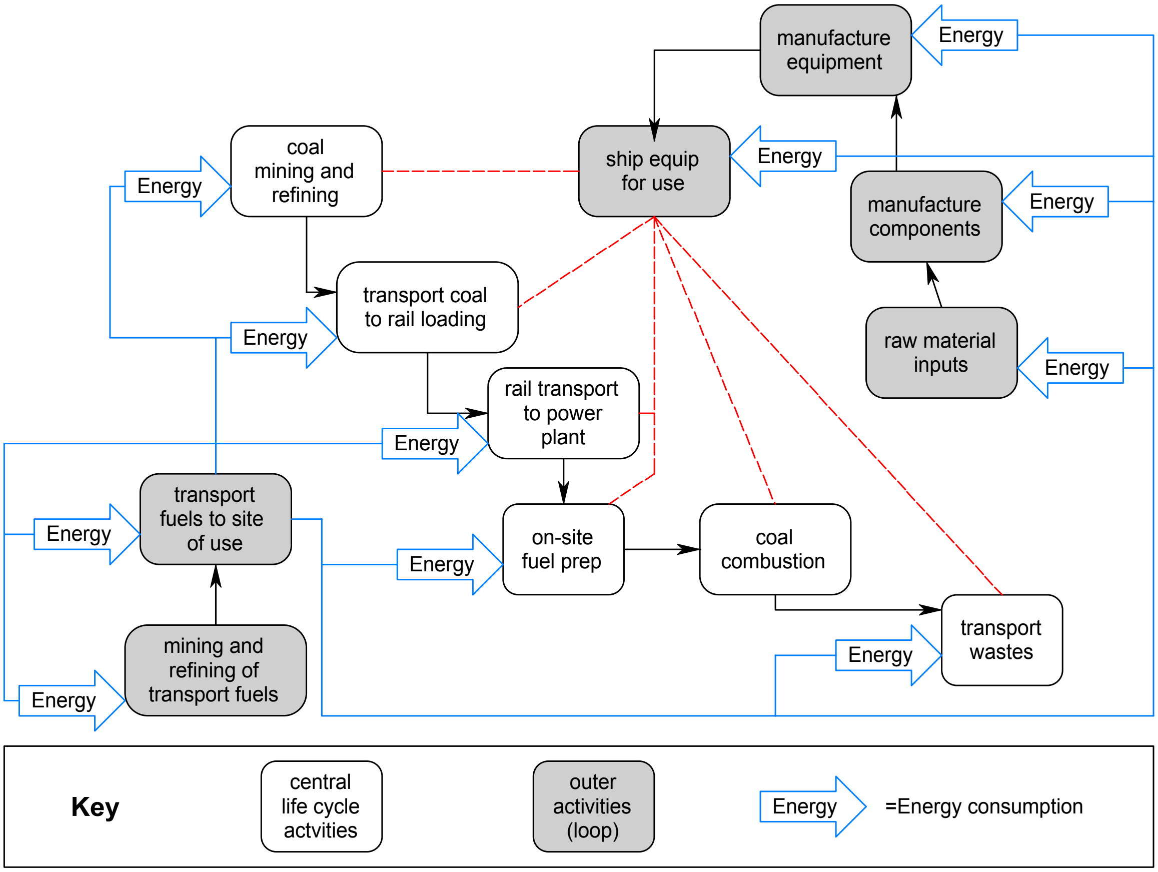


Table 2. Greenhouse Gas-Emitting Stages of Coal Consumption

Process	Aspect Creating Emission	Greenhouse Gas
<u>Primary Direct Emissions</u>		
Coal mining and transport	Methane-exposed coal	CH_4
Transport mine to rail loading	Methane-exposed coal	CH_4
Combustion	Fuel combustion	CO_2,CH_4,N_2O
<u>Primary Indirect Emissions</u>		
Coal mining and refining	Energy used	CO_2,CH_4,N_2O
Fuel preparation	Energy used	CO_2,CH_4,N_2O
Transport mine to rail loading	Energy used	CO_2,CH_4,N_2O
Rail transport to power plant	Energy used	CO_2,CH_4,N_2O
<u>Secondary Direct Emissions</u>		
Transport of combustion waste	Energy used	CO_2,CH_4,N_2O

Within the outer loops are activities that support the primary activities of the coal life cycle. These outer loop activities include secondary emission-generating activities, such as the manufacture of mining equipment, locomotives, and rail cars, or the processing of petroleum into fuel products for use by this equipment. While these activities cause significant emissions on a national scale, their contribution is thought to be small in comparison to the contribution of the primary direct and indirect emissions of the life cycles of switchgrass and coal. This is particularly true since the temporal scale of this analysis would include only a fraction of the life cycles of these products. For example, a farm tractor could be used for decades. Emissions arising from production of that tractor would be factored over each year of use. The picture is further clouded by the difficulty associated with quantifying the emissions from these more distant processes, as was discussed in the literature. A decision on inclusion of secondary activities is be reached later.

The switchgrass life cycle is presented in figure 3, with key steps and the greenhouse gases emitted, listed in table 3. Similar structure is utilized within the graphic, with primary activities located on the diagonal from upper left to lower right.

