Switchgrass as an Alternate Feedstock for Power Generation: Integrated Environmental, Energy, and Economic Life-Cycle Analysis

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Abstract - Biomass conversion into forms of energy is receiving current attention because of environmental, energy supply and agricultural concerns. This objective of this paper is to report on the environmental, energy, economic, and technological aspects of using switchgrass (*panicum virgatum*) as a replacement for coal in power generation. To examine the effects of such a substitution, an environmental biocomplexity approach is used to analyze the interactions of agricultural, technological, economic, and environmental factors. In particular, lifecycle analysis (LCA) is used. The three-dimensional economic, energy and environmental analysis shows that the most effective technologies for switchgrass preparation are harvesting loose switchgrass for hauling and chopping and then transporting after compression into modules. The greenhouse gas (GHG) mitigation during co-firing of switchgrass with coal is found to be greater per ton of switchgrass used than the GHG mitigation for switchgrass fired alone with the GHG effects of 58.1 g CO_2-Eq /kWhr for 5% switchgrass co-fired with coal and 90.5 g CO_2-Eq /kWhr for switchgrass fired alone. This paper discusses the sensitivity of this finding to varied co-firing ratios, coal prices, hauling distances, and per acre yields.

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Fossil fuel usage is a key human-related factor contributing to the production of green house gases (GHGs). Of total 2002 U.S. carbon dioxide emissions, 98.0 percent, or 5,682 million metric tons, resulted from fossil fuel combustion (Mintzer, 2003). Overall, total U.S. emissions have risen by 13 percent from 1990 to 2002 (Hockstad and Hanle, 2004). As energy usage increases, the rate of increase of atmospheric CO_2 concentration also rises. The Intergovernmental Panel on Climate Change indicates this, in the absence of any emissions reductions, could lead to a temperature increase of between 1.4°C to 5.8°C over the period 1990 to 2100, projecting a decadal increase of between 0.15°C and 0.35°C. The maximum average temperature increase that the environment can withstand without damage is estimated at 0.1°C per decade. Therefore, many feel that CO_2 emissions must be decreased (Watson and Albritton, 2002).

Several policies and energy consumption related actions have been proposed to limit net GHG emissions. A key example is the Kyoto Protocol ratified by numerous countries. In the US, despite rejecting the opportunity to ratify the Kyoto protocol, the “Clear Skies Initiative”, announced by President Bush, calls for an 18% reduction in the intensity of GHG emissions per unit gross domestic product (Winters, 2002).

One mechanism that can be used to mitigate GHG emissions is cofiring. Studies for evaluating the feasibility and cost of direct injection cofiring of 10% switchgrass with coal appear promising (Boylan *et al.*). Substitution of bioenergy feedstocks replaces fossil fuels and their inherent emissions with recycling where carbon is withdrawn from the atmosphere via photosynthesis during feedstock growth and then is released upon combustion. The main questions regarding such a substitution are

- How cost competitive is such an action?
- What are the environmental implications of this action?
- What is the net GHG balance considering the GHGs emitted across the life of the biofuel feedstock versus the replaced fossil fuel?

This paper summarizes the results of an investigation into these questions using an environmental biocomplexity approach that addressed agricultural, technological, economic, and environmental factors along with their interaction. This paper attempts to:

- Provide an economic, energy and environmental evaluation of the prospects for switchgrass as a bioenergy feedstock for electricity generation using lifecycle analysis.
- Develop an environmental biocomplexity and a lifecycle-based approach that permits identification of most effective technological enhancement possibilities and alternative material handling procedures.
- Examine how potential environmental policy alternatives might influence the relative efficiencies of alternative technologies and other strategies as well as the power generation market penetration of biomass.
- Implement a framework for additional evaluations to be done in the future.
- Examine the sensitivity of the findings to a wide spectrum of possibilities in switchgrass production, preparation and delivery as well as the degree of desirable co-firing of power plants.

The scope of the Life Cycle Analysis approach will include

- Switchgrass production items include plowing, disking, seeding, lime, herbicide and fertilizer application, and harvesting.
- GHG emissions from the cultivation of soil.
- Emissions and energy consumption during planting, management, harvest and transport of switchgrass.
- Lime soil reaction.
- Carbon in switchgrass.
- Carbon sequestration in the soil.

- Hauling, storing, and moving switchgrass from the farm to the point of combustion. This includes loss of switchgrass that is scattered and embedded in the soil during transportation that leads to GHG emissions upon degradation.
- Energy and emissions from switchgrass combustion versus coal consumption. This includes post combustion control of SO_x and transport of combustion waste to a land fill.
- Energy consumed during the production and transport of lime, fertilizers and herbicides.

1 Background: Switchgrass to Energy

Biomass conversion into forms of energy is an old idea but one that is receiving increasing attention largely because of environmental, energy supply and agricultural market condition concerns (McCarl and Schneider, 2001). Specifically, the wise use of biomass-based fuels, power, and products can make important contributions to U.S. energy security, agricultural welfare, and environmental quality. However, wise use is a challenging concept that must be based on a holistic consideration of the numerous agricultural, economic, technological, energy, and ecological elements. Wise use involves decisions on appropriate research strategies for biomass production and processing enhancement as well as policies to promote environmentally sound practices. Such decisions involve identification of the biomass strategies to emphasize the development and the formation of policies and rules that facilitate appropriate biomass production and use.

It is important to recognize that despite being considered for more than 30 years, biomass still has not achieved a great deal of market penetration in the power generation feedstock industry due to cheaply available fossil fuels and the relatively high costs and current low yields of biomass energy feedstocks. A mix of technological, market and policy actions are needed to enhance biomass feedstock competitiveness. Several societal trends and developments portend an expanded role for biomass to energy. These involve

1. A desire to manage GHG emissions globally and the role that biomass through carbon recycling or emissions management might play.

2. A continued desire for rural income support and the bolstering of farm prices and or income opportunities as well as a desire to increase the stability of farm and rural incomes.
3. An enhanced desire for a cleaner environment and a move to reduce emissions from liquid fuel consumption and emissions from coal fired power plants.
4. Continued concern over the degree of energy dependency on foreign sources of petroleum.

On the other hand, one must also be careful not to trade one environmental problem for another. In this regard, environmental biocomplexity provides an attractive approach, because it causes one to achieve a holistic understanding of biomass-to-energy alternatives. Environmental biocomplexity refers to highly interactive phenomena that arise through interactions among the biological, physical, and social components of the Earth's diverse environmental systems (e.g., El-Halwagi, 2003).

Perennial, herbaceous energy crops such as switchgrass can be used for developing bioenergy and bioproducts. In the United States, switchgrass is considered the most valuable native grass for biomass production on a wide range of sites. It is noted for its heavy growth in late spring and early summer. It is also valuable for soil stabilization, erosion control and as a windbreak.

In order to be profitable, energy crops need to

- produce high yields of biomass,
- contain low concentrations of water, nitrogen and ash, and
- contain high concentrations of lignin and cellulose.

The quality of switchgrass for fuel depends on concentration of energy, primarily derived from cell walls and particularly from lignin and cellulose. Also, some elements such as potassium, sodium, chlorine, silica, etc. cause problems when burned (erosion, slagging and fouling), decreasing efficiency and increasing maintenance costs [Sami *et al*, 2001].

2 Background : Policy

At present, the cost differences between using biomass versus coal as a power plant feedstock is generally not enough to cover the capital cost of plant conversion and still be profitable. However, two types of policy options are currently being considered that could promote biomass as an energy feedstock.

One policy option is to promote markets for GHG credits as a vehicle for reducing emissions of GHGs as manifested in the Kyoto Protocol. The emergence of such a market could improve biofuel competitiveness, as there is potentially a large GHG offset relative to coal use depending on the amount of fossil energy used in producing the biomass. The net carbon emissions from a switchgrass fired power plant amount to approximately 5 percent of the emissions from an energy equivalent amount of coal. Power plants could operate with substantially less emissions. This would be a way to reduce emissions to mandated or targeted levels. Implementing policies encourging GHG credits would, in effect, create subsidies for biomass planting and, thus, enhance biomass growth and acceptance.

The second policy option is legislation such as the four pollutants bill or the clear skies initiative that could favor biofuels production. There is proposed legislation to limit SO_X, $NO_{X,}$ and mercury emissions from power plants. Burning switchgrass offers the potential to reduce these emissions as biomass has virtually no sulfur (often less than 1/100th of that in coal), low nitrogen (less than 1/5th of that in coal), and low-ash content [Hughes *et al*, 2000]. Additionally, switchgrass burning leads to cost savings as expensive emissions control equipment for SO_x and NO_x would no longer be required. Its chemical properties make switchgrass a desirable, green and clean technology that aids in complying with looming environmental legislation.

Another action that would be helpful in commercialization of biomass would be to relax the standards of the coal ash used in cement manufacturing [Hughes *et al*, 2000]. This would help plants co-firing up to 10 or 15% switchgrass provide ash for use in the cement industry.

3 Analysis of Switchgrass Lifecycle

Lifecycle analysis on the production of electricity from switchgrass includes two stages - switchgrass preparation and power generation. Costs, emissions and energy consumption of all processes during the transformation of switchgrass to electricity were quantified using material and energy balances.

3.1 Switchgrass preparation

This stage is based on the model established by Smith *et al*. It includes processes for switchgrass establishment, growth, harvest and transportation to the power plant. The overall approach for use of switchgrass is shown in Fig.1.

