

A COMPARATIVE LIFE-CYCLE ASSESSMENT OF BRIQUETTING LOGGING RESIDUES AND LUMBER MANUFACTURING COPRODUCTS IN WESTERN UNITED STATES



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ABSTRACT. *Timber harvest activities in the western United States have resulted in large volumes of low- to no-value logging (forest) residues. Alternatives to pile-and-burning are needed to best utilize this material and to mitigate the resultant environmental impacts. Briquetting (densifying) forest residues near-woods is one such option and is the focus of this study. This study presents a cradle-to-grave life-cycle assessment (LCA) performed to evaluate the overall environmental impacts associated with briquetting post-harvest forest residues and dry sawmill residues (sawdust) in the Pacific Northwest (PNW) region of the United States. Environmental impacts resulting from the two briquette production systems were compared with firewood and propane production, which are common residential heating sources in rural areas of the PNW, on a per 1 MJ of useful energy for domestic heating. In the briquetted post-harvest forest residue system, the feedstock preparation stage had the largest share in global warming (GW) impact, mainly resulting from the drying process (69.5%), followed by transportation. Valorization of post-harvest forest residues, in combination with a briquetter, to produce a bioenergy carrier was revealed to be advantageous in smog, acidification, and eutrophication impact categories, with considerable environmental benefits from avoided pile-and-burn emissions. With all scenarios investigated, briquette production from post-harvest forest residues with high dryer efficiency showed lowest GW impact compared to briquetting sawmill residues and firewood supply chain. For a scenario analysis, LCA showed that using a diesel generator to support the forest residue briquetter operation resulted in 45% higher GW impact compared to use of a wood-gas-powered generator.*

Keywords. *Bioenergy, Biomass densification, Briquette, Forest residues, Life-cycle assessment, Sawdust.*

Use of biomass as an energy source is currently a major focus because biomass is considered to be a promising feedstock to produce alternative renewable fuel, replacing fossil fuels (Tilman et al., 2009; Lippke et al., 2012; Jakes et al., 2016). The biomass resource has been used as a major energy source for many years and continues to be commonly used in remote and rural areas (Carvalho et al., 2016). Yet, it has been gaining more attention as a renewable energy source over the past two decades with growing environmental concerns, including the impact on climate change, from burning fossil fuels (IPCC, 2014). In 2016, biomass and waste fuels contributed to 2% of the overall U.S. electrical generation, about 71.4 billion

kWh (USEIA, 2017). In addition, the U.S. Energy Information Administration (EIA) projections through the year 2040 state that biomass use in energy generation will increase by an average of 3.1% per year (USEIA, 2015).

In the United States, forest residues, a byproduct of timber harvest, have high potential to be utilized as a biomass feedstock for energy generation (Tilman et al., 2009). According to the 2016 billion-ton report baseline scenario (assuming moderate growth in housing starts and low growth in biomass for energy), about 93.1 million dry tons of forest residues and whole-tree biomass from clear cutting and thinning operations will be available in 2022 (USDOE, 2016). Yet, forest residues are currently underutilized and wasted because large amounts of post-harvest residues generated during commercial timber harvesting operations (i.e., slash) are often left on-site to decay or are burned on-site (USEPA, 2007; USDOE, 2011; Cross et al., 2013; Trofymow et al., 2014). In addition, forest residues left on-site increase the risk of wildfires and diseases; the majority of fires result from overstocked forest land (Dennison et al., 2014; Giuntoli et al., 2015; USDOE, 2016). These risks can be mitigated by purposely burning the material in the forest. Pile and burning, particularly in the Pacific Northwest (PNW), is one way and is becoming more common because it is the most economical way of burning. Prescribed burning is another way but has associated complexities such as seasonal

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restrictions, distance from urban areas, fire safety concerns and variability of its impacts on soil, local air quality and subsequent health effects (Wright et al., 2010; Springsteen et al., 2011; Aurell et al., 2017; Page-Dumroese et al., 2017). Regardless of approach, uncontrolled emissions are released that affect the environment (Johansson et al., 2004; Aurell et al., 2017). However, alternative ways of using forest residues are being explored, including valorization of low-value forest residues to produce solid biofuel (Crandall et al., 2017), thus avoiding these uncontrolled emissions. This effort to generate bioenergy products may assist sustainable forest management and result in considerable environmental benefits, and it is the focus of this study.

Densification technology can be used to overcome the challenges of forest residue availability as biofuel. It improves the quality of biomass by increasing energy density and volume density, allowing for easier transportation and storage (Bergman and Zerbe, 2008). Also, densification increases fuel quality, where lower moisture prevents spoilage (rot) and increased density results in efficient and longer burn and better combustion compared to wood logs (Grover and Mishra, 1996; *Canadian Biomass Magazine*, 2010). Briquettes made from biomass can be used as fuel at hot water boilers and wood furnaces and stoves, substituting for conventional fuels (e.g., heating oil, propane, or cordwood) (Roy and Corscadden, 2012).

Two major technologies used for biomass densification are briquetting and pelletization. Many studies investigated technological performance, mechanism of densification, and end-product quality (Stelte et al., 2012; Tumuluru et al., 2011; Oladeji, 2015). Briquetting requires less energy and is more flexible in terms of feedstock input (size and moisture content) and can handle bark (Nemeth et al., 2012), which makes it a suitable technology for processing forest residues, a less homogenous feedstock than sawdust, which is primarily used in pellets.

The U.S. Department of Agriculture (USDA) and the U.S. Department of Energy (DOE) are both strongly dedicated to increasing biomass as an energy source. Both agencies are looking to replace 30% of current U.S. petroleum consumption with biofuels by 2030 (Perlack et al., 2005). Production of biomass fuels and products can lower the requirement for oil and gasoline imports while supporting the growth of agriculture, forestry, and rural economies (Naik et al., 2010; USDOE 2016). The Biomass Research and Development Initiative (BRDI) was created by USDA and DOE as an interagency program to support the creation of a biomass-based industry in the United States for energy production and environmental safety. This study was part of one of these BRDI projects called Waste to Wisdom (www.wastetowisdom.com) in which the team conducted an investigation of biomass feedstock logistics, near-woods product production, distribution, and end use, focusing on integrating three biomass conversion systems utilizing post-harvest forest residues near the woods where the timber harvest occurred, hence the term near-woods.