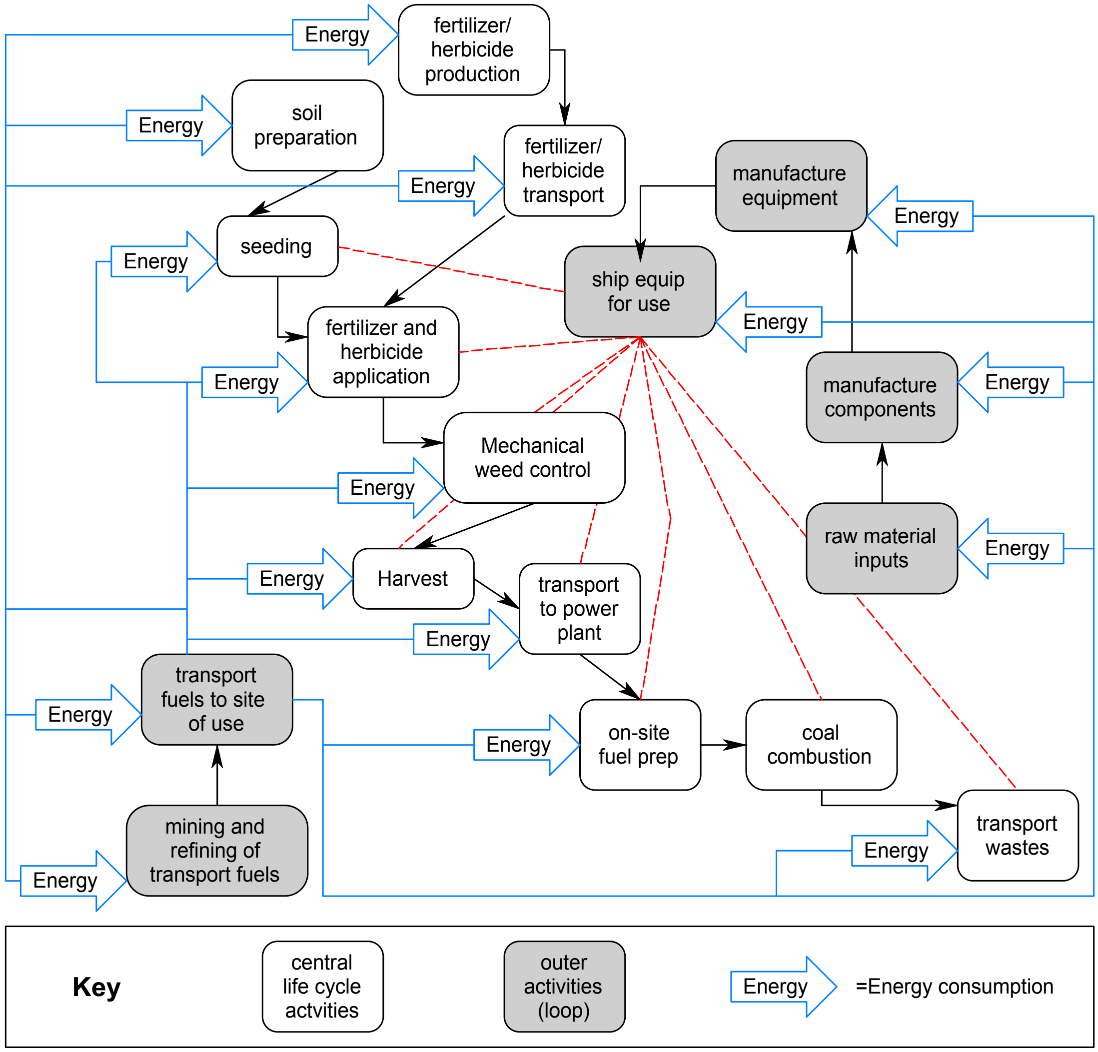
Important steps in the switchgrass life cycle include soil preparation activities, seeding, fertilization and weed control, through harvest, transport to the power plant, preparation of the fuel for combustion in the power plant boilers, and transport of ash waste streams. As in the coal life cycle analysis, the emissions from fuel consumed in performing these primary activities are considered an indirect emission from the primary activity. Manufacture of agricultural implements, and processing of petroleum products upstream of the final consumption are denoted as secondary activities.

Table 3. Greenhouse Gas-Emitting Stages of Switchgrass Consumption

Process	Aspect Creating Emission	Greenhouse Gas
<u>Primary Direct Emissions</u>		
Plant growth	Carbon uptake	CO_2
Fertilizer application	N volatilization	N_2O
Soil Carbon Sequestration	Carbon uptake	CO_2
Lime application	Direct emission	CO_2
Alternative land use	Alternative land use	CO_2
<u>Primary Indirect Emissions</u>		
Soil preparation	Energy used	CO_2,CH_4,N_2O
Seeding	Energy used	CO_2,CH_4,N_2O
Chemical application	Energy used	CO_2,CH_4,N_2O
Fertilizer application	Energy used	CO_2,CH_4,N_2O
Mechanical weed control	Energy used	CO_2,CH_4,N_2O
Harvest	Energy used	CO_2,CH_4,N_2O
Transport to OGS	Energy used	CO_2,CH_4,N_2O
Fuel preparation	Energy used	CO_2,CH_4,N_2O
Combustion	Fuel combustion	CO_2,CH_4,N_2O
<u>Secondary Direct Emissions</u>		
Transport of chemicals to field	Energy used	CO_2,CH_4,N_2O
Transport waste to landfill	Energy used	CO_2,CH_4,N_2O
<u>Secondary Indirect Emissions</u>		

Fertilizer production	Energy used	CO_2,CH_4,N_2O
Herbicide production	Energy used	CO_2,CH_4,N_2O

Figure 3. Elements of The Switchgrass Production and Utilization Cycle Considered in the Analysis of Greenhouse Gas Emissions



