Wood count: 7,741

Life Cycle Assessment of Co-Firing Coal and Wood Pellets in the Southeastern United States

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Abstract

Coal-fired power plants produce nearly 40% of the electricity in the United States, contributing more than three-quarters of all carbon dioxide emissions from the electricity sector. While many European coal-fired power plants have been transitioning to wood pellets to abate carbon dioxide emissions, such a changeover has not occurred in the United States electricity sector. This analysis examines the environmental implications of co-firing coal and wood pellets in the Southeastern United States, where the vast majority of wood pellet exports to Europe originate. Utilizing primary data from existing wood pellet manufacturers, a life cycle inventory is presented that characterizes the full cradle-to-grave environmental performance of co-firing coal and wood pellets for electricity generation. Furthermore, the avoided life cycle emissions related to shipping wood pellets to Europe are calculated. Life cycle assessment modeling scenarios for co-firing wood pellets in existing coal-fired power plants within the Southeastern United States result in reductions in eight of nine impact categories. The results presented here indicate that co-firing with wood pellets could be a viable interim solution for the aging fleet of coal-fired power plants within the Southeastern United States, particularly if stricter emission regulations and renewable portfolio standards are implemented.

Key Words

Bioenergy, Life Cycle Assessment, Industrial Ecology, Sustainable Systems,
Thermoelectric Power Generation

1. Introduction

As political agendas take action against climate change, much of the effort focuses on curbing carbon dioxide (CO₂) emissions released to the atmosphere through anthropogenic activities. Throughout the European Union, sustainable energy policies requiring the use of renewable energy and the abatement of greenhouse gas (GHG) emissions have created a massive demand for a new renewable energy commodity: wood pellets (Abt et al., 2014). In pursuant to the European Union's target of 20% renewable energy use by 2020, many European power producers have converted, or are in the process of converting, coal-fired power plants to utilize wood pellets in lieu of coal (Goetzl, 2015).

Wood pellets offer a consistent, uniform supply of biomass, in which the pelleted form yields double the energy density of unprocessed wood (assuming 50% moisture content) (Spelter and Toth, 2009; Goetzl, 2015). Existing coal-fired power stations can either be converted to run entirely on wood pellets or retrofitted to co-fire coal and wood pellets. Co-firing, in which a percentage of pellets is substituted in place of coal, exemplifies one of the most straightforward and easily adopted technology options for increasing the share of renewable electricity generation (Ehrig and Behrendt, 2013; Lempp, 2013).

Insufficient local forestry resources within the European Union means power producers have to increasingly source wood pellets from foreign markets. The Southeastern United States has witnessed the emergence of a burgeoning wood pellet export industry, with 34 operating wood pellet production facilities (Figure 1) as of December 2015 (Nunez, 2014; Wong and Bredehoeft, 2014; Lowenthal-Savy, 2015).

Traditionally, North America wood pellet production facilities were located in close proximity to a sawmill, where pellet producers could capitalize on the abundant supply of dry fiber residues in the production of residential grade pellets (Harper, 2011). However, with the 2008-2009 recession in the United States, and the subsequent decline of the sawmill sector, new Southeastern United States wood pellet mills have been constructed to process roundwood, as opposed to processing strictly wood mill residues (Cocchi et al., 2011). Furthermore, with the growth of the industrial wood pellet market in Europe, most of the wood pellet exporters now utilize roundwood in their production in order to meet European consumers' stringent quality requirements (Qian and McDow, 2013).

Despite the emergence of the wood pellet export sector, electric utilities in the United States are not employing the bioenergy technology of co-firing wood pellets within existing coal power plants (Xian et al., 2015). As of November 2015, wood biomass accounts for less than half a percent (0.38%) of net electricity generation in the United States (EIA, 2016a). Wood-based bioenergy in the United States has struggled to gain traction, given the need to balance wood use for energy with wood use for conventional purposes (Goetzl, 2015). Existing use of wood pellets is confined to the northern portion of the United States, where pellets are utilized for residential heating.

Via the use of primary data, this paper explores the environmental and economic implications of co-firing coal and wood pellets within the Southeastern United States, where power plants currently represent the largest concentrated source of GHG emissions among stationary sources (EPA, 2015). Life cycle assessment (LCA) methodology – which affords a comprehensive, system-based analysis of the environmental performance of a product system – is utilized to assess three primary objectives: (1) to calculate the

environmental impacts from generating one kilowatt hour of electricity from wood pellets in the Southeastern United States; (2) to calculate the environmental impacts from co-firing wood pellets with coal in existing coal-fired power plants in the Southeastern United States; (3) to calculate the averted environmental impacts from not exporting wood pellets to the European Union. Furthermore, the cost of retrofitting existing coal-fired power plants to co-fire wood pellets is assessed.