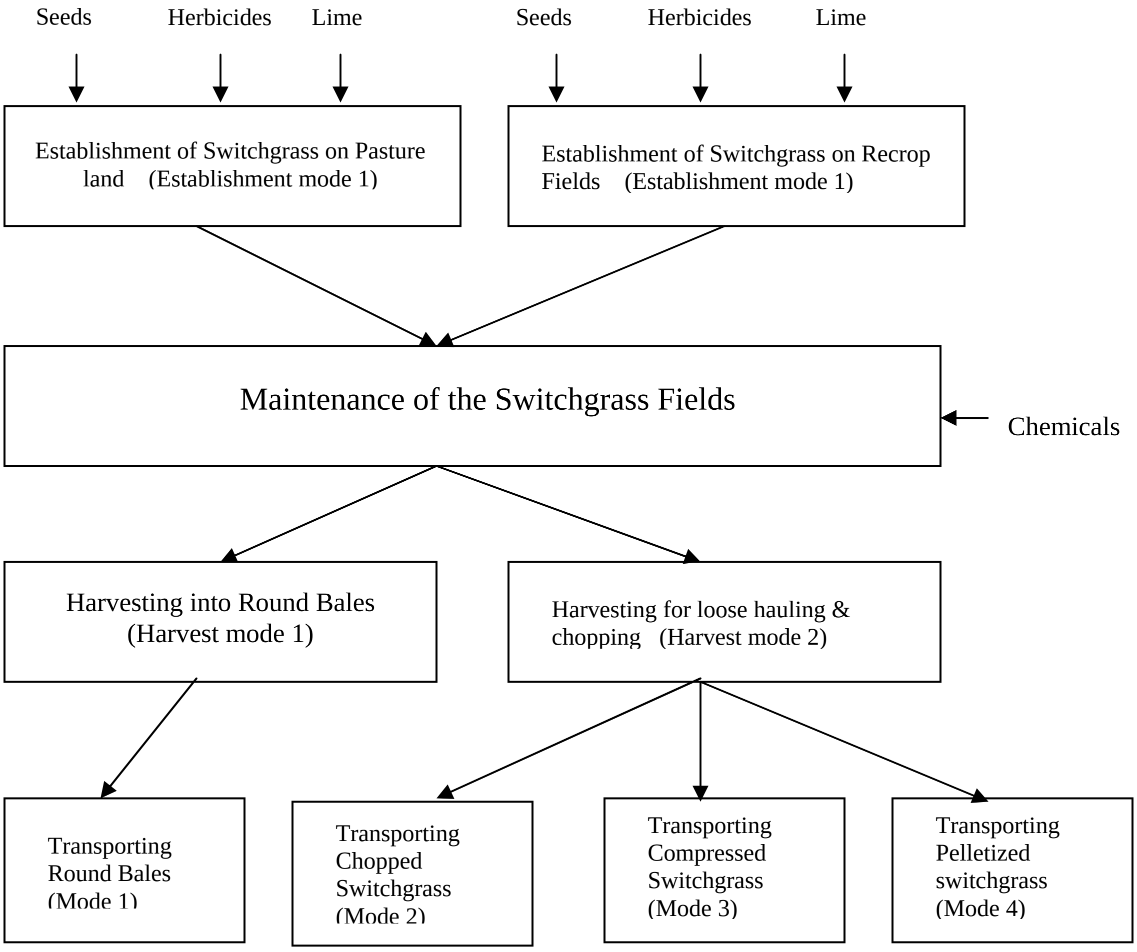
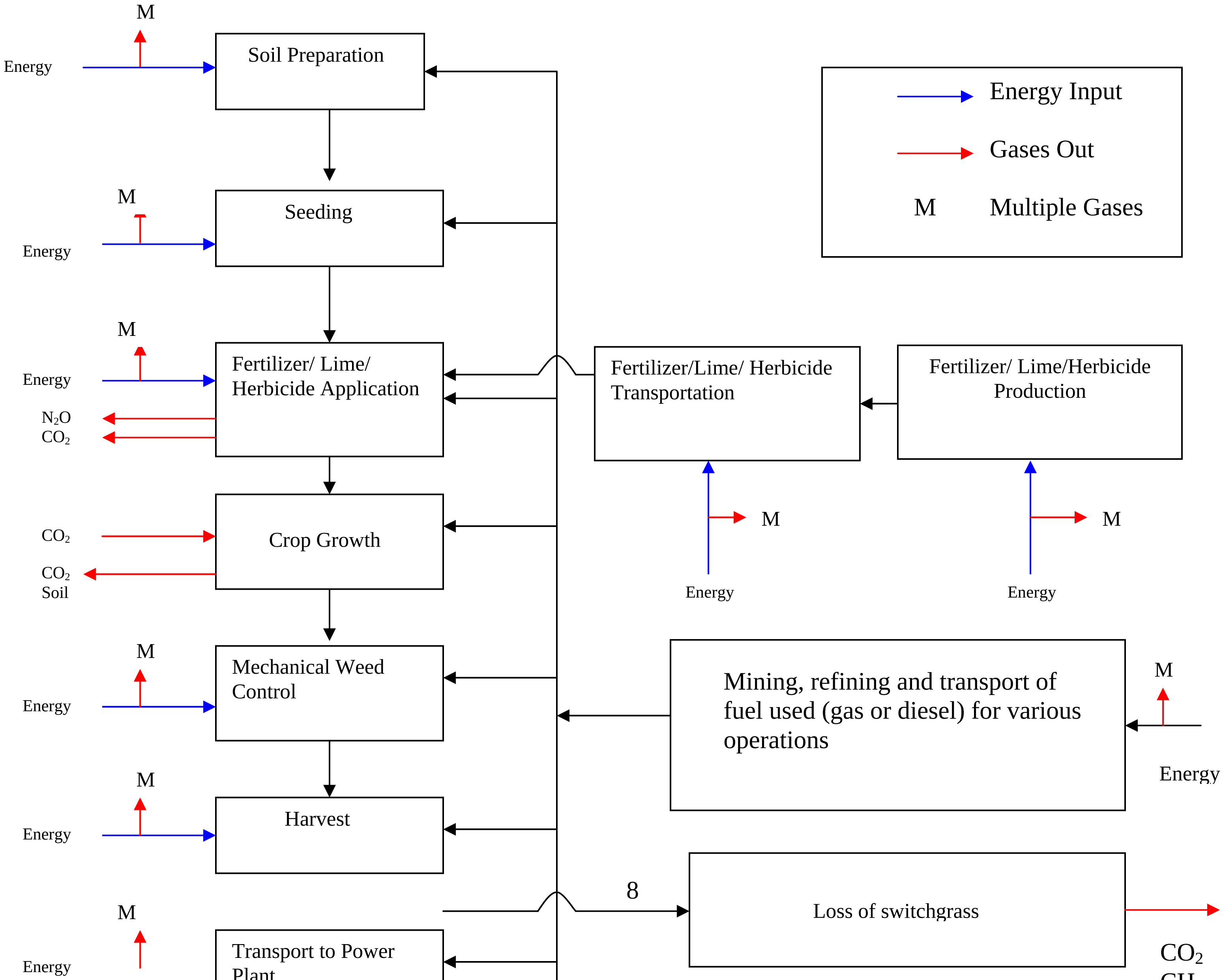


Fig.1: Overall approach for switchgrass preparation including delivery to power plant.

Figure 2 illustrates the key life-cycle stages and processes associated with GHG emissions and energy consumptions for switchgrass as an alternate feedstock for power generation.

Fig. 2: Emission and energy Pathways for Switchgrass.



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3.1.1 Switchgrass Data used for this analysis

The switchgrass chemical composition used as a basis for computations of the GHG emissions is shown in Table 1.

Table 1: Switchgrass proximate analysis.

Component	% By weight (kg)
Water	11.99
Ash	4.61
Carbon	42.04
Hydrogen	4.97
Oxygen	35.44
Nitrogen	0.77
Sulfur	0.18

The higher heating value (HHV) of switchgrass can be estimated by the following equation:

$$HHV = 35160C + 116225H - 11090O + 6280N + 10465S$$

Where, HHV is the higher heating value in kJ/kg, and C, H, O, N and S represent the mass fractions on a dry ash free basis for carbon, hydrogen, oxygen, nitrogen and sulfur in the fuel, respectively. Calculated HHV for switch grass is 16,694 kJ/kg. The tested HHV for switchgrass, which is employed in this model, is 15,991 kJ/kg [Sami *et al*, Aerts *et al*].

The agronomic traits and cell wall constituents for the switchgrass used for analysis are listed in Table 2 [Lemus *et al*, 2002].

Table 2: Cell wall constituents of switchgrass.

Constituent	% By bone dry weight base
Cellulose	37.10
Hemi cellulose	32.10
Fixed Carbon	13.60
Lignin	17.20

The carbon content of the cellulose and hemi cellulose is found by using their respective structural monomers as shown in Figs. 3 and 4.

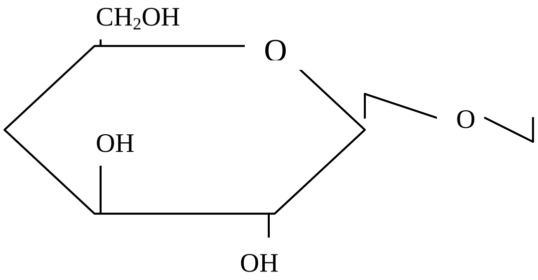
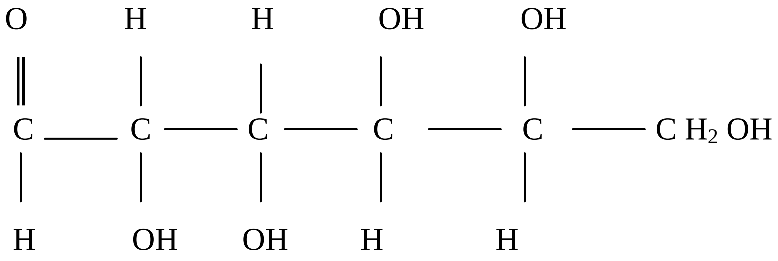


Fig. 3: Structural Monomer of Cellulose.



$$\begin{array}{ccccccccccc} O & & H & & H & & OH & & OH & & \\ \parallel & & | & & | & & | & & | & & \\ C & - & C & - & C & - & C & - & C & - & CH_2OH \\ | & & | & & | & & | & & | & & \\ H & & OH & & OH & & H & & H & & \end{array}$$

Fig. 4: Structural Monomer of Hemi cellulose.

The above characteristics were used in this analysis and provide the basis on which the yield, loss, and firing ratio of switchgrass feedstock were calculated. The switchgrass yield is assumed to be 10 tons per year, the stand life as 10 years and the transportation distance as 50 miles.

3.1.2 Economics of Switchgrass preparation

An economic analysis of switchgrass preparation for use in power generation was accomplished by following the scheme set by Sladden *et al*. and Smith *et al*. Machines, fuel, and energy requirements for all farm operations were taken into consideration. Appropriate financial parameters such as interest rate, tax rate, insurance rate, cropland rental value, and fuel prices were used in cost calculations.

After calculating all the costs for the establishment, growth, harvest and transportation, a total cost budget for switchgrass preparation was estimated. The total cost per ton of switchgrass for various combinations of alternative activities is shown in Fig. 5.

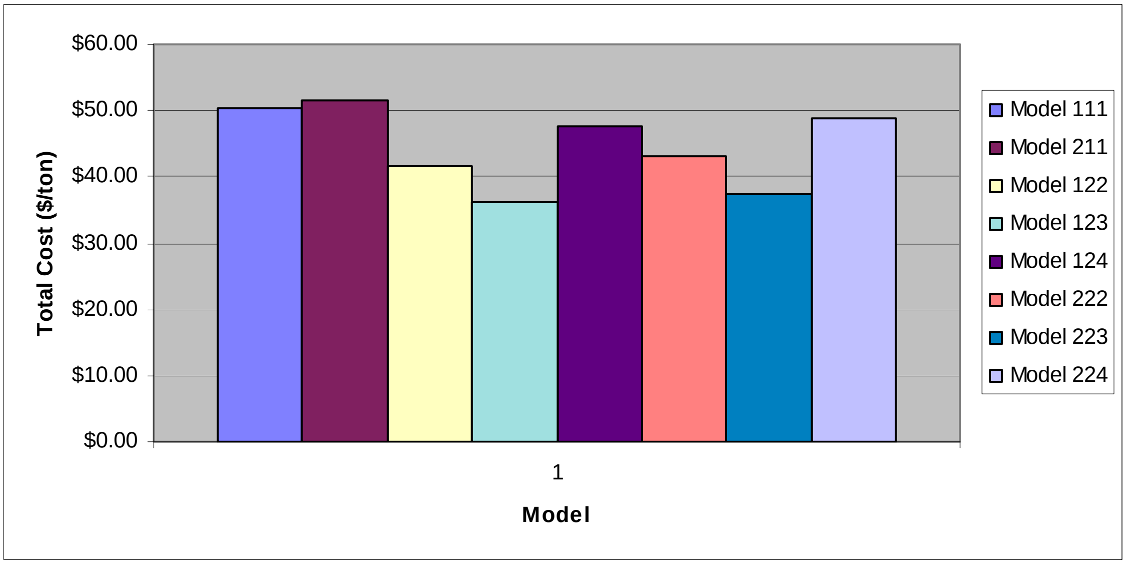


Fig.5: Comparison of various combinations of alternative activities of switchgrass preparation for Cost Evaluation.