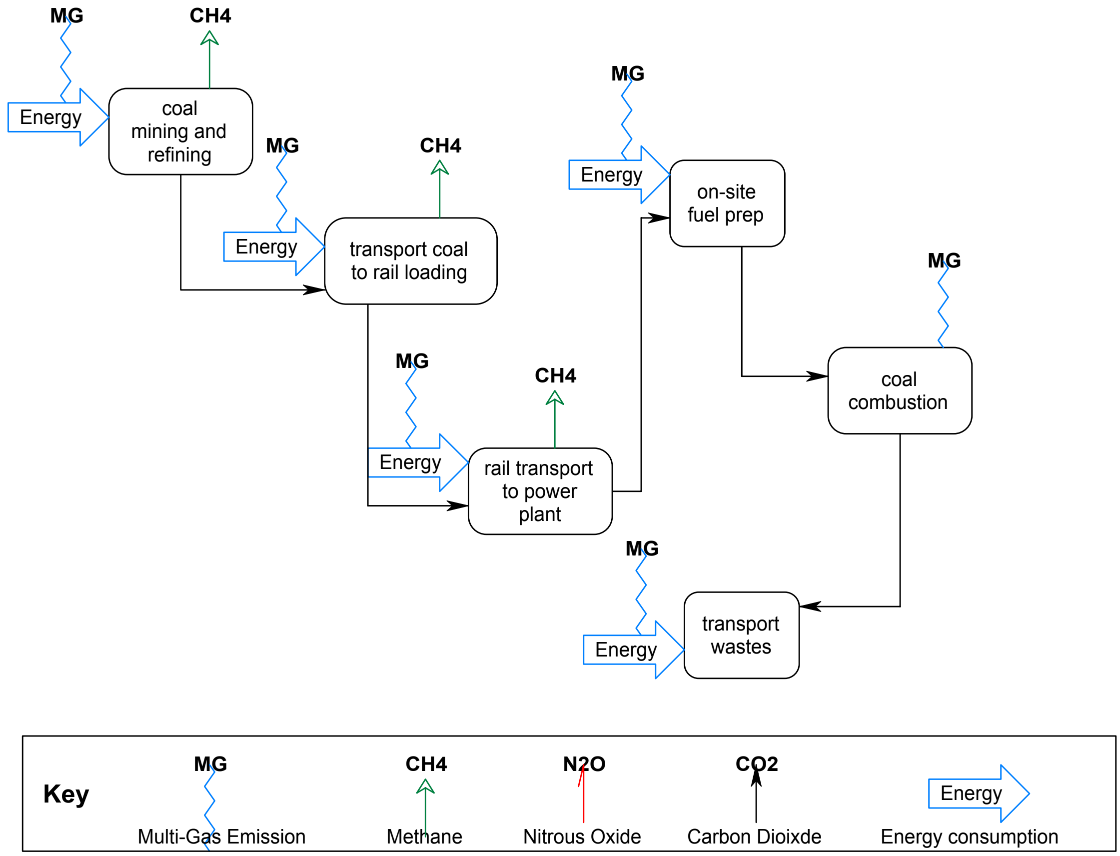
Determining Greenhouse Gas Emissions from Life Cycle Activities

The second step of the process is to determine the gross emissions from each major component of the fuel life cycle. The terminology selected for the analysis is intended to provide an indication of the importance of the activity within the life cycle, as well as an indication of the spatial and temporal boundaries that will come into play. Figures 4 and 5 illustrate the greenhouse gas-emitting events that take place in the fuel life cycles. For purposes of providing an incremental analysis, the emitting processes are categorized into levels within the fuel life cycle. The analysis is centered upon the major activity of fuel combustion, and the analysis is then expanded radially from that point. Processes that are most closely linked to preparing the fuel for combustion form the primary level of analysis. The levels defined:

- Primary, direct emissions are those that occur from the activities central to the coal or switchgrass life cycles. For switchgrass, this level includes emissions from the farming activities needed to produce the crop such as plowing of the soil or nitrous oxide emission from fertilizer application, or the energy expended during power plant on-site fuel preparation and combustion.

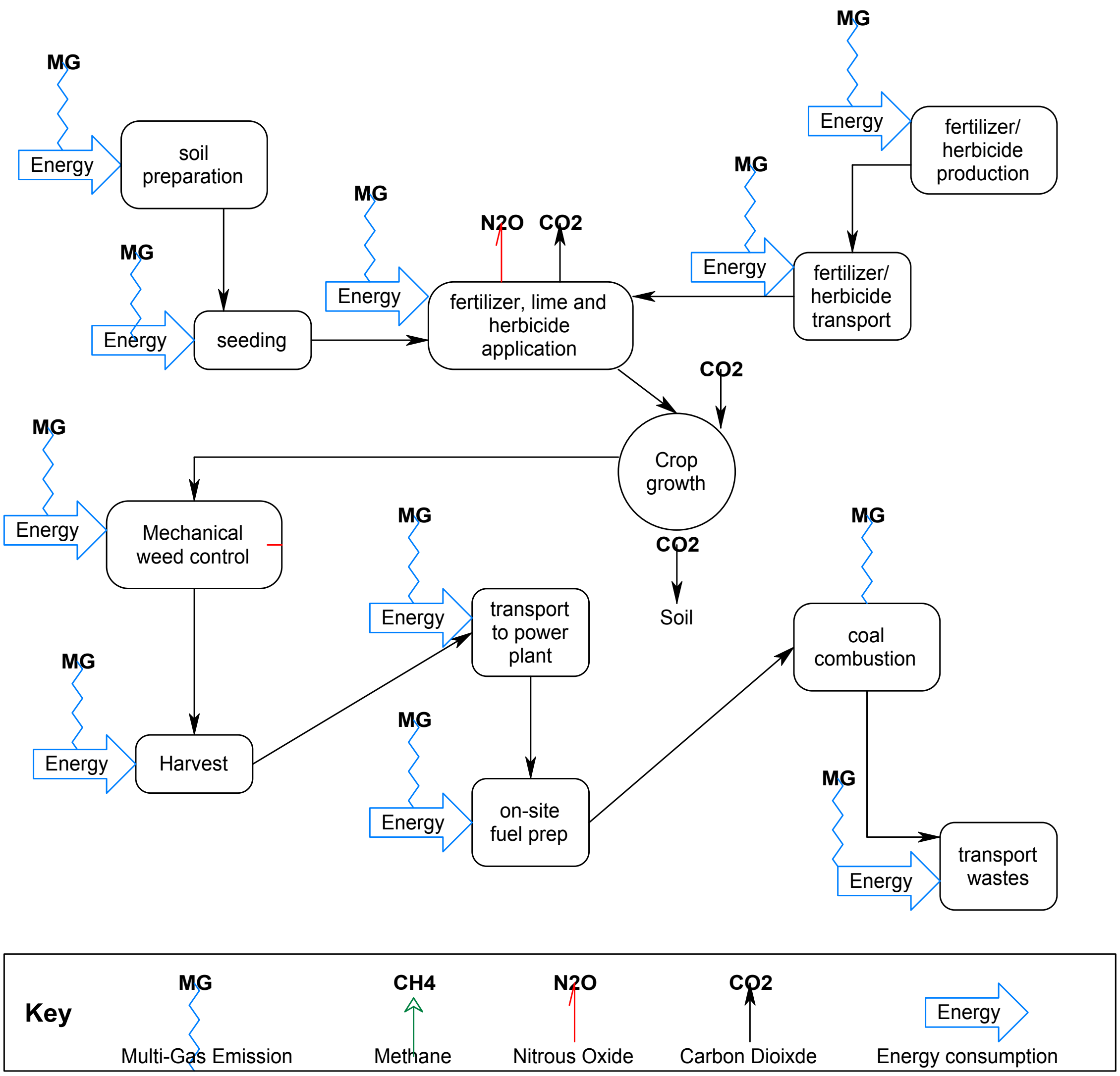
- Primary, indirect emissions are defined as those generated in support of primary direct activities. These primary indirect sources of emissions include the fuels combusted during performance of the primary activity. Thus emissions from fuels combusted in the agricultural machinery, or in transporting the fuels are classifies as primary but indirect sources.