The life-cycle assessment (LCA) tool has been widely used for sustainability assessment of product systems (ISO, 2006a; 2006b). It is composed of four stages: 1) goal and scope, which describe the purpose and breadth of the project,

2) life-cycle inventory (LCI), which covers data collection and quantification of inputs and outputs, 3) life-cycle impact assessment (LCIA), which uses LCI outputs to estimate specific environmental and human health impacts, and 4) interpretation, which construes what is happening and what can be done to improve the environmental performance of the studied product.

Several studies have focused on the environmental aspects of pellet production using various feedstocks, such as switchgrass (Bergman et al., 2015), olive husk (Kylili et al., 2016), and wood (Reed et al., 2012; Giuntoli et al., 2015; Adams et al., 2015) using LCA tool. Pa et al. (2013) reported that substituting firewood with wood pellets produced using sawmill byproducts for residential heating in British Columbia, Canada, would result in a decrease in values in climate change, human health, ecosystem quality, and primary energy use impact categories even with a slight increase in impacts resulting from preprocessing. Another study investigated cradle-to-gate pellet wood production from industrial wood waste and showed that more than 90% of the impact at most impact categories was due to electricity consumption in the pelletization process (Laschi et al., 2016). Previous studies mainly focused on densification via pelletization, whereas environmental performance of wood briquette production from forest residues using a near-woods briquetter systems was not investigated to the best of our knowledge.

METHOD

This study evaluates the environmental performance of three functionally compatible wood-biomass-fueled heating systems with different production processes, along with a propane system, using the LCA tool. All woody biomass moisture content (MC) values were provided on a wet basis, as is typical for wood fuels (Bergman and Zerbe, 2008). Data were generated through a small-scale decentralized briquetting unit that is suitable for physical conversion of post-harvest forest residues and that can be placed close to the biomass resource. LCA analyses were performed using the SimaPro 8.2 software (PRé Consultants, 2017).

GOAL AND SCOPE

The goal of this study was to evaluate environmental sustainability of near-woods briquetting of post-harvest logging slash or forest residues in the PNW region of the United States in 2016 for energy production and compare with two alternative biomass fuels. Avoided emissions from pile-and-burning of forest residues were considered in the analysis for forest residue briquettes and were separated out to show their environmental impact.

The scope of this LCA study reflected cradle-to-grave system boundaries. For this study, cradle-to-grave LCA analysis primarily covered extraction and transportation of raw material, product production and transportation, and use (combustion) life-cycle stages. For forest residue briquettes, the system boundary covered the collection, transportation, and conversion of post-harvest forest residues to briquetted biomass and ended with briquette combustion (i.e., usable domestic ther-

mal energy from residential combustion system). The life-cycle level impacts of briquetted biomass production were evaluated and compared with briquette production from sawmill coproducts and firewood production to interpret the LCA results in the context of bioenergy systems. In addition, to explore their relative environmental performance, the bioenergy systems were evaluated against propane as the most common fossil fuel energy source in the studied area as a fossil fuel substitution. The LCA was performed for these systems to deliver the same function, 1 MJ of useful thermal heat output for domestic heating. For the three wood energy product systems, wood combustion occurred in wood stoves capable of heating a whole house. Combustion efficiency of each product system was considered.

A sensitivity analysis was conducted to examine the effect of key system inputs on the resulting impact. The sensitivity of the GW impact to selected parameters was examined. Furthermore, alternative options for the electricity source to support briquetter and dryer electricity demand at the remote site (near forest) were compared. Two remote power generation technologies taken into account were wood gasifier and diesel fuel generator sets that were compared to grid electricity.

SYSTEMS INVESTIGATED

This study investigated the production and utilization of briquettes from two woody biomass sources: forest residues and sawmill coproducts, scenario 1 and scenario 2, respectively; firewood production, a conventional biomass source used for domestic heating, was also evaluated (scenario 3). In addition, various system alternatives for scenarios 1 and 2 were analyzed, for a total of eight scenarios (table 1). For Scenario 1, these alternatives included different power sources for the near-woods briquetter and dryer (S1a and S1b) and a different dryer heat requirement (S1c). For scenario 2, different allocation choices for sawdust generated at the lumber production facility (i.e., sawmill) were evaluated. When conducting LCA analysis, allocation choices are part of multi-product systems like sawmills, so selection of allocation or partitioning of inputs or output environmental flows for the incoming feedstock, sawdust from sawmills, must occur (ISO 2006b). Sawmills are multi-product systems because they produce sawdust, chips, bark, and shavings along with main product, lumber, at various processing stages (Bergman and Bowe 2008). Jungmeier et al. (2002a, 2002b) investigated the methodological approaches used to address multi-functionality concerns in wood product production and considered alternatives (i.e., volume, mass, economic allocation, and system expansion); they concluded

that avoiding allocation by system expansion is the best option, but if allocation cannot be avoided, they recommended that different allocation methods should be reported. Jungmeier et al. (2002b) assessed examples for the different allocation methods and recommended mass (or volume) for forestry activities and mass or economic for primary and secondary wood product manufacturing. Economic (S2) and mass (S2a) allocation approaches were selected for this study. Unlike sawdust briquettes, forest residue briquettes are a single-product system thus no allocation was required.

Characteristics of the biomass products investigated are provided in table 2; feedstocks used and briquette product are shown in figure 1. Details of four production processes are described in the following sections. Each product system has life-cycle stages along with unit processes as part of the individual life-cycle stages.

Process flowcharts and cradle-to-grave system boundaries included in the scope of this study for the four energy product systems are shown in figure 2.