Figure 1. Existing wood pellet locations within the Southeastern United States, as of December 2015 (Biomass Magazine, 2015). Nautical mileage (nm) to the United Kingdom is shown (Sea-distances.org, 2015). Within the eight states depicted, there are 172 coal-fired power generation units (EIA, 2016b).

2. Literature Review

Despite the recent increases in wood pellet production, a scarcity of relevant data has made it difficult to obtain reliable information from the research community about

the United States' wood pellet industry's production characteristics (Pirraglia et al., 2010). There remains a need to investigate the environmental performance for the production of wood pellets for the energy sector (Taskhiri et al. 2016). Of the existing literature, much has focused predominantly on GHG impacts of wood pellet energy chains (e.g., Peterson Raymer, 2006; Magelli et al., 2009; Pa et al., 2011; Sjølie and Solberg, 2011; Katers et al., 2012; Pa et al., 2012; Dwivedi and Khanna, 2014). Hossain et al. (2016) analyzed the environmental impacts of using pelletized recycled wood products in place of coal for electricity generation in Hong Kong. Few studies have focused specifically on wood pellet production in the Southeastern United States (Reed et al., 2012). Spatially explicit data in regards to the industrial use of forestry feedstocks is necessary in order to accurately address the feedbacks and synergies of the emergent industrial bio-based economy (Golden and Handfield, 2014; Golden et al., 2015; Morrison and Golden, 2015)

Dwivedi et al. (2011) calculated the global warming impact (GWI) of imported wood pellets from the southern U.S – in particular Florida – for electricity production in the Netherlands. Stephenson and MacKay (2014) assessed scenarios of GHG impacts and energy input requirements of utilizing North American woody biomass for electricity generation in the United Kingdom. Dwivedi et al. (2014) calculated relative GHG savings for a unit of electricity in the United Kingdom (UK) generated using imported wood pellets from the Southeastern U.S. Röder et al. (2015) evaluated emissions and impacts of imported wood pellets in the UK in an effort to identify critical steps necessary to maximize the emission reduction potential. Morrison and Golden (2016) assessed the cradle-to-gate impacts of wood pellet manufacturing within the Southeastern United

States, under the premise that all wood pellets were delivered to a U.S port for delivery to the European Union.

To the best of our knowledge, no study has examined the environmental implications of co-firing coal and wood pellets in the Southeastern United States. Zhang et al. (2010) quantified GHG emissions from co-firing wood pellets with coal in Ontario Canada. Relatedly, Xian et al. (2015) analyzed co-firing from an economic perspective, but did not consider environmental implications.

3. Methods

A comparative cradle-to-grave, attributional LCA was conducted in this assessment, with a comprehensive supply chain scope that included all steps from forest establishment through the combustion of the wood pellets. This work adheres to the procedures for conducting LCAs as published by the International Organization for Standardization (ISO) (ISO, 2006a, 2006b). The ecoinvent database, version 2.2, (ecoinvent, 2015) was employed in this analysis, utilizing openLCA software version 1.4.2 (openLCA, 2015). The Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI) assessment method is utilized to assess the impacts resulting from the production of wood pellets. This method was chosen as TRACI was developed specifically for the United States (EPA, 2014), utilizing input parameters that are consistent with U.S locations for the following impact categories: acidification, smog formation, eutrophication, human cancer, human non-cancer, and human criteria effects. TRACI utilizes a 100-year time horizon, consistent with the guidance of the United Nations Framework Convention on Climate Change (UNFCCC).

A time horizon of 100-years has been adopted as an informal standard within the LCA community (Dyckhoff and Kasah, 2014).

3.1 Functional Unit and System Boundary

For this analysis, the functional unit is defined as one kilowatt hour (kWh) of electricity produced in the Southeastern United States. Initial LCA results for the generation of one kWh of electricity generation were then scaled within OpenLCA to encompass electricity generation for the entire region depicted in Figure 1. Electricity generation for the entire region was calculated utilizing existing operating statistics for coal-fired power stations in the Southeastern United States (EIA, 2016b). For each existing power station, net summer generating capacity was acquired, and then multiplied by an average availability factor, in hours per year, to calculate the maximum yearly electricity generation. Multiplying by an average capacity utilization factor results in an annual electricity production potential for each power station, which was then summed for the entire region.

Following industry conversations, two different supply chains for wood pellet production were assessed, as depicted in Figure 2. The first supply chain analyzes the production of wood pellets produced directly from loblolly pine roundwood, while the second analyzes the production of wood pellets that are produced utilizing sawmill residues. Both wood pellet production scenarios exist within the current production schemes of wood pellets (Biomass Magazine, 2015). The wood pellet supply chain involves are steps from woody biomass procurement through distribution and combustion. As noted by Murphy et al. (2015), the wood pellet production process is an

energy intensive process, requiring large quantities of electricity. During the actual production process, wood feedstock is debarked and chipped, and then dried via a single pass drum dryer. Biomass is utilized to fuel the drum dryer, as indicated in discussions with industry sources and detailed in Table 1. The dried wood feedstock is then processed through a hammer mill, which reduces the size of the wood material. Finally the feedstock material is processed into pellet form via a specialized press. Though the energy and resources that are required to construct the wood pellet production facilities and the capital equipment needed to produce the pellets should certainly be considered, such inputs are excluded from the assessment as the resource use and environmental impacts would be quite small (below a cut-off criteria threshold) when attributed to the amount of pellets produced during the lifetime of the facility.

Power generation from coal was modeled within OpenLCA for an average coal-fired power plant within the SERC Reliability Corporation (SERC) region of the North American Electricity Reliability Corporation. SERC is one of eight regional electric reliability councils under the North American Electric Reliability Corporation (NERC) authority. Portions of the eight states in Figure 1 all fall within the geographic extent of SERC. Coal-fired power plant operating statistics are based upon existing power stations in the latest year on record within the dataset (2004). Criteria emissions control technologies are factored into the assessment results, with the amounts of pollutants retained based upon the difference between uncontrolled averages in comparison to actual region-specific emissions data.

Figure 2. System boundary for the cradle-to-grave life cycle assessment of the production and utilization of wood pellets for electricity generation in the Southeastern United States. Two differing production scenarios of wood pellets were considered: (1) roundwood from a forest harvesting operation or (2) sawmill residues. The supply chain utilized for this analysis was delineated both by previous literature (e.g., Magelli et al., 2009; Dwivedi et al., 2011; Dwivedi et al., 2014; Röder et al., 2015) and via industry consultation.

3.2 Allocating Environmental Impacts to Sawmill Residues

When a production process contributes to several products, the total environmental load of the system has to be allocated among all the products. Accordingly, the sawmill process is a multiple output process as it simultaneously produces a main product (i.e., lumber) in addition to several co-products: bark, sawdust, wood chips and shavings (Garcia and Freire, 2014). Therefore, two allocation procedures are examined in this analysis: mass allocation and economic allocation.

For the mass allocation, the total sawmill electricity consumption was divided by the percentage of incoming wood (40%) that results in residues (excluding bark), which are available to be transformed into wood pellets (INRS, 2007, 2009; Richardson, 2015). When utilizing mass allocation, biomass receives a greater allocation of energy requirements.

Economic allocation of the sawmill process was also included as wood pellets are produced for achieving economic gain (Tillman, 2000). Furthermore, mass allocation may not be an appropriate figure to describe the technical value of a product (Dolezal et al., 2014). The economic value of sawmill products – lumber (\$564 USD per dry metric ton (mt); 87.9% of total value), wood chips (\$72/mt; 9.3%), sawdust/shavings (\$37/mt; 2.4%), and bark (\$8/mt; 0.4%) – was derived from previous literature (AEBIOM, 2013). Of the listed co-products, wood chips and sawdust/shavings can be utilized for wood pellets. Accordingly, the economic allocation of sawmill products for wood pellets was determined to be 12%.

4. Data and results

4.1 Life Cycle Inventory Data

Given (1) the uncertainty surrounding the impact of the combustion of biogenic carbon within the existing literature (e.g., Johnson, 2009; Zhang et al., 2010; Holtsmark, 2011; McKechnie et al., 2011), (2) the assessment of biogenic carbon within LCAs (e.g., Levasseur et al., 2010; Levasseur et al., 2013; Dyckhoff and Kasah, 2014), (3) the carbon neutrality of biomass under existing European Union legislation (Bourguignon, 2015), and (4) the ongoing flux within the United States of both the U.S Environmental

Protection Agency's (EPA) Clean Power Plan (CPP) and the EPA's proposed framework to account for biogenic CO₂ emissions from stationary sources (Bracmort, 2016), the assessment of biogenic carbon within the combustion of wood pellets was left for future research.

Table 1 presents Life Cycle Inventory (LCI) data for a representative wood pellet production facility in the Southeastern United States. This research addressed previous gaps in the existing wood pellet literature by utilizing data obtained via industry consultation through both interviews and site visits. Data from seven different wood pellet production facilities (21% of all existing wood pellet production facilities in the Southeastern United States) and four sawmill locations in the Southeastern United States were utilized in order to produce the LCI data in Table 1. Additional supporting data, where necessary, were derived from existing academic literature or industry reports.

A listing of all existing coal-fired power plants in the United States was retrieved from the U.S Energy Information Administration (EIA, 2016b). Data were managed to include eight states within the Southeastern United States, as depicted in Figure 1. In total, 73 coal-fired power facilities were identified, for a cumulative total of 172 generation units. Summary statistics for existing coal-fired power plants, as depicted in Table 1, were retrieved from existing literature.

The underlying electricity mix utilized in our analysis represents the existing average electricity mix for the eight states depicted in Figure 1. Existing electricity generation mixes were retrieved from the U.S. Energy Information Administration (EIA), and averaged together to create an electricity generation profile for the Southeastern United States. The largest contributing electricity sources are: natural gas (43%), nuclear

(32%), and coal (18%). Within renewable electricity generation, hydroelectric was the largest contributing source (3%). Variations in future electricity generation mixes (e.g., a reduction in coal and an increase in natural gas) could certainly impact the assessment results, and is an area necessary of further study.

Silviculture / Logging Operation			
Process	Activity	Value	Source
Production of one metric ton of softwood forestry feedstock (Moisture content 50%)	Diesel fuel use	0.013 kg	Author calculations utilizing values retrieved from industry consultation of forestry production practices of pellet mill suppliers, in conjunction with values in Röder et al. (2015)
		0.006 kg glyphosate	
	Forest management (e.g., pesticides, herbicides, fertilizers)	0.005 kg urea	
		0.005 kg DAP	
		0.017 kg herbicides	
	Kerosene fuel use	0.034 kg	
	Truck-tractor trailer transport (one-way)	61.225 km	Average distance based on industry consultation
Sawmill Operation			
Production of one metric ton of residue from a modern softwood sawmill facility	Roundwood Feedstock Required	2.500 MT	Author calculation based on INRS (2007, 2009) and Richardson (2015)
	Electricity use (grid)	73.53 kWh/MT	Author calculation based on Redmond (2015)
	Truck-tractor trailer transport (one-way)	79.470 km	Average distance based on industry consultation
Wood Pellet Production Process			
Production of one metric ton of wood pellets (Average moisture content 7%)	Energy use for drum dryer (biomass)	589 MJ	Values retrieved from industry consultation
	Electricity use (grid)	202.790 kWh	
	Diesel fuel use	2.060 kg	Author conversions utilizing values retrieved from industry consultation
	Propane	0.006 kg	
	Lubricants	0.275 kg	
Transport: Wood Pellet Mill to Power Plant			
Transport of one metric ton of finished wood pellets	Truck-tractor trailer transport (one-way)	150 km	Dwivedi et al. (2014)
Electric Power Generation in the United States			
Operating statistics for existing coal-fired electricity generation in Southeastern United States	Capacity factor	61%	EIA, 2016c
	Efficiency factor	34%	Campbell, 2013
	Plant availability	85%	Tidball et al., 2010
	Average existing coal-fired capacity	327 MW	EIA, 2016b
	Calorific value of	17 MJ/kg	Chau et al., 2009

wood pellets		
Co-fire retrofit	\$285	EIA, 2015
cost	USD/kWh	

Table 1. Life Cycle Inventory (LCI) data for the cradle-to-gate life cycle assessment of wood pellets produced in the Southeastern United States. Data were collected for all relevant processes within the system boundaries, and adjusted accordingly to the functional unit.

4.1.1 Quantification of Wood Pellets Required for Electricity Production

Previous work by Dwivedi et al. (2011) was applied to quantify the amount of wood pellets required for the production of one kilowatt hour (kWh) of electricity in the Southeastern United States. The average capacity of the 172 coal-fired generation units in the Southeastern United States is 327 megawatts (MW). Assuming the power plant run 24 hours per day, for 310 days (i.e., 85% availability), it will operate for 7,440 hours per year. Maximum annual electricity production potential for the coal-fired unit can then be calculated by multiplying by the total capacity. Multiplying by the capacity factor (61%) provides an estimate of actual annual electricity production potential. Assuming a conversion efficiency of 34%, the amount of heat required to generate electricity was estimated for each operating unit. Dividing by the calorific value (CV) of wood pellets – 17 megajoules per kilogram (MJ/kg) (Chau et al., 2009) – yields the annual requirement of wood pellets needed for generating electricity each year. Finally, dividing this by the estimated annual electricity production yields the amount of pellets needed to produce one kWh of electricity in the Southeastern United States: 0.62 kg.

Converting all coal-fired operating units in the Southeastern United States to run solely on wood pellets would require nearly 159 million metric tons (MMT) of pellets per year. However, a 10% co-firing rate would only require approximately 16 MMT of pellets. Current wood pellet production capacity in the United States is estimated at just

over 18 MMT (Biomass Magazine, 2015). Future wood pellet production in the Southeastern United States – estimated at nearly 16 MMT by 2019 (Greene, 2015) – is on par with the amount of wood pellets required for 10% co-firing of existing coal power plants.

4.1.2 Exported Pellets to the United Kingdom

Utilizing wood pellets domestically in the Southeastern United States in lieu of importing them to the European Union would avoid emissions attributed to the transoceanic shipment of wood pellets. The largest market for exported pellets from the United States is the United Kingdom, which received 73% (2.9 million metric tons) of total wood pellet exports from the United States in 2014, the last full year in which data is available (Lowenthal-Savy, 2015). Wood pellet exports originate nearly entirely (99% of total) in the southeastern and lower Mid-Atlantic regions of the United States (Wong and Bredehoeft, 2014).

Based on industry consultation, the average wood pellet transoceanic shipment load is 43,000 metric tons. Therefore, the United Kingdom received approximately 68 transoceanic shipments of wood pellets from the United States in 2014. The average shipping distance from the eight ports denoted in Figure 1 is 4,199 nautical miles (7,777 kilometers).

4.4 Environmental Life Cycle Assessment of Electricity Generation

Table 2 displays the life cycle impact assessment results for the generation of one kWh of electricity from four modeled analyses: wood pellets produced from loblolly pine roundwood; wood pellets produced from sawmill residues using a mass allocation (MA); wood pellets produced from sawmill residues using an economic allocation (EA); and

electricity produced from coal. Descriptions of each impact category are provided by Bare (2012). With the exception of Ozone Depletion Potential, electricity generation from wood pellets led to a reduction in all midpoint impact category results in comparison to electricity generation from coal. Reductions ranged from 65-93%, depending on the midpoint impact category and the wood pellet production scenario considered. Given the transport distances of the forestry resources and finished wood pellets, in addition to the diesel fuel and herbicide use during the management of forestry resources, the utilization of wood pellets resulted in a larger Ozone Depletion Potential than the utilization of coal.

Regarding the different allocation approaches in the sawmill wood pellet scenarios, small differences in results can be observed between mass and economic allocation, ranging from zero percent change in the Ozone Depletion Potential, to an 11% difference in the Carcinogenic Potential. Differences in values are associated with the greater proportion of allocation in the mass allocation scenario (40%) in comparison to the economic allocation scenario (12%).

Impact Category	Midpoint Impact	Roundwood	Sawmill Residues-MA	Sawmill Residues-EA	Coal	Reference Unit
Environment	Acidification	0.04	0.05	0.04	0.40	Moles of H ⁺ -Eq.
	Ecotoxicity	0.06	0.07	0.07	0.93	kg 2,4-D-Eq.
	Eutrophication	2.54x10 ⁻⁵	3.19x10 ⁻⁵	3.12x10 ⁻⁵	1.30x10 ⁻⁴	kg N
	Global Warming	0.09	0.11	0.10	1.16	kg CO ₂ -Eq.
	Ozone Depletion	5.27x10 ⁻⁹	6.93x10 ⁻⁹	6.91x10 ⁻⁹	5.13x10 ⁻⁹	kg CFC-11-Eq.
	Photochemical Oxidation	3.30x10 ⁻⁴	4.20x10 ⁻⁴	4.10x10 ⁻⁴	2.33x10 ⁻³	kg NOx-Eq.
Human Health	Carcinogenic	1.60x10 ⁻⁴	1.90x10 ⁻⁴	1.70x10 ⁻⁴	1.28x10 ⁻³	kg benzene-Eq.
	Non-carcinogenic	0.72	0.83	0.77	2.07	kg toluene-Eq.
	Respiratory Effects, avg.	2.00x10 ⁻⁴	2.20x10 ⁻⁴	2.10x10 ⁻⁴	1.51x10 ⁻³	kg PM2.5-Eq.

Table 2. Life Cycle Impact Assessment (LCIA) results for the production of one kilowatt hour (kWh) of electricity generation from four modeled analyses. Abbreviations: MA = Mass Allocation; EA = Economic Allocation.

The LCA results for the generation of one kWh of electricity were utilized to examine the environmental implications of co-firing wood pellets – at a rate of 10% - with coal in the Southeastern United States. Co-firing LCA results are provided in Table 3.

Impact Category	Reference unit	Coal	Co-Fire Roundwood	% Change	Co-Fire Sawmill-MA	% Change	Co-Fire Sawmill-EA	% Change
Global warming	kg CO ₂ -Eq	2.96x10 ¹¹	2.68x10 ¹¹	-9.39%	2.69x10 ¹¹	-9.23%	2.68x10 ¹¹	-9.29%
Acidification	moles of H ⁺ -Eq	1.02Ex10 ¹¹	9.22x10 ¹⁰	-9.19%	9.24x10 ¹⁰	-9.01%	9.23x10 ¹⁰	-9.08%
Carcinogenic	kg benzene-Eq	3.28x10 ⁸	2.99x10 ⁸	-8.90%	2.99x10 ¹⁰⁸	-8.70%	2.99x10 ⁸	-8.80%
Respiratory effects, avg.	kg PM _{2.5} -Eq	3.87x10 ⁸	3.53x10 ⁸	-8.86%	3.54x10 ⁸	-8.68%	3.53x10 ⁸	-8.76%
Ecotoxicity	kg 2,4-D-Eq	2.39x10 ¹¹	2.16x10 ¹¹	-9.48%	2.16x10 ¹¹	-9.41%	2.16x10 ¹¹	-9.45%
Eutrophication	kg N	3.21x10 ⁷	2.95x10 ⁷	-8.13%	2.96x10 ⁷	-7.61%	2.96x10 ⁷	-7.66%
Ozone depletion	kg CFC-11-Eq	1314.38	1315.91	0.12%	1358.22	3.34%	1357.73	3.30%
Non-carcinogenic	kg toluene-Eq	5.30x10 ¹¹	4.94x10 ¹¹	-6.69%	4.97x10 ¹¹	-6.17%	4.96x10 ¹¹	-6.43%
Photochemical oxidation	kg NO _x -Eq	5.98x10 ⁸	5.45x10 ⁸	-8.73%	5.48x10 ⁸	-8.35%	5.47x10 ⁸	-8.39%

Table 3. TRACI midpoint impacts from coal-fired electricity generation in comparison to impacts from 10% co-firing of wood pellets with coal. Percentage change refers to switching from coal-fired generation to co-firing generation. Abbreviations: MA = Mass Allocation; EA = Economic Allocation.

As exhibited in Table 3, co-firing with wood pellets, no matter the production scenario, resulted in lower environmental midpoint impact category results. The largest percentage decreases in midpoint impact categories were exhibited in Ecotoxicity, Global Warming Potential (GWP), and Acidification, respectively.

The Ecotoxicity Potential of coal results almost entirely from the mining of coal (98%), attributable in large part to the blasting of rock that is required to extract the coal resource. In each of the wood pellet production scenarios, more than 50% of the total Ecotoxicity Potential is attributable to the underlying electricity mix used to produce the pellets, followed by the burning of biomass (more than 30% of total) for drying the wood pellets.

The GWP of coal is almost entirely (93% of total) attributed to the combustion of coal. The supply chain for coal (e.g., transportation, mine electricity use, diesel fuel use) accounts for only seven percent of total GWP. For wood pellets produced in a sawmill, the underlying electricity use of the pellet mill accounts for 60% of the total GWP, followed by the emissions from the sawmill process (27% for mass allocation and 22% for economic allocation). In the roundwood scenario, the underlying electricity use of the pellet mill accounts for 72% of the total GWP, followed by the transport of the finished pellets (14%).

For coal electricity generation, 90% of total Acidification Potential results from the combustion of coal. The remaining 10% is attributed to the supply chain of coal, including the mining and transport of coal to the power plant. For the wood pellet scenarios, the underlying electricity mix accounts for more than 60% of total Acidification Potential. For the sawmill scenarios, sawmilling activities account for an additional 20% of total Acidification Potential. In the roundwood scenario, the transportation of the finished wood pellets is the next largest contributing factor at 13% of total Acidification Potential.

4.5 Sensitivity Analysis of Co-firing Rates

The main objective of this research was to quantify the environmental impacts of co-firing wood pellets with coal in the Southeastern U.S. Following an initial evaluation of the midpoint impact categories resulting from a 10% co-firing rate, additional LCA iterations were assessed with varying co-firing percentage rates. Figure 4 presents the resulting variations in GWP associated with differing co-firing rates. As the co-firing rate increases, the GWP of the assessment decreases, albeit at a rate less than the rate of co-firing. As noted by Mann and Spath (2001), the efficiency losses attributed to co-firing serve to decrease the magnitude of GWP, as more wood pellets – which have a smaller carbon footprint than coal – must be used per unit of coal avoided to produce the same amount of electricity.

Figure 4. Rate of reduction of global warming potential (GWP) given variations in the co-firing percentage. Percent reduction refers to a base case scenario with no co-firing.

4.6 Environmental Life Cycle Assessment of Avoided Transoceanic Shipping Impacts

Barring a substantial increase in production, the increased domestic utilization of wood pellets in the Southeastern United States would surely lead to the decrease in the export of wood pellets to the European Union. Table 4 depicts the avoided midpoint category impacts attributable to the transoceanic shipment of wood pellets from the Southeastern United States to the United Kingdom, which currently represents the largest market share of wood pellet exports.

Impact Category	Midpoint Impact	Result	Reference Unit
Environment	Acidification	2.79×10^8	Moles of H ⁺ -Eq.
	Ecotoxicity	1.76×10^7	kg 2,4-D-Eq.
	Eutrophication	2.16×10^5	kg N
	Global Warming	2.05×10^8	kg CO ₂ -Eq.
	Ozone Depletion	25.66	kg CFC-11-Eq.
	Photochemical Oxidation	3.19×10^6	kg NOx-Eq.
Human Health	Carcinogenic	2.34×10^{10}	kg benzene-Eq.
	Non-carcinogenic	2.95×10^8	kg toluene-Eq.
	Respiratory Effects, avg.	9.44×10^5	kg PM2.5-Eq.

Table 4. Avoided impacts attributable to the transoceanic shipment of wood pellets to the United Kingdom in 2014.

With the exception of Ozone Depletion Potential, the majority of avoided impacts stem from the transoceanic operation of the vessels, ranging from 49% (Non-carcinogenic Potential) to 96% (Photochemical Oxidation Potential). Nearly the entirety (99%) of the Ozone Depletion Potential results from the production and extraction of crude oil. In relation to Global Warming Potential, 87% of the total results from the operation of transoceanic freight ships, while 12% results from the production and refining of heavy fuel oil. The importance of the Human Health Impact Categories may be overstated, given that most of the environmental pollutants result from the operation of the ship, which occurs away from population regions. Port activities were excluded from this analysis, given that port reception facilities handle a variety of products and cargo.

4.7 Cost of Co-Firing Conversion

The primary component of the total cost of electricity generation is the amortized capital costs of building the generating facility (Strauss, 2014). Accordingly, retrofitting existing coal power plants – those that have been in service for more than 30 years – presents low capital costs, given that the facilities are by-and-large paid-off or amortized (Simbeck, 2001). As of 2014, the average age of coal-fired power plants in the United States is 42 years old (EPA, 2015). Therefore, for an existing pulverized coal power plant, the only new capital costs in converting to wood pellet fuel would be modest alterations to the boiler and fuel handling and storage systems.

Retrofitting existing coal power stations to co-fire with wood pellets requires a capital investment for boiler modifications and fuel handling, estimated at \$285 per kilowatt (kW) of biomass capacity (EIA, 2015). The 172 coal generating units have a combined nameplate capacity of 5.63×10^4 megawatts (MW). Co-firing at a rate of 10% with wood pellets would amount to 5.63×10^6 kW of biomass capacity. As a result, it would cost just over \$1.6 billion to retrofit existing coal power plants in the Southeastern United States to co-fire with wood pellets. While this is a significant expense, it pales in comparison to the infrastructure cost requirements for the aging fleet of coal power plants.

Even in the absence of additional environmental regulation against coal-fired power plant emissions, utilities can be expected to invest in the next generation of power production, attributable to the age of existing assets and infrastructure (EPA, 2015). Given deterioration with age and use, the efficiencies of coal-fired power plants decrease over time, which ultimately results in more CO₂ being emitted per unit of electricity

generated (Campbell, 2013). Resultantly, after 25-30 years of operation, retrofits to coal power plants are warranted in order to restore operating efficiency, which in turn serves to decrease CO₂ emissions. Such retrofits involve substantial outlay, resulting in costs of \$100-200 million per unit (Henderson, 2013). Retrofitting the 172 coal-fired generation units in the Southeastern United States would cost between \$17.2-34.4 billion; or more than ten times the cost of co-firing modifications.

5. Discussion

The results presented here are in line with previous studies. Dwivedi et al. (2011) recorded a savings of 82% if wood pellets were utilized within Florida for electricity generation. Zhang et al. (2011) reported GHG reductions of 91-92% for electricity generated from wood pellets as opposed to coal in Canadian power plants. Relatedly, Röder et al. (2015) calculated a base case GHG emission for generating electricity from forest residue and sawmill residue pellets to be 132 g carbon dioxide equivalent (CO₂e) and 140 g CO₂e kWh, respectively. Excluding the transport phase of the supply chain, which in their analysis included the transoceanic shipment of pellets and was responsible for 39% and 36% of total GHG emissions, the resulting impacts of electricity generation from wood pellets are 84-85g CO₂e/kWh. These results are in line with the results of our study, which also include the impacts of transportation.

When surveyed, energy utilities in the Southeastern United States noted that feedstock cost and securing a consistent, local supply were the two largest obstacles preventing the utilization of wood pellets. This is in line with previous research, which has shown that the development of a domestic power-utility demand for wood pellets –

given the current availability of cheap natural gas – would require significant government support, via either an alternative energy subsidy or a tax on existing fossil fuels (Xian et al., 2015). As detailed by Mobini et al. (2014), torrefied wood pellets, in which a thermal treatment is applied to the pellets, which in turn increases bulk and energy densities by removing oxygen and other volatiles, present a lower cost alternative to traditional wood pellets. However, significant government incentives would be needed to spark the widespread adoption of wood pellets within the electricity sector.

Even if significant government incentives were enacted in support of renewable energy generation, securing a sufficient, and consistent, local supply of biomass may be a formidable challenge, given the existing export of U.S wood pellets to Europe. As long as European wood pellet production costs remain higher than import prices, the importation of energy (i.e., wood pellets) is predicted to continue in lieu of domestic European development (Nunes et al., 2014).

The future utilization of biomass energy in general, and wood pellets in particular, in the United States may ultimately depend upon the carbon status of biopower, as determined by the legislative system of the United States. The U.S EPA, itself, recognizes that utilizing certain biomass-derived fuels can play a role in controlling and moderating atmospheric CO₂ levels (EPA, 2015). However, in order to maximize the benefits of biomass energy, feedstocks must be sourced responsibly, including the accurate accounting of biogenic carbon emissions via dynamic life cycle assessment. If the Clean Power Plan, which is currently stayed by the United States Supreme Court (EPA, 2016), is reinstated, it may depend on the Congress of the United States to address carbon accounting for biopower as federal environmental regulatory control already

exists for the primary environmental concerns associated with biopower production: air quality (Clean Air Act), use of public land (Federal land Policy and Management Act), and water discharges (Clean Water Act). The future utilization of wood pellets in the Southeastern United States may therefore ultimately be influenced not only by economic and environmental factors, but also on legislative action.

6. Conclusion

This study analyzed the environmental impacts associated with producing electricity from wood pellets and coal. Overall, utilizing wood pellets in lieu of coal results in a GWP reduction of 90-92% per kWh of electricity generation, depending upon which wood pellet production scenario is utilized. Subsequent LCA modeling then determined the environmental impacts of co-firing wood pellets within existing coal-fired power stations in the Southeastern United States. Modeling results determined that co-firing wood pellets within existing coal power stations leads to reductions in eight of nine impact categories. Financial calculations determined it would cost just over \$1.6 billion to retrofit existing coal power plants in the Southeastern United States to co-fire with wood pellets. Such a conversion would not only provide environmental benefits during electricity generation, but would also prevent the deleterious impacts associated with the transoceanic shipping of wood pellets to the European Union, which in this study were calculated to annually amount to 2.05×10^8 kg CO₂-equivalent.

Acknowledgements: The authors would like to thank the various industry sources that provided valuable data, information, and insight for this analysis. No conflicts of interest exist, and no industry funding was received for this research project.

Funding: This work was supported by the U.S. National Science Foundation Partnerships for International Research & Education (PIRE): Water and Commerce-Technologies to Enable Environmental Sustainability in Global Markets [grant number 1243433]. The Duke Center for Sustainability and Commerce also jointly supported this research.

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