Figure 4. The Coal Life Cycle Emission Pathways



- Secondary emissions are defined as those occurring from processes that create a product for use within the primary level. The greenhouse gas emissions that arise from the production of a product, such as fertilizer or herbicide are considered secondary emissions. Emission of nitrous oxide from fertilizer production is considered a secondary direct emission. Emissions from the combustion of fuel sources to create the secondary product are secondary, indirect emissions.

Figure 5. Switchgrass Life Cycle Emission Pathways



QUANTIFYING GREENHOUSE GAS EMISSIONS

Coal Primary Direct Emissions

Greenhouse gas emissions from key activities are estimated using the most current guidance from USEPA (EIIP, 1999), beginning with emissions occurring directly from primary life cycle activities.

Coal Mining (Methane Losses)

Exposure of a coal seam to the atmosphere allows the escape of methane gas trapped within the porous structure of the coal. The emission of this potent greenhouse gas can become significant. In the Emission Inventory Improvement Program document, "Introduction to Estimating Greenhouse Gas Emissions," emission factors are provided to estimate the amount of methane lost from opening the coal seam to the atmosphere (EIIP, 1999). The emission factors are specific to location of the coal mine, and the mining method. Coal burned at OGS is a western sub-bituminous coal that is surface-mined. Emission of methane is estimated to occur at the rate of 30.6 cubic feet per ton of coal mined (EIIP, 1999).

Coal Transportation (Methane Losses)

Methane is also lost from the coal as it is transported across the country. During transport, the coal is estimated to emit 5.0 cubic feet per ton of coal, which is the equivalent of 4.44 pounds of CO_2-eq emission per ton of coal transported (EIIP, 1999).

Coal Combustion

The combustion of coal, as with any fuel, releases several pollutants to the atmosphere. Of principal concern for this modeling effort are the greenhouse gases, CO_2, CH_4 and N_2O. USEPA, the Energy Information Administration (EIA), and IPCC provide emission factors for these pollutants (Table 4). The use of stack effluent test data will be utilized where possible, to further reduce uncertainties about the estimated emission rates.

Table 4. Summary of Theoretical GHG Emission Rates From OGS Coal Combustion

Greenhouse Gas	Emission Rate (lbs/MMBtu)	Source
Carbon Dioxide	212.7000	EIA, 1999
Methane	0.0023	EIIP, 1999
Nitrous Oxide	0.0037	EIIP, 1999

Coal Primary Indirect Emissions

Coal Mining and Refining (Energy Use)

It takes energy to mine and prepare coal for use as a combustion feedstock. Coal is mined from the earth, washed, crushed, screened and sorted prior to loading into transportation equipment. For a first approximation of the magnitude of these emissions, the GREET Fuel Cycle Model is employed (Wang, 2000). Created by Michael Wang of Argonne National Laboratory, the GREET model provides estimates of emissions of greenhouse gases related to the production and consumption of fuels, fertilizers and herbicides used in ethanol production.

Fuel preparation (Energy Use)

Coal must be handled and prepared at the facility for combustion in the boiler. Typical operations include crushing, conveying and screening. The coal is conveyed to large storage bins for later conveyance into the boiler. Alliant Energy has computed the energy consumed in this process as 2.2 hp/ton. The electricity consumption, which is drawn internally from OGS production, is related to greenhouse gas emissions by the fuel combusted in the generation process, and by inefficiencies in the process. As a conventional steam turbine generation facility, conversion efficiencies from input energy to output energy are 33 percent. For baseline purposes the input fuel is 100 percent coal.

Coal Secondary Direct Emissions

Coal Transportation (Energy Consumption)

The transportation of coal from mine mouth to power plant involves several steps, including transport from the mine to the rail loading point, rail transport to the power plant, (or in some cases rail transport to coal piles outside of the plant boundary), and truck transportation of coal within the facility (or from a remote storage area to the facility). The GREET model (Wang, 2000) is utilized to estimate energy consumption and resulting emissions from the transportation activities.

Transport of Coal Combustion Residue to Landfill (Energy Use)

Unburned materials are collected and must be transported to off-site storage facilities. For coal combustion, the waste stream is composed primarily of bottom-ash and captured fly ash. For our computation of ash generation rates, it has been assumed that all of the ash identified in the ultimate analyses (Black & Veatch, 1995) will be captured and removed as waste. The movement of this material results in the expenditure of energy in the form of fuel oil for the truck hauling the waste. Transportation fuel consumption data are presented from the GREET model (Wang, 2000) and are coupled with fuel oil carbon dioxide emission values from USEPA (EIIP, 1999).

