Technical Note

Using Life-Cycle Assessments to Demonstrate the Impact of Using Wood Waste as a Renewable Fuel in Urban Settings for District Heating

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Abstract

The use of wood waste for heating in urban settings provides an opportunity for communities to reduce annual fossil emissions by directly reducing the amount of fossil fuel used. Life-cycle assessments (LCA) comparing the environmental impacts of alternative processes or products provide the essential information to better understand opportunities for improvement. An LCA was performed on a Seattle, Washington, district heating system that provides thermal energy to a large number of buildings in downtown Seattle. This study presents annual impacts in terms of carbon emissions for heat production generated using a new boiler design fuel mix including wood wastes as well as natural gas. Results are compared with the results from the 100 percent natural gas boiler that was previously used. The LCA includes results from both a life-cycle inventory of all inputs and outputs and a life-cycle impact assessment comparing alternatives. Results show that global warming potential (GWP) was reduced by 57 percent for the mix fuel design boiler compared with an all natural gas boiler. When 100 percent woody biomass is used, the reduction increases to 104 percent. Transportation and collection of feedstocks contributed minimally (8%) to the overall impact, while the combustion life-cycle stage accounted for 92 percent of the total GWP.

District heating systems distribute heat generated in a centralized location to local users. They are capable of producing steam, hot water, or chilled water at a central point and piping it underground to individual buildings, where it is used for heating, hot water consumption, or air conditioning. Some of the environmental and economic benefits to the community are improved energy efficiency, fuel flexibility, ease of operation and maintenance, reliability, and decreased life-cycle and environmental costs. Andrews (2009) reported that district heating systems with combined heat and power have one of the lowest carbon footprints. Several boiler systems—Seattle, Washington, and St. Paul, Minnesota, for example—have converted from fossil fuels to renewable biomass. Using wood wastes to generate heat reduces fossil emissions from natural gas or other fossil fuels. In a recent study, substituting wood-based fuels with fossil fuels in sawmill operating boilers resulted in a 66 percent reduction in carbon emissions (Puettmann and Lippke 2012).

Burning wood residue in boilers for heat generation has historically been restricted to those industries where biomass or ‘‘hogged fuel’’ is readily available as a by-product, primarily in the forest products industry. There is recognition that biomass resources in the United States have been largely underutilized for the production of fuels (Gan and Smith 2006). Reports have suggested that over 1.3 billion bone dry tons (BDT) are available for fuel alone in the United States (Fernholz et al. 2009). With increasing fossil fuel prices and rapid technological advances in biomass conversion processes the interest in biofuels is growing.

In addition to burning mill hogged fuel, other options for heat generation include collecting and using forest residuals commonly left in the forest for ‘‘slash’’ burning or decay and ‘‘clean demolition material’’ normally fated for the landfill. A recent report for Washington State (Jamison et al.

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2012) shows current calculated forest residual biomass to be around 4.4 million bone dry tons[1] (MM BDT), with a peak occurring at 6.5 MM BDT by 2015. In fact, they predict that over the next 20 years biomass volumes should remain well above 5.5 MM BDT.

Background

Seattle Steam Company (SSC) commissioned a biomass steam generator and began generating thermal energy primarily from waste wood in 2010. SSC is a district heating system that provides needed heat and cooling to nearly 200 buildings in the central business district and First Hill neighborhoods located in Seattle, Washington, via 18 miles (29 km) of underground pipe. SSC operates a dual fuel boiler system, using both natural gas and woody biomass. The natural gas boilers were constructed in the 1960s and can burn both natural gas and fuel oil. Concerns over pollution and carbon emission impacts have been raised.

The exhaust from the wood-fired boiler is directed into a baghouse for abatement of paritculate matter (ash) emissions. This boiler also uses urea injection for control of nitrogen oxides (NO_x), sodium hyroxide for control of acid gases, and limestone injection for control of sodium dioxide (SO_2). The limestone injection reduces SO_2 emissions by 50 percent. The injection of sodium sulfate reduces hydrogen chloride by 99 percent and SO_2 an additional 45 percent. The baghouse exhaust stack is equipped with a continuous emission monitoring system (CEMS) and a continuous opacity monitoring system. The CEMS includes an extractive sample conditioning system that delivers samples to the emission monitors. The monitors measure opacity and the dry concentrations of NO_x, carbon monoxide, and oxygen.

Methods

Primary life-cycle data were collected from SSC. Data included heat output from both natural gas and biomass boilers for a 1-year production cycle. Annual consumption of feedstock and type of feedstock, fuel and electricity consumption, transportation distances of feedstock to boiler site, solid waste produced, and emissions associated with on-site heat production were reported. This article reports a comparative life-cycle assessment (LCA) of SSC annual energy output using 56 percent biomass and 44 percent natural gas (referred to as the design boiler) fuel inputs to that of their annual energy output based on 100 percent natural gas for the prior heat production system.

The cradle-to-grave system boundary for the SSC biomass boiler is represented in Figure 1. The different feedstocks used by SSC are as follows: (1) mill residuals, (2) clean demolition material, (3) forest residuals. Mill residuals were reported as bark, a co-product from lumber or plywood production previously analyzed by Milota et al. (2005). A total of 30,350 BDT (27,533 metric tons (t)) of bark was used in the SSC wood boiler annually (Table 1). Clean demolition material (CDM) feedstocks were assumed to be collected at the demolition site or at a central distribution center. The life cycle of this feedstock began at the time of collection (Fig. 1). It was assumed that the alternative fate of this product would have been a landfill. CDM represented 35 percent or 19,315 BDT (17,522,272 kg) of the total woody feedstock input to the SSC wood boiler (Table 1). Forest residual collection started at the time the biomass was piled in the forest after final harvest (Fig. 1). These by-products of harvesting operations are piled in the forest and then loaded, hauled, and chipped at a reload site or chipped on site and hauled to a reload location (Johnson et al. 2012). The chips are then reloaded onto long haul trucks for transportation to SSC. Input of this feedstock type was 5,519 BDT (5,006,752 kg) annually, or 10 percent of the total feedstock input (Table 1). The analysis does not include the change in forest carbon from not collecting forest residuals to collecting forest residuals (Lippke and Puettmann 2013). The feedstock supply varies over time affecting the mix; hence, the potential for each source is important. The biomass boiler had an annual output of 703,596 million British thermal units (MMBtu) (742,333 GJ) or 56 percent of the total.

The SSC natural gas boiler consumed 650,517,020 ft^3 (18,420,593 m^3) of natural gas annually, with an annual output of 556,127 MMBtu (586,745 GJ; 44% of the total annual heat output). Data for all nonwoody resources, fuels, and transportation were from the US Life-Cycle Inventory (LCI) Database (US LCI 2012).

Most of the annual electricity (5,625 MWh) demand was used by the biomass boiler (87%). All of the SSC electricity demand is generated by Seattle City Light (SCL), a hydroelectric project located on the Skagit and Pend Oreille Rivers. Nearly 88 percent of SCL electricity is generated from hydroelectric power sources, followed by 6, 2, 2, and 1 percent from nuclear, coal, wind, and natural gas, respectively. An average western electricity grid's fuel is composed of 28 percent hydroelectric, 32 percent coal, 23 percent natural gas, 11 percent nuclear, and 4 percent residual fuel oil, biomass, wind, and geothermal (US LCI 2012).

An LCA model was developed using SimaPro, an international LCA software. All environmental impacts were determined using the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI; Bare 2011). There are several guidelines published to conduct LCAs. The most widely accepted methods are set forth in the International Organization for Standardization (ISO) 14000 series of standards (ISO 2006). At every stage during product life, energy and resources are consumed and emissions and waste are released into the environment. Defined by ISO, the LCA is a multiphase process consisting of four interrelated steps: (1) goal definition and scoping, (2) life-cycle inventory, (3) life-cycle impact assessment (LCIA), and (4) improvement assessment. The LCI is an objective, data-based process of quantifying energy and raw material requirements, air, water, and solid environmental releases occurring within the system boundaries. The LCIA process characterizes and assesses the effects of environmental releases identified in the LCI into impact categories such as global warming potential, acidification, eutrophication, respiratory effects, smog, and fossil energy use. Outcomes from LCAs can be used to suggest more ''environmentally friendly'' products or sustainable production methods and may also provide insights regarding material use, resource conservation, and emissions and waste output reduction.

Results

The total cradle-to-grave energy consumption for annual heat production from the SSC design boiler system and a

[1] Bone dry tons = short tons = 2,000 lb/ton.

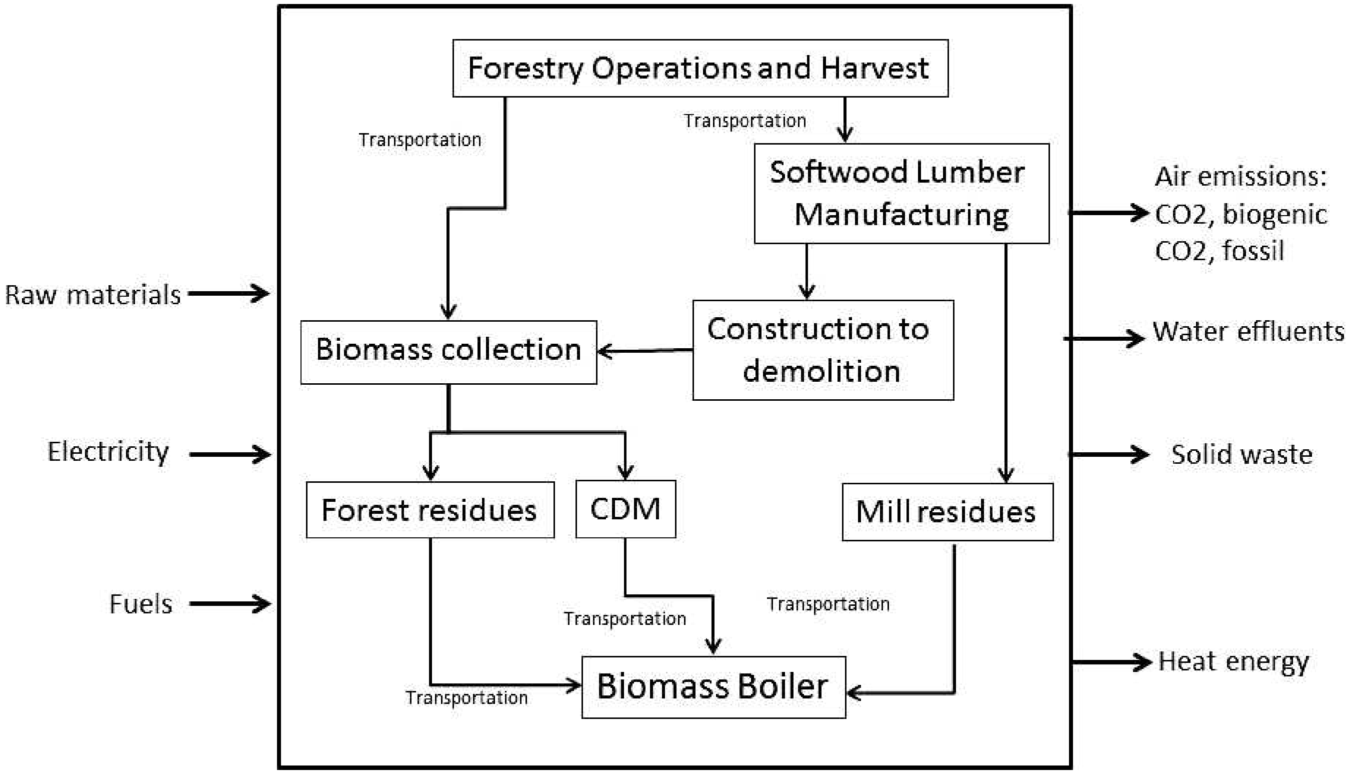

Figure 1.—Cradle-to-grave system boundary for wood biomass resources used in the Seattle Steam Company design boiler system.

Table 1.—Average annual feedstock input to the biomass boiler.

Fuel	Input: Bone dry tons	Input: Metric tons	Input: %	Transportation distance (mi)	Moisture content, green basis (%)
Building materials (clean demolition material)	19,315	17,522	35	15	25
Forest residues	5,519	5,007	10	30	50
Sawmill residues	30,350	27,533	55	20	35
Total	55,184	50,062	100		

natural gas boiler are shown in Table 2. SSC environmental releases in the form of air emissions, water effluents, and waste to landfills can be sourced from a variety of activities from the use of extraction equipment, transportation of feedstock and raw materials, electricity production, fuel production, and fuel combustion (Puettmann 2012). Carbon dioxide (CO_2) emissions were the greatest emissions released for both the SSC design boiler and the all natural gas boiler system. A total of 143,792 tons (130,446 t) of CO_2 (t CO_2) were released annually from the SSC design boiler system, with 67 percent released from the combustion of biomass, leaving only 33 percent fossil-based CO_2. Carbon dioxide emissions from the combustion of natural gas were all fossil based. Total annual CO_2 emission from the combustion of natural gas was 97,840 tons (88,759 t), a 106 percent increase in fossil emissions over the SSC design boiler system.

Table 2.—Total annual heat production in million British thermal units (MMBtu) and gigajoules (GJ) from Seattle Steam Company design boiler system.

Design boiler system	MMBtu	GJ	%
Biomass	703,596	742,333	56
Natural gas	556,127	586,745	44
Total heat energy	1,259,723	1,329,078	100

A comparison of the net global warming potential (GWP) was made between the SSC design boiler and a natural gas boiler (Table 3). The table contains the GWP calculated in t CO_2 eq (metric tons of CO_2 equivalent) per annual heat output of 1,259,723 MMBtu (1,329,078 GJ). The results span the entire life cycle of the product, from extraction of raw materials to fuel production and fuel combustion. The SSC design boiler system emitted 136,000 t CO_2 eq (149,914 tons) annually, while the all natural gas boiler system releases 99,600 t CO_2 eq (109,790 tons). Although the SSC design boiler system produced a higher GWP, net GWP was reduced by 57 percent over the all natural gas system, which produced nearly zero amounts of biomass-

Table 3.—Net annual carbon emissions (global warming potential), as metric tons CO_2 equivalents (t CO_2 eq), for the production of 1,329,075 GJ of heat (annual production).

	t CO_2/annual heat production		
	Design boiler system	100% natural gas	Difference
t CO_2 absorbed from the atmosphere	−93,700	−29	−93,671
t CO_2 eq released	136,000	99,600	+36,400
Net GWP emissions (t CO_2 eq)	42,300	99,500	−57,200

based CO_2. If SSC sourced all their annual heat output from woody biomass sources, the net GWP emission would total –3,370 t CO_2 eq (3,715 tons), an annual reduction of 108 and 103 percent over the SSC current design boiler and a 100 percent natural gas boiler system, respectively.

The source of fuel used to generate electricity has a major impact on the types of emissions resulting from electricity production. The differences in environmental impacts are very clear between SCL electricity production and the average western grid. As a result of the high percentage of electricity generation from hydroelectric sources, sourcing SSC electricity needs from SCL for their design boiler showed a 2 percent reduction in GWP when compared with an average western grid fuel mix.

The SSC design boiler system scored higher in two of the five impact categories compared with an all natural gas boiler (Table 4). Eutrophication and smog were the two impact categories where natural gas scored lower. Eutrophication is expressed in mass of nitrogen equivalents that impact the current system via the upstream processes for the production of woody mill residues and forestry operations. In the Pacific Northwest forestry system, seedlings are grown and fertilized in greenhouses prior to planting, resulting in nitrogen impacts from the fertilizer production and use.

Feedstock sources are expected to vary over time, with generally small impacts from the feedstock collection process but greater concerns over the impact of changes in the carbon removed from the forest. In a recent assessment by Lippke and Puettmann (2013), the use of forest residuals, sawmill residuals, and clean demolition material resulted in different impacts on forest carbon and the efficiency of wood use in displacing natural gas. A reduction in carbon emissions of about 0.62 unit of carbon for every unit of carbon in the wood combusted was reported. Using forest or sawmill residuals or clean demolition material to displace natural gas can increase carbon mitigation in the Pacific Northwest from 4.7 to 5.5 t CO_2/ha/y.

Table 4.—Cradle-to-grave impact assessment for the production of 1 GJ of heat energy.

Impact category	Unit	Design boiler system	100% natural gas
Global warming	kg CO_2 eq/GJ	102.59	74.92
Acidification	H^+ moles eq/GJ	19.32	33.10
Respiratory effects	kg PM2.5 eq/GJ	0.0070	0.0053
Eutrophication	kg N eq/GJ	0.0000	0.0000
Smog	g NO_x eq/GJ	0.1503	0.0826

Conclusions

- Spanning the entire life cycle of the fuel feedstock, from extraction of raw materials to fuel production and fuel combustion, the SSC design boiler reduces GWP by 57 percent. Increasing the percent of woody biomass lowers GWP further.
- The biomass boiler (56% of energy generation) required more than 5,007 t of woody feedstock to produce 472,333 GJ of heat energy annually.
- The natural gas boiler consumed 18,420,593 m^3 of natural gas to produce 586,745 GJ (44% of the annual energy generation).
- If SSC were to produce the same heat production, 1,329,078 GJ, from 100 percent woody biomass sources, it could potentially have a negative annual GWP. The biomass boiler would emit less carbon than could be sequestered by trees.
- SSC benefits from electricity production produced by SCL. Sourcing SSC electricity needs from SCL showed 2 percent reduction in GWP when compared with an average western grid fuel mix.

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