Propane Production (Scenario 0)

Propane product system boundary included four major life-cycle stages: crude oil extraction, propane production, distribution, and use phase (i.e., combustion at furnace for domestic heating) (fig. 2: S0). Propane is a byproduct of natural gas production and crude oil refining. The first step is crude oil extraction followed by crude oil refinery, where propane is recovered during oil refining. Distribution of propane produced at refinery to user was done using barges, pipelines, train, and trucks. Transportation of raw material (crude oil) to the processing facility was accounted for and included in the processing stage. At the use phase, propane was assumed to be combusted in a domestic heating system with 80% combustion efficiency (FPL, 2004; CMHC, 2010). The propane model was retrieved from U.S. LCI Database (NREL, 2017).

Table 2. Properties of biomass energy products produced for analysis^[a].

	Briquette Forest Residue	Briquette Sawmill Residue	Firewood
Average density, kg/m ³	861.67 (8)	811.00 (10)	671.86 ^[b]
Moisture content (wet basis), %	6.13 (16)	11.30 (14)	13.00 ^[c]
Energy density (HHV) ^[d] , MJ/kg	17.78 (2)	17.66 (3)	16.39 (4)

^[a] Coefficient of variation, % (CV) values are provided in parenthesis.

^[b] Niemiec et al. (1995).

^[c] Pierobon et al. (2015).

^[d] High heating value.

Table 1. A review of the scenarios investigated.

Scenario	Process	Feedstock	Densification Power Source	Avoided Emissions from Pile and Burn	Dryer Heat Requirement (MJ/kg waster removed)	Allocation
S0	Propane production					
S1	Briquette production	Forest residues	Wood gasifier	50%	5	
S1a	Briquette production	Forest residues	Diesel	50%	5	
S1b	Briquette production	Forest residues	Grid electricity	50%	5	
S1c	Briquette production	Forest residues	Wood gasifier	50%	3	
S2	Briquette production	Sawdust	Grid electricity			Economic
S2a	Briquette production	Sawdust	Grid electricity			Mass
S3	Firewood production	Logs				



Figure 1. Images of biomass feedstocks used and briquette product; (a) forest residues, (b) sawdust residue from sawmill, (c) wood chips from forest residues used in briquette production, and (d) briquetted biomass.

Briquette Production (Scenario 1): Forest Residue Utilization

Forest residue briquette production system boundary included seven major life-cycle stages: feedstock procurement (loading and hauling), feedstock preparation (chipping, screening, and drying), briquetting, briquette transportation, packaging, distribution, and use (combustion) phases (fig. 2: S1). Wood chips are densified into briquettes using RUF200 model briquetter (RUF Inc., 2017). Transportation of materials between processes was accounted for, including hauling to packaging/storage facility and distribution to end user. The biomass feedstock supplied to the system was post-harvest forest residue (i.e., logging slash), which is a byproduct of commercial timber harvesting operations left to air-dry. Air-drying forest residues for future collection is not typically part of forest operation activities because the cost of returning to forest for collection can be prohibitive. However, alternative harvesting techniques as part of the overall Waste-to-Wisdom (WTW) project were conducted to largely reduce these costs (Kizha and Han, 2016). The feedstock used in this study was obtained from timber harvesting operations in the western United States, specifically northern California, which was a mix of wood species. We assumed that whole-tree harvesting is used, which is commonly applied in the United States (Allen et al., 2008; Dodson et al., 2014; USDOE, 2016), and therefore logging residues as part of the whole tree were delivered to the primary landing and then separated.

Post-harvest residues left at the primary landing for a year of field drying were then loaded onto a haul vehicle, which was assumed to be a dump truck, for transportation and shut-

tled to a secondary landing, the biomass conversion technology (BCT) site. The BCT was located close to the feedstock source, near woods, thus eliminating long transport distances. Transport distance from the primary landing to the BCT was assumed to be 4.0 km (2.5 miles) (Johnson et al., 2012). Transport distance and lubricant and fuel consumption for the loader were adopted from Johnson et al. (2012) and Han et al. (2015). Feedstock preparation (screening, chipping, and drying) and densification processes occurred at the BCT site. Additional (forced) drying was applied using a propane-fueled drying system before the briquetting process to decrease moisture content of the biomass feedstock to the desired level for proper product quality (Kizha et al., 2015). Moisture content of the chipped biomass input to the briquetter was about 6.13%. Volatile organic carbon (VOC) emissions resulting from field drying and forced drying were accounted for in the analysis. Complete details of LCI development for gate-to-gate briquetted biomass production from post-harvest forest residues are described by Alanya-Rosenbaum and Bergman (2016). The earlier study documented the details of the unit processes of briquetted biomass production, including feedstock preparation (chipping and screening), drying, and briquetting.

The briquetter unit used was a mobile unit designed for near-wood operations. The aim was to be able to process the forest residues closer to the primary landing, before the bio-energy product is shipped to the user. This mobility also allows the unit to be easily transported between forest operation sites closer to the source. All electricity for the system, dryer, and briquetter, was generated on-site using a wood gasifier (Power Pallet-PP20 gasifier, All Power Biomass, Berkeley, Calif.) with engine generator rated at