Switchgrass Primary Direct Emission Mechanisms

Establishment Considerations

Experience in the Chariton Valley Biomass Project has shown that establishment of the switchgrass crop generally requires a two-year period. For fields that are successfully established, first year harvest reaches about 2 tons per acre, with second year harvest at near full production of 4 tons dry matter per acre. For the 25 percent of fields that are not successfully established during the first year, no production is taken from the land, re-seeding follows with no harvest during the second year. In the third year for these lands, production reaches the full 4 tons dry matter per acre. In keeping with the framework proposed for this analysis, the time period reviewed is selected to represent a six-year emission trading contract period. Final greenhouse gas emission reduction calculations therefore account for a 2-year establishment period, followed by full-scale production in the remaining years.

Switchgrass Combustion

Greenhouse gas emissions from switchgrass combustion are not as well documented as emissions from coal combustion. An ultimate analysis of the switchgrass is utilized to estimate emissions of carbon dioxide, sulfur dioxide and nitrogen oxides from combustion. The ultimate analyses show an average carbon content of 44 percent by weight, with nitrogen content (dry basis) averaging about 0.6 percent by weight. Carbon dioxide emissions are estimated by scaling the carbon content with that of coal, which has well-known emission factors.

The impact of N_2O emissions on the overall greenhouse gas balance between switchgrass and coal has not been calculated due to a lack of data. Analysis of the fuel nitrogen contents indicates that fuel nitrogen inputs are equivalent, with coal containing 0.93 lbs N per MMBtu and switchgrass containing 0.92 lbs N per MMBtu (Black and Veatch, 1995). Unfortunately, preliminary stack testing of emissions from OGS during a co-fire test in late 2000 did not measure N_2O emissions. The results of the tests are discussed in further detail later in this report.

Plant growth (Carbon in harvestable matter)

During the first two years of establishment, yields are highly variable. Crops that establish well can produce 2 tons dry matter per acre at the end of the first year, and full production of 4 tons dry matter per acre in the second year. Crops that establish poorly are not harvested during the first year, are replanted and again not harvested in the second year. Current yields on established grounds have been 3.5 to 4 tons of harvestable dry mass per acre (Braster, 2000). These fields have not yet received the level of management expected for production fields, for which expected yields would be 4 to possibly 5 tons harvestable dry matter per acre. Of the dry matter harvested, approximately 44 percent is carbon, per ultimate analysis (Black & Veatch, 1995).

Soil Carbon Accumulation

The emission of CO_2 from switchgrass combustion is offset by the annual uptake of carbon during plant growth. The conversion of annual row-crop agricultural land to perennial switchgrass production also has the potential to increase the amount of carbon retained in the soil storage reservoir. Soil carbon accumulation studies made by the Oak Ridge National Laboratory have been utilized to estimate sequestration rates. These studies indicate that perennial grasses add 1.1 Mg per hectare per year to the top 30 cm of Midwestern soils (McLaughlin, 1998). This value equates to 980 pounds of carbon per acre or 1.79 tons of carbon dioxide sequestered into the soil per acre. The studies indicate that perennial crops rapidly build carbon into the soil when introduced into carbon-depleted soils. A study of Chariton Valley switchgrass fields has revealed that fields with 3 - 14 year switchgrass stands add soil organic carbon (SOC) at a rate of 1.5 tons/acre/year. The study was unable to quantify SOC storage rates during the first three years of crop establishment, due to either detectability issues or baseline selection (Burras and McLaughlin, 2002). For this analysis, the value of 0.49 tons/acre/year (McLaughlin, 1998) will be used for the establishment case and 1.5 tons/acre/year (Burras and McLaughlin, 2002) will be employed for the mature crop scenario.

Fertilizer and Lime Application

Application of nitrogen fertilizer leads to the formation of nitrous oxide emissions form the soil. No nitrogen is applied during establishment year, however, during production years, 100 pounds of nitrogen are applied per acre (Braster, 2000). Greenhouse gas emissions from nitrogen fertilization come from two pathways. Nitrous oxide is emitted directly from soils through nitrification and denitrification processes as shown in equations 1 through 3. Nitrous oxide is also emitted indirectly from atmospheric deposition of volatilized nitrogen (NH_3 and NO_x) (equation 4) leading to subsequent emissions of N_2O from the soil (again through nitrification and denitrification). Lastly, fertilizer nitrogen leaching and runoff enters groundwater and surface water systems, a portion of which is emitted as N_2O (EIIP, 1999).

(1) denitrification $NO_3^- \rightarrow N_{2(g)}$
(2) partial denitrification $NO_3^- \rightarrow N_2O$
(3) nitrification $NH_4^+ + 2O_2 \rightarrow NO_3^+ + H_2O + 2H^+$
(4) ammonia volatilization $NH_4^+{}_{(aq)} \rightarrow NH_{3(g)} + H^+$

For commercial fertilizers, 10 percent of applied nitrogen is assumed to volatilize. One percent of these volatilized forms of nitrogen react to form nitrous oxide. Of the 90 percent of nitrogen that remains non-volatilized nitrification and denitrification processes release 0.0125 ton N_2O per ton nitrogen (EIIP, 1999). An estimated 30 percent of non-volatilized nitrogen is assumed to leach or runoff, forming 0.025 tons N_2O per ton N_2 in leachate or runoff (EIIP, 1999). The application of lime also results in a direct emission of CO_2 as the lime dissolves into the field (see Appendix for calculations).

Switchgrass Primary Indirect Emission Mechanisms

Soil preparation (Energy Use)

During initial soil preparation for the first year of planting, the soil is disturbed. For conversion of corn or soybean acreage to switchgrass production, tillage requirements indicate disking once or twice, harrow once, and culti-pack. Lime is also applied for control of pH. A firm seed bed is needed for successful switchgrass seeding. Each trip over the field utilizes an 80 to 120 horsepower tractor. Seeding can also be accomplished in existing pasture or through no-till operations with use of herbicides for control of existing vegetation. Soil preparation for re-seeding, which is required in up to 25 percent of fields does not involve reopening of the soil.