Based on the analysis, the most cost effective switchgrass preparation methods were to establish switchgrass on pasture land, harvest loose for hauling and chopping, and transport by compression into modules (Model 123), an overall cost of $36.14/ton, and to establish switchgrass on recrop fields, harvest loose for hauling and chopping, and transport by compression into modules (Model 223), an overall cost of $37.47/ton.

3.1.3 Environmental and energy assessment

The analysis of the GHG emissions associated with the preparation of switchgrass needs to take into account the total mix of activities required for growing switchgrass and transporting it to the power plant. All the activities require inputs such as fossil fuels, chemicals, fertilizers and herbicides that produce GHG emissions when they are manufactured. This analysis also considers the carbon in plants and soils plus the carbon that would have been released by coal combustion. In addition, GHG emissions due to the mining, refining and transportation of fuels were included.

3.1.3.1 Emissions and energy consumption from machinery operations for switchgrass preparation

The energy consumption and GHG emissions were calculated for the four stages of switchgrass preparation; establishment, growth, harvest, and transport. Based on the machines used at each stage, the fuel consumed was calculated and used to calculate the GHG emissions by using the emission and energy factors.

Table 3: GHG emissions and energy consumption from preparation of switchgrass.

Switchgrass preparation stage	Alternative operations	Energy Consumption (Btu/kg switchgrass)	CO_2 emissions (grams/kg switchgrass)	N_2O emissions (grams/kg switchgrass)	CH_4 emissions (grams/kg switchgrass)	CO_2-eq emissions (grams/kg switchgrass)
Establishment	Pasture (1)	10.1595	0.7955	0.00002	0.0010	0.8251
	Recrop Fields (2)	4.6022	0.3594	0.000009	0.00049	0.3733
Growth	Growth	24.1617	1.8946	0.000045	0.0024	1.9636
Harvest	Round Bales (1)	189.8694	15.0315	0.00071	0.01960	15.6913
	Loose, hauling and chopping (2)	59.2774	4.6774	0.00011	0.00536	4.8329
Transport	Round bales(1)	859.03	67.4959	0.0016	0.0811	69.8305
	Loose, chopped(2)	846.46	66.4646	0.0015	0.0799	68.7663
	Loose, compressed (3)	414.80	33.0063	0.0019	0.0386	34.4576
	Loose, palletized (4)	1087.18	75.4029	0.0012	0.1014	78.0764

Analyzing the various pathways for switchgrass production for the lowest GHG emissions, the optimal combination of activities was establishing switchgrass after existing cropping, harvesting switchgrass loose for hauling and chopping, then transporting after compression into modules (Model 223). Field chopping switchgrass is preferable to baling as it leads to savings in transportation costs (Boylan *et al*). Figure 6 below shows total GHG emissions from machinery operation for delivered switchgrass.

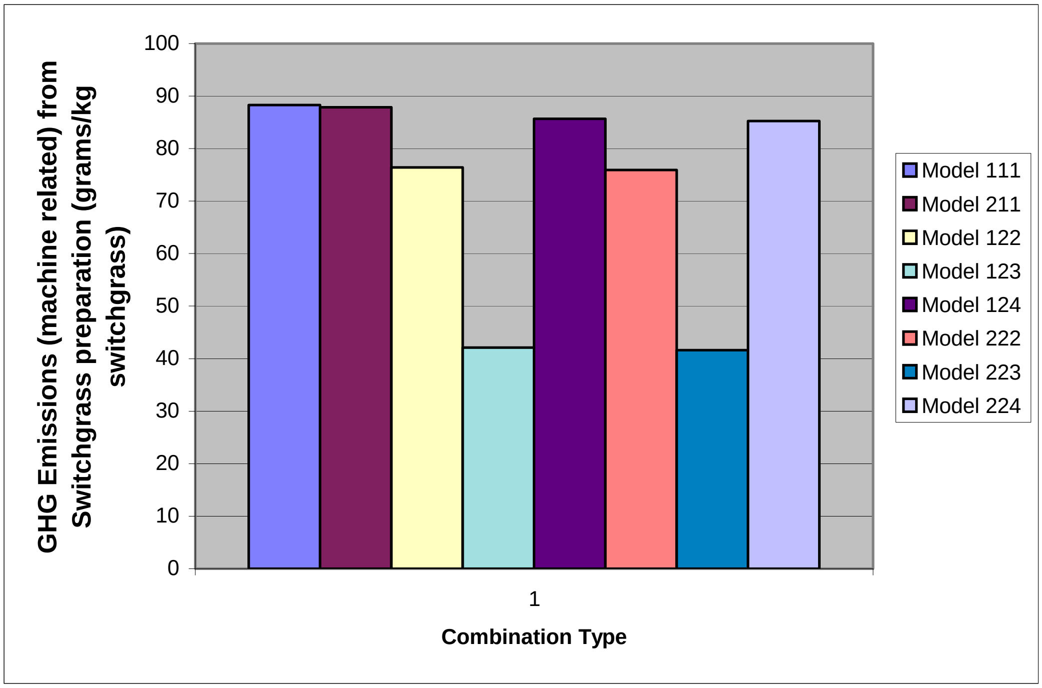


Fig. 6: Total machinery related GHG emissions for switchgrass preparation

3.1.3.2 GHG emissions and energy consumption of production inputs

During switchgrass establishment and growth, lime, fertilizers and herbicides are applied. GHG emissions are generated in their production. The net emissions from these activities are based on the annual recommended per acre usage rates for these materials from Smith *et al.* and Ney *et al.* which are 2 lbs atrazine, 100 lbs nitrogen, 40 lbs P_2O_5, 40 lbs K_2O fertilizer and 2 tons agricultural lime ($CaCO_3$) (the latter only during the establishment stage).

The lifecycle emission and energy consumption factors for atrazine and fertilizer production are drawn from the GREET model (Argonne National Laboratory).

The application of nitrogen fertilizer leads to the formation of nitrous oxide emissions from the soil. Based on assumptions by Ney et al., 36.892 grams N_2O are released from 1 kg fertilizer nitrogen used. This will lead to emissions of 0.203 grams N_2O/kg switchgrass in the model.

Emissions and energy consumption from the manufacture and transportation of lime are calculated based on the limestone manufacture and transport processes. The reactions of lime in the soil will lead to direct CO_2 emission. The mechanism is summarized as follows:

$$CaCO_3 + H_2O + CO_2 \rightarrow Ca(HCO_3)_2$$

The partial pressure of CO_2 in soil is high enough to force above reaction to the right.

$$Al^{3+} + H^{+} + 2Ca(HCO_3)_2 \leftrightarrow 2Ca^{2+} + Al(OH)_3 + H_2O + 4\,CO_2\uparrow$$

$$Al^{3+} + H^{+} + 2CaCO_3 + H_2O \leftrightarrow 2Ca^{2+} + Al(OH)_3 + H_2O + 2\,CO_2\uparrow$$

Over time, the soluble Ca^{2+} ions are removed from the soil by the growing crop or by leaching.

The overall GHG emissions due to the use of lime and chemicals are summarized in Table 4.

Table 4: GHG Emissions and energy consumption from use of lime and chemicals.

Emission species	Energy	CO_2	N_2O	CH_4	CO_2-Eq
Emissions and energy consumption from fertilizer and Atrazine (g or btu/kg switchgrass)	441.18	28.19	2.03E-01	6.46E-02	89.86
Emissions and energy consumption from agriculture lime (g or btu/kg switchgrass)	5.64	9.23	1.01E-05	5.03E-04	9.25
Emissions and energy consumption from all chemicals (g or btu/kg switchgrass)	446.82	37.42	2.03E-01	6.46E-02	99.11

3.2 Net carbon uptake of switchgrass and soil

3.2.1 Carbon absorption by switchgrass

Photosynthesis is the process by which plants use the energy from sunlight to produce sugar, which is then converted into ATP (adenosine triphosphate) by cellular respiration. ATP is the “fuel” used by all living things. The overall reaction of this process can be written as:

$$6H_2O + 6\,CO_2 \rightarrow C_6H_{12}O_6 + 6O_2$$

It is assumed that all the carbon in switchgrass is converted from CO_2. Therefore, the CO_2 used by switchgrass can be calculated from the carbon content of switchgrass, i.e. 1540.5 g CO_2/kg switchgrass in this model. This carbon will be released upon combustion but is assumed to result in zero net combustion related emissions because photosynthetic uptake matches combustion releases.

3.2.2 Carbon dioxide sequestration in the soil

Soil carbon sequestration is also associated with switchgrass production. McLaughlin et al. analyzed soil carbon gains in the soil surface horizon across a total of 13 research plots to document anticipated increases associated with root turnover and mineralization by switchgrass. These include measurements made after the first 3 years of cultivation in Texas, and after 5 years of cultivation in plots in Virginia and surrounding states. Their studies indicated that carbon accumulation is comparable to, or greater than the 1.1 tonne carbon per hectare-year reported for perennial grasses [McLaughlin *et al*, 1999]. Several years of switchgrass culture are required to realize the benefit of coil carbon sequestration (Ma *et al*). Using a conservative estimation, the credit for soil carbon dioxide sequestration was 179.9 g/kg switchgrass. However, after growing switchgrass on the same fields for 15 years, CO_2 accumulation in the soil is likely to reach a saturation value as found in West and Post, which should be taken into account into any long-term studies.

3.2.3 GHG emissions due to switchgrass losses

During harvest, transportation, and storage, a some switchgrass will be lost. A series of experiments conducted by Texas A & M University show that baling losses from switchgrass including those gleaned from the stubble and collected at the baler ranged from 1.8% to 6%. Switchgrass losses during handling and transporting switchgrass over 11 miles were only 0.4% of the baled weight. Experiments also pointed out that these losses could be reduced by careful machine operation and management [Sanderson *et al*, 1997]. These experiments show that switchgrass losses in bales stored outside either on sod or gravel were 5.6 and 4.0% of the original bale dry weight, respectively. No weight losses were detected in the bales stored inside. Based on these experiments, a total switchgrass lost 4% of the net yield (fired in the power plant) was assumed. Among the losses, 90% were assumed scattered on the field and road surface or lost during storage, and the rest were embedded in the soil.

Although the degradation of the lost switchgrass may take a long time, GHG emissions from the degradation were considered as if they occurred in the same harvesting season. The mechanism of biomass degradation in A Life Cycle Assessment of Biomass Co-firing in a Coal-fired Power Plant [Mann *et al*, 2001] was adopted in this study.

The contents of cellulose and hemi cellulose in switchgrass were taken from the study of Lemus, R. et al., 371g for cellulose and 321g for hemi cellulose (based on 1 kg bone dry switchgrass) (Lemus *et al*, 2002). The carbon contents of cellulose and hemi cellulose were calculated from the repeating unit. The rest of the carbon was assumed to link with lignin. Therefore, a tree model was used for analysis (Fig. 7).

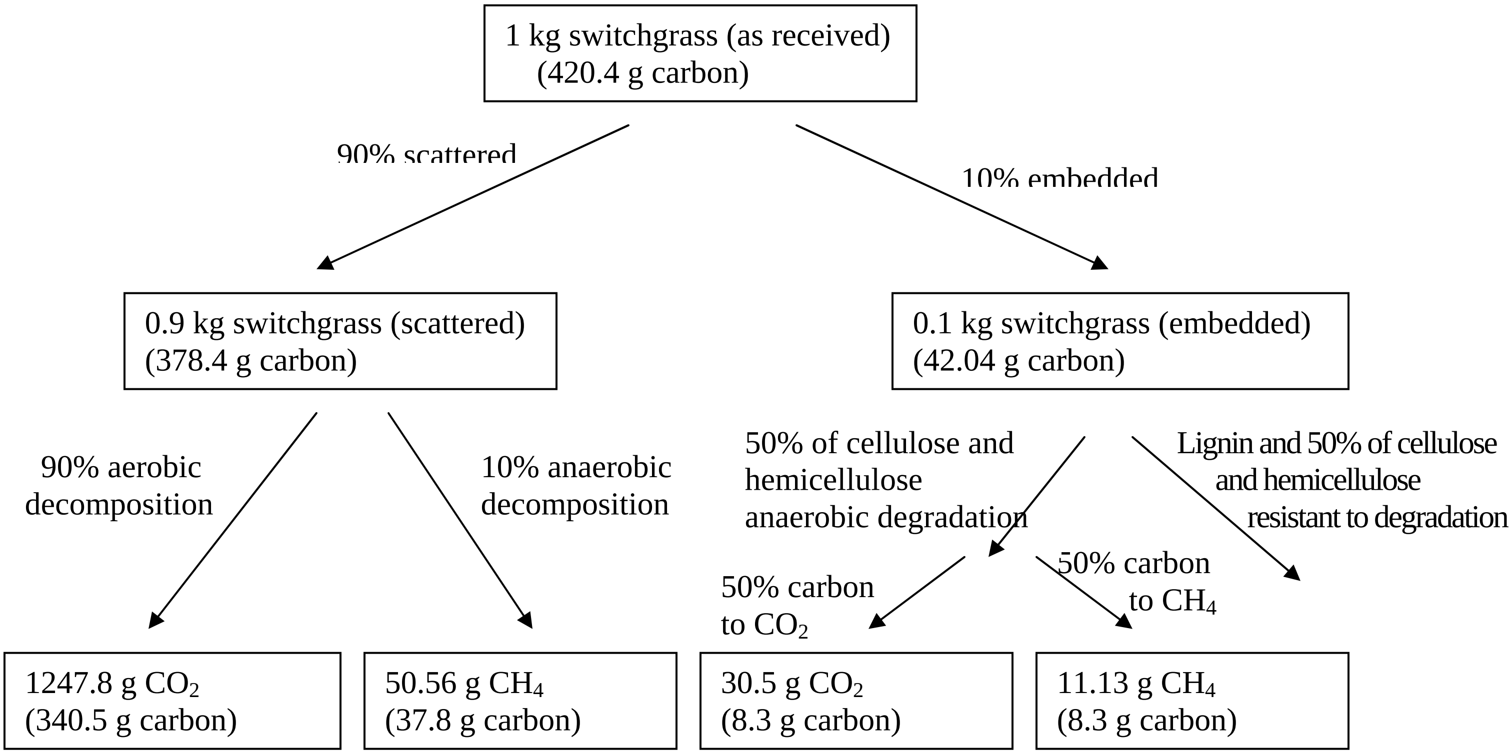


Fig. 7: Tree model for losses of switchgrass.

Taking the ratio of GHG emissions from the lost switchgrass to net switchgrass yield (fired in the power plant), the following emissions based on 1 kg switchgrass yield are obtained as shown in Table 5.

Table 5: GHG Emissions from lost switchgrass.

Emission species	CO_2	N_2O	CH_4	CO_2-Eq
Emission factors (g/kg switchgrass net yield)	51.1	0	2.47	107.9

3.3 GHG EMISSIONS FROM POWER GENERATION

Only direct-fired and co-fired biomass power systems were considered in this analysis. Power generation using biomass or coal produces air-borne emissions including sulfur dioxide (SO_2), nitrogen oxides (NO_X), methane (CH_4) and carbon dioxide (CO_2). Further, after the combustion, part of the generated waste needs to be transported to a land fill and the SO_x generated has to be treated or reduced. Power generation can be divided into two sections: combustion and post combustion activities.

3.3.1 Combustion

Two alternatives were considered for combustion-switchgrass as the sole feedstock and switchgrass co-fired with coal.

3.3.1.1 Switchgrass fired alone

Although, switchgrass has not been used as the sole feedstock on a production basis for a commercial power plant, a case was constructed based on extrapolation of results from wood-fired power generation.

Emission factors due to switchgrass combustion were assumed to be the same as those for dry wood residue (moisture content less than 20%) combustion in boilers, which was adapted from an EPA report External Combustion Sources (EPA, 5th Ed., Vol 1). The results are shown in Table 6.

Table 6: Emission factor of biomass-fired boiler.

Emission species	N_2O (lb/mmBtu)	CH_4 (lb/mmBtu)	SO_x (lb/mmBtu)	NO_x (lb/mmBtu)	CO (lb/mmBtu)
Emission factors	0.013	0.021	0.025	0.49	0.60

Emission factor for carbon dioxide (EF_{CO2}) was calculated as follows:

$$EF_{CO2} = P_c*BF_c*MW_{CO2}/MW_c/HHV_{sw}$$

In this model, EF_{CO2}=222 lb/mmBtu.

The amount of switchgrass fired ($Q_{sw,bn}$) and the corresponding electricity (Q_{elec}) generated are a function of net plant heat rate (NPHR):

$$Q_{elec} = Q_{sw,bn}/ NPHR_{sw,bn} = HHV_{sw}*W_{sw,bn}/ NPHR_{sw,bn}$$

Existing biomass power plants have heat rates ranging from 13.7 to 21.1 MJ/kWhr or even higher, which correspond to high-heating-value (HHV) efficiencies from 25% to 17% or lower [Hughes *et al*, 2000]. An average value of 17.4 MJ/kWhr was used as the default net plant heat rate (NPHR) of switchgrass fired alone case. The emissions from switchgrass combustion for electric generation are summarized in Table 7.

Table 7: Emissions from switchgrass-fired alone.

	CO_2	N_2O	CH_4	SO_x	NO_x	CO
g/kg switchgrass	1525	0.0893	0.144	0.172	3.366	4.122
g/kWhr by switchgrass	1660	0.0972	0.157	0.187	3.663	4.485

3.3.1.2 Switchgrass co-fired with coal

Currently the application of biomass as the sole source of fuel for power plants with large capacity is not common or economical. The nature of biomass also brings other problems to power generation such as slagging and fouling. However, recent studies proved that co-firing could overcome these problems and perhaps be environmentally beneficial (Boylan *et al*). In particular

- Total CO_2 emissions can be reduced because the amount of CO_2 released in biomass combustion is largely recycled, being captured during biomass growth so net emissions are low compared to coal alone.
- Most biomass fuels have very little sulfur. Therefore, co-firing high sulfur coal with biomass would reduce the SO_2 emission [Hughes *et al*, 2000]. Moreover, because of more alkaline ash in biomass, some of the SO_2 from the associated

coal would be captured during combustion, which would lead to an additional reduction of SO_2.

- Typically, woody biomass contains very little nitrogen on a mass basis as compared to coal, which would lead to the reduction in NO_x emissions. The synergetic effects of co-firing coal and biomass will thus also lead to reduction of NO_x emission [Tillman *et al*, 2000]. The hydrocarbons released along with volatile matter during pyrolysis of biomass or coal can be used to reduce NO_x. Another possible advantage of biomass cofiring stems from the potential catalytic reduction of NO_X by naturally present NH_3 in biomass.

Most co-firing studies have been conducted with biomass percentage of less than 20% by mass of the total fuel. Within this range, the problems brought by firing biomass alone are not as significant, but the synergetic effects of co-firing on emission reduction can be quite effective.

One more significant feature of co-firing is that the simultaneous use of coal can improve the heat rate of co-fired biomass. When the heat input of biomass is in the range of 7-10% of the total heat input, overall boiler efficiency only drops 0.3-1.0 points from a coal fired boiler efficiency of 85-90% Compared to the large difference between burning biomass alone and burning coal alone, the efficiency of biomass in co-firing is relatively high [Hughes *et al*, 2000]. For simplicity, the typical value of 11.6 MJ/kWhr was assumed as the net plant heat rate of co-fired switchgrass, while for coal the national average NPHR is 10.9 MJ/kWhr.

The relation of electricity generated and corresponding fuel needed ($W_{fuel,co}$) was expressed by following equations from which the quantities of coal and switchgrass can be calculated.

$$Q_{elec,co} = \Sigma\,(HHV_{fuel} * W_{fuel,co} / NPHR_{fuel,co})$$

$$R_{sw,thermal} = HHV_{sw} * W_{sw,co} / \Sigma(HHV_{fuel} * W_{fuel,co})$$

Co-firing 5% switchgrass (on a thermal input basis) with coal to generate 1kWhr of electricity requires 0.442kg coal and 0.034kg switchgrass. Tests of co-firing switchgrass with coal have been conducted including co-firing switchgrass in a 50MW pulverized coal boiler at Madison Gas and Electric CO. (MG&E) [Aerts *et al*, 1997] and co-firing switchgrass in a 725MW gross (675MW net) tangentially-fired pulverized coal boiler at Ottumwa Generating Station (OGS) in Chillicothe, Iowa [Amos *et al*, 2002].

Unfortunately in these tests the GHG emissions from co-firing switchgrass were not well documented, and the NO_x changes were inconsistent. However, the tests indicate SO_x emission decreased compared with the coal-only firing. The OGS test also showed that switchgrass co-firing did not normally contribute to higher CO readings. Other biomass co-firing studies have confirmed this conclusion, such as the co-firing test by Spliethoff H. & Hein K.R.G. That test showed that compared with coal-only firing, CO emission did not show any change for biomass shares up to 50% of the thermal input [Spliethoff *et al*, 1998].

Based on these test results and facts, following assumptions are made in the co-firing model:

- Carbon burning fraction of coal and switchgrass are both 99%.
- N_2O emissions from co-firing are proportional to the emissions of coal fired alone and biomass fired alone according to their thermal input.
- The amount of CH_4 emission from co-firing is the same per unit electricity output as that arising from a coal-only firing.
- SO_x emission is proportional to that of coal-fired alone and switchgrass- fired alone according to their thermal input. Because switchgrass contains much less sulfur, the SO_x emission of co-firing is lower.
- NO_x emissions from switchgrass still remain uncertain.
- National average emission factors and properties of coal were adopted in this model. Emissions of carbon dioxide and HHV of coal were derived from EPA’s report (GHG sinks and sources, 2002),
- Sulfur dioxide emission was calculated from sulfur content provided by EPA’s report (Electric power annual 2002).

Table 8: National average emission factors of coal fired electric generation.

Emission species	CO_2	N_2O	CH_4	SO_x	CO
Emission factors (g/kg coal)	2085	0.0313	0.022	17.16	0.25
Emissions (g/kWhr)	967	0.0145	0.010	7.95	0.12

Based on the aforementioned assumptions, co-firing 5% switchgrass (thermal input) with coal will generate following amount of emissions.

Table 9: GHG Emissions from co-firing 5% switchgrass with coal.

Emission species	CO_2	N_2O	CH_4	SO_x	CO
Emissions (g/kWhr)	973	0.0169	0.010	7.58	0.12

3.4 Post-Combustion Activities

The activities involved in post-combustion include post-combustion control of SO_x and waste transportation to a land fill.

3.4.1 Switchgrass-fired alone

Because of the low sulfur content in switchgrass, switchgrass alone firing generates very little SO_x, (well below than the emission standards required by EPA). Therefore, no post-combustion SO_x treatment is required when switchgrass alone is fired. Also, because of the ash characteristics of switchgrass, no waste from combustion was reused and all of it was transported 5 miles to a land fill. The following items were considered as waste in this model: all ash, unburned carbon and captured sulfur. These will result in waste of 51.85 g/kg switchgrass burned or 56.42 g/kWhr electricity generated by switchgrass-fired alone.

The waste transportation was assumed to be transported by a heavy-duty truck with load capacity of 25 tons. The following table gives the calculated GHG emissions from post combustion activity (waste transport) of switchgrass-fired alone.

Table 10: GHG emissions from post combustion activities of switchgrass-fired alone.

Emission species	CO_2	N_2O	CH_4	CO_2-Eq
Emission factors (g/kg switchgrass)	0.073	1.70E-6	8.37E-5	0.075
Emissions (g/KWh)	0.079	1.85E-6	9.10E-5	0.082

3.4.2 Switchgrass co-fired with coal

Co-firing will occur in an existing coal-fired power plant, so the equipment should have the same capacity for post-combustion control of SO_x. The decrease of SO_x emission due to switchgrass co-firing will be regarded as a positive credit that can be used for SO_x offset trading. Post combustion control of SO_x will generate three different sources of GHG emissions, i.e. limestone production and transportation, chemical reaction of limestone and SO_x, and transportation of generated waste. Table 11 lists all the GHG emission contributions of post combustion control of SO_x emission from 5% switchgrass co-firing with coal.

The reused waste of co-firing is also assumed to be equal in amount to that of coal-fired alone. Waste has a steady market and the quality of co-firing waste is acceptable to the market. Thus, the total waste from co-firing ($W_{waste,co}$) can be calculated as follows:

$$\begin{aligned} W_{waste,co} = {} & (P_{ash,sw} + P_{c,sw}*(1-BF_{c,sw}) + P_{s,sw}*MW_{SOx}/MW_S)*W_{sw,co} \\ & +[P_{ash,coal} + P_{c,coal}*(1-BF_{c,coal}) + P_{s,coal}*MW_{SOx}/MW_s]*W_{coal,co} - \\ & E_{SOx,co} - E_{CH4,co} - E_{CO,co} + W_{CaSO4} + W_{CaCO3}*(R_{CaCO3/SOx}-1) - W_{waste,reused} \end{aligned}$$

where $W_{CaSO4} = W_{SOx,contr}*MW_{CaSO4}/MW_{SOx}$

The total waste of the 5% switchgrass co-firing would be 38.84 g/kWhr assuming it is transported 5 miles from the power plant. The GHG emissions due to this transportation are listed in Table 11.

Table 11: GHG Emissions from post combustion activities.

Emission Category	CO_2	N_2O	CH_4	CO_2-Eq
Emission from limestone production,	2.37	2.74E-6	1.4E-4	2.38

transportation, reaction (g/kWhr)				
Emission from waste transportation (g/kWhr)	0.09	2.05E-6	1.0E-4	0.09
Total emission from post combustion activities (g/kWhr)	2.46	4.80E-6	2.4E-4	2.47

4 Summary of Reults

4.1 Cost Evaluation

The strategies of establishing switchgrass on pasture or crop lands followed by loose harvest then transport after compression into modules are both cost effective. Model 123 which is associated with establishment of switchgrass on pasture land leads to an overall production cost of $36.14/ton. Model 223 in which switchgrass is established on crop lands leads to production cost of $37.47/ton. Switchgrass will likely replace pasture lands first providing little or no net gain in carbon sequestration (Bransby *et al*), but the extent of pasture land is limited and also the yield of switchgrass on pasture land is lower. Hence a combination of both strategies would be required with switchgrass being established on previously cropped fields.

Before biomass arrives at the power plant, energy is consumed during the processes of establishment, growth, harvest, transportation as well as the processes of production and transportation of chemicals used for switchgrass production. The total energy consumed in this process on a tons of delivered product basis is listed in Table 12 with the smallest value of 949.67 btu/kg switchgrass for Model 223 and largest value of 1627.61 btu/kg switchgrass for Model 124, which corresponds to a switchgrass net energy gain (based on HHV) of 93.73% and 89.25% respectively.

Table 12: Net energy gain of switchgrass as a bioenegy feedstock.

Switchgrass processing model	223	111	211	122	123	124	222	224
Total energy consumption prior to	950	1530	1524	1387	955	1628	1381	1622

power plant (btu/kg switchgrass)								
Used energy (based on tested HHV)	6.3%	10.1%	10.3%	9.2%	6.3%	10.8%	9.1%	10.7%
Net energy efficiency (based on tested HHV)	93.7%	89.9%	89.9%	90.8%	93.7%	89.3%	90.9%	89.3%

4.2 Lifecycle GHG emissions

By analyzing the alternatives for their GHG emissions, the lifecycle GHG emissions from switchgrass-fired alone and co-fired to generate 1 kWhr of electricity can be found. The GHG mitigation during co-firing is better than switchgrass fired alone. The lifecycle analyses for GHG emissions of switchgrass as the energy feedstock for power generation with the Model 223 is listed in the Table 13. CO_2-Eq emissions from 5% switchgrass co-firing of 998.8 g/kWhr can be compared with 1031.4 g/kWhr CO_2-Eq emissions for coal burnt alone. The GHG emissions for a co-firing ratio of 10% are 900 g/kWhr and for 15% are 850 g/kWhr.

Table 13: GHG Emissions from switchgrass burnt alone and from 5% co-firing of switchgrass with coal.

(Shouldn't Sox be in this table????)

Emission species	CO_2	N_2O	CH_4	CO_2-Eq
GHG Emissions for switchgrass-fired alone model (g/kWhr)	-72.6	0.321	2.96	90.5
GHG Emissions for 5% switchgrass co-firing model (g/kWhr)	949.5	0.025	1.25	985.6
GHG Emissions assigned to switchgrass in 5% co-firing model (g/kWhr from switchgrass)	-48.5	0.214	1.88	58.1

(It appears to me that if I generate 1 kWhr with only switchgrass I get 90.5 CO2-Eq. If I generate 1kWhr from 5% co-fire I get 985.6 CO2-Eq. If the goal is to reduce GHG emissions wouldn't I pick the switchgrass fired alone plant? It appears that switchgrass is an even more efficient emissions reducer when burned with coal, however, this advantage is grossly overridden by the emissions from the coal burned in the co-firing. I don't think the 90.5 CO2-Eq switchgrass fired alone can be compared to the 58.1 CO2-Eq 5% co-fire because in the 5% co-fire case the power plant had to generate 20 kWhr before the same quantity of switchgrass to was used to generate 1 kWhr in the switchgrass alone case and the coal emissions for generating 20 kWhr were not taken into account in calculating the 58.1 CO2-Eq. I can't see how a co-fired plant would ever be a lower emitter that a switchgrass alone plant. How is this number negative?)

5 Discussion

5.1 Comparison of GHG mitigation of alternative preparation methods

Assuming switchgrass from different processing combinations has the same quality and combustion characteristics, the effects of combination on GHG emissions can be judged by comparing the GHG emissions from different processing combinations of switchgrass preparation. Another intuitive approach is to compare the GHG mitigation of switchgrass before combustion. The GHG mitigation data demonstrates how switchgrass performs as a GHG emissions mitigating energy feedstock. The advantage of Models 123 and 223 is obvious, with the later being even more advantageous as shown in Fig. 8.

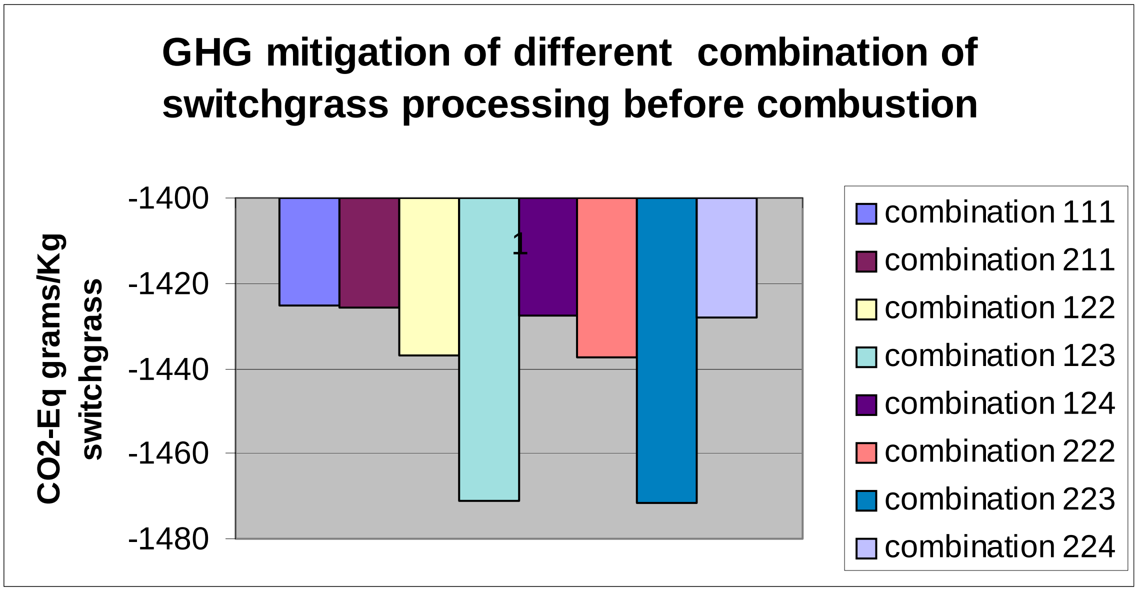


Fig. 8: GHG mitigation of switchgrass processing before combustion for different alternative activity combinations.

5.2 GHG emission relative to switchgrass co-firing ratio

Figure 9 shows the trend of GHG emissions ($E_{GHG,co}$) with the co-firing ratio of switchgrass thermal input based on Model 223 . The simulated relation gives a linear function as

$$E_{GHG,co} = -915.93\ R_{sw,co} + 1031.7$$

The linear relation basically is due to the model which fixed the thermal efficiency of switchgrass during the discussed co-firing ratio and the reduction in GHG emissions being the effect on CO_2.

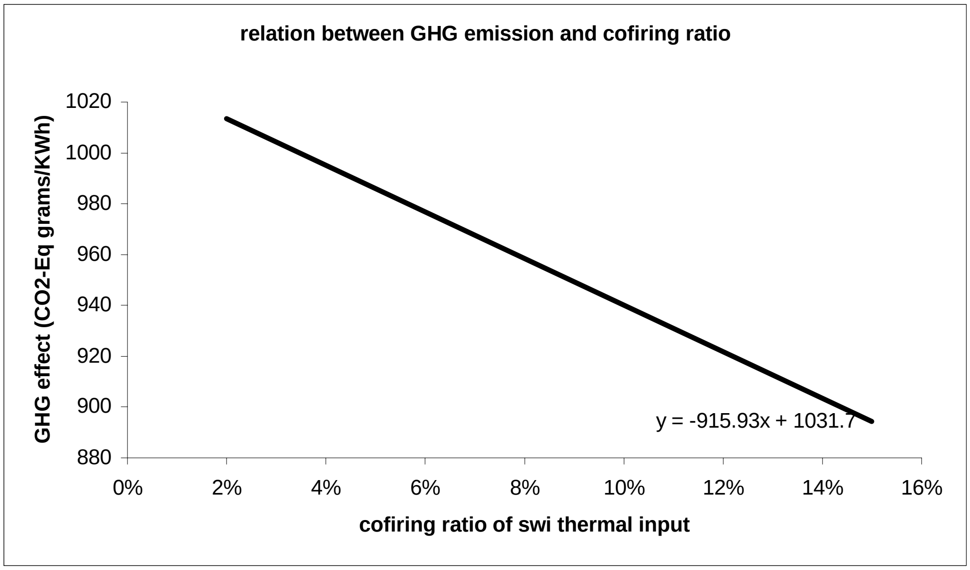


Fig. 9: GHG Emissions as a function of co-firing ratio.

5.3 Carbon-dioxide-Equivalent Offset Subsidy

Lifecycle analyses of biomass and coal as the energy sources for power generation indicate that biomass will generate less GHG emissions. But biomass co-firing would only be economical if the cost savings by replacing coal with switchgrass can more than offset the capital modification cost in the plant and any additional labor and maintenance costs to operate the co-firing plant. For biomass to become a practical method to mitigate GHG emissions from power generation, the high cost of biomass must be overcome.

Technical progress in biomass growth and transportation are crucial to reducing costs. Imposing a carbon cost on carbon emitters will make the commercialization of biomass even more practical. The major costs in the co-firing operation include the cost of fuel and the capital cost of modification of the power plant to enable biomass fuel to be co-fired with coal. The difference between the cost for switchgrass and the cost of coal displaced by switchgrass is taken into account by valuing the CO_2-Eq offset. The calculation of CO_2-Eq offset subsidy is based on the idea that to generate equal amount of electricity, the cost of coal fired alone should be equal to the cost of switchgrass fired alone or the cost of switchgrass co-fired with coal after CO_2-Eq offset subsidy is added. Thus, to make switchgrass an economically viable biomass power generation fuel, the need for the CO_2-Eq offset subsidy would have to be eliminated. The sensitivity of CO_2-Eq offset subsidy to various factors will indicate which factors should be researched to make switchgrass economically viable.

For switchgrass fired alone:

$$C_{coal}*W_{coal,bn}+C_{GHG}*E_{GHG,coal,bn,lc} = C_{sw}*W_{sw,bn}+C_{GHG}*E_{GHG,sw,lc}$$

For switchgrass co-firing with coal:

$$C_{coal}*W_{coal,bn}+C_{GHG}*E_{GHG,coal,bn,lc} = C_{coal}*W_{coal,co}+ C_{sw}*W_{sw,co} +C_{GHG}*E_{GHG,co,lc}$$

The delivered cost of coal is taken as $28.13/tonne of coal based on the 2002 US national average data from EIA/EPA-2002.

Besides the fuel costs and CO_2-Eq offset subsidy, the extra cost due to power plant modification for switchgrass co-firing in coal fired power plants and the allowance for SO_x reduction were also taken into account. Theoretically, the change of NO_x should be considered too, but because of the inconsistent conclusions about the NO_x emissions of switchgrass co-firing and the trade of NO_x offsets is not nationwide, we will leave this issue for future work. Thus the CO_2-Eq offset subsidy can be calculated from the following formulae:

For switchgrass fired alone:

$$C_{coal}*W_{coal,bn}+C_{GHG}*E_{GHG,coal,bn,lc} = C_{sw}*W_{sw,bn}+C_{GHG}*E_{GHG,sw,lc}+C_{SOx}$$

For co-firing switchgrass with coal:

$$C_{coal}*W_{coal,bn}+C_{GHG}*E_{GHG,coal,bn,lc}= C_{coal}*W_{coal,co}+ C_{sw}*W_{sw,co}+C_{GHG}*E_{GHG,co,lc}+C_{modi}+C_{SOx}$$

where cost of power plant modification and allowance of SO_x reduction can be calculated as shown in the following sections.

5.3.1 Cost of power plant modification

The modification cost for co-firing capability is \$50-100/kW for blending feed and \$175-200/kW for separate feed (kW of biomass power capacity) (Hughes *et al*, 2000). A 100 MW boiler co-fired at 5%, which has a \$200/kW cost of capital modifications would cost \$ 943764.94 to modify. With a salvage value of 10% of initial value and a 10 year useful life, the straight-line depreciation cost per year per unit would be \$0.85/kW/year, or \$0.12/MWhr (assuming 300 days of operation per year, and 24 hours operation per day). At 10% co-firing, the depreciation expense becomes \$0.24/MWhr and at 15%, \$0.36/MWhr. The cost of modification (\$kWhr) is found to be a function of co-firing as $C_{modi}=18*R_{Sw,thermal}+3*10^{-15}$. (To increase co-firing does more equipment have to be installed. If not, the deprecation cost should not go up with the co-firing %)

5.3.2 Allowance for SO_x reduction

The reduction of SO_x emissions due to switchgrass co-firing will be regarded as a positive credit as traded under the Acid Rain program. The credit for SO_x is the difference between the amount of SO_x generated from coal fired and co-fired power plants for a given amount of electricity generated. Dividing the credit by the electricity generated, the per unit electricity SO_x reduction at this switchgrass co-firing ratio was determined. This reduction multiplied by the SO_x trading price gives the cost allowance for SO_x reduction. The general formula for calculating the reduction of SO_x emission is:

$W_{SOx,co,credit}=W_{sw,co}*HHV_{sw}/NPHR_{sw,co}*NPHR_{coal}*EF_{SOx,coal}-W_{sw,co}*HHV_{sw}*EF_{SOx,sw}$

This formula can also be used for biomass fired alone plants to calculate the SO_x credits due to the replacement of coal with biomass for electric generation.

Assuming the SO_x credit trading price is \$250/ton SO_x [Tharakan *et al*], the formula indicates that from the value of SO_x reduction when generating 1 kWhr electricity through switchgrass co-firing is related to the switchgrass co-firing ratio as:

C_{SOx}=0.0021*$R_{sw,thermal}$ – 10^{-16}.(for switchgrass fired alone what would be the value of Sox reduction be at $250/ton?)

5.3.3 CO_2-Eq offset subsidy and cost of coal

Figure 10 illustrates CO_2 offset subsidy as a function of the costs of coal and switchgrass. It shows the cost of coal ($/tonne) relative to the cost of switchgrass ($/ton) for CO_2 offset subsidy to breakeven. Figure 11 shows the grid for the breakeven points as the switchgrass cost is varied from $ 10/ton to $ 60/ton. The CO_2-Eq offset breakeven price relative to coal for switchgrass is highlighted and the striped box shows the current cost of coal and switchgrass. It shows that with the current cost of switchgrass, it would take almost doubling of the coal cost for switchgrass to break even with coal.

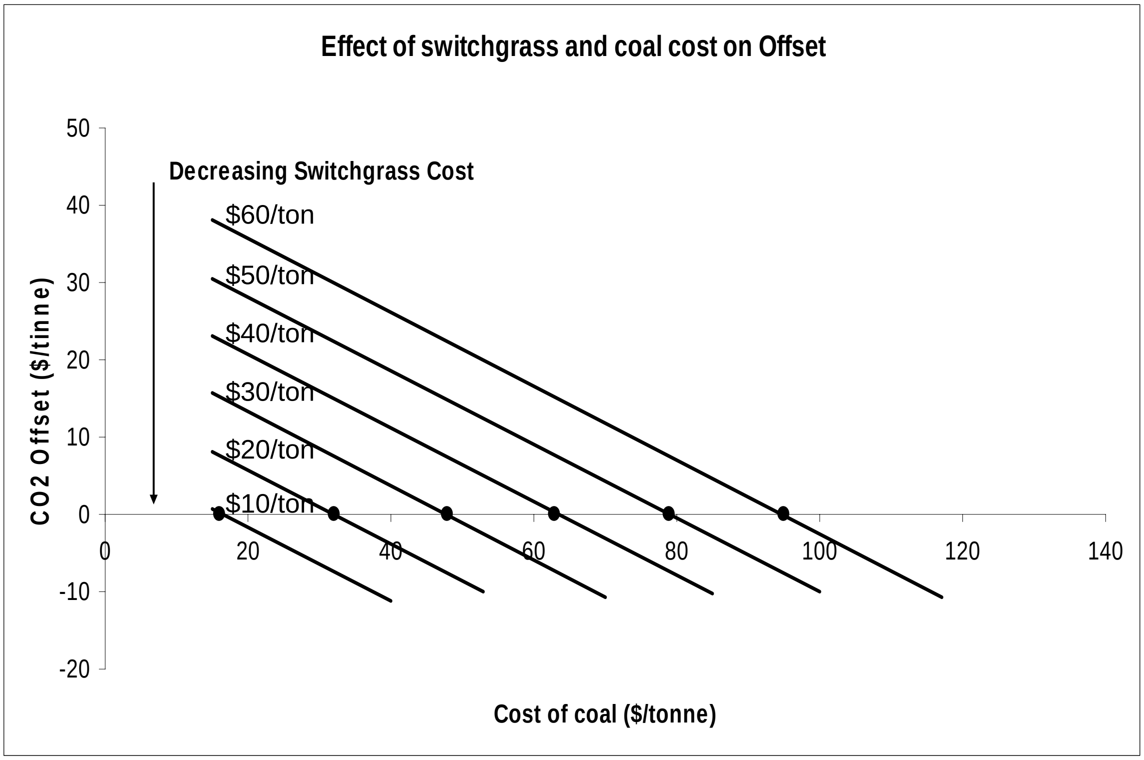
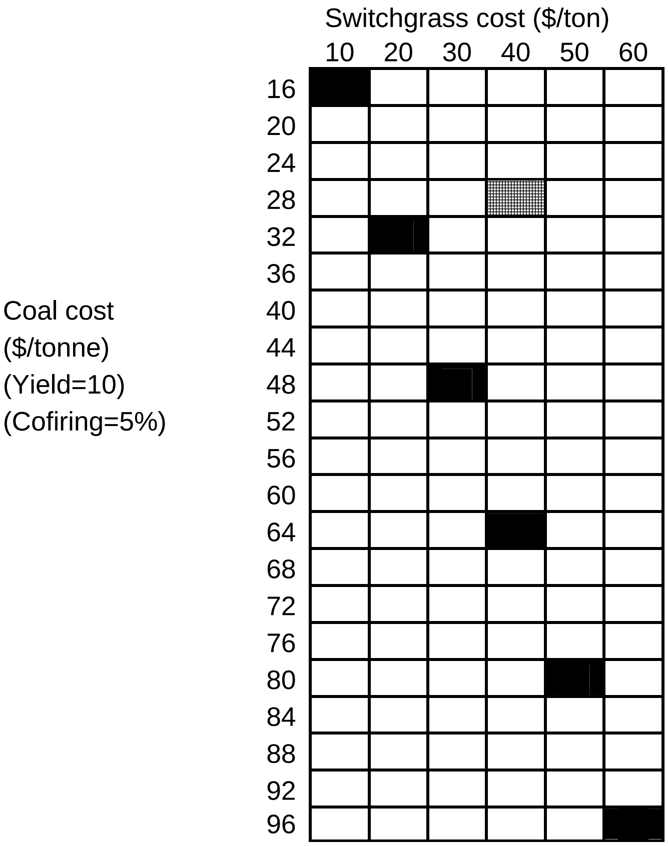


Fig 10: Effect of switchgrass and coal cost as CO_2 offset subsidy breaks even.



Switchgrass cost ($/ton)

Coal cost ($/tonne) (Yield=10) (Cofiring=5%)	10	20	30	40	50	60
16	■					
20						
24						
28				▨		
32		■				
36						
40						
44						
48			■			
52						
56						
60						
64				■		
68						
72						
76						
80					■	
84						
88						
92						
96						■

Fig. 11: Grid illustrating CO_2 offset subsidy break even points.

(Should there be three calculations here, current coal price and estimated switchgrass costs what is the subsidy? Current coal price and current carbon trading price what is the breakeven for switch grass? Current carbon trading price and estimated switchgrass cost where would the price of coal have to go? Also farmer will not grow switchgrass at breakeven, but maybe for breakeven plus $30 /acre I don't wuite understand the picture)

5.3.4 CO_2-Eq offset subsidy and switchgrass co-firing ratio

The resultant CO_2-Eq offset price that causes co firing to be cost competitive with coal is approximately $16.50/tonne CO_2-Eq(does not include the coal emissions), with minor changes, across the range of co-firing alternatives till 20%. The reason for such a behavior is the constant net plant heat rate used up to 20% co-firing and CO_2 being the lone emission. This can be compared with $32/tonne CO_2-Eq for firing switchgrass alone. Most practical tests have been done with co-firing of up to 20%, beyond which the problems associated with the nature of biomass cause difficulty. The trend for offset subsidy as a function of co-firing beyond 20% is shown as a dashed line. The net plant heat rate for firing switchgrass up to 20% with coal is taken as 11.6MJ/kWhr and that for firing switchgrass alone is taken as 17.4MJ/kWhr, with a linear increase from 20% to firing switchgrass alone. Further, SO_x reduction allowance and plant retrofit cost are assumed linear for all cofiring ratios.

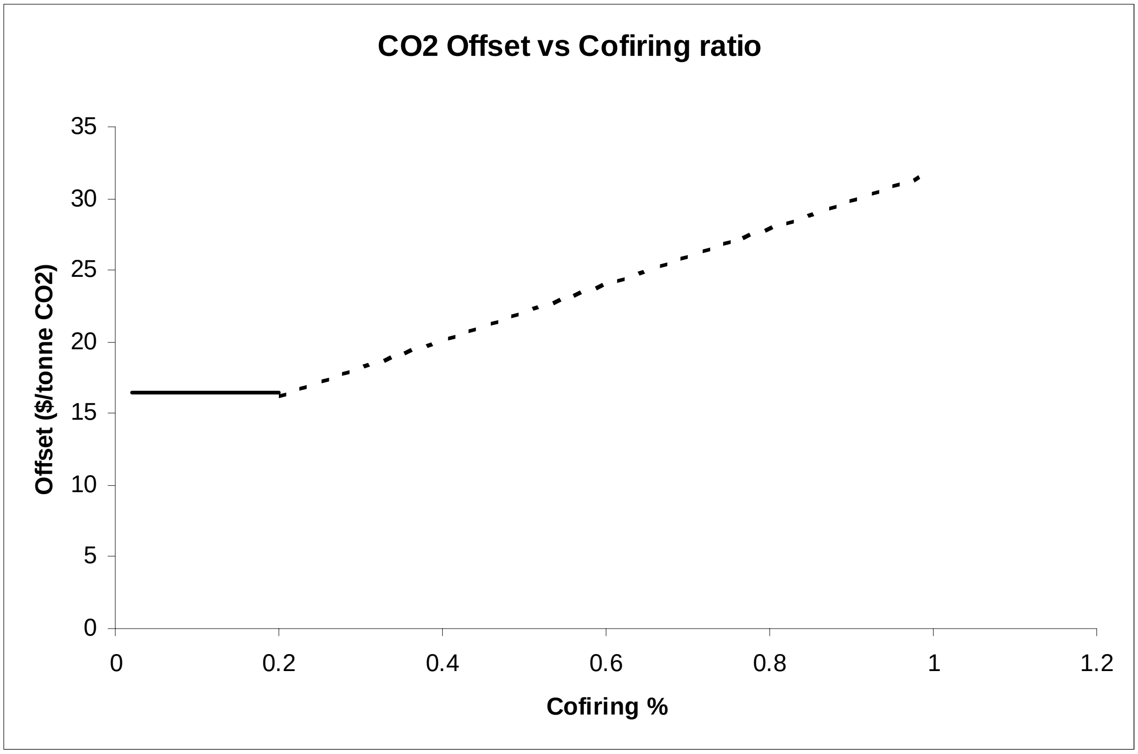


Fig 12: CO_2 offset subsidy as a function of co-firing ratio.

5.3.5 CO_2-Eq offset subsidy and hauling distance

Hauling distance is one of the key barriers for biomass commercialization as an energy feedstock. Transportation costs depend on the distance between the production site and the power plant and the road conditions. Noon et al estimated that average cost of transporting switchgrass in Alabama is $8.00/dry tonne for hauling distance of 25 miles [Noon *et al*, 1996]. As the transportation cost changes with the hauling distance, the CO_2-Eq offset subsidy will also change with the distance. Model results show that the change for different co-firing ratios is negligible for the ratios analyzed. For changes in the parameters of yield or stand life and for firing switchgrass alone, the CO_2-Eq offset subsidies changes are shown in Figure 13. Compared with the base case (5% co-firing, Y=10, SL=10), a change of switchgrass yield gives the largest impact on CO_2-Eq offset subsidy, which indicates that enhancing the switchgrass yield is important to reducing

CO_2 offset subsidies. Also, as stand life increases with the co-firing ratio and yield constant, the CO_2-Eq offset subsidy decreases.

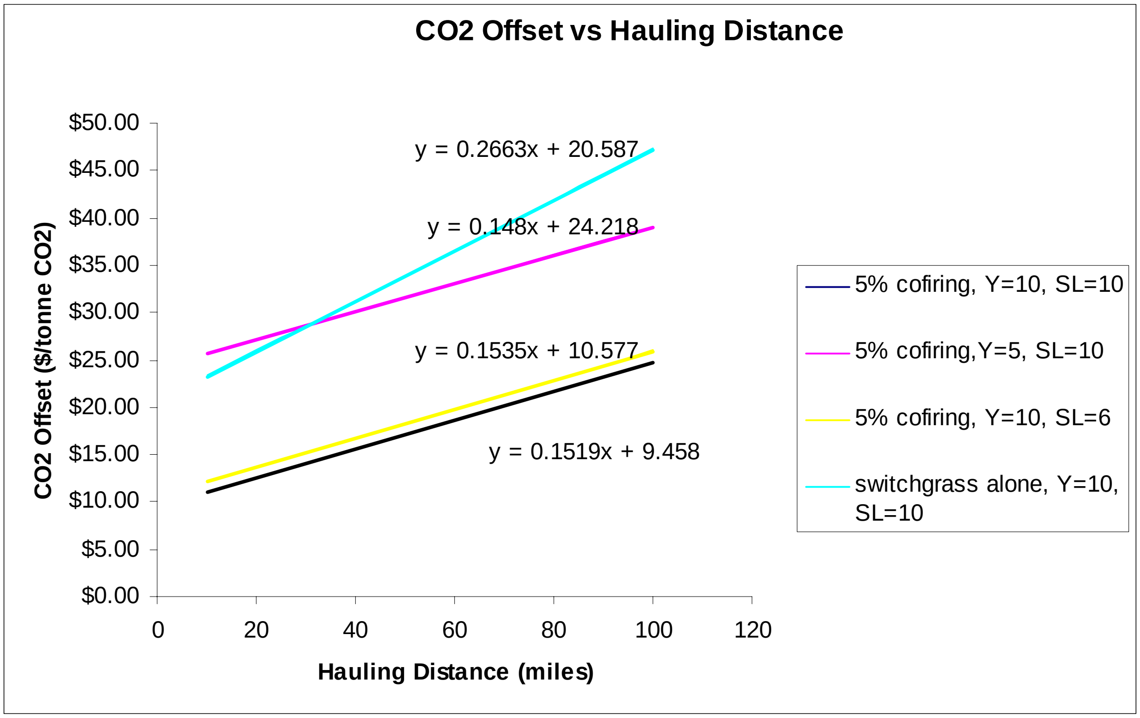


Fig. 13: CO_2 offset as a function of the hauling distance of switchgrass.

Under the same parameters of yield and stand life, the CO_2-Eq offset breakeven price relative to coal for switchgrass fired alone is much higher than switchgrass co-firing because heat efficiency of switchgrass fired alone is lower than when switchgrass is cofired with coal. Also, higher yield and longer stand life would reduce the CO_2-Eq offset subsidy. Further, the slopes of equations of the three co-firing cases with different yields and stand lives are around 0.15, but the slope of switchgrass fired alone equation is approximately 0.27. This indicates that a switchgrass fired alone plant would be much more dependent on switchgrass fields located far away from the plant and thus have much higher switchgrass transportation costs per unit hauled.

5.3.6 CO_2-Eq offset subsidy and switchgrass density(switchgrass density and hauling distance indicate the same concept. I think we should have one or the other, probably delete this section I actually prefer the second)

Figure 14 illustrates the effect of switchgrass density and yield on the offset subsidy. As the switchgrass density is increased, the hauling distance and the corresponding switchgrass cost decreases, but the decrease is only minor. For a particular yield, the CO_2 offset subsidy decreases very slightly with increase in the switchgrass density, but on increasing the yield, the offset subsidy decreases significantly.

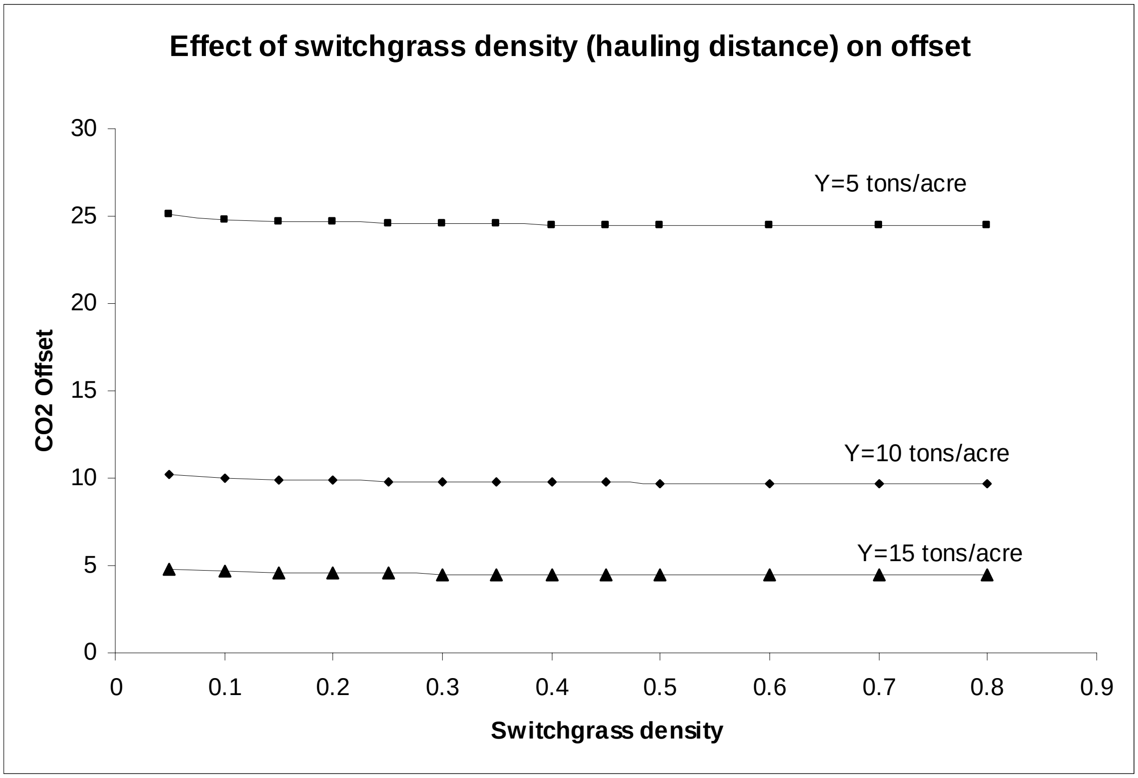


Fig. 14: CO_2 Offset as a function of switchgrass density.

5.3.7 CO_2-Eq offset subsidy and yield

Ther is potential to increase the yield of switchgrass by increasing the row placing and higher nitrogen application rate (Ma *et al*). As the yield of switchgrass (tons/acre) is increased (keeping the plant capacity and the stand life fixed at 100 MWhr and 10 years, respectively), the CO_2 offset subsidy decreases exponentially, independent of the co-firing percentage. The sensitivity analysis shows that with lower yield, less than about 8 tons/acre, the CO_2 offset subsidy would need to be relatively large, but as the yield is increased, the needed subsidy decreases. For switchgrass yields above 12 tons/year, the decrease of CO_2 offset subsidy is less than $1/tonne CO_2-Eq for each additional ton of yield. The trend is the same for offset subsidy when the hauling distance is also varied keeping the switchgrass density fixed at 20%, with the only difference being that the offset subsidy is a little higher than before endogenizing hauling distance (50 miles).

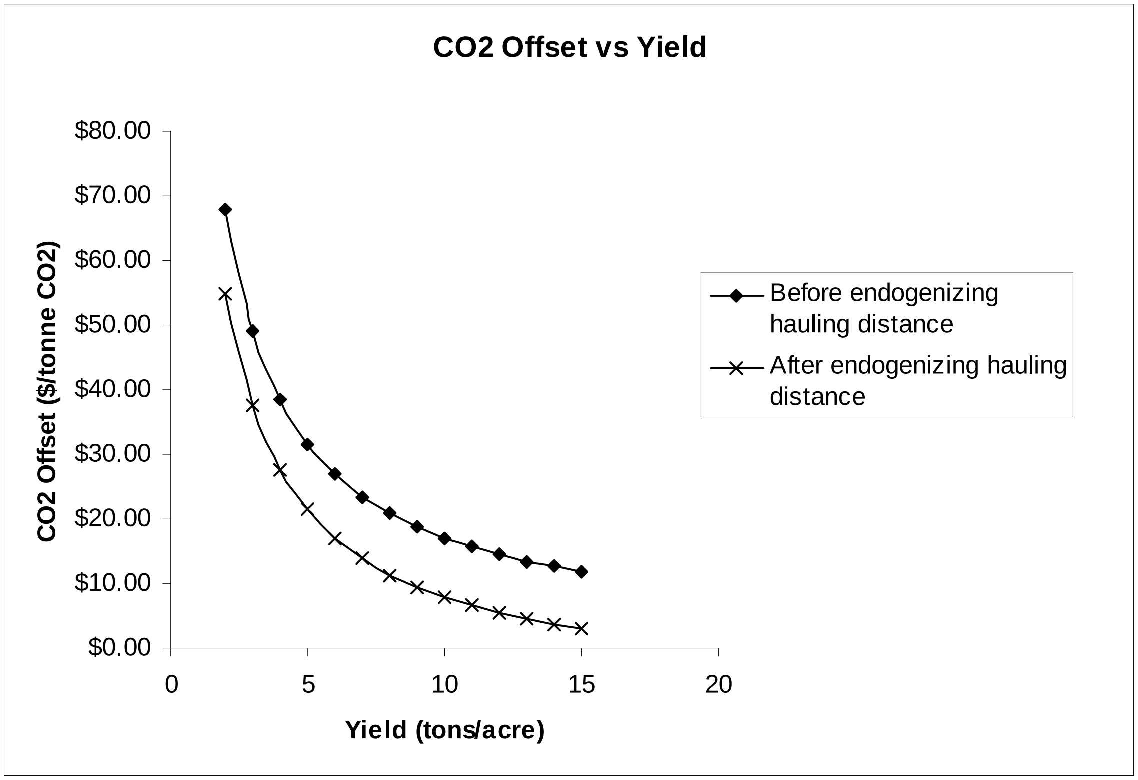


Fig. 15: CO_2 offset subsidy as a function of yield of switchgrass.

6 Conclusions and Recommendations

An integrated approach has been developed to examine the economic, energy and GHG issues of using switchgrass as an alternate or a supplementary feedstock for power generation. A life-cycle analysis model has been developed and incorporated into a pathway analysis for the screening of various phases of growth, harvesting, transportation, utilization, and discharge. The analysis shows shows that the most effective technologies for switchgrass preparation are establishing switchgrass on pasture and previously cropped fields, harvesting loose for hauling and chopping, and then transporting by compression into modules, which cost \$36.14 and \$37.47 per ton of switchgrass produced, respectively. The energy consumption for establishment of switchgrass on existing cropped fields, harvest and transportation is 502.84 btu/kg switchgrass and GHG effects are 41.62 CO_2-Eq g/kg switchgrass. The total energy consumed before switchgrass is sent for combustion into power generation ranges from 949.67 btu/kg switchgrass to 1627.61 btu/kg switchgrass, which corresponds to a switchgrass net energy gain (based on HHV) of 93.73% and 89.25% respectively. The GHG mitigation during co-firing is better than switchgrass fired alone with the GHG effects of 90.5 g CO_2-Eq /kWhr for switchgrass fired alone and 58.1 g CO_2-Eq /kWhr for 5% switchgrass co fired with coal. This paper analyzed the CO_2–Eq offset subsidy as a function of co-firing ratio, hauling distance, yield, and stand life. Enhancing switchgrass yield is the most important way to reduce CO_2 offset subsidies needed to use switchgrass as a biofuel. Reducing the hauling distance of switchgrass to the power plant also will reduce needed CO_2 offset subsidies.

If switchgrass is to become competitive with coal as power generation fuel, either a CO_2 offset market price is needed or costs must fall dramatically. To make switchgrass an economically viable power generation fuel, under current prices, agronomic research must improve switchgrass yields, develop lower cost establishment and growing practices, determine more efficient and lower costs harvest and transportation processes. Procurement planning should be pursued by power companies to develop the organizational and legal framework for establishing switchgrass on all agronomically suitable available land nearest the power plant. Engineering research should be conducted into more efficient methods of co-firing and reducing the non-CO_2 emissions of switchgrass. Research should also explore potential uses for waste after co-firing.

7 **Acknowledgment:** The financial support of this work by a grant from the US Department of Agriculture, Natural Resources Conservation Center (grant # USDA NRCS 68-3A75-3-152) is gratefully acknowledged.

8 Nomenclature

BF_c : Burning fraction of carbon which is 99% (as used by EPA)

$BF_{c,coal}$: Burning fraction of carbon of coal

$BF_{c,sw}$: Burning fraction of carbon of switchgrass

C_{coal} : National Average Cost of coal

C_{GHG} : Offset subsidy of carbon dioxide equivalent

C_{modi} : Cost of modification of plant to cofire switchgrass with coal

C_{Sox} : Cost of allowance of SO_x reduction

C_{sw} : Cost of switchgrass (includes preparation and delivery)

$E_{CH4,co}$: Emissions of CH_4 in cofiring

$E_{CO,co}$: Emissions of CO in cofiring

EF_{CO2} : Emission factor for Carbon dioxide

$EF_{SOx,coal}$: Emission factor of SO_x for coal

$EF_{SOx,sw}$: Emission factor of SO_x for switchgrass

$E_{GHG,co}$: Emissions of Greenhouse Gases during cofiring

$E_{GHG,co,lc}$: Greenhouse Gas Emissions during cofiring (lifecycle)

$E_{GHG,coal,bn,lc}$: Greenhouse Gas Emissions from coal burnt alone (lifecycle)

$E_{GHG,sw,lc}$: GHG Emissions from switchgrass burnt alone (lifecycle)

$E_{SOx,co}$: Emissions of SO_x during cofiring

HHV_{fuel} : High heating value of fuel

HHV_{sw} : High heating value of switchgrass

MW_c : Molecular weight of C

MW_{CaSO4} : Molecular weight of $CaSO_4$

MW_{CO2} : Molecular weight of CO_2

MW_s : Molecular weight of sulfur

MW_{Sox} : Molecular weight of SO_x

$NPHR_{fuel,co}$: Net plant heat rate of fuel cofired

$NPHR_{sw,bn}$: Net plant heat rate of switchgrass burned alone

$NPHR_{sw,co}$: Net plant heat rate of switchgrass cofired

$P_{ash,coal}$: Ash content in coal

$P_{ash,sw}$: Ash content in switchgrass

P_c : Carbon content in fuel

$P_{c,coal}$: Carbon content in coal

$P_{c,sw}$: Carbon content in switchgrass

$P_{s,coal}$: Sulfur content in coal

Q_{elec} : Electricity generated

$Q_{elec,co}$: Electricity generated by cofiring

$Q_{sw,bn}$: Electricity generated by burning switchgrass alone

$R_{CaCO3/SOx}$: Ratio of $CaCO_3$ to SO_x in SO_x treatment

$R_{sw,co}$: Switchgrass cofiring ratio

$R_{sw,thermal}$: Switchgrass cofiring ratio (thermal input)

W_{CaCO3} : Weight of $CaCO_3$

W_{CaSO4} : Weight of $CaSO_4$

W_{CaSO4} : Weight of $CaSO_4$

$W_{coal,bn}$: Weight of coal burnt alone

$W_{coal,co}$: Weight of coal in cofiring

$W_{coal,co}$: Weight of coal used in cofiring

$W_{fuel,co}$: Weight of the fuel cofired

$W_{SOx,co,credit}$: Weight of SO_x used in cofiring that is credited

$W_{SOx,contr}$: Weight of SO_x controlled

$W_{sw,bn}$: Weight of switchgrass burnt alone

$W_{sw,bn}$: Weight of switchgrass for switchgrass burnt alone

$W_{sw,co}$: Weight of switchgrass used in cofiring

$W_{sw,co}$: Weight of switchgrass cofired

$W_{sw,co}$: Weight of switchgrass cofired

$W_{waste,co}$: Total amount of waste from cofiring

$W_{waste,reused}$: Weight of waste that can be reused

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