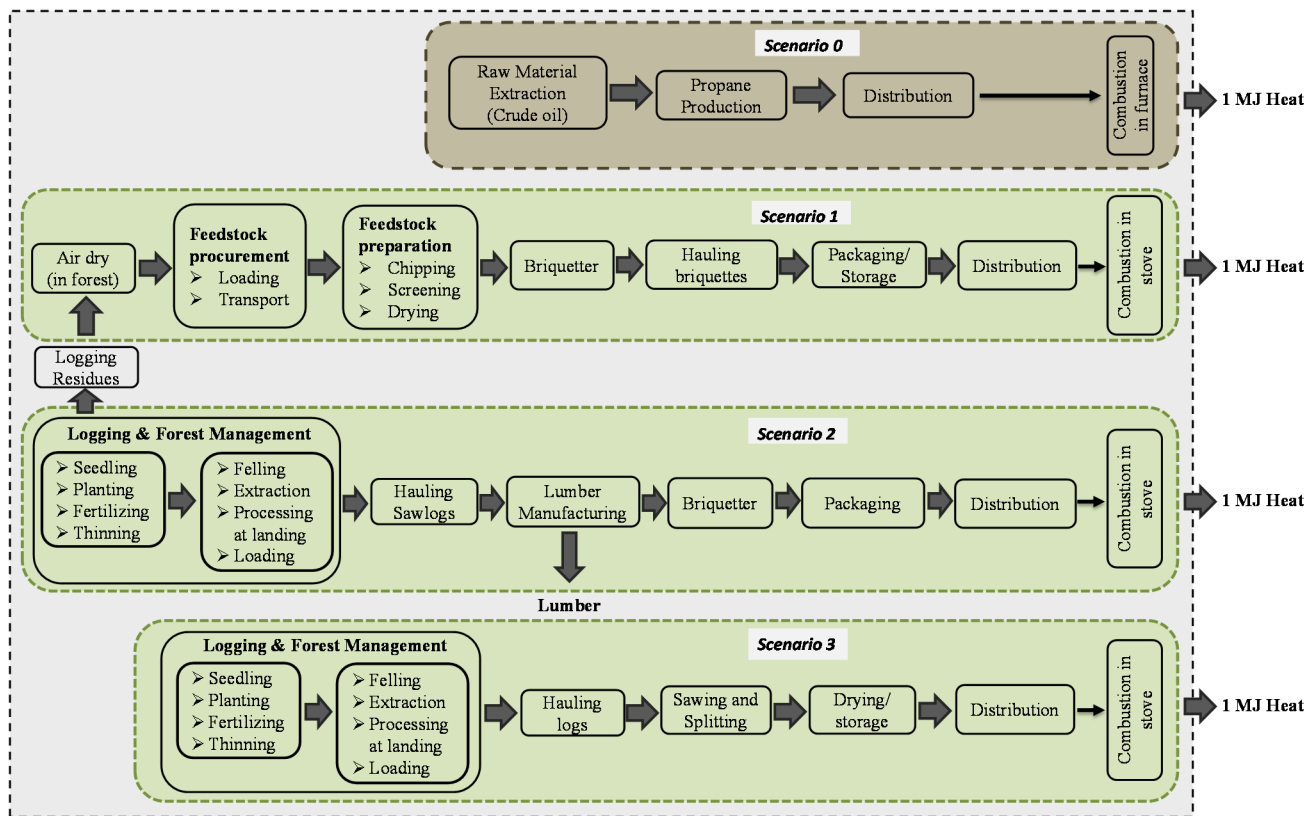


Figure 2. Process flow chart and cradle-to-grave system boundaries of the energy systems investigated. Base Scenario (S0): propane production system; Scenario 1 (S1): briquette production from post-harvest logging residues; Scenario 2 (S2): briquette production from dry sawmill residues; Scenario 3 (S3): firewood production.

20 kW. This unit was tested for remote power generation (All Power Labs, 2016). Combustion efficiency of burning briquettes at domestic stove was assumed to be 80% (FPL, 2004; CMHC, 2010).

Briquette Production (Scenario 2): Sawmill Residue Utilization

Sawdust briquette production system boundary included seven life-cycle stages: forest resource management and logging activities, sawlog transportation, generation of sawdust and planar shaving as coproduct at lumber facility, briquette production, packaging, distribution, and combustion at domestic heating system for thermal heat generation. Scenario 2 represents a conventional sawmill facility with an integrated briquetting system that was used to transform sawmill coproducts to solid biofuels. Input biomass feedstock to briquetter was sawmill coproducts (i.e., dry sawdust). This analysis considered only dry sawdust as an input.

Cradle-to-grave LCI was generated representing forest operations and waste biomass coproducts produced in softwood lumber production facilities in the PNW region of the United States. The first stage is forest operations, where the primary product is sawlogs at forest road. Forestry operations include growing seedlings, regeneration, site preparation, planting, thinning, fertilization, and final harvesting (Johnson et al., 2005; Puettmann et al., 2013; Bergman and Alanya-Rosenbaum, 2016). Forest operations modeled as inputs to production processes were based on forest resource LCI data inputs from the PNW softwood forests developed by Johnson et al. (2005). LCI data inputs were for logs from

the PNW softwood forests. Based on mill surveys performed in the PNW region, average haul distance from the harvest site to sawmill was about 108 km (Milota, 2015).

Sawdust and planar shavings are generated as coproducts of planar process at sawmill. Planar process takes place after drying, so feedstock did not need further drying before densification. The LCI of softwood lumber production in the PNW region used to model production of sawdust as a coproduct was retrieved from Milota (2015). After densification, briquettes were packaged and distributed to end user to be used for domestic heating. Combustion efficiency of burning briquettes at domestic stove was assumed to be 80% (FPL, 2004; CMHC, 2010).

Firewood Production (Scenario 3)

Firewood production system boundary included six life-cycle stages: forest resource management and logging activities, log transportation, sawing and splitting, drying and storage, distribution, and combustion at domestic heating system for thermal heat generation. In firewood production scenario, similarly, forest resources stage was modeled as input to the firewood production facility and was based on forest resource LCI data (Johnson et al. 2005; Oneil et al., 2010). During logging, trees, typically hardwood species, were cut and transported to the landing. At the landing, the low-quality (energy) logs were loaded onto logging trucks by diesel-powered loaders and hauled 108 km to the firewood production facility (Milota, 2015). Low-quality logs are used for firewood because high-quality logs are used for higher-value lumber- and veneer-type products (FPL, 2010;

Jakes et al., 2016; Ramage et al., 2017). These whole logs received were then cut and split to produce firewood using a saw and splitter machine (Cavalli et al., 2014). Energy required at cutting and splitting process was retrieved from Pierobon et al. (2015). It was assumed that the firewood was stored for air drying and equilibrated to about 13% MC (Pierobon et al., 2015). The firewood was assumed to be delivered to end user in bulk, therefore packaging process was not accounted for. Firewood is then used for thermal energy generation at wood stove. Combustion efficiency of an advanced wood stove was assumed to be 76% (FPL, 2004; CMHC, 2010).