Table 5. Summary of Average GHG Emissions from Energy Used For Soil Preparation for Establishment of the Switchgrass Field

Activity	Passes per acre	Gallons per Pass/ac	CH_4 lb CO_2-eq/ac	N_2O lb CO_2-eq/ac	CO_2 lb CO_2-eq/ac	Total (lb CO_2-eq/ac)

Lime Application	1.00	0.75	61.7	144.4	16.8	222.9
Disking	1.00	0.75	61.7	144.4	16.8	222.9
Harrowing	1.00	0.55	45.3	105.9	12.3	163.5
Culti-Pack	1.00	0.44	36.2	84.7	9.8	130.8

Note: See Appendix for calculations.

In order to ensure that emissions from farming activities are not under-reported, in all cases where a range of engine sizes is given the higher rated engine is assumed. In addition, it has been assumed that the majority of switchgrass to be burned at OGS will be planted on lands requiring initial tilling for seeding (a conservative assumption to avoid over-prediction of greenhouse gas reductions).

Seeding (Energy Use)

Recommended seeding rates of 10 pounds of live seed per acre are applied mixed with fertilizer using a 60-foot boom truck with flotation tires, or using drill or brillion seeder pulled by a 80 to 120 horsepower tractor. Re-seeding is required in up to 25 percent of fields using the same methods as in the establishment year (see Appendix for calculations).

Chemical application (Energy Use)

During site preparation an initial application of atrazine is recommended at 2 pounds per acre. Application is accomplished using custom spray equipment “Row Gator” sprayer. During plant growth, an additional 2 pounds per acre of atrazine may be applied by Row Gator sprayer. For up to 25 percent of fields re-seeding is required with an additional 2 pounds of atrazine applied per acre (see Appendix for calculations).

Fertilizer application (Energy Use)

During the establishment year, no fertilizer is applied during seeding. In subsequent years, if reseeding is not required, fertilizer application is accomplished using a 60 foot boom truck on flotation tires (see Appendix for calculations).

Mechanical Weed Control (Energy Use)

A sickle or rotary mower bush hog pulled by a 50 to 100 horsepower tractor is utilized in the establishment year, and then again in subsequent years for weed control (Braster, 2000) see Appendix for calculations).

Harvest (Energy Use)

The crop is mowed and conditioned, raked, and baled, each trip pulled by a 80 to 120 horsepower tractor. The bales are then staged at the side of the field using a 100 horsepower tractor with front-end scoop or loader and stabber. Alternatively a tractor-pulled bale carrier wagon is employed for fields greater than 40 acres which would involve a ¼-mile haul to roadside. Finally, a 100-hp tractor with front-end scoop or loader is used to load the bales on a semi trailer for transport to OGS. Emissions are summarized in table 6.

Table 6. Summary of Greenhouse Gas Emissions from Harvest Activities-Mature Case

Activity	Passes per acre	Gallons per pass/ac	Energy (MJ/ac)	CH_4 lb CO_2-eq/ac	N_2O lb CO_2-eq/ac	CO_2 lb CO_2-eq/ac	Total (lb CO_2-eq/ac)
Mowing	1	0.57	110,670	46.9	109.8	12.7	169.4
Baling	1	0.47	81,158	38.7	90.5	10.5	139.7
Stacking	1	0.85	64,926	70.0	163.7	19.0	252.7

Note: See Appendix for calculations.

Transport to Power Plant (Energy Use)

A typical load for a semi-trailer is expected to be 18 tons. Average distance traveled is calculated to be 50 miles (Braster, 2000). A transport fuel use rate figure was taken from the GREET model from Argonne National Laboratory. This value, 1,056 Btu per ton per mile, was then applied to the average load weight and distance to calculate diesel fuel consumption (see Appendix for calculations).

Fuel preparation (Energy Use)

According to the preliminary design by R.W. Beck, upon reaching the power plant site, a 100 horsepower tractor with front-end scoop or loader pulls the bales from the trailer. Three to four lift trucks will then be required to feed the bales to the combustion system within the OGS facility. The fuel handling train at OGS, as proposed by designers R.W. Beck (Table 7), includes the following equipment for each of two 12.5 ton per hour (TPH) handling trains.

Table 7. Switchgrass Processing Equipment Energy Requirements

Equipment	Horsepower Required
De-Baler	50
Fluidizing Air Fan	40
De-Stoner	25
Vibrating Pan Feeder	25
Materials Handling Blower (return from baghouse)	5
Baghouse Blower	10
Hammermill Shredder	300
Main Materials Handling Blower	100
Rotary Lobe Compressor	125
Rotary Solids Feeder	10
Materials Handling Blower (return from baghouse)	30
Total horsepower requirement for two trains (25 TPH)	1440

Source: R.W. Beck, 1999.

It is assumed that the electric power used to drive these motors will come directly from the OGS plant, and the conversion efficiency of the plant is assumed to be 33 percent. Thus it is assumed that a delivered kilowatt-hour, equaling 3,413 Btu, was created by input of nearly 10,340 Btu of coal. As in the case of internal power plant electricity used to process coal, the electricity consumption is related to greenhouse gas emissions by the fuel combusted in the generation process, and by inefficiencies in the process. As a conventional steam turbine generation facility, conversion efficiencies from input energy to output energy are 33 percent. For baseline purposes the input fuel is 100 percent coal. Emission calculations can be found in Appendix.

Switchgrass Secondary Emission Mechanisms

Transport of chemicals to field (Energy Use)

The Argonne National Laboratory has provided quantification of emissions of greenhouse gases related to the transport of fertilizers for agricultural use (Wang, 2000). The figures are incorporated into the GREET Model which is a life cycle model designed to return life cycle emission values for comparison of various transportation fuels (Wang, 2000). The transportation of fertilizer from production site to farm involves an interim stop at a bulk holding/mixing facility. No appreciable quantities of nitrous oxide (N_2O) are emitted during the transportation process. The transport of herbicide is analogous to fertilizer transport with values duplicated per pound of herbicide. Emission calculations can be found in Appendix.

Transport of Switchgrass Combustion Residue to Landfill

Unburned materials are collected and must be transported to off-site storage facilities. For switchgrass combustion, the waste stream is composed primarily of bottom-ash and captured fly-ash. For our computation of ash generation rates, it has been assumed that all of the ash identified in the ultimate analyses will be captured and removed as waste. The movement of this material results in the expenditure of energy in the form of fuel oil for the truck hauling the waste. Fuel consumption data from the GREET model (Wang, 2000) coupled with fuel oil carbon dioxide emission rates from EIIP (see Appendix for calculations).

Switchgrass Secondary Indirect Emission Mechanisms

Fertilizer and Herbicide production (Energy Use)

The fertilizer production process involves the input of significant amounts of energy. The use of this energy leads to the release of greenhouse gas emissions which are characterized from the GREET model (Wang, 2000). The GREET model also provides estimates of emissions from production of four major types of herbicide, Atrazine, Metolachlor, Acetochlor, and Cyanazine. Switchgrass production utilizes atrazine in a pre- and post-emergence application for weed control.

Alternative Land Uses

Similar to investigation of the no-action alternative during environmental impact assessments performed under the National Environmental Policy Act, the model must consider the greenhouse gas balances in the absence of the bioenergy production. The bioenergy crop in the Chariton Valley will largely be planted in place of two alternatives: Conservation Reserve Program set-aside (fallow), or traditional row-crop agriculture which is predominantly corn acreage. The type of crop and cropping practices used can have significant effect on soil carbon sequestration rates as well as emission balances of N_2O and CH_4 (Robertson, et al, 2000).

Conservation Reserve Lands

Lands that are set aside under the CRP program are generally undisturbed, and natural biomass cover is allowed to grow. Some mowing may take place during the ten-year contract period. An analysis of the mature switchgrass case can lead to an estimate of the impact of this alternative land use. It is assumed that the land is not actively managed, therefore there would be no soil preparation and no energy expended in mowing or harvesting the materials from CRP, no fertilizers or herbicides applied, no energy expended for fuel preparation and combustion, and no transport of combustion waste to the landfill. This means that CRP lands have virtually no emission of greenhouse gases to the atmosphere. The remaining impact of this alternative land use lies in its ability to store carbon into the soil. Reliable data are not available regarding the soil carbon storage potential of unmanaged prairie grasses. However, Garten and Wullschleger (1996) do indicate that soil carbon below fallow plots is roughly equivalent to that found under switchgrass plots. Soil carbon inventories below fallow plots range between 87 percent and 107 percent of switchgrass plots studied. Robertson also found that unmanaged, early successional set-aside plots were effective at storing carbon in the soil (Robertson, 2000). Thus if CRP lands are replaced by switchgrass bioenergy production, the emission benefit of a coal to switchgrass fuel switch would be reduced by approximately 3,584 lbs CO_2-eq per acre, effectively canceling the soil carbon sequestration benefit from the switchgrass production.

Row Crop Agriculture

Annual row-crop agriculture, using today's standard farming practices, neither stores nor decreases the soil's organic content (Paustian, 1997 and Robertson, 2000). Row-crop agricultural practices are also more energy intensive than those of switchgrass production, with more frequent trips through the field, and more application of nitrogen fertilizers. Thus a conservative estimate would be that row-crop inputs are equal to switchgrass. Addition of nitrous oxide emissions created through the standard application rate of 125 pounds of nitrogen per acre (Hallberg, 1996), adds N_2O emissions of 200 pounds CO_2-eq per acre. Thus if switchgrass were planted in lieu of row-crop agriculture, a minimum additional emission benefit of 200 pounds CO_2-eq per acre would be realized due to avoided N_2O emission.

Computing Emission Balances

The wide variety of sources for energy consumption data, and emission estimation procedures for the range of activities within the fuel life cycles, lead to emission estimates in dissimilar terms. To facilitate comparison of greenhouse gas emissions between the coal and switchgrass life cycle activities, all emission rates are converted to a per energy input value basis (per MMBtu). This is also accomplished to reduce concerns of differing combustion efficiencies per unit mass. Since combustion of both fuels is occurring in the same boilers and burner configurations, it is believed that electric generation efficiency will not be affected, particularly given the relatively small amount of switchgrass burned in the co-firing process. Table 8 summarizes the greenhouse gas emissions from each activity. The appendix contains details of the computation process.

Table 8. Comparison of ILCA Greenhouse Gas Emissions from the Switchgrass and Coal Life Cycles to Determine Net Emission Reductions (lb CO_2-eq/MMBtu)

Activity	Bioenergy Emission	Bioenergy Sequestration	Fossil Fuel Emission Avoided
Coal Combustion CO_2	-	-	212.70
Coal Combustion CH_4	-	-	0.05
Coal Combustion N_2O	-	-	1.10
Switchgrass Combustion CO_2	-137.63	-	-
Switchgrass Combustion CH_4	-0.73	-	-
Switchgrass Combustion N_2O	-0.29		-
Plant Carbon Sequestration	-	144.87	-
Soil Carbon Sequestration	-	190.02	-
Fertilizer Application N_2O	-6.82	-	-
Lime Application CO2	-4.17	-	-
Coal Mining CH_4	-	-	1.78
Post-Mining CH_4	-	-	0.29
Soil Preparation	-4.28	-	-
Seeding	-0.84	-	-
Herbicide Application	-2.44	-	-
Fertilizer Application	-1.54	-	-
Lime Application	-1.29	-	-
Mechanical Weed Control	-3.95	-	-
Harvest	-12.19	-	-
Bioenergy Transport to Power Plant	-0.00	-	-
Bioenergy On-Site Prep	-8.85	-	-
Coal Mining/Refining	-	-	1.95
Coal Transport	-	-	1.18
Coal On-Site Prep	-	-	0.26
Bioenergy Waste Transport	-0.02	-	-
Fertilizer Production	-9.67	-	-
Fertilizer Transport	-0.28	-	-
Herbicide Production	-1.30	-	-
Herbicide Transport	-0.00	-	-
Coal Waste Transport	-	-	0.01
Subtotal	-193.97	334.89	219.33
Net Emission **Reduction** from Using Switchgrass in Place of Coal (-193.97 + 334.89 + 219.33) lbs CO_2-eq/MMBtu			360.25

Switchgrass values are computing using a 6-year cycle to account for higher greenhouse gas impacts during establishment of the crop, generally, years 1 and 2. The six year period is also selected to represent the lifetime of an emission trading contract. The longer the contract, the more positive effect the switchgrass operations have on overall greenhouse gas balances because the relative importance of the establishment period decreases over time. It is also important to note that although yields of 4 tons dry matter per acre have been assumed for this analysis in mature stands, practical yields are already seen to be exceeding this value on a limited basis. As the growers gain experience with the switchgrass crop it is quite feasible that the average yield will be higher, thus providing more greenhouse gas reductions.

Economic Impacts of Emission Trading

Through emission trading the protection of the environment can be brought explicitly into the economic cost-benefit equations that drive personal and business decisions. This will decrease the power of economic arguments against environmental protection and will provide an economic boost for clean technologies.

Greenhouse Gas Emission Reduction Trading

At full operation of a 5 percent co-fire the Chariton Valley Biomass Project would result in combustion of 200,000 tons of switchgrass, requiring the farming of nearly 50,000 acres. Net greenhouse gas reductions for switchgrass displacing coal would total 509,000 tons CO_2-eq annually. Assigning direct economic value to these emission reductions is presently difficult given the lack of a formally operating marketplace at this time. This report will utilize the 2010 forecast price that was derived for compliance with the Kyoto Protocol, \$4.96 per ton CO_2–eq (Yellen, 1998). Some estimates of greenhouse gas emission reduction values ranged as high as \$95 per ton CO_2-eq. If the lower price forecast is achieved, greenhouse gas emission reductions from the Chariton Valley Biomass Project could provide a value of nearly \$2.5 million annually, adding to the economic value of the switchgrass crop by \$3.13 per ton, or \$12.50 per acre.

Table 9. Comparison of GHG Benefits From Establishment, Mature Crop, and 6-Year Emission Trading Contract Scenarios

Case	Net Benefit (lbs CO2-eq/mmbtu)	Net GHG Reduction (tons CO2-eq/year)
Establishment	284.285	363,885
Mature Crop	398.228	509,732
6-Year Contract	360.247	461,116

Sulfur Dioxide Emission Reduction Trading

The market value of SO_2 credits has been defined by nearly a decade of emission trading under the Acid Rain Program. Recently SO_2 allowances have been trading at \$120 per ton. At 0.3 percent sulfur, the coal burned at OGS is a low sulfur coal. With 1.25 million tons of coal combusted in 1996, a mass balance estimate of uncontrolled sulfur dioxide emissions is equal to 7,500 tons (assuming full oxidation of fuel-bound sulfur to SO_2). With controlled emissions reported as 2,708 tons SO_2 for 1996 (Ney and Schnoor, 1998) controls at the facility are estimated to remove approximately 64 percent of available sulfur. Thus, replacement of five percent coal (heat content basis) with 200,000 tons of switchgrass at 0.04 percent sulfur (Black and Veatch, 1995) yields a mass balance reduction of 1,040 tons of SO_2 before control, or 374 tons of controlled SO_2 emission. At the market value of \$120 per ton, this reduction possesses an emission trading value of \$44,880.

Nitrogen Oxides Emission Trading

Analysis continues on stack test results from a November/December 2000 test burn conducted with 2.5 percent switchgrass and 97.5 percent coal. The tests appear to confirm that emissions of nitrogen oxides will remain flat or decrease slightly, while confirming reductions in CO_2, SO_2 and particulate emissions. The fuel-bound nitrogen content of coal (0.93 lbs N/MMBtu) is equivalent to fuel nitrogen content of the switchgrass (0.92 lbs/MMBtu).

There is presently no program for NO_x emission trading in the state of Iowa, where the OGS facility is located. State and regional trading plans have been undertaken east of the Mississippi River in attempt to reduce ozone concentrations over the eastern U.S. Due to the high cost of installing and operating control equipment for NO_x emission reduction, NO_x emission allowances are valued from $1,000 to $5,000 per ton, depending on the location of the source within the U.S. Thus changes in NO_x emissions from the co-firing of switchgrass could have a measurable effect on environmental economics should the state of Iowa become involved in a NO_x emission trading program.

Summary

It appears that substitution of switchgrass in place of coal for electric generation will have positive effects on the environment. Analysis of the fuel cycles of switchgrass and coal using an Incremental Life Cycle Analysis method estimates that every million Btu of switchgrass burned in place of coal will reduce greenhouse gas emissions by 239 pounds. At a 5 percent co-firing rate in the OGS powerplant this would result in annual greenhouse gas emission reductions totaling more than 509,000 tons with mature switchgrass fields. With the advent of emission trading as a tool to achieve compliance with future requirements to reduce overall greenhouse gas emissions, the project would generate greenhouse gas emission reduction credits worth $2.5 million annually if a conservative forecast credit price of $4.96 per ton materializes. In addition to positive impacts on overall greenhouse gas emission balances, the project would also appear to lead to a reduction of sulfur dioxide and particulate emissions, while emissions of nitrogen oxides may remain flat.

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APPENDIX. GREENHOUSE GAS EMISSION CALCULATIONS FOR THE CHARITON VALLEY BIOMASS PROJECT USING THE INCREMENTAL LIFE CYCLE ANALYSIS METHODOLOGY