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Switchgrass as an alternate feedstock for power generation: an integrated environmental, energy and economic life-cycle assessment

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Abstract An environmental biocomplexity analysis is done on the environmental, energy, economic and technological implications of using switchgrass (*Panicum virgatum*) to replace coal in power generation. We evaluate cost, environmental impact and net greenhouse gas emissions. In the analysis, alternatives for production and transport are considered. The analysis shows that the most effective technologies for switchgrass preparation are harvesting loose material for hauling and chopping and then compressing it into modules and transporting. The GHG emission mitigation is found to be substantial with the mitigation contribution under cofiring found to be greater per ton of switchgrass than for switchgrass fired alone. This paper also analyzes the implications of switchgrass use under alternative cofiring ratios, coal prices, hauling distances and per acre yields.

Keywords Biomass utilization · Switchgrass · Life cycle analysis · Greenhouse gases · Carbon tax

List of Symbols

BF_c	Burning fraction of carbon which is 99% (as used by USEPA)
$BF_{c,coal}$	Burning fraction of carbon of coal
$BF_{c,sw}$	Burning fraction of carbon of switchgrass
C_{coal}	National average cost of coal
C_{GHG}	Emission price in $ per metric ton of carbon dioxide equivalent
C_{modi}	Cost of modification of plant to cofire switchgrass with coal
C_{SO_x}	Cost of allowance of SO_x reduction
C_{sw}	Cost of switchgrass (includes preparation and delivery)
$E_{CH_4,co}$	Emissions of CH_4 in cofiring
$E_{CO,co}$	Emissions of CO in cofiring
EF_{CO_2}	Emission factor for carbon dioxide
$EF_{SO_x,MO}$	Emission factor of SO_x for coal
$EF_{SO_x,sw}$	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)
$E_{SO_x,co}$	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_{CaSO_4}	Molecular weight of $CaSO_4$
MW_{CO_2}	Molecular weight of CO_2
MW_s	Molecular weight of sulfur
MW_{SO_x}	Molecular weight of SO_x
$NPHR_{fuel,co}$	Net plant heat rate of fuel cofired

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$NPHR_{sw,bn}$	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_{CaCO_3/SO_x}	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_{CaCO_3}	Weight of $CaCO_3$
W_{CaSO_4}	Weight of $CaSO_4$
W_{CaSO_4}	Weight of $CaSO_4$
$W_{coal,bn}$	Weight of coal burnt alone
$W_{coal,co}$	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
$W_{sw,co}$	Weight of switchgrass used in cofiring
$W_{waste,co}$	Total amount of waste from cofiring
$W_{waste,reused}$	Weight of waste that can be reused

Introduction

Fossil fuel usage is a large contributor to the production of anthropogenic GHG emissions. Mintzer et al. (2003) estimate that in 2002, 98.0% or 5,682 million metric tons of total US carbon dioxide emissions resulted from fossil fuel combustion with about half from each of the coal fired electrical production and petroleum products usage. Overall, total US GHG emissions have risen by 13% from 1990 to 2002 (Hockstad and Hanle 2004). Expectations are that in the near term this will continue to rise. The Intergovernmental Panel on Climate Change projects that continued emissions will lead to a temperature increase between 1.4 and 5.8°C over the period 1990–2100, or a decadal increase between 0.15 and 0.35°C, which is argued to be greater than the estimated maximum average

temperature increase that the environment can withstand without damage (0.1°C per decade). Therefore, the IPCC and others suggest that the future amount of carbon dioxide (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. In USA, despite rejecting ratification of 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 substitution of less emission intensive alternative fuels for fossil fuels. One such source is bioenergy where agriculturally grown biomass is used as a feedstock for energy production. When bioenergy feedstocks are used in place of fossil fuels, net carbon emissions decrease because carbon is withdrawn from the atmosphere via photosynthesis during feedstock growth. Switchgrass use in electrical generation is such an alternative.

Biomass conversion into forms of energy is an old idea but one that is receiving increasing attention is 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 USA 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 largely 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 developments are occurring that may make biomass feedstocks competitive. These involve:

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

- 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.
- An enhanced desire for a cleaner environment and a move to reduce emissions from fossil fuels.
- Continued concern over the degree of energy dependency on foreign sources of petroleum.

Studies evaluating the feasibility and cost of replacing coal use with switchgrass indicate that the prospect appears promising (e.g., Boylan et al. 2000). However, if switchgrass or other biofuels are to expand as a feedstock, society must 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 (El-Halwagi 2003).

In order to be profitable, energy crops need to

- Produce high yields of biomass.
- Contain low concentrations of water, nitrogen and ash.

Perennial, herbaceous energy crops such as switchgrass can be used for developing bioenergy and bioproducts. In USA, switchgrass is considered a promising prospect for bioenergy production in a wide range of regions. It is noted for its heavy growth. It is also valuable for soil stabilization, erosion control and as a windbreak. The energy that can be generated from switchgrass 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).

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

- The use of markets for GHG emission credits as a vehicle for reducing emissions of GHGs as manifest in the Kyoto Protocol. Such a market would improve biofuel competitiveness, as there is a large GHG offset relative to coal use. This would, in effect, create subsidies for biomass use and, thus, enhance biomass growth and acceptance.
- Legislation such as the four pollutants bill or the clear skies initiative would limit sulfur oxides (SO_x), nitrous oxides (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), low mercury and low-ash content (Hughes 2000). Additionally, switchgrass burning leads to cost savings and expensive emissions control equipment for SO_x and NO_x would no longer be required. Another action that would be helpful in commercialization of biomass would involve a relaxation of the standards for ash usage in cement manufacturing (Hughes 2000). This would help plants cofiring up to 10 or 15% switchgrass provide ash for use in the cement industry.

This paper uses technical, environmental and economic data to analyze the implications of switchgrass use, examining alternatives from production to transport to power generation to waste disposal. In all scenarios, cost and emission issues are discussed.

Overall approach

In order to assess switchgrass use implications for cost, environmental impact and GHGs, a life cycle based environmental biocomplexity analysis was used. Interactions among technical, agricultural, economic and environmental factors were taken into account. The steps involved include growth, harvesting, preprocessing, power generation, postcombustion and disposal. Figure 1 gives a schematic representation of the steps as well as the energy and the GHG inputs and outputs. For each one of these steps, the material and energy flows were studied. In particular, the following issues were studied:

- Switchgrass production operations including plowing, disking, seeding, lime, herbicide and fertilizer application and harvesting.
- Lime soil reaction.
- 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 and associated GHG emissions upon degradation.

Fig. 1 Activities in ecological cycle of switchgrass to power (*M* represents a mixture of GHGs)
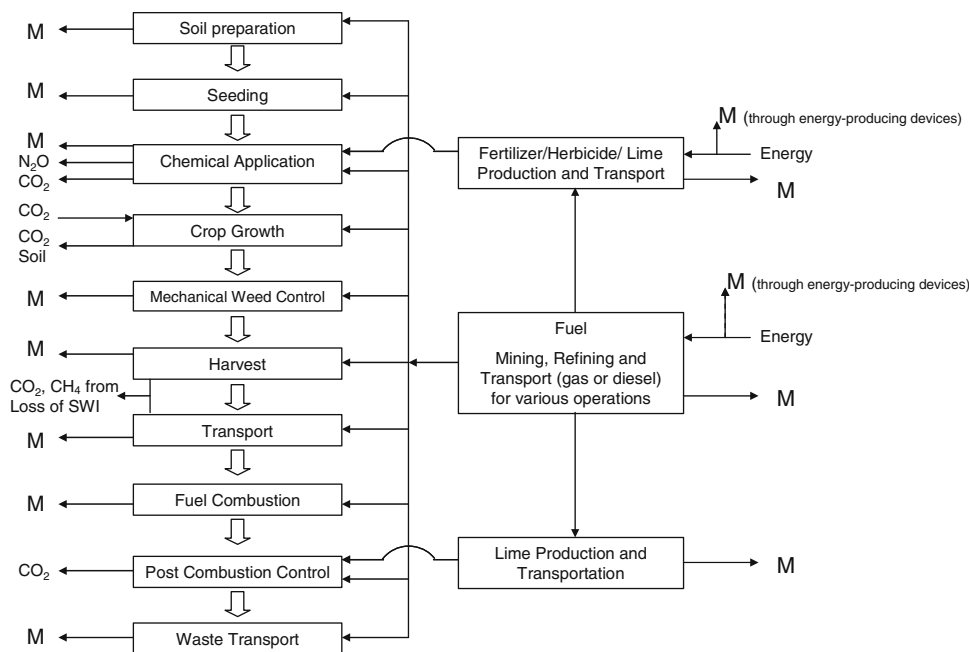
- Switchgrass versus coal combustion. This includes the net carbon balance when combusting switchgrass along with the postcombustion control of SO_x and transport of combustion waste to a landfill.

Various alternatives were screened in interaction. Finally, sensitivity analysis was conducted to identify key technological, environmental and economic insights and to determine dominating factors in the analysis. The following sections present details.

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.

Switchgrass preparation

Switchgrass preparation involves establishment, growth, harvest and transportation to the power plant as overviewed in Fig. 2. In analyzing the consequences, we follow the production practices and input usages recommended in Smith and Bransby (2005).

Switchgrass chemical composition is a key input to computations of GHG and other emissions. The assumed switchgrass composition (as received) used for

all calculations in this paper is based on Sami et al. (2001) and Aerts et al. (1997) and is shown in Table 1

The tested high heating value (HHV) for switchgrass, which is employed in this model, is 15,991 kJ/kg (Sami et al. 2001; Aerts et al. 1997).

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

The carbon content of the cellulose and hemi-cellulose is found by using their respective structural monomers.

The switchgrass yield is assumed to be 10 tons per acre year, the stand life (the number of years switchgrass is harvested before the grower re-establishes the stand for better economics) as 10 years and the transportation distance is assumed to be 25 miles.

Cost of switchgrass preparation

A cost analysis of switchgrass preparation for use in power generation was done following Sladden et al. (1991) and Smith and Bransby (2005). Component cost for all processing stages were evaluated by taking into consideration the variable, fixed and labor costs which include costs such as machinery, fuel, energy requirements, chemicals, etc. for all farm operations. Appropriate financial parameters such as interest rate, tax rate, insurance rate, cropland rental value and fuel prices were used in cost calculations.

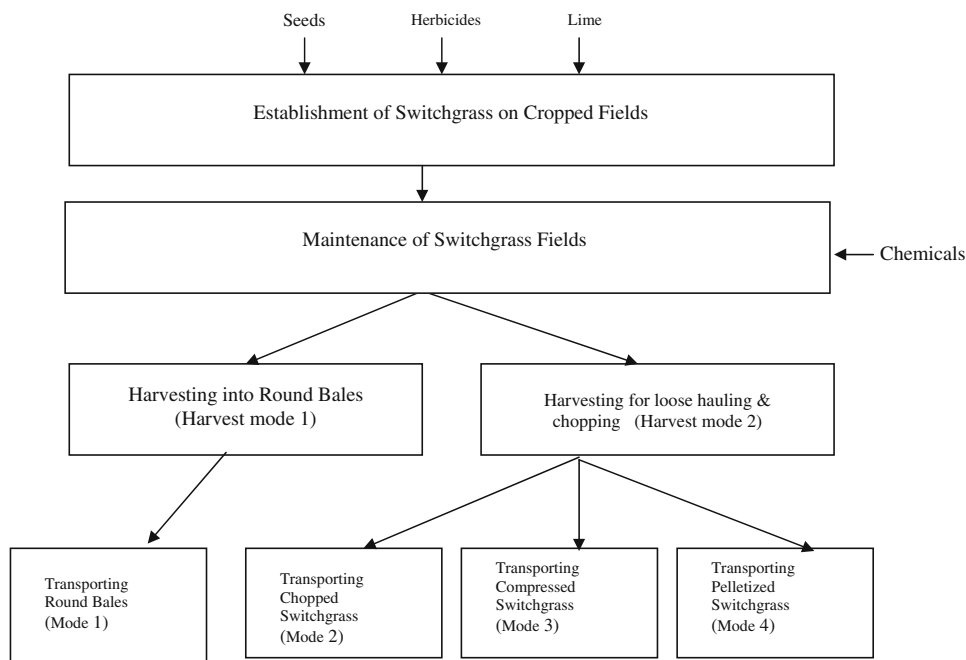**Fig. 2** Switchgrass preparation including delivery to power plant

Table 1 Switchgrass ultimate analysis

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

After calculating the component costs for establishment, growth, harvest and transportation, a total preparation cost budget was assembled. The total cost per ton of switchgrass for various combinations of alternative activities is shown in Fig. 3.

During the study we examined various pathways for switchgrass production involved with land type used, harvest method and transport method. Each of these possibilities generated a case which we designate as "model ab", where

Table 2 Cell wall constituents of switchgrass

Constituent	Percent on a bone dry weight base
Cellulose	37.10
Hemi cellulose	32.10
Fixed Carbon	13.60
Lignin	17.20

- 'a' gives harvesting method including round baling (1) or chopping and loose harvest (2).
- 'b' gives hauling preparation and resultant transport method including moving round bales (1), or moving loose material (2); compressed loose material (3) or pelletized loose material (4).

Based on the analysis, the most cost effective switchgrass preparation method was to establish switchgrass harvested loose for hauling and chopping, and transported by compression into modules (Model 23), an overall cost of $32.53 per ton.
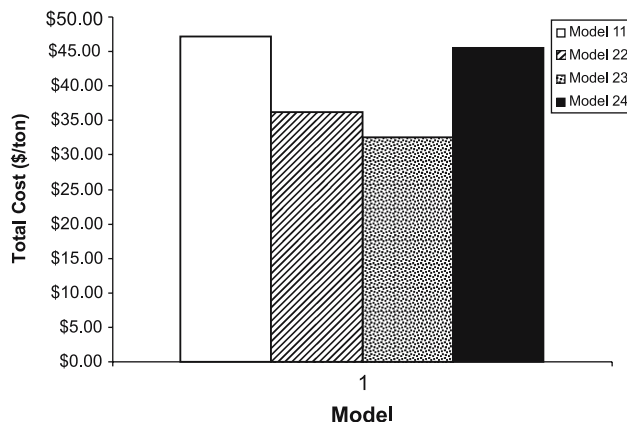

Fig. 3 Comparison of various combinations of alternative activities of switchgrass preparation for cost evaluation

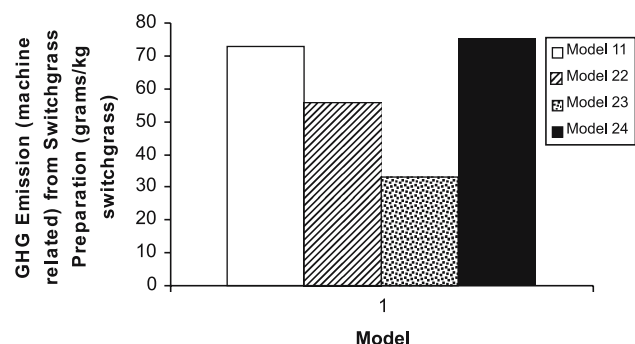**Table 3** GHG emissions and energy consumption from preparation of switchgrass

Switchgrass preparation stage	Embodied operations	Energy consumption (Btu/kg switchgrass)	CO_2 emissions (grams/kg switchgrass)	Nitrous oxide emissions (g/kg switchgrass)	Methane emissions (g/kg switchgrass)	CO_2-eq emissions (g/kg switchgrass)
Establishment	Land preparation	5	0.4	0.9E-5	0.5E-3	0.4
Growth	Growth	24	1.9	4.5E-5	2.4E-3	2.0
Harvest	Round bales (1)	190	15.0	7.1E-4	2.0E-2	15.7
	Loose, hauling and chopping (2)	59	4.7	1.1E-4	0.5E-2	4.8
Transport	Round bales(1)	672	52.8	1.2E-3	6.4E-2	54.7
	Loose, chopped (2)	598	46.9	1.1E-3	5.7E-2	48.5
	Loose, compressed (3)	311	24.7	1.4E-3	2.9E-2	25.8
	Loose, pelletized (4)	963	65.6	0.9E-3	9.0E-2	68.0

Environmental and energy assessment for switchgrass preparation

The GHG emissions is associated with switchgrass span activities for growing switchgrass and transporting it to a power plant plus any sequestered carbon in plants and soils. Emissions are also incurred when manufacturing inputs such as fossil fuels, chemicals, fertilizers and herbicides. We also considered the carbon that would have been released by coal combustion. Finally, GHG emissions due to fossil fuel mining/production, refining and transportation were included.

Emissions and energy—machinery operations for switchgrass preparation Energy consumption and GHG emissions were calculated for four stages of switchgrass preparation; establishment, growth, harvest and transport based on the machines used at each stage (Table 3). The emission and energy factors used were adopted from Wang and Santini (2000).

Considering all of the pathways for switchgrass production for the lowest GHG emissions, the least emission combination involved harvesting switchgrass loose for hauling and chopping, then transporting after compression into modules (Model 23). Field chopping switchgrass is preferable to baling as it leads to savings in transportation costs (Boylan et al. 2000). Figure 4 below shows total GHG emissions from machinery operation for delivered switchgrass.

GHG emissions and energy consumption of production inputs Lime, fertilizers and herbicides are applied during switchgrass establishment and growth. GHG emissions are generated when producing these inputs. Per acre input usage rates based on Smith and Bransby (2005) and Ney and Schnoor(2002) 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). In turn, we used lifecycle emission and energy consumption factors for atrazine and fertilizer production from the GREET model (Wang and Santini 2000).

We then find that the application of nitrogen fertilizer leads to the formation of nitrous oxide emissions from the soil. Ney and Schnoor (2002) estimated that 36.892 g N_2O was released from 1 kg nitrogen fertilizer used. This will lead to emissions of 0.203 g N_2O/kg switchgrass.
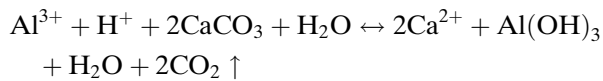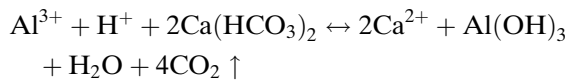
Emissions and energy consumption from the manufacture and transportation of lime are calculated based on the chemistry of the lime manufacture and transport processes. The reactions of lime in the soil will lead to direct CO_2 emission. The mechanism is summarized as follows:

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

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

Fig. 4 Total machinery related GHG emissions for switchgrass preparation

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	28.2	2.03E-1	6.5E-02	89.9
Emissions and energy consumption from agriculture lime (g or Btu/kg switchgrass)	6	9.2	1E-05	5E-04	9.2
Emissions and energy consumption from all chemicals (g or Btu/kg switchgrass)	447	37.4	2.03E-01	6.5E-02	99.1

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

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

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.

GHGs in switchgrass and soil

In tracking carbon uptake and release associated with the growth and preparation of switchgrass, the following issues must be considered: photosynthesis, sequestration in soil and GHG emissions due to switchgrass losses. The following are key information associated with these steps.

GHG in plants from photosynthesis Photosynthesis is the process by which plants use the energy from sunlight to produce sugar. The overall reaction of this process can be written as:

$$6H_2O + 6CO_2 \rightarrow C_6H_{12}O_6 + 6O_2$$
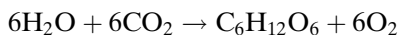
It is assumed that all the carbon in switchgrass is converted from CO_2. The resultant computed uptake is 1,540.5 g CO_2/kg switchgrass. It is assumed that 99% of this carbon is released upon combustion (as used by USEPA).

Carbon dioxide sequestration in the soil Soil carbon sequestration is also associated with switchgrass production. McLaughlin et al. (1999) 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, as well as after 5 years of cultivation in Virginia and surrounding states. Their studies indicated that carbon accumulation is comparable to, or greater than the 1.1 metric ton carbon per hectare-year reported for perennial grasses. Several years of switchgrass culture are required to realize the benefit of coil carbon sequestration (Bransby et al. 1998; Ma et al. 2000a, b, 2001). 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, carbon accumulation in the soil is likely to reach a saturation value as found in West and Post (2002), which should be taken into account for any long-term studies.

Because switchgrass is not now used as a bioenergy feedstock, this model included a credit for the soil sequestration of carbon from the growing of switchgrass. With the wide adoption of switchgrass as a bioenergy feedstock, soil carbon levels eventually reach a new saturation or equilibrium state. As a new switchgrass induced soil carbon saturation state is reached, this soil carbon credit component of the model should be reduced to zero.

GHG emissions from lost switchgrass During harvest, transportation and storage, some switchgrass will be lost. A series of experiments by Sanderson et al. (1997) show that baling losses ranged from 1.8 to 6%. Switchgrass losses during handling and transporting were estimated at 0.4%. Experiments also pointed out that these losses could be reduced by careful machine operation and management (Sanderson et al. 1997). Bales stored outside either on sod or gravel lost 5.6 and 4.0% of the original bale dry weight, respectively. No losses were detected in the bales stored inside. In consideration of these estimates, a total loss of 4% was assumed. Of the lost volume, 90% was assumed scattered on the field and road surface or lost during storage, and the rest was assumed embedded in the soil.

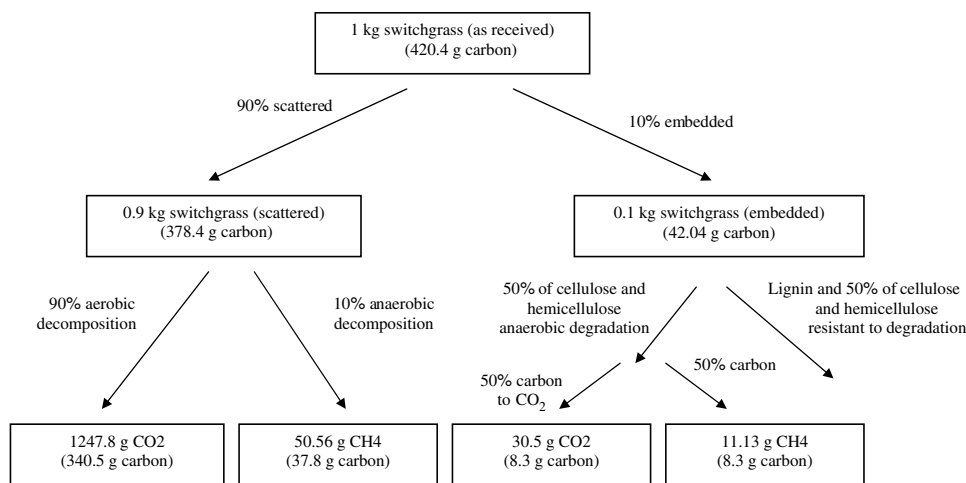**Fig. 5** Tracking model for GHG emissions from lost switchgrass

Table 5 GHG emissions from lost switchgrass

Emitted GHG	CO_2	N_2O	CH_4	CO_2-eq
Emissions (g/kg switchgrass)	51.1	0	2.47	107.9

The lost switchgrass degrades in the process and emits GHGs. GHG emissions from the degradation were considered as if they occurred in the same harvesting season. The mechanism of biomass degradation in Mann and Spath (2001) was adopted in this study employing a tree model (Fig. 5) and involves consideration of the cellulose and hemi-cellulose content. The cellulose and hemi-cellulose content were assumed to be those found in Lemus et al. (2002), equaling 371 g cellulose and 321 g hemi-cellulose (per 1 kg bone dry switchgrass).

Taking the ratio of GHG emissions from the lost switchgrass to net switchgrass yield (fired in the power plant), the computed emissions per kilogram switchgrass are given in Table 5.

GHG emissions from power generation

Direct-fired and cofired power systems were considered. Power generation produces air-borne emissions including SO_x, NO_x, CH_4 and CO_2. After combustion, the SO_x generated has to be treated or reduced. Also a volume of waste needs to be transported to a landfill.

Our analysis is divided into combustion and postcombustion sections.

Combustion

Two alternatives were considered: switchgrass as the sole feedstock and switchgrass cofired with coal. Both alternatives are discussed in the following sections.

Switchgrass fired alone

Although switchgrass has not been used as the sole feedstock for a commercial power plant, we constructed such a case by extrapolating results from wood-fired power generation.

Emission factors for switchgrass combustion in boilers were assumed to be the same as those for dry wood residue (moisture content less than 20%), which was adapted from the USEPA external combustion sources report (USEPA 2003). The resultant emission factors are shown in Table 6.

The carbon dioxide (EF_{CO2}) emission factor was calculated as follows:

$$EF_{CO_2} = P_c \times BF_c \times MW_{CO_2}/MW_c/HHV_{sw}$$
$$= 222 \, lb/MMBtu.$$

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

Table 6 Emission factors for switchgrass firing

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

Table 7 Emissions from switchgrass-fired alone

Emission species	CO_2	N_2O	CH_4	SO_x	NO_x	CO
Gram per kilogram switchgrass	1,525	0.09	0.14	0.17	3.37	4.12
Gram per kilowatt hour by switchgrass	1,660	0.10	0.16	0.19	3.66	4.49

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

Existing biomass power plants have heat rates ranging from 13.7 to 21.1 MJ/kWh or even higher, which correspond to HHV efficiencies from 25 to 17% or lower (Hughes 2000). An average value of 17.4 MJ/kWh (4.83 MJ/MJ) was used as the default NPHR of switchgrass fired alone. The emissions from switchgrass combustion for electric generation are summarized in Table 7.

Switchgrass cofired with coal

Currently, the application of switchgrass as the sole source of fuel for power plants with large capacity is not common or economical. The nature of the feedstock also brings other problems such as slagging and fouling. Recent studies indicate that cofiring could overcome these problems and perhaps be environmentally beneficial (Boylan et al. 2000). In particular

- Total CO_2 emissions can be reduced because of recycling through photosynthesis as discussed above.
- Switchgrass has very little sulfur. Therefore, cofiring reduces SO_2 emissions (Hughes 2000). Moreover, because of the more alkaline ash that arises, some of the SO_2 from coal would be captured during combustion.
- Typically, switchgrass contains very little nitrogen on a mass basis as compared to coal, which might lead to reductions in NO_x emissions (Tillman et al. 2000). However, the thermal NO_x may be higher, hence NO_x emissions from switchgrass use are inconsistent. The hydrocarbons released along with volatile matter during pyrolysis of biomass or coal can be used to reduce NO_x.

Most cofiring studies have been conducted with biomass percentages below 20% by mass. Within this range, the slagging and fouling problems brought by firing switchgrass are not very significant, but the synergetic effects of cofiring on emission reduction can be significant.

Another important feature of cofiring is that the simultaneous use of coal can improve the heat rate of the cofired switchgrass. To examine this we used the Plasynski et al. (1999) cofiring boiler efficiency loss equation, i.e.,

$$y = 0.0045x^2 + 0.0005x - 0.0044$$

where y is the boiler efficiency loss in percentage and x is the biomass-cofiring ratio on a mass basis.

The typical power plant coal thermal efficiency level of 34.13% was used to calculate the switchgrass thermal efficiency. The calculated switchgrass thermal efficiency versus the cofiring ratio is shown in Fig. 6 (the dashed part of the line gives the hypothetical extension to ratios higher than 20%). The reason for the lower efficiency of switchgrass is the small unit size and high moisture content (Hughes 2000).

This shows that the efficiency of switchgrass in cofiring is relatively higher when compared to burning it alone (which falls between 25 and 17%).

The relation of electricity generated and fuel needed ($W_{fuel,co}$) was also examined using the following equations.

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

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

Cofiring 10% switchgrass with coal requires 0.419 kg coal and 0.047 kg switchgrass to generate 1 kWh of electricity.

Tests of cofiring switchgrass with coal have been conducted including cofiring switchgrass in a 50 MW pulverized coal boiler at Madison Gas and Electric CO. (MG&E) (Aerts et al. 1997) and cofiring switch-
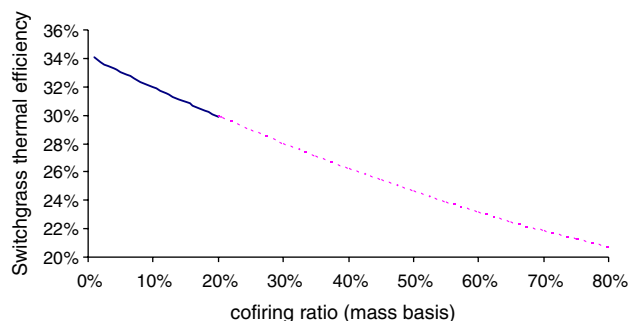

Fig. 6 Switchgrass thermal efficiency as a function of cofiring ratio

grass in a 725 MW gross (675 MW 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 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 cofiring did not normally contribute to higher carbon monoxide (CO) readings. Other biomass cofiring studies have confirmed this conclusion. For example, Spliethoff and Hein (1998) found that compared with coal-only firing, CO emission did not show any change for biomass shares up to 50% of the thermal input.

Based on these test results and facts, the following assumptions were made in the cofiring model:

- Carbon burning fraction of coal and switchgrass are both 99%.
- N_2O emissions from cofiring are proportional to the emissions of coal fired alone and biomass fired alone according to their thermal input.
- The amount of CH_4 emission arising from cofiring is the same as that arising from a coal-only firing per unit electricity output.
- SO_2 emissions were calculated based on the sulfur content of the feedstocks as drawn from Electric Power Annual 2002 (USDOE/EIA 2003). Because switchgrass contains much less sulfur, the SO_x emission of cofiring is lower.
- NO_x emissions from switchgrass still remain uncertain and were assumed unchanged.
- National average emission factors and properties of coal were used for CO_2 and were derived from USEPA's report on GHG sinks and sources (Hockstad and Hanle 2004) as listed in Table 8.

Based on the aforementioned assumptions, combustion of 10% switchgrass with coal generates the following emissions per kilowatt hour of total electricity generated (Table 9).

Postcombustion activities

The activities involved in postcombustion include SO_x control and waste transportation. Again, they will be evaluated for 100% switchgrass firing and cofiring.

Table 8 Average emission factors of coal fired electric generation

Emission species	CO_2	N_2O	CH_4	SO_x	CO
Emission factors (g/kg coal)	2,085	0.031	0.022	17.16	0.25
Emissions (g/kWh)	935	0.014	0.016	7.69	0.11

Table 9 GHG emissions from combustion of 10% switchgrass with coal

Emission species	CO_2	N_2O	CH_4	SO_x	CO
Emissions (g/kWh)	944	0.017	0.016	7.19	0.11

Table 10 GHG emissions from postcombustion activities of switchgrass-fired alone

GHG emitted	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

Switchgrass-fired alone

Because of the low sulfur content of switchgrass, 100% firing generates very little SO_x, (well below than the emission standards required by USEPA). Therefore, no postcombustion SO_x treatment is required.

Because of the ash characteristics of switchgrass which cannot be reused, the postcombustion waste was all transported to a landfill. Our waste estimate consists of all ash, unburned carbon and captured sulfur, and amounts to 51.9 g/kg switchgrass burned or 56.4 g/kWh electricity generated. The waste was assumed to be transported by a heavy-duty truck with a load capacity of 25 tons to a landfill assumed to be 5 miles away. In turn, the following table gives the calculated GHG emissions from waste transport for switchgrass-fired alone (Table 10).

Switchgrass cofired with coal

We assumed that cofiring will occur in an existing coal-fired plant, so the equipment should have the same capacity for postcombustion control of SO_x. The decrease of SO_x emission due to switchgrass cofiring will be regarded as a positive credit that can be used for SO_x offset trading. Postcombustion control of SO_x involves three activities that in turn have GHG emission implications: limestone production and transportation, chemical reaction of limestone with SO_x and transportation of generated waste. Table 11 lists the computed GHG emissions related to postcombustion control of SO_x emissions for the 10% cofiring case.

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

Table 11 GHG Emissions from postcombustion activities of 10% switchgrass with coal

Emission category	CO_2	N_2O	CH_4	CO_2-eq
Emission from limestone production, transportation, reaction (g/kWh)	2.2	2.5E-6	1.3E-4	2.2
Emission from waste transportation (g/kWh)	0.1	2.1E-6	1.0E-4	0.1
Total emission from postcombustion activities (g/kWh)	2.3	4.6E-6	2.3E-4	2.3

$$
\begin{aligned}
W_{\text{waste,co}} = &(P_{\text{ash,sw}} + P_{\text{c,sw}}(1 - \text{BF}_{\text{c,sw}}) + P_{\text{s,sw}} \\
&\times \text{MW}_{\text{SOx}}/\text{MW}_{\text{s}})W_{\text{sw,co}} + [P_{\text{ash,coal}} \\
&+ P_{\text{c,coal}}(1 - \text{BF}_{\text{c,coal}}) + P_{\text{s,coal}} \\
&\times \text{MW}_{\text{SOx}}/\text{MW}_{\text{s}}]W_{\text{coal,co}} - E_{\text{SOx,co}} \\
&- E_{\text{CH4,co}} - E_{\text{CO,co}} + W_{\text{CaSO4}} \\
&+ W_{\text{CaCO3}}(R_{\text{CaCO3/SOx}} - 1) - W_{\text{waste,reused}}
\end{aligned}
$$

where $W_{\text{CaSO4}} = W_{\text{SOx,contr}} \times \text{MW}_{\text{CaSO4}}/\text{MW}_{\text{SOx}}$

The total waste generated under 10% switchgrass cofiring is calculated at 38.8 g/kWh. This waste is assumed to be transported to 5 miles. The resultant calculated GHG emissions are listed in Table 11.

Key results

Cost and energy evaluation

The strategy for establishing switchgrass on crop land and using loose harvest and transport after compression into modules is the most cost effective with an overall production cost of $32.53 per ton.

Energy is consumed during the processes of switchgrass establishment, growth, harvest and transportation as well as in the production and transportation of chemicals used. The total energy consumed on a ton of delivered product basis is given in Table 12. The smallest amount used is 846 Btu/kg switchgrass for Model 23 and largest is 1,498 Btu/kg for Model 24. If we compute the embodied energy consumption for switchgrass preparation and compare it with the tested HHV of switchgrass, this corresponds to a net energy gain (based on HHV) of 94.4 and 90.1%, respectively.

Lifecycle GHG emissions

Lifecycle GHG emissions from switchgrass-fired alone and cofired are now computed per kilowatt hour of electricity. The GHG emissions with the Model 23 are listed in Table 13. CO_2-eq emissions from 10% switchgrass firing amount to 935.1 g/kWh overall life cycle CO_2 emissions in comparison with 997.5 g/kWh from coal burnt alone, a 6.3% reduction. The GHG emission by varying the cofiring ratio to 5% was 966 g/kWh (3.2% reduction) and 20% was 875.6 g/kWh (12.2% reduction). We find that GHG emissions per ton of switchgrass are lower under cofiring than those under switchgrass fired alone because of the higher thermal efficiency of switchgrass under cofiring.

Table 12 Net energy gain of switchgrass as a bioenergy feedstock

Switchgrass preparation model	23	11	22	24
Total energy consumption prior to power plant (Btu/kg switchgrass)	846	1337	1132	1498
Used energy (based on tested HHV) (%)	5.6	8.8	7.5	9.9
Net energy efficiency (based on tested HHV) (%)	94.4	91.2	92.5	90.1

Table 13 GHG emissions from 100% switchgrass and from 10% cofiring of switchgrass with coal

Emission species	CO_2	N_2O	CH_4	CO_2-eq
GHG emissions for switchgrass-fired alone model (g/kWh)	− 68.9	0.27	2.50	68.5
GHG emissions for 10% switchgrass cofiring model (g/kWh)	898.7	0.03	1.22	935.1
GHG emissions assigned to switchgrass in 10% cofiring model (g/kWh from switchgrass)	− 53.0	0.21	1.82	50.4

Sensitivty analysis

The above analysis is quite complex and is affected by several interacting factors. This sensitivity analysis aims to identify the effects of variation in key parameters. Additionally, the effects of CO_2 emission prices are examined.

Comparison of GHG mitigation of alternative preparation methods

Assuming that switchgrass has the same quality and combustion characteristics across all preparation methods, we first examine how preparation method affects GHG emissions (Fig. 7). The advantage of Model 23 is obvious.

GHG emission relative to switchgrass cofiring ratio

Figure 8 shows the dependency of GHG emissions ($E_{\mathrm{GHG,co}}$) on the cofiring ratio based on Model 23. The simulated relation gives an essentially linear relation for low cofiring ratios (below 20%)

$$E_{\mathrm{GHG,co}} = -606 R_{\mathrm{sw,co}} + 996.13$$

CO_2 equivalent emission market prices

Lifecycle analyses indicate that switchgrass use lowers GHG emissions. However, the total generating costs are currently higher per kilowatt hour. Thus, switchgrass cofiring is only economic if some other factor can offset the additional feedstock cost plus the power plant capital modification cost, additional labor and maintenance costs. Imposing a CO_2 emission cost on net power plant emissions would make biomass more
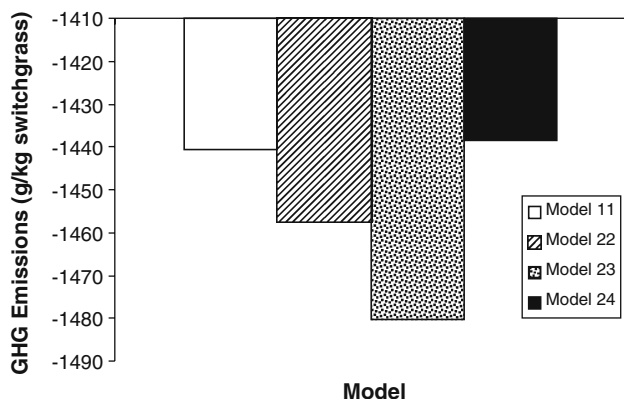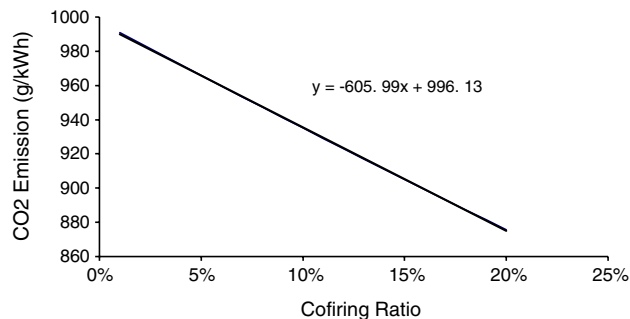
Fig. 8 GHG emissions as a function of cofiring ratio

competitive. We computed a breakeven CO_2-eq emission price.

The calculation of the breakeven CO_2-eq emission price is based on the idea that to generate equal amount of electricity, the cost of generation with switchgrass should be at least as low as the cost of coal based generation after CO_2-eq emissions are priced. We also include the extra power plant capital costs associated with switchgrass use due to power plant modification for switchgrass cofiring 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 cofiring and the trade of NO_x offsets is not nationwide, we will leave this issue for future work. Thus, the breakeven CO_2-eq emission price can be calculated from the following formulae by solving the following formulae for C_{GHG}

For switchgrass fired alone:

$$C_{\mathrm{coal}} \times W_{\mathrm{coal,bn}} + C_{\mathrm{GHG}} \times E_{\mathrm{GHG,coal,bn,lc}} = C_{\mathrm{sw}}$$
$$\times W_{\mathrm{sw,bn}} + C_{\mathrm{GHG}} \times E_{\mathrm{GHG,sw,lc}} + C_{\mathrm{SO_x}}$$

For cofiring switchgrass with coal:

$$C_{\mathrm{coal}} \times W_{\mathrm{coal,bn}} + C_{\mathrm{GHG}} \times E_{\mathrm{GHG,coal,bn,lc}}$$
$$= C_{\mathrm{coal}} \times W_{\mathrm{coal,co}} + C_{\mathrm{sw}} \times W_{\mathrm{sw,co}} + C_{\mathrm{GHG}}$$
$$\times E_{\mathrm{GHG,co,lc}} + C_{\mathrm{modi}} + C_{\mathrm{SO_x}}$$

where

- The cost of delivered coal is taken as \$28.13 per metric ton of coal based on the 2002 USA national average data from EIA/EPA-2002.
- The modification cost for cofiring capability is \$50–100 per kilowatt for blending feedstocks and \$175–200 per kilowatt for separate feedsocks (kilowatt of biomass power capacity) (Hughes 2000). A 100 MW boiler cofired at 5%, which has a \$200 per

Fig. 7 GHG mitigation of switchgrass processing before combustion for different alternative preparation models

kilowatt cost of capital modifications would cost $ 943,764.94 to modify. A salvage value of 10% of initial value and a 10 year useful life were used in this analysis.

- The reduction of SO_x emissions due to switchgrass cofiring 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 cofired power plants for a given amount of electricity generated. Dividing the credit by the electricity generated, the per unit electricity of SO_x reduction at this switchgrass cofiring ratio was determined. This reduction multiplied by the SO_x trading price ($250 per ton SO_x was used in this study; Tharakan et al. 2005) gives the cost allowance for SO_x reduction. The general formula for calculating the reduction of SO_x emission is:

$$W_{SO_x,co,credit} = W_{sw,co} \times HHV_{sw}/NPHR_{sw,co} \times NPHR_{coal} \times EF_{SO_x,coal} - W_{sw,co} \times HHV_{sw} \times EF_{SO_x,sw}$$

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.

Relation of breakeven cost between switchgrass and coal costs

Currently, switchgrass is not cost competitive with coal. This can be eliminated with either a CO_2 emission price as examined above or an increase in coal prices. Figure 9 shows the breakeven cost of switchgrass and coal at 5 and 20% cofiring without a CO_2 emission price. Taking the average coal cost of $28.13 per metric ton, the breakeven switchgrass cost must be about 20.20 and $18.60 per metric ton at the two cofiring ratio
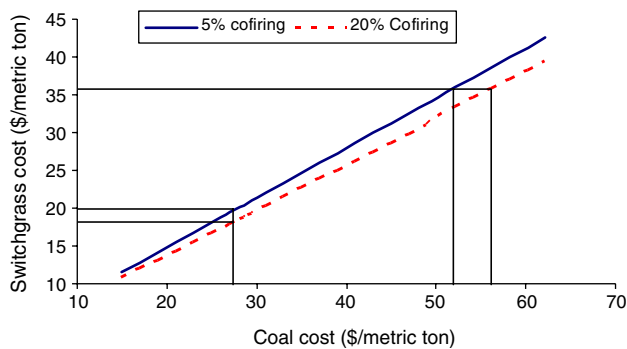
respectively, which is much lower than the real cost—at best $34.70 per metric ton in this analysis. Switchgrass only matches when the cost of coal reaches $50–55 for these cases, almost twice the current average coal cost.

CO_2-eq emission price and switchgrass cofiring ratio

As mentioned above, cofiring is the most promising way to reduce GHG and other pollutants' emissions without serious technical and practical problems. The most important factor for this analysis is the cofiring thermal efficiency, which will directly influence the values of most other aspects. The efficiency implication introduced above is simulated based on tests of cofiring ratios up to about 20%. Experimentation with cofiring ratios over 20% is rare. To give an overall picture, we extended the relation of reported efficiencies to higher cofiring ratios. Synthesized cost of cofiring was introduced for illustrative convenience. That cost includes fuel cost (including both coal and switchgrass) and cost of equipment modification, less SO_x credits. Figure 10 shows the component and synthesized cost of cofiring change with the cofiring ratio. The curve parts for cofiring ratio over 20% were illustrated with the discontinuous curves. The value of synthesized cost of cofiring above the baseline (100% coal firing) is the extra cost of cofiring, which tends to accelerate with the increase of cofiring ratio. It is even explicit in Fig. 11. While the CO_2-eq GHG reduction of cofiring relative to coal firing alone increases, as does the extra cost, the corresponding breakeven CO_2 emission price is to be approximately linear.

The resultant breakeven CO_2-eq emission price that causes cofiring to be cost competitive with coal is about
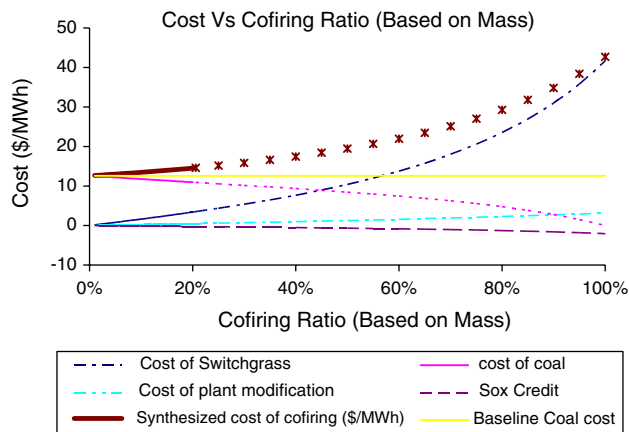

Fig. 9 Switchgrass and coal cost breakeven

Fig. 10 Synthesized cost of cofiring as the function of cofiring ratio

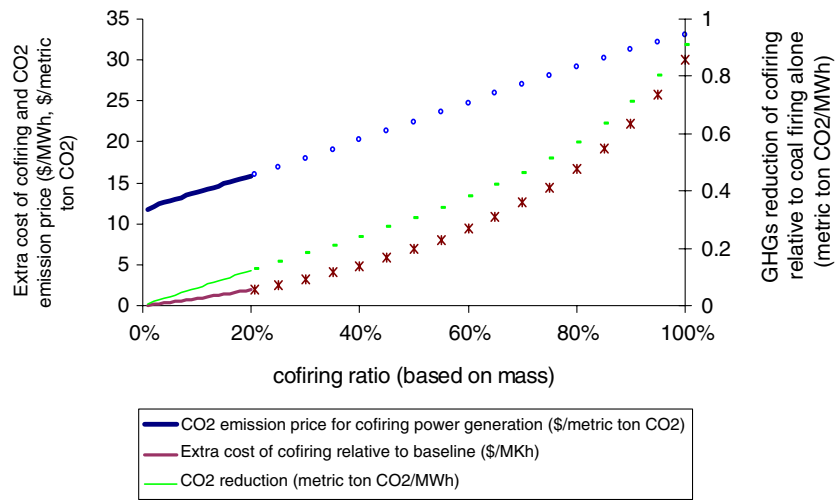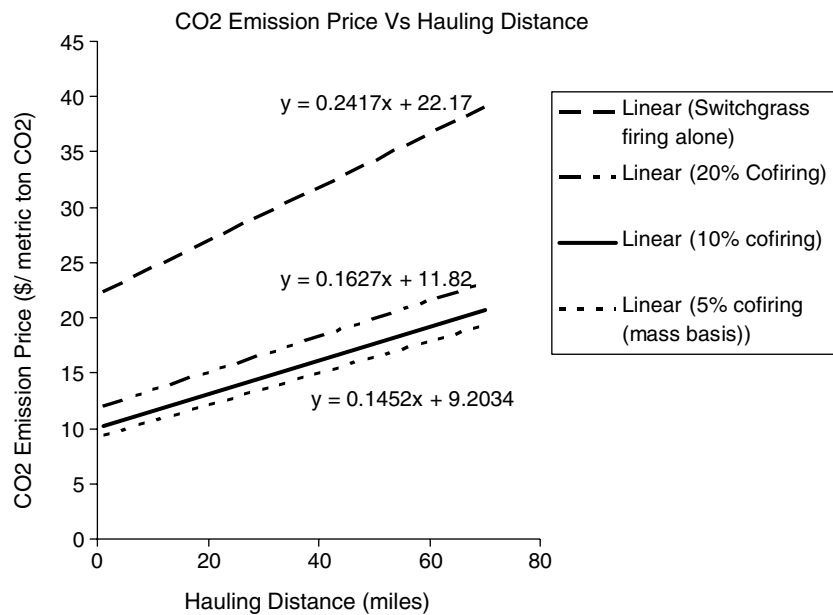**Fig. 11** Breakeven CO_2 price as a function of cofiring ratio

Fig. 12 Breakeven CO_2-eq emission price as a function of the hauling distance of switchgrass

12.80, 13.80 and $15.90 per metric ton CO_2 at switchgrass cofiring ratios of 5, 10 and 20%, respectively. Such a cost may be in the feasible range as current prices in the European markets ($20.83/metric ton CO_2) are above these levels (Point Carbon 2005).

Breakeven CO_2-eq emission price 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. (1996) estimated that average

cost of transporting switchgrass in Alabama is $8.00 per dry ton for hauling distance of 25 miles. As the transportation cost changes with the hauling distance, the breakeven CO_2-eq emission price will also change with the distance. Model results show that under the same parameters of yield and stand life, the breakeven CO_2-eq emission price appears as linear increase with the hauling distance. It also goes up with the increase of cofiring ratio, which is consistent with the result above. Further, the slopes of breakeven CO_2-eq emission price change equations gradually increase with the increase of cofiring ratios. This indicates that cofiring with higher ratio is even more sensitive to the hauling distance than a lower ratio cofiring (Fig. 12).
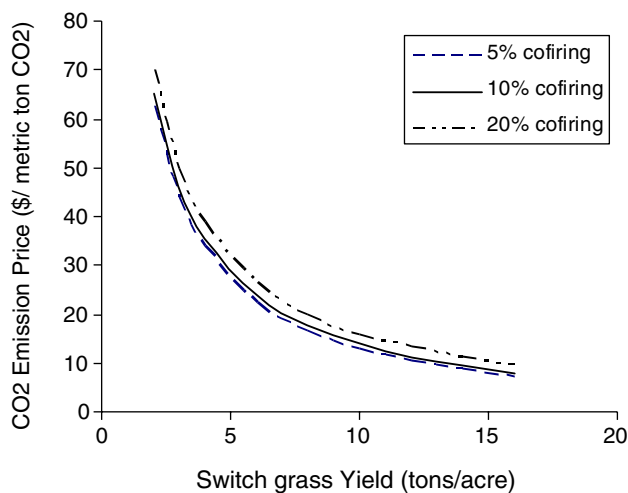
Fig. 13 Breakeven CO_2 emission price as a function of yield of switchgrass

Fig. 14 Cost of cofiring as a function of switchgrass thermal efficiency enhancement

Breakeven CO_2-eq emission price and yield

There is potential to increase the yield of switchgrass by decreasing the row spacing, increasing the nitrogen application rate (Ma et al. 2001) and doing plant breeding work. As the yield of switchgrass (tons/acre) is increased (keeping the plant capacity and the stand life fixed at 100 MWh and 10 years, respectively), cost per ton produced decreases, and the breakeven CO_2 emission price decreases exponentially, independent of the cofiring percentage. The sensitivity analysis shows that with lower yield, less than about 8 tons/acre, the CO_2 emission price would need to be relatively large, but as the yield is increased, the needed price decreases. For switchgrass yields above 12 tons/year, the decrease of CO_2 emission price is less than $1 per metric ton CO_2-eq for each additional ton of yield (Fig. 13). The high sensitivity of breakeven CO_2 emission price to the switchgrass yield, especially in the low yield situation, demonstrate that enhancing switchgrass yield is overwhelmingly important in realizing the strategy of commercializing switchgrass to power generation.

Cofiring cost as a function of switchgrass efficiency enhancement

Assuming that switchgrass efficiency will be enhanced in the future by new, improved and efficient generating equipment, the cost of cofiring would decrease. Figure 14 demonstrates this concept. The left most point in the curves for all cofiring ratios is the current switchgrass thermal efficiency, which is about 32 for 10% cofiring, 30 for 20% cofiring, 26 for 40% cofiring, 23 for 60% cofiring and 20 for switchgrass fired alone.
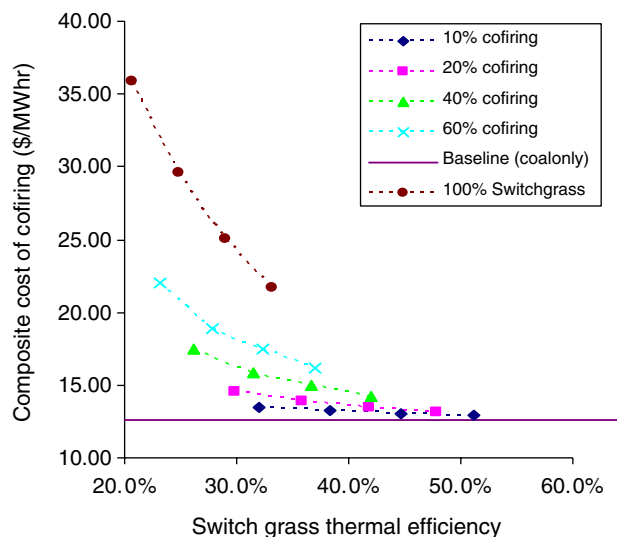
The switchgrass thermal efficiency is then assumed to increase (by 20, 50 and 70% as shown by the points in Fig. 14) in the future decreasing the cofiring cost. The rate of decrease is less for lower cofiring ratios and is higher for higher cofiring ratios. The curves also illustrate that for lower cofiring ratios of up to about 20%, cofiring switchgrass can become competitive with firing coal alone with a small subsidy for switchgrass. However, for higher cofiring ratios, large emission price would be required to breakeven with coal. Also, the cost of coal, assumed to be constant, would in practice increase over time. This would lead to cofiring being cost competitive, without any subsidy, with a small enhancement in switchgrass thermal efficiency for cofiring ratios of up to about 40%.

Conclusions and recommendations

An integrated biocomplexity/lifecycle analysis approach was applied to examine the economic, energy and GHG implications of using switchgrass as an alternate or a supplementary feedstock for power generation. Costs and emissions were examined for alternatives from production to transport to power generation to waste disposal. The analysis shows that the most effective technology was harvesting loose switchgrass for hauling and chopping, and then transporting by compression into modules, which yields a cost of $32.53 per ton produced. The total energy consumed before switchgrass was sent for combustion into power generation ranges from 846 to 1,498 Btu/kg switchgrass, which corresponds to a switchgrass net

energy gain (based on HHV) of 94.4 and 90.1%, respectively. The GHG mitigation per ton of switchgrass used during cofiring is better than switchgrass fired alone with the GHG effects of 68.5 g CO_2-eq per kilowatt hour for switchgrass fired alone and 50.4 g CO_2-eq per kilowatt hour for 10% switchgrass co fired with coal.

This paper analyzed the breakeven CO_2-eq emission price needed to make switchgrass competitive relative to coal as a function of cofiring ratio, hauling distance, and yield. Enhancing switchgrass yield is the most important way to reduce CO_2 emission price needed to make switchgrass competitive. Cofiring is more favorable than switchgrass firing alone for power generation. Reducing the hauling distance of switchgrass to the power plant also will reduce needed CO_2 emission price.

If switchgrass is to become competitive with coal for power generation, either higher coal prices, a CO_2 emission price or lower production costs are needed. In terms of production costs, agronomic research is needed to improve switchgrass yields, develop lower cost establishment and growing practices or determine lower cost harvest and transportation processes. Engineering research should be conducted into more efficient methods of cofiring and reducing the non-CO_2 emissions of switchgrass. Research should also explore potential uses for waste after cofiring.

Conversion factors

1 Btu	1.0551 kJ
1 acre	4,046.8730 m^2
1 ha	2.4710 acre
1 lb	0.4536 kg
1 ton	907.1847 kg
1 ton	2,000 lb
1 ton	0.9072 metric ton
1 kWh	3.6 MJ

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