Material and Energy Inputs and Outputs

Primary source data for the briquetter relied on the operational runs of the distributed-scale briquetting unit. Table 3 shows the cradle-to-grave inputs and outputs developed for Scenario 1 that were used for the LCIA of briquette production from forest residues. These relevant material and energy flows associated with the unit processes included in the cradle-to-grave system boundary of briquette production, from collection of forest-harvest residues to producing wood briquettes, were used to develop a cradle-to-grave LCA. This includes data for the dryer and briquetting processes. In addition, diesel consumption data of chipper and screener were based on tests performed by Humboldt State University, which were generated as a part of the WTW project (Han Sup Han and Joel Bisson, personal communication, May 2016). Propane fuel consumed for forced drying was not provided, therefore heat requirement at drying process was assumed to be 5 MJ/kg water removed (Adams et al., 2015) to obtain propane fuel consumption of 2.87 mL per functional unit. Propane HHV was 54.05 MJ/kg and density was 0.49 kg/L (Hodgman, 1955; Salazar and Meil, 2009; Todreas and Kazimi, 1990). Primary data generated were complemented with secondary data sources in order to develop cradle-to-grave LCIs of three biomass energy product systems. The secondary data, such as supply of electricity and propane, manufacturing of the chemicals, plastic packaging, transport, and waste disposal, came from U.S. LCI Database and peer-reviewed literature (NREL, 2017).

Data for the logs grown and harvested and lumber production in the PNW region used in Scenario 2 and hardwood harvest operations in Scenario 3 were pulled from recent Consortium for Research on Renewable Industrial Materials (CORRIM) reports (Johnson et al., 2005; Oneil et al., 2010; Milota, 2015; Bergman and Alanya-Rosenbaum, 2016). In firewood scenario, incoming fresh hardwood logs had a density of 1,169 kg/m³ and moisture content of 50% (Milota, 2015; OWIC, 2017). Transportation distances for hauling of logs to production facility and distribution of the product to end user was assumed to be same for scenarios S2 and S3 for consistency and fair comparison. For the sawdust briquette scenario, the sawdust carried the environmental burdens forward from the planning operations. Distribution of solid biomass fuel to end user was assumed to be 81 km, in line with recommendations on firewood transport (NFTF, 2017). It is assumed that plastic packaging with low-density polyethylene (LDPE) in 15-kg capacity bags was used for briquettes (Laschi et al., 2016). A detailed summary of the cradle-to-

Table 3. Cradle-to-grave inputs and outputs for 1 MJ of heat generated by combustion of briquetted forest residues (Scenario 1).

Feedstock Procurement	Unit	
VOC	mg	58.59
Lubricant	mL	0.0011
Diesel	mL	0.0604
Transport	km	4.00
Feedstock Preparation		
Chipper		
Diesel	mL	0.20
Lubricant	mL	0.0017
Screen		
Diesel	mL	0.13
Dryer		
Electricity	Wh	0.47
Propane	mL	2.87
VOC emission	mg	11.43
Waste heat emission	MJ	0.03
Briquetter		
Electricity	Wh	2.22
Lubricant	mL	0.0003
Product Transportation		
Loader diesel	mL	0.0471
Loader lubricant	mL	0.0008
Transport	km	108.00
Package/Storage		
LDPE ^[a]	gr	0.0440
Distribution		
Transport	km	80.47
Combustion (Use phase)		
CO	mg	187.5
NO _x	mg	125
SO ₂	mg	13.75
CH ₄	mg	3.75
NM VOC	mg	6.25
N ₂ O	mg	0.75
PM	mg	38.75
Biogenic CO ₂	g	121.1

^[a] Low density polyethylene

grave input and output data used in Scenarios 2 and 3 is provided in table 4.

Drying wood results in VOC emissions, which was accounted for in the analysis. According to findings of Milota (2013), emission levels mainly depend on species and are higher for drying fresh woody biomass than for drying aged material. He concluded that only 10% to 20% of the total hydrocarbon emissions occur below 20% MC. In this study, it was assumed that 20% of the VOC emissions were emitted during the force drying process, whereas the rest (80%) were emitted in the forest during field drying. The data on VOCs emitted during field drying in the forest as well as during forced drying were derived from literature (Lavery, 1988; Milota and Mosher, 2008).

In the analysis, various combustion parameters were considered. The avoided pile-and-burn emissions resulting from converting forest residues to solid biofuel were considered as an environmental credit. Considering the uncertainty in the portion of post-harvest residues that is subject to pile and burn, it was assumed that only 50% residue burn occurred. The combustion emissions profile from residential wood combustion was generated through literature that represented the thermal energy generation systems under investigation (Giuntoli et al., 2015). The U.S. LCI Database within the SimaPro LCA software was used for modeling domestic heating through propane (NREL, 2017). Combustion efficiency of burning briquettes at domestic stove was assumed

Table 4. Summary of cradle-to-grave inputs and outputs for modeling S2 (sawdust briquette) and S3 (firewood production) scenarios.

