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Life cycle energy and environmental benefits of generating electricity from willow biomass

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Abstract

Biomass is a key renewable energy source expected to play an important role in US electricity production under stricter emission regulations and renewable portfolio standards. Willow energy crops are being developed in the northeast US as a fuel source for increasing biomass energy and bioproduct demands. A life cycle inventory is presented that characterizes the full cradle-to-grave energy and environmental performance of willow biomass-to-electricity. A willow biomass production model is developed using demonstration-scale field experience from New York. Scenarios are presented that mimic anticipated cofiring operations, including supplemental use of wood residues, at an existing coal-fired generating facility. At a cofiring rate of 10% biomass, the system net energy ratio (electricity delivered divided by total fossil fuel consumed) increases by 8.9% and net global warming potential decreases by 7–10%. Net SO_2 emissions are reduced by 9.5% and a significant reduction in NO_x emissions is expected. In addition, we estimate system performance of using willow biomass in dedicated biomass gasification and direct-fired generating facilities and demonstrate that the pollution avoided (relative to the current electricity grid) is comparable to other renewables such as PV and wind.

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1. Introduction

Electricity generation in the US contributes significantly to many current environmental challenges including acid deposition, regional haze, ground-level ozone and smog formation, mercury pollution, and global warming. In response to these challenges, numerous proposals for a coordinated emissions reduction policy have been introduced in recent US Congressional sessions [1]. While differing in approach and target emission limits, each of the bills introduced into the 106th and 107th Congresses contains provisions to reduce power plant emissions of NO_x, SO_2, CO_2, and Hg over the next decade. In addition, several bills in Congress call for the establishment of a national renewable portfolio standard (RPS) in order to stimulate growth in non-hydroelectric renewable energy fields. Biomass, along with wind, is a key renewable resource expected to play an important role in future electricity production under stricter emission regulations and RPS [2].

To date, biomass has been a relatively small portion of the overall US energy budget, supplying about 3% of the 104 EJ (98 quadrillion BTU) consumed in 2000 [3]. The vast majority of this biomass is used for cogeneration of steam and electricity within the pulp and paper industry. Business-as-usual projections show modest increases in biomass use in the electricity generation sector, but under aggressive RPS scenarios and in scenarios that assume CO_2 reductions based on the Kyoto Protocol, electricity generation from biomass increases substantially [4,5]. Estimates of biomass resources show that there are 535 million wet tonnes of biomass available in the US on an annual basis, with 18 million wet tonnes (about 3 GW of capacity) available today at prices of $1.25 per million BTU or less [6]. Biomass resources included in this estimate are agricultural residues; forestry residues; urban wood waste and mill residues; and dedicated energy crops such as switch grass, hybrid poplar, and willow.

A demonstration program under the auspices of the The Salix Consortium is developing and facilitating the commercialization of willow biomass short rotation woody crops in the Northeastern and Midwestern regions of the US. To date, over 200 ha of willow have been established in western and central New York. In the near-term, the harvested willow biomass will be used to supplement new cofiring operations at an electricity generating facility in western NY. Longer term potential uses for the biomass include the production of bioproducts that would otherwise be made from petroleum and electricity generation using gasification and fuel cells.

As policy-makers and regulators attempt to address multiple environmental goals and electricity generators plan for compliance to yet uncertain standards, thorough assessments of technologies are necessary. Life cycle assessment (LCA) methodology offers such a comprehensive, system-based analysis of the energy and environmental performance of a product system [7]. In LCA, the material and energy inputs and outputs are quantified throughout a product's life, from raw material acquisition through production, use and disposal. Potential environmental impacts of the product system are then assessed based on this life cycle inventory.

This paper describes an LCA model of the agricultural production of willow biomass feedstock and the cofiring of this biomass with coal to generate electricity.

Willow biomass production modeling is based on demonstration-scale field experience from NY and scenarios are presented that mimic anticipated cofiring operation at the Dunkirk, NY generating facility. Results focus on system energy performance and criteria air emissions. In addition, we estimate system performance of using willow biomass in dedicated biomass gasification and direct-fired generating facilities. The air pollution prevented from using willow biomass as a substitute for coal and national-average grid electricity is examined. Finally, the energy and environmental performance of the willow system is compared with photovoltaic and wind electricity generating systems.

2. Methods

LCA methodology follows the ISO 14040 guidelines [7]. The model was developed using the software program, Tools for Environmental Analysis and Management (TEAM 3.0), by Ecobalance, Inc. Modules for generalized practices such as raw material extraction, large market chemical production, average grid electricity generation, transportation fuel production, and transport emissions were taken from Ecobalance's Database for Environmental Analysis and Management (DEAM 3.0). The net greenhouse effect was calculated using global warming potentials from the Intergovernmental Panel on Climate Change (IPCC) (direct effect, 100-year time horizon) [8].

The goal of this study is to evaluate the energy and environmental performance of the biomass-to-electricity system under development by the Salix Consortium. Willow biomass crops are to be cofired in an existing pulverized coal boiler at the Dunkirk facility in Dunkirk, NY. The willow biomass will be supplemented with waste wood residues. The system boundaries for the cofiring LCA include all operations required for production of willow biomass, coal mining and processing, coal and biomass transportation, manufacturing of cofiring retrofit equipment, and the avoided operations of wood residue landfill disposal (Fig. 1). The functional unit is 1 MWh of generated electricity delivered to the grid.

2.1. Biomass feedstock

Two cofiring scenarios, both at a 10% (by energy) cofiring ratio but involving different biomass mixes, are considered. In the first, which is based on likely operating conditions at Dunkirk, 5% (by weight) of the annual biomass supply to the power plant is willow and the remainder is wood residues (residue/willow blend). In the second scenario, all of the biomass necessary for a 10% cofire is willow (all-willow). Providing a continual supply of willow biomass may require alternative harvesting and storage techniques from those modeled here. Thus, the second scenario is an approximation of an all-willow cofiring system. The following sections contain modeling and allocation details for biomass feedstock production.

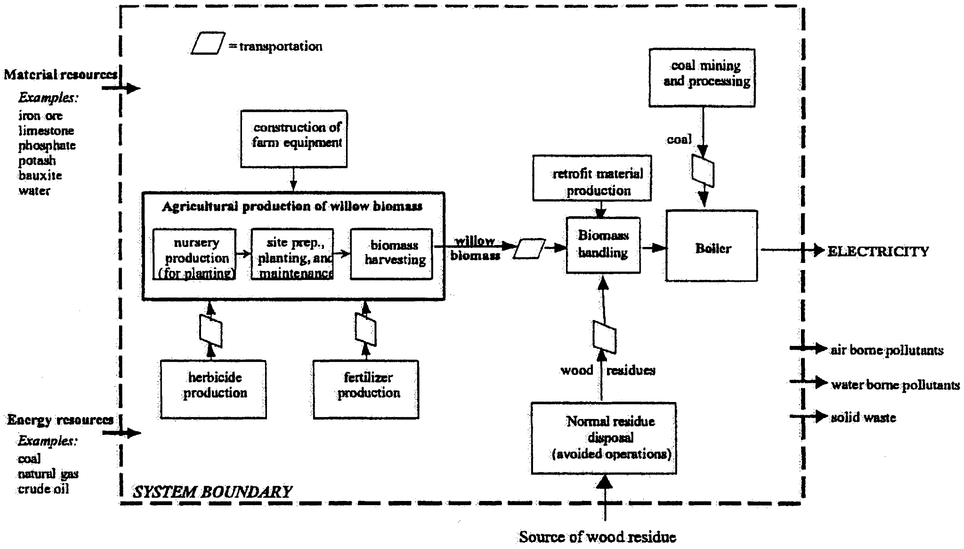

Fig. 1. Schematic of biomass cofiring system boundary.

2.1.1. Willow production

The willow biomass production system is an agricultural-based system similar to perennial cropping systems currently in use by farmers [9], but requiring specialty planting and harvesting equipment. Willow clones (*Salix* spp.) selected for fast growth are planted in a "double row" system of 15,300 trees/ha, and harvesting of above-ground stem biomass occurs every 3–4 years during winter months. As part of a large-scale demonstration supported by US Department of Energy and Department of Agriculture, over 200 ha of willow biomass crops have been established in western and central New York. A life cycle inventory of the willow biomass cropping system based on experience in New York has been developed and described in detail in a previous communication [10]. The inventory is averaged over the biomass harvested from seven 3-year rotations and includes the production of planting stock in a nursery, field preparation, planting, maintenance, and harvesting activities. Based on experience in NY, the model uses average yields of 13.6 odt/ha/year. Ammonium sulfate (100 kg N/ha) is added once per rotation (every 3 years). Herbicides are used only during field preparation and willow establishment [9].

Results from the biomass cropping system assessment indicate that willow biomass production has a net energy ratio (energy stored in biomass at farmgate/fossil energy consumed) of 55. System greenhouse gas flows, including emissions from direct and indirect fuel use, N_2O emissions from applied fertilizer and leaf litter, and carbon sequestration in below ground biomass and soil carbon, total to 3.7 Mg CO_2 eq./ha over 23 years of willow energy crops, or 0.68 g CO_2 eq./MJ of biomass energy produced [10].

2.1.2. Wood residues

Cofiring operations at Dunkirk will use a mixture of willow biomass and wood residues. Wood residues can come from a variety of sources including forestry residues from logging and timber stand improvement operations, bark and wood residues from primary wood product mills, construction and demolition residues, woody yard trimmings, and other wood wastes that would otherwise be landfilled [11]. The source of residues used at Dunkirk will be dictated by availability and market. In this model, we assume representative residues from a ready-to-assemble furniture manufacturer in western New York. In the event of a saturated market for biomass residues, such manufacturing wastes would be landfilled. The assumed wood residue characteristics are shown in Table 1. Note that the high nitrogen content of the wood residue (higher than that of coal or willow biomass) is due to resins from the furniture manufacturing process.

2.1.3. Residue avoided operations

Willow biomass is grown specifically for the purpose of supplying biomass energy. A credit is thus taken for the absorption of CO_2 during the growing cycle that directly offsets the stack CO_2 emissions attributable to combustion. The supplemental residue biomass does not receive this credit, in part because the original production and primary use of the residues are poorly characterized and not included within the system boundary. Instead, the emissions, resource consumption,

Table 1
Fuel characteristics

	Dry weight %			
	Furniture manufacturing sawdust (specific residue)[a]	Generic wood residues[b]	Willow biomass[c]	Eastern bituminous coal[d]
Carbon	49.61	50.62	49.4	75.5
Sulfur	0.05	0.03	0.05	2.19
Oxygen	38.39	41.40	42.9	6.64
Hydrogen	8.68	5.76	6.01	4.83
Nitrogen	2.52	0.25	0.45	1.48
Ash	0.75	1.94	1.24	9.25
Moisture (as received) (wt%)	12.69	50	37.7	1.65
Heating value (MJ/od kg)[e]	19.8	18.30	19.8	30.60

[a] [12].

[b] [13], based on data from wood cofiring tests conducted by EPRI and DOE.

[c] [14].

[d] [15].

[e] Three-year average (1996–1998) heating value of coal to Dunkirk as reported by EIA.

and energy use (or generation) that would have occurred during the alternative disposal of the biomass are credited to the life cycle inventory as avoided operations [13]. In this study, it was assumed that the alternative route of disposal would be landfill.

Landfill decomposition of woody residues follows the model proposed by Mann and Spath [13], with 34.8% of the carbon in the landfilled biomass decomposing to a gas approximated as a mixture of 50% CO_2 and 50% methane. It was assumed that 10% of the landfill methane is either chemically oxidized or converted by bacteria to CO_2, thus reducing methane atmospheric emissions [13,16]. Many landfill facilities operate gas recovery systems and recovered gas is either flared or utilized to generate electricity. The furniture manufacturer that is the source of residues assumed in this model operates plants serviced by the Chautauqua County Landfill (Jamestown, NY) and the Lakeview Landfill (Erie, PA). Based on facility production, we assume 25% of the generated residue would be disposed at the Lakeview site and the remainder at Chautauqua County. Chautauqua has a landfill gas recovery system which according to US Environmental Protection Agency (EPA) models recovers 50% of generated landfill gas, all of which is currently flared. Lakeview landfill claims that their gas recovery is 85% efficient and utilizes 82% of that gas to generate electricity (6 MW capacity) with the remainder being flared. Combining practices at the two landfills, it is assumed that 17.4% of the generated gas is captured and used to generate electricity, 41.3% is captured and flared (i.e. converted to CO_2 with no power generation), and 41.3% is emitted directly to the atmosphere. Thus, avoided wood residue landfill avoids some electricity generation. This avoided electricity generation, along with associated energy requirements and emissions, is substituted in the life cycle inventory with grid electricity representative of the Northeast Power Coordinating Council (NPCC).

For comparison, a "generic" wood residue scenario is also considered. The fuel characteristics for this scenario are also included in Table 1. Landfill operations assume the same 34.8% carbon decomposition and 10% methane oxidation, but gas recovery is based on national averages. According to the most recent estimates from the EPA, 49% of all methane from landfills is generated at sites with landfill gas recovery, and these sites average 75% recovery efficiency [17]. Using these national averages, we assume 36.75% of the methane is combusted and thus converted to CO_2, and 49% of the collected landfill methane is utilized to generate electricity [17].

2.2. Biomass transport

The distance from existing willow plantations and the Dunkirk Power Plant is approximately 40.2 km (25 miles). This transportation distance is used for the residue/willow blend scenario. The wood residue transportation distance used is the distance between Dunkirk and Jamestown and Dunkirk and Erie, PA, weighted by the amount of residue produced in each facility. The resulting transport distance is 76.5 km.

For generic residue transport and hypothetical scenarios with expanded willow plantations (all-willow scenarios), it is assumed that the biomass origin would be within an 80 km (50 miles) radius of the power plant. Average transportation distance can then be calculated by

$$d = \frac{2}{3} R_0 \tau \tag{1}$$

where R_0 is the containing radius and τ the tortuosity factor (ratio of actual travel distance to line of sight).

For a regular rectangular road grid, $\tau = 1.27$; for a broken landscape (hilly, lakes, swamps), $\tau = 3$ [18]. For this model, $\tau = 1.8$, giving an average transportation distance of 96 km (60 miles).

Biomass transportation is by 40 short ton diesel truck, and the empty return is included. Fuel consumption at maximum load is 39 l per 100 km. Emissions associated with truck transportation are from the DEAM database. Material requirements for manufacturing of the truck are as follows: 900 kg aluminum, 272 kg iron, 13,790 kg steel, 370 kg tire. For truck decommissioning, it was assumed that 50% of the tractor (remainder is salvaged for parts) and the entire trailer is shredded for scrap. The shredding process is modeled as in a previous study [19]. Manufacturing and decommissioning burdens are allocated on a per km of transport basis by assuming a useful truck life of 15 years, with an average annual mileage of 48,280 km (30,000 miles). A 2% haul loss was assumed for biomass transport.

2.3. Energy conversion—cofiring

The energy conversion portion of the life cycle inventory makes use of the model developed by Mann and Spath and described in detail in [13,20], with modifications noted here.

The cofiring model is based on anticipated operations at Dunkirk Power Plant Unit #1. Originally built in the late 1940s, this is a tangentially fired pulverized coal boiler with uncontrolled SO_2 emissions and low NO_x burners with close-coupled overfire air (OFA) NO_x controls. The operating parameters used in this model are summarized in Table 2. The anticipated cofiring rate at the Dunkirk plant is

Table 2
Dunkirk unit #1 operating assumptions

	No cofire	10% cofire
Gross plant capacity (MW)	96	96
Capacity factor	88.2%[a]	88.2%[a]
Net plant heat rate	10.69 MJ/kWh	10.86 MJ/kWh
Net plant efficiency	33.7%	33.17%
Net annual electricity (to grid) at capacity factor	694,021 MWh	683,714 MWh
Coal feed rate (as received basis)	349.3 kg/net MWh	319.4 kg/net MWh
Biomass feed rate		63.7 kg/net MWh

[a] This capacity factor calculated by matching the 3-year average heat inputs to Dunkirk unit #1 (1996, 1997, and 1998) as reported at (http://www.epa.gov/airmarkets/picturethis/ny/2554_95.htm).

10–15%. Data from cofiring tests at the Dunkirk plant are not yet available. Thus, parameters for cofiring operation are estimates based largely on experience at other cofiring power plants [21]. The addition of biomass handling equipment is expected to result in a slight increase in plant parasitic load, although the increase in load from biomass handling will be largely offset by reduced coal pulverizer activity [22]. There is also an expected slight decrease in boiler efficiency due to the higher moisture content of biomass compared with coal.

2.3.1. Facilities manufacturing

At cofiring rates above about 2%, modest power plant modifications are necessary to accommodate receiving, handling, and feeding of biomass fuel [21]. Approximate material requirements for the cofiring retrofit, based on experience at Dunkirk [23], were included in the inventory (Table 3). Data for materials production are from the DEAM database. The retrofit construction burden was allocated per MWh over an assumed 15-year equipment life. Retrofit construction is not included in the coal-only (no-cofire) scenario. Manufacture of the original coal-fired boiler was not included in this LCA. Approximations based on previous coal-powered boiler LCAs [20] suggest that excluding plant manufacturing affects major system indicators (energy, global warming potential) by less than 1%.

2.3.2. Coal mining and transport

Modeling of coal mining and transport follows Spath et al. [20], with coal characteristics, mine type, transportation distance, and transportation mode modified to reflect the Pittsburgh seam eastern bituminous coal received by the Dunkirk plant (Table 1). Energy Information Administration (EIA) data were used to derive the following parameters for coal received at Dunkirk in 1999: mine type: 82.9% underground, 17.1% surface; transportation distance: 250 miles, 84.4% by rail, 6.7% by truck, 8.9% by barge [24–26]. A 5% haul loss is assumed [20].

2.3.3. Baseline emissions (coal only)

Baseline emissions for the coal-only (no cofiring) operation were established using the average of 1996, 1997, and 1998 emissions for Dunkirk Unit #1 as reported by EPA [27] and emission calculations provided by NREL [20] (Table 4).

2.3.4. Cofiring emissions

Changes in power plant air emissions for cofiring scenarios are based primarily on fuel-bound effects; i.e. SO_2 emissions decrease to the extent that biomass fuel has lower sulfur content than coal. It is expected that cofiring will provide an

Table 3
Modeled material requirements for biomass handling retrofit

274.5 kW (100 hp) hammer mills	6168 kg steel, each
Storage silo, 272 ton capacity	15,000 kg steel
Fuel hopper, 31.8 ton capacity	2450 kg steel
Bucket elevator, 16.7 m, 14 × 9 buckets	10,320 kg steel
Concrete slab, 28.3 m^3	65,300 kg concrete

Table 4
Dunkirk Unit #1 baseline air emissions (no cofiring)

Compound	Emission (kg/MWh net electricity)
CO_2	932.1
NO_x (as NO_2)	1.583
SO_2	15.022
CO	0.105
VOC	0.012
Particulates	0.135
Ash (dry)	31.62

additional reduction in NO_x emissions due to the higher volatility and moisture content of biomass. Correlations presented by Tillman predict a 16.1% and 26.4% reduction in NO_x emissions at 10% and 15% cofire (energy basis), respectively [28]. These effects depend largely on boiler configuration and operation, however. Since emissions data are not currently available for cofiring in the Dunkirk boiler, we present NO_x emissions cases based on "fuel-bound effects" and compare them with results based on Tillman's correlation.

2.4. *Estimates of dedicated biomass electricity generation and comparison with other renewables*

In order to consider the performance of a dedicated willow biomass electricity generating system, the willow biomass production and transportation models were linked to sets of power plant emission factors for biomass gasification and direct-fired operations. Specified conversion efficiencies were used to establish feedstock (i.e. willow biomass) production and transportation flows that were then combined with power plant emissions (Table 5) to provide rough estimates of system performance. Note that these estimates do not include power plant construction and decommissioning or additional operational demands of the power plant.

Table 5
Dedicated biomass power plant emission data

	NREL gasification[a]	EPRI gasification[b]	EPRI direct-fired[b]
Conversion efficiency	37.2%	36%	27.7%
Emission factors (g/MWh_{elec})			
CO	0.86	206	2019
NMHC	515.5	96	269.2
NO_x	479	645	67.3
Particulates (unspecified)	3.7	na	na
SO_2	254	818	na

[a] [29].
[b] [21].

Results from willow gasification and direct-fired scenarios are presented in terms of the pollution prevention achieved relative to US "composite kWh" average grid electricity generation. Data for this average grid generation are from the DEAM database and includes production, combustion, and waste management of the five main fuels in the following proportions (1996 values): coal (56.6%), nuclear (22%), hydroelectricity (10.6%), natural gas (8.6%), heavy fuel oil (2.2%).

For comparison, avoided pollution realized across the life cycle of two other important renewable energy sources, building-integrated photovoltaic (BIPV) and wind-powered electricity generation, are presented. The BIPV system is an amphorous silicon PV with a 6% conversion efficiency affixed to a standing seam roof located in New York, NY. A description of the life cycle inventory analysis is presented in Keoleian and Lewis [30]. The wind-powered generation system presented is a 9 MW (18×500 kW units) land-based Danish wind farm analyzed by Schleisner [31]. Avoided pollution is again presented relative to average US grid electricity generation.

3. Results

3.1. Biomass cofiring

3.1.1. Energy analysis

Generating electricity with coal alone consumes 11,496 MJ/MWh$_{elec}$ across the full life cycle, 93% of which is coal used directly at the plant. Due to the large quantity of coal processed, upstream energy consumption (i.e. energy not used directly as fuel at the plant) is dominated by coal mining, transportation, and losses (Fig. 2). Substituting biomass for coal decreases this energy consumption somewhat, but also introduces additional upstream energy consumption in producing the biomass. As a result, total upstream energy consumption remains nearly unchanged with cofiring. Note that if coal haul losses are not included, upstream energy consumption for the no-cofire case decreases to 273 MJ/MWh$_{elec}$, while the residue/willow blend and all-willow cofire are 320 and 304 MJ/MWh$_{elec}$, respectively.

Net energy ratio, defined as the electricity produced by the system divided by the total fossil fuel energy consumed, is a useful indicator of system performance. The net energy ratio for the no-cofire case is 0.313. This increases to 0.341 with 10% cofiring, with very little difference in net energy ratio between the two cofiring scenarios.

3.1.2. Global warming potential

In our model, generating electricity from coal alone releases 978 kg CO_2 eq./MWh, 95% of which is released in the form of CO_2 at the power plant. Mining and transportation of the coal compose the balance, contributing 42.8 and 7.6 kg CO_2 eq./MWh, respectively. Fig. 3 demonstrates how the greenhouse gas emissions are distributed in the cofiring scenarios. GHG emissions from coal mining, transport, and combustion are reduced by replacing coal with biomass during cofiring. CO_2 absorbed in the growing of willow biomass is credited to the system in the "willow

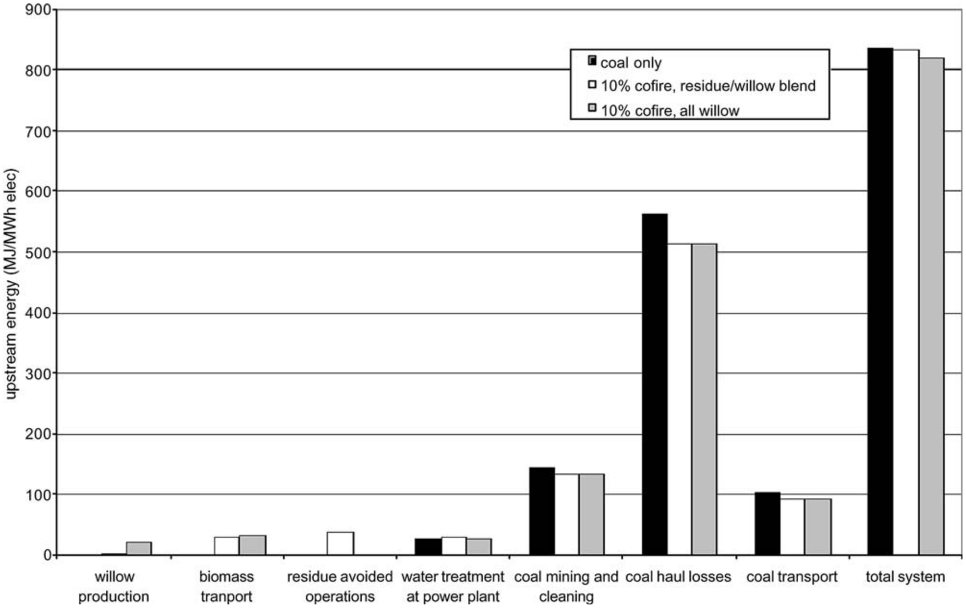

Fig. 2. Distribution of upstream energy consumption (energy not used directly as fuel in the power plant) for biomass cofiring.

production” step, but is directly offset by the willow biomass contribution in “power plant emissions”, resulting in a neutral contribution. Contributions of CO_2 emissions from tractor operation during willow production, as well as N_2O emissions from fertilized agricultural soils, are relatively small (see [10] for details). While the system is not credited for CO_2 absorption during the growth of woody residues, a credit is taken for landfill methane and CO_2 emissions *avoided* in utilizing the residues in cofiring.

Replacing the specific “furniture residues” case with more generic residue biomass and national-average landfill statistics has a modest impact on overall system GHG emissions (Table 6). The generic residue has a lower heating value and thus greater carbon content per MJ, resulting in increased stack CO_2 emissions. Since less methane is combusted in the “generic” landfill scenario, methane emissions increase and CO_2 from biomass (resulting from combustion of methane) decreases. On the other hand, a larger fraction of the combusted landfill methane is used for electricity generation in the national-average scenario. Since this LFG generation is replaced in the model with grid electricity when landfill disposal is avoided, there is a corresponding increase in fossil CO_2 emissions (from grid electricity generation).

3.1.3. Air emissions

Cofiring biomass provides a significant reduction in SO_2 emissions, due to the very low sulfur content of biomass (Fig. 4). This reduction changes little with biomass type (Table 7). NO_x emissions predictions based on fuel-bound N demon-

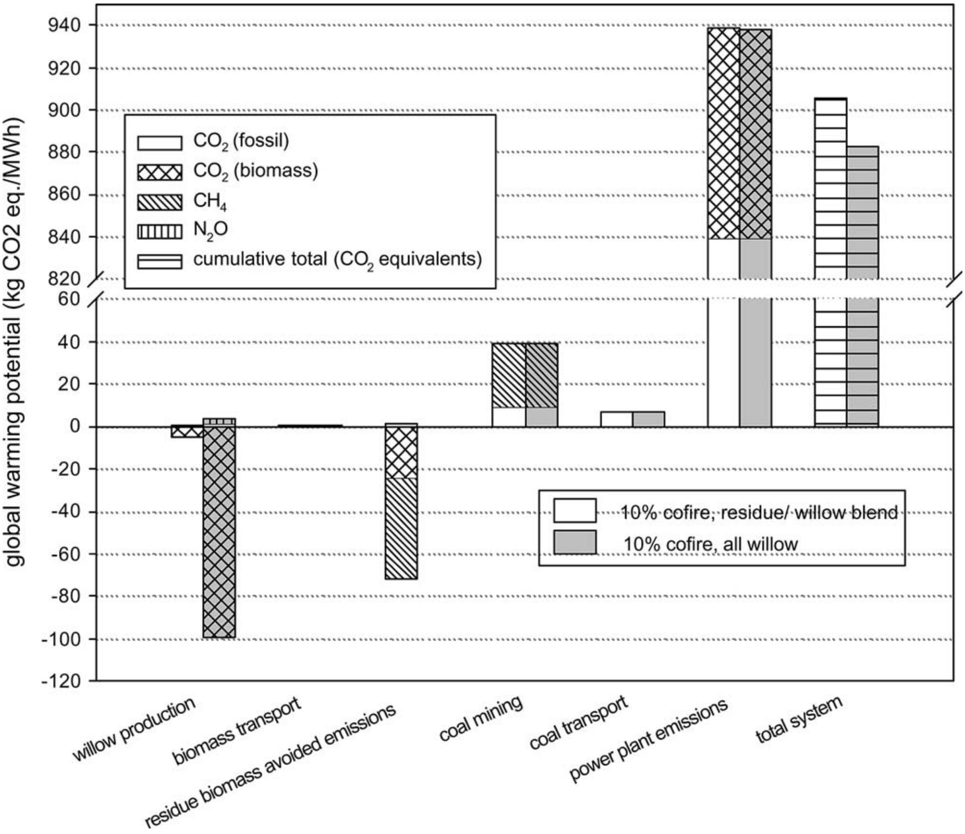

Fig. 3. Distribution of greenhouse gas emissions by life cycle stages and contributing gas species.

strate an increase in NO_x emissions when cofiring the furniture residue/willow blend (Fig. 4, Table 7). This is due to the high nitrogen content of the furniture wood residues. A 5% reduction in total system NO_x emissions is realized with a 10% cofire of all willow (Table 7). The generic residue scenario provides a similar

Table 6
Greenhouse gas emissions (kg CO_2 eq./MWh_{elec}) for the "generic" residue scenario, with 10% cofiring of residue/willow blend. Values in parentheses are percent change from the "specific" residue scenario

	Total system	Residue transport	Avoided residue disposal	Power plant emissions
Cumulative total	909.6 (0.4%)	0.8 (80.7%)	−76.8 (8.8%)	948.4 (1.0%)
CO_2 (biomass)	865.1 (23.8%)	0.0 (80.7%)	−17.9 (−27.5%)	109.5 (9.9%)
CO_2 (fossil)	852.6 (0.0%)	0.7 (80.7%)	0.7 (−41.0%)	838.9 (0.0%)
CH_4	−29.9 (71.1%)	0.0 (80.7%)	−59.6 (26.4%)	0 (0.0%)

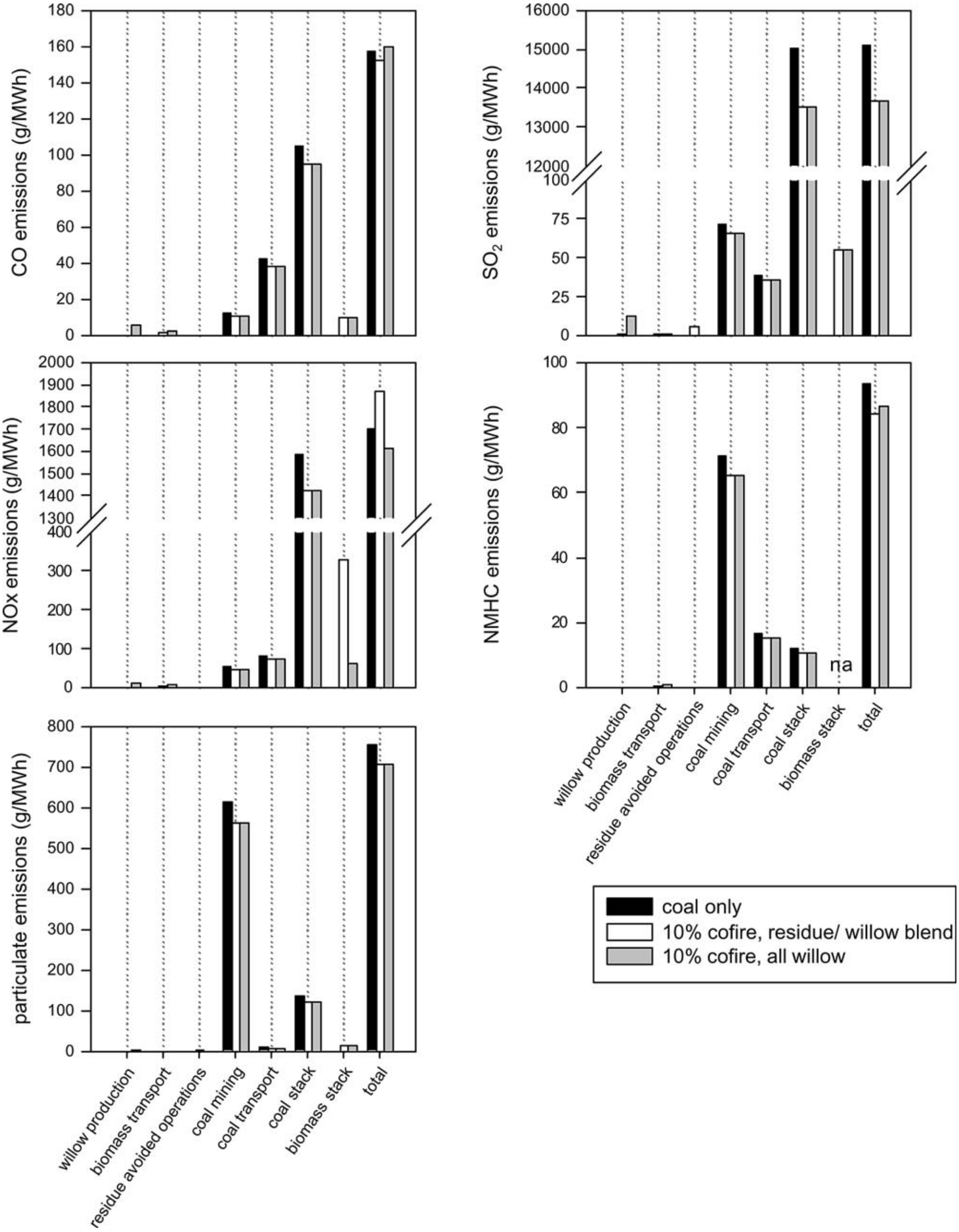

Fig. 4. Distribution of air emissions across life cycle stages for cofiring of biomass with coal.

reduction in NO_x emissions due to low N content of the biomass (data not shown). The empirical correlation presented by Tillman [28] predicts a 16.1% reduction in stack NO_x emissions at a 10% cofire. This results in total system emissions of 1440

Table 7
Total system air pollutants, global warming potential, and net energy ratio for biomass cofiring, dedicated willow biomass electricity generation, and other renewable energy sources

	CO (g CO/MWh$_{elec}$)	NO$_x$ (g NO$_2$/MWh$_{elec}$)	SO$_2$ (g SO$_2$/MWh$_{elec}$)	Non-methane hydrocarbons (g/MWh$_{elec}$)	Particulates (unspecified size) (g/MWh$_{elec}$)	Global warming potential (kg CO$_2$ eq./MWh$_{elec}$)	Net energy ratio
10% cofire, residue/willow blend[a]	152 (−3.2%)	1870 (9.7%)	13,700 (−9.6%)	84.1 (−10.1%)[b]	708 (–6.3%)	906 (−7.4%)	0.341
10% cofire, all willow[a]	160 (1.7%)	1610 (−5.2%)	13,700 (−9.5%)	86.4 (−7.6%)[b]	706 (–6.6%)	883 (−9.9%)	0.342
Average US grid[c]	417	3330	3210	44.1	2140	989	0.257
Willow production and transport with...[d]							
NREL gasifier	69.9 (−83.2%)	645 (−80.6%)	374 (−88.3%)	525 (1090%)	34.0 (–98.4%)	38.9 (−96.1%)	13.3
EPRI gasifier	277 (−33.5%)	817 (−75.5%)	942 (−70.6%)	106 (139%)	>31.4 (–98.5%)[e]	40.2 (−96.0%)	12.9
EPRI direct-fired	1770 (324%)	279 (−91.6%)	>161 (−95.0%)[e]	236 (435%)	>40.8 (–98.1%)[e]	52.3 (−94.7%)	9.9
BIPV[d]	43.3 (−89.6%)	248 (−92.6%)	512 (−84.0%)	67.5 (53.0%)	575 (–73.1%)	59.4 (−94.0%)[f]	43
Wind[d]	na	30 (−99.1%)	20 (−99.4%)	na	na	9.7 (−99.0%)[h]	30.3

[a] Parentheses are percent change relative to coal-only (no cofire) operation.

[b] Biomass contribution to stack emissions not available.

[c] TEAM database, version 3.0 (Ecobalance).

[d] Parentheses are percent change relative to average US grid.

[e] Power plant stack emissions not specified; values shown are from feedstock production and transportation only.

[f] BIPV, building-integrated photovoltaic. Ref. [30].

[g] [31].

[h] Global warming potential contains CO$_2$ contributions only.

and 1456 g NO_x/MWh for the residue/willow blend and the all-willow scenario, respectively (15% and 14% system reduction relative to no cofire, respectively).

The model also predicts a roughly 6% reduction in particulate emissions with 10% cofiring, all of which is realized through reduced coal mining operation (Fig. 4, Table 7). However, the model assumes that there is no change in power plant particulate emissions with cofiring of biomass.

Cofiring biomass also provides significant reductions in mercury emissions. Metal analysis of willow biomass indicates an average mercury content of 0.005 mg/od kg [14] (Hg content not available for residue biomass). Assuming that all the biomass-derived Hg volatilizes during combustion, a 10% cofire of all willow would reduce the system air emissions of Hg by 8.4%. Contributions of mercury from willow production are negligible. Note that there is a *potential* for biomass to contain other heavy metals of concern. Metal content in the biomass is a function of metal concentrations in the soil where the crop is grown and tree uptake efficiency [32,33].

3.2. Dedicated willow biomass electricity generation in comparison with other renewables

Table 7 also contains the estimated emissions for dedicated willow biomass to electricity system, using both direct-fired and gasification conversion technologies. In these scenarios, it is assumed that willow biomass supplies all of the feedstock energy to the power plant. Emissions from the production and transportation of willow are combined with power plant emission factors contained in Table 5. Significant pollution prevention (relative to the current US electricity grid) is realized with biomass-generated electricity. The high net energy ratios demonstrate the fossil energy leveraging of a renewable energy source. For example, 13 units of electricity are generated for every one unit of fossil energy consumed *across the full life cycle* of willow gasification.

Comparisons with example LCAs of other renewable energy technologies reveal that biomass affords relatively similar levels of avoided pollution (Table 7). Biomass outperforms BIPV from an energy perspective (as well as the closely correlated global warming potential) but does not score as well as wind generation. It should be noted, however, that these studies do not take into account the power fluctuation of the different generating systems. Both wind and solar are intermittent sources, while biomass permits continual base load generation.

4. Discussion

Cofiring biomass with coal provides numerous environmental benefits. While the upstream energy consumed in growing or processing and transporting biomass roughly balances the reduced consumption from mining, processing, and transporting less coal (Fig. 2), the system realizes an overall benefit through reduced fossil fuel consumption at the power plant (reduced coal use), which is reflected in increased net energy ratios. Cofiring also imparts reductions in system greenhouse effect that scale with the cofiring rate, although our model demonstrates that the extent of these reductions can be dependent on the source and type of biomass as well as the modeling procedure adopted.

Willow biomass is grown specifically for electricity generation and thus willow production is considered to be within the power generation system boundary. As a result, electricity generation with willow biomass is nearly GHG neutral (40–50 kg CO_2 eq./MWh_{elec}). However, the original growth of residue biomass is not considered within the power generation system boundary and a CO_2 absorption credit is not taken for the growth of this biomass. Utilizing biomass residues for electricity generation avoids other means of disposal (in this case, landfill) and in turn avoids the GHG emissions that would have occurred as a result of that disposal. While not all of the carbon in the residue biomass decomposes to gaseous products in our landfill model, methane generation through anaerobic decomposition contributes strongly to the net greenhouse effect due to methane's relatively high equivalent global warming potential ($GWP_{CH_4} = 23$ kg CO_2 eq./kg CH_4 [8]). Decomposition of 100 kg of residue biomass in the "specific residue" landfill scenario releases 127.2 kg total CO_2 eq., whereas complete aerobic decomposition (or complete combustion) releases 181.9 kg CO_2. Thus, in this situation, landfilled biomass has a lower global warming potential than combustion, but there is a significant loss of potential for power generation. Under the "specific" landfill scenario, 100 kg of biomass generates 0.03 kWh electricity through landfill gas capture but the same 100 kg of biomass represents 132 kWh of generation potential in a cofiring operation. Comparison of the different residue scenarios indicates that small changes in biomass characteristics, transportation distances, and disposal management can influence the resulting greenhouse gas benefit. Under the "generic" landfill scenario, 100 kg of biomass leads to 166.2 kg total CO_2 eq. A previous report that considered a combination of residue disposal through landfill and utilization as mulch found that disposal of 100 kg of biomass releases 248.2 kg total CO_2 eq. [13]. Clearly, such allocation procedures must be standardized if they are to be used in CO_2 emission regulation and/or trading.

Cofiring biomass reduces emissions of SO_2, Hg, and (in most cases) NO_x. The extent to which biomass cofiring will reduce NO_x remains case-specific, as it is dependent on not only biomass composition but also boiler configuration and operating conditions. Dedicated biomass generation, which in new power plants will most likely use gasification technology, also provides significant reductions in SO_2, NO_x, and Hg emissions relative to the current coal-dominated electricity mix.

Recent forecasts by the Energy Information Administration at the US Department of Energy predict little to no addition of biomass-powered electricity generation, or indeed any renewable energy sources, when tightened three-pollutant (NO_x, SO_2, Hg) regulations are adopted [4]. Power generators are expected to instead choose the less expensive option of installing emission control equipment while maintaining coal as the primary fuel source. However, cases that consider stringent CO_2 reductions or aggressive RPS predict significant increases in the use of biomass, both in cofiring operations and dedicated biomass power plants. When a CO_2 cap at 7% below the 1990 level is assumed, biomass cofiring is predicted to increase to 50 billion kWh by 2020, more than 700% above the Annual Energy Outlook reference case. Adopting the goal of 20% RPS by 2020 is forecasted to increase total biomass-fueled generation to 526 billion kWh by 2020, with 85% of this from dedicated power plants. Under this 20% RPS scenario, biomass composes 10% of the total electricity generation [4].

Establishing energy crops, of course, requires arable land, and there is concern over the availability of this limited resource. According to our model, supplying enough willow to support a 10% cofire of all willow at the Dunkirk facility would require an estimated 2925 ha of plantation. This is 2.5% of the open land with suitable soils and slopes for willow biomass production within an 83 km radius around the Dunkirk plant (note that Dunkirk is on the shore of Lake Erie, so much of the area around the plant is unavailable) [34]. Operating a 100 MW gasifier at 37% efficiency and 80% capacity would require 26,865 ha of willow plantation, or only 1.3% of the *total* area within an 80 km radius. In an expanded biomass energy market, however, willow energy crops will be one of many biomass sources including urban, agricultural, and forestry residues and other energy crops such as switchgrass. A recent EIA report estimates that 3.9–5.8 million ha of energy crops will be needed to meet the 20% RPS by 2020 projection [6]. The report also points out that it is possible to grow biomass energy crops on Conservation Reserve Program (CRP) land, and that this projected energy crop acreage represents 24–37% of the current allowable CRP land. In addition, acreage devoted to farms and ranches has been declining steadily since the 1950s [35]. Thus, land use for biomass energy crops is not expected to conflict with land requirements for food and feed crop production.

5. Conclusions

Life cycle analysis demonstrates that electricity generation with willow energy crops, either by cofiring with coal or in dedicated biomass power plants, leads to significant reductions in many of the environmental impacts of coal-based electricity production. Consumption of non-renewable resources (coal) is reduced, as are net greenhouse gas emissions and criteria air pollutants including SO_2, Hg, and likely, NO_x. Cofiring biomass at 10% increases the net energy ratio of producing electricity by 8.9%. Similarly, the net energy ratio for dedicated biomass gasification is estimated to be 13, indicating that 13 units of electricity are produced for every unit of fossil energy consumed across the entire system life cycle. For comparison, the net energy ratio of the current US electricity grid is 0.26.

This study suggests that the environmental impacts from producing electricity with willow biomass energy crops are similar to using woody residues and that the pollution prevented is comparable to other renewable energy sources (solar and wind). Additional data and experience are needed to determine whether the small differences reported here are indeed significant. It should be noted that choice of modeling parameters and allocation procedures can have significant effects on results. Life cycle assessment based on ISO 14040 guidelines offers a valid means of quantifying potentially regulated and/or tradable emissions such as SO_2, NO_x, and greenhouse gases, but additional standardization will be needed to assure consistency. The current study presents results useful for evaluating biomass electricity generation as an emerging technology as well as forwarding the discussion of method standardization.

In addition to the environmental benefits quantified in this LCA, willow biomass crops will provide other benefits as they are deployed across the landscape. These include rural development through the creation of new markets and jobs, enhanced landscape diversity and wildlife habitat, and reduced erosion potential. Such benefits, while important features of willow biomass crops, are not readily captured by life cycle methodology.

Market-based forecasts show that the multiple benefits of renewable energy fuel sources such as willow biomass will not be realized without proper regulatory or legislative incentive. While other less costly options exist to reduce air pollutants from existing fossil fuel power plants, biomass energy presents an opportunity to reduce air pollutants while also cutting greenhouse gas emissions and lowering non-renewable energy consumption.

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