Process	Unit	Value		Reference
		Sawdust Briquette (S2)	Firewood (S3)	
Harvesting	m ³ / b.d.t ^[a]	2.34	1.71	USLCI Database “Softwood logs with bark, harvested at average intensity site, at landing, PNW/US” “Roundwood, hardwood, average, at forest road, NE-NC/RNA- AWC”, Oneil et al., 2010
Hauling				
Transport	km	108	108	Milota, 2015
Loader diesel	L/ b.d.t	0.72	0.72	Han et al., 2015
Loader lubricant	L/ b.d.t	0.01	0.01	Han et al., 2015
Briquetter				
Sawdust	b.d. ton/ b.d.t	1.00		USLCI Database “Sawdust, softwood, kiln dried, at planer, kg / PNW_US”
Electricity	kWh/ b.d.t	33.80		Operational data
Lubricant	mL/ b.d.t	4.99		Operational data
LDPE packaging	gr/ b.d.t	0.67		Laschi et al., 2016
Firewood production				
Cutting and Splitting	KWh/m ³		15.00	Pierobon et al., 2015
Distribution				
Transport	km	81	81	NFTF, 2017
Combustion (Use phase)				
CO	mg/ MJ input	150.00	5000.00	Giuntoli et al., 2015
NO _x	mg/ MJ input	100.00	110.00	Giuntoli et al., 2015
SO ₂	mg/ MJ input	11.00	11.00	Giuntoli et al., 2015
CH ₄	mg/ MJ input	3.00	4.90	Giuntoli et al., 2015
NMVO	mg/ MJ input	5.00	350.00	Giuntoli et al., 2015
N ₂ O	mg/ MJ input	0.60	1.00	Giuntoli et al., 2015
PM	mg/ MJ input	31.00	200.00	Giuntoli et al., 2015

^[a] Bone dry ton.

to be 80%, whereas it was about 76% for firewood (FPL, 2004; CMHC, 2010). Firewood stove efficiency of 76% was for advanced residential log stove and is consistent with literature (CMHC, 2010; Giuntoli et al., 2015).

Data quality within LCA studies are one of the most important factors to consider. In this study, to ensure data quality and reliability the data collected were in line with the data quality requirements outlined by ISO 14044 (ISO 2006b). To further support this effort that the best data possible was analyzed, material and energy balances were also performed from primary and secondary data.

Assumptions and Limitations

Due to insufficient information on the briquetting technology investigated, the manufacturing, maintenance, and disposal of equipment used in the system were considered outside the scope of the LCA. As previously noted, because primary data were not available, VOC emissions from forced drying process and air drying were calculated based on the data retrieved from literature.

Moisture content of firewood was assumed to be 13%, which may vary based on the length of air drying and a region’s climate (Simpson 1998; Bergman 2010). In addition, combustion efficiency and emission profile data were retrieved from peer-reviewed literature. It is important to note that combustion efficiency is highly variable and depends on the MC of biomass fuel and domestic combustion system used and tends to be lower at higher moisture content.

Life-Cycle Impact Assessment

The environmental impacts were assessed using the Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI) LCA impact assessment tool (Bare, 2011). The ten impact categories examined in this

study included global warming (GW (kg CO₂-eq)), acidification (ACD (kg SO₂-eq)), eutrophication (EUT (kg N-eq)), ozone depletion (OD (kg chlorofluorocarbons-11-eq)), smog formation (kg O₃-eq), carcinogenics (CTUh), noncarcinogenics (CTUh), respiratory effects (kg PM_{2.5}eq), ecotoxicity (CTUe), and fossil depletion (FD (MJ)). TRACI is a mid-point level impact assessment model developed by the U.S. Environmental Protection Agency and is specifically representative for the United States using input parameters consistent with U.S. conditions. The TRACI v2.1 impact category method is within the SimaPro 8.2 LCA software, developed by PRé Consultants used for modelling the studied systems (PRé Consultants, 2017).

Sensitivity Analysis

Key parameters that have high influence on the impact assessment results were investigated through sensitivity analysis. Sensitivity analysis for cradle-to-grave briquette production using post-harvest residues (Scenario 1) was performed using certain parameters (i.e., heat requirement at drying process, briquetter electricity consumption, hauling distance, distribution distance, moisture content of the feedstock received, and heating content of the biomass used). Variations of the parameters were selected based on realistic range representing operation conditions. For variation in incoming feedstock, it is assumed that the feedstock received has a moisture content of 30%; for variation in energy content of the wood feedstock, use of poplar with higher heating content (about 21.9 MJ/kg on an oven-dry basis) was assumed to be used (Ince, 1979).

In addition to parameter sensitivity scenario analysis performed, the effect of the power source used in the forest residue briquetter product system was examined. The briquetter

unit was operated near the forest and was designed to be mobile so that available biomass can be utilized onsite, close to timber operations. Therefore, the system requires remote power generation to support briquetter and dryer processes. Two remote power sources investigated were the biomass gasifier (Scenario 1) and diesel power (Scenario 1a) generators. The use of a remote power source was also compared to use of grid electricity (Scenario 1b). Western Electricity Coordinating Council (WECC) grid electricity data, year 2008, were used, which are representative of the electrical grid mix used in the PNW region (NREL, 2012). Remote power options for the other systems were not considered because the sawdust briquetter would be part of the production line at the lumber manufacturing facility and would not need a remote power source. The sensitivity of the GW impact is investigated based on the choice of allocation method comparing use of mass versus economic allocation for the generation of sawdust as a coproduct at the lumber manufacturing facility. The allocation issue is widely discussed in LCA of wood products. Mass allocation was commonly used for the North American wood product LCAs particularly because pricing for wood products and coproducts are volatile and thus difficult to quantify on a consistent basis (Taylor et al., 2017).

RESULTS AND DISCUSSIONS

The LCA results obtained showing the environmental impacts associated with the four product energy systems analyzed are provided in the following sections. Specifically, results of the cradle-to-grave comparative assertions of forest residue briquette system with two biomass-based heat production systems and the fossil-based alternative are presented.

IMPACT ASSESSMENT OF UTILIZATION OF FOREST RESIDUES AS BRIQUETTES

The cradle-to-grave LCA results regarding the contribution of each process to the overall environmental impact of S1 for six impact categories are presented in table 5. Negative values in table 5 represent environmental benefits due to avoided air emissions from not burning logging slash in the forest but instead converting the slash to a usable energy

product. The impact assessment results revealed that the feedstock preparation step had a significant portion in the overall environmental performance of the system, with above 73% contribution for OD, GW, and FD impact categories. This was due to propane fuel consumed in the dryer process to generate heat. The second major contributor to the three aforementioned categories was transportation, both hauling from in-forest to BCT operation site to packing/sorting facility and distribution to end user. Use phase accounts for a large portion, more than 68%, of the impact for the rest of the impact categories (i.e., smog, ACD, and EUT), mainly the result of combustion emissions, including carbon monoxide, nitrous oxide, and sulfur dioxide. Contribution of briquette production stage to all environmental impact categories was minor relative to other stages (about 2%). The environmental benefits associated with avoided emissions from not burning the forest residues had a considerable impact on LCA results.

COMPARATIVE LCA OF THE SCENARIOS INVESTIGATED

Three biomass-based fuels along with propane were analyzed in this study in various scenarios. The overall environmental impacts resulting from eight scenarios for the selected impact categories are presented in table 6. The LCA results are presented for the same function, which is to generate 1 MJ of thermal energy from domestic heating system.

Among all domestic heating alternatives investigated, the base scenario, fossil fuel alternative, scored worst compared to its bioenergy alternatives in all categories. Scenario 1c appears to be the most favorable system configuration for GW, smog, ACD, and EUT impact categories, where the major benefits originated from not piling and burning the forest residues.

Global warming impact results per MJ of energy generated for domestic heating are presented in figure 3. Both the total impact results for each scenario (a) and the contribution percentages of the different processes to the overall impact (b) are reported. Substantial GHG reduction mitigation occurred during controlled combustion of the post-harvest forest residue briquette by avoiding methane emissions from pile and burning (fig. 3b). Comparative data regarding the

Table 5. Process contribution to overall impact in ozone depletion (OD), global warming (GW), smog formation, acidification (ACD), eutrophication (EUT), and fossil depletion (FD) per 1 MJ of thermal heat generated by combustion of briquettes produced from forest residues (Scenario 1).

Life-Cycle Stages	OD kg CFC-11eq	GW kg CO ₂ eq	Smog kg O ₃ eq	ACD kg SO ₂ eq	EUT kg Neq	FD MJ
Feedstock procurement	2.5%	2.6%	6.6%	2.0%	2.0%	2.8%
Feedstock preparation	73.6%	79.8%	17.0%	17.0%	18.6%	80.9%
Chipping	6.8%	7.1%	6.0%	2.6%	5.9%	7.5%
Screening	3.0%	3.2%	2.7%	2.6%	2.6%	3.3%
Drying	63.8%	69.5%	8.4%	11.7%	10.1%	70.1%
Briquette production	0.8%	0.8%	2.0%	2.2%	2.0%	0.9%
Hauling	8.7%	9.8%	4.0%	4.3%	4.1%	9.6%
Storage/Packaging	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Distribution	5.3%	6.0%	1.9%	2.1%	2.0%	5.8%
Use phase	9.0%	1.0%	68.5%	69.2%	71.3%	0.0%
Combustion	0.0%	1.0%	68.5%	69.2%	63.9%	0.0%
LDPE disposal	9.0%	0.1%	0.0%	0.0%	7.4%	0.0%
Total impact	3.77E-13	8.71E-03	4.54E-03	1.46E-04	8.66E-06	1.72E-02
Avoided impact (Pile & Burn)	0.00E+00	-2.14E-03	-3.27E-03	-1.26E-04	-5.76E-06	0.00E+00
Net impact	3.77E-13	6.57E-03	1.27E-03	2.01E-05	2.90E-06	1.72E-02

Table 6. Results of cradle-to-grave comparative LCA analysis using selected impact assessment methods.

Scenarios		OD kg CFC-11 eq	GW g CO ₂ eq	Smog kg O ₃ eq	ACD kg SO ₂ eq	EUT kg N eq	FD MJ
S0	Propane	4.06E-12	1.02E+02	5.40E-03	2.79E-04	1.42E-05	2.04E-01
S1	Briquette/gasifier power	3.77E-13	6.57E+00	1.27E-03	2.02E-05	2.90E-06	1.72E-02
S1a	Briquette/diesel power	4.90E-13	9.53E+00	1.29E-03	2.43E-05	3.06E-06	2.29E-02
S1b	Briquette/grid electricity	3.91E-13	7.99E+00	1.24E-03	2.93E-05	2.86E-06	1.88E-02
S1c	Briquette/higher dryer efficiency	2.74E-13	3.97E+00	1.13E-03	1.30E-05	2.54E-06	1.20E-02
S2	Sawdust briquette/economic allocation	2.18E-13	4.93E+00	4.13E-03	1.47E-04	8.30E-06	8.84E-03
S2a	Sawdust briquette/mass allocation	8.73E-13	1.11E+01	5.30E-03	2.13E-04	1.05E-05	1.90E-02
S3	Firewood	1.50E-13	4.56E+00	4.89E-03	1.54E-04	8.24E-06	8.13E-03

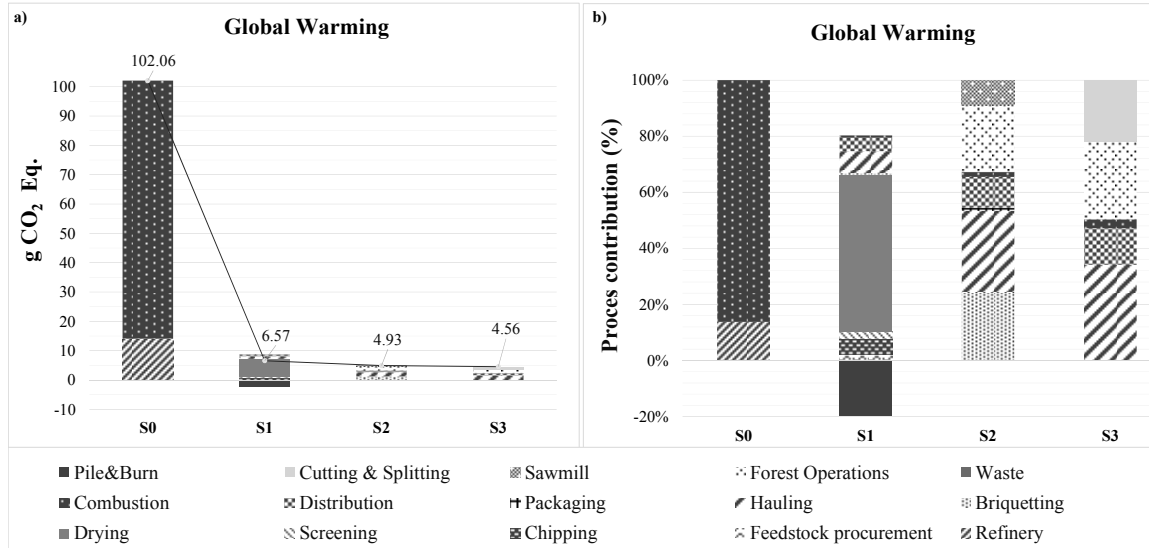


Figure 3. Global warming per 1 MJ of thermal energy generated for domestic heating (a) Net global warming impact resulting from four product systems investigated, (b) processes contribution to the overall impact.

total GW impact revealed that Scenario 1 was the least favorable alternative after fossil fuel scenario, with dryer having the highest share (about 70%), followed by transportation with about 16% of overall impact. Transportation, including both hauling and distribution of product to end user, had a considerable portion, about 47%, in the GW impact of firewood supply chain. Transportation of logs, hauling to production facility, had the highest share in GW impact in Scenario 2, whereas transportation of briquettes to packaging facility had a minor contribution in Scenario 1.

The LCA results of the scenario analysis revealed that about 31% reduction in GW impact was achieved by substituting diesel fuel generator (Scenario S1b) with wood gas power (Scenario S1) for remote electricity generation (fig. 4). Considering the lower contribution of transportation to GW impact in Scenario 1, running the briquetter system close to the biomass source using biomass-based remote power generation can be considered as a viable option for optimized dryer process for GHG mitigation efforts. Scenario analysis showed that dryer energy consumption had a notable effect on the resulting global warming impact. In the literature, heat required in drying ranges between 2.4 and 9 MJ/kg water removed, and a conservative approach was followed for S1 by assuming it to be about 5 MJ/kg water removed (Arrieche et al., 2011; Adams et al., 2015; Parkhurst et al., 2016). Scenario 1c, using a dryer with an energy requirement of 3 MJ/kg water removed resulted in

40% decrease in GWP and was revealed to be the best scenario. Allocation was used in lumber production, where the sawdust was generated as a coproduct. The choice of allocation method used has a large effect on the overall impact resulting from the sawdust-briquette supply chain. GW impact from Scenario 2, where economic allocation (S2) was used instead of mass allocation (S2a), resulted in 2.3 times less

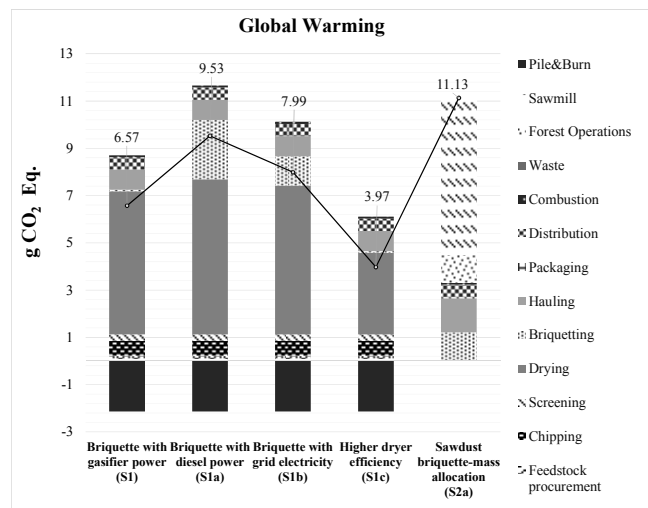


Figure 4. Net global warming impact resulting from five alternative scenarios.

impact. GW reduction was expected (Reed et al., 2012; Bergman et al., 2015), but the results were dramatic. This result shows how a single life-cycle stage can dominate others and how selecting an allocation approach generates large changes in environmental performance.

The contribution of core processes to the resulting environmental impact in OD, EUT, smog, and ACD categories for all scenarios examined are illustrated in figure 5. Impacts from feedstock procurement in forest residue-briquette scenarios and forest operations in S2 and S3 scenarios appeared to be minor for all impact categories. For S1, S1a, S1b, and S1c scenarios, the environmental benefits of the avoided pile-and-burn credit were notable in EUT, smog, and ACD impact categories. Use phase accounts for a large portion of the impact for these categories for all scenarios, greater than 63% at S1, 66% at S2, and 75% at S3.

The contribution of transportation was about 33% to 36% higher in the firewood scenario than in the briquetter scenario, mainly due to the benefits of briquetting forest residues near-woods while eliminating transportation of biomass feedstock to production facility. The environmental benefits of increasing mass and energy density of the briquettes made from forest residues were observed in environmental impacts resulting from hauling, where the other bioenergy products had higher contributions in Scenario 2 and Scenario 3, particularly in GW, ozone depletion and fossil fuel depletion impact categories. Global warming and ozone depletion impact of hauling the bioenergy product in Scenario 2 were about 68% and 67% higher, respectively,

compared to Scenario 1, whereas it was about 83% to 82% for Scenario 3.

Four toxicity impact categories and process contribution associated with 1 MJ of useful energy generated for domestic heating is depicted in figure 6. Major processes that contribute to toxicity categories, except respiratory effects category, were forest operations and hauling in Scenario 2 and Scenario 3, whereas drying dominated these categories in Scenario 1. Respiratory effects category was found to be dominated by combustion process, where the avoided slash burn credit had a high influence in S1 process because it is a major source of particulate matter (PM) emissions. Regarding toxicity impacts, the feedstock procurement stage at S1 was almost minor.

SENSITIVITY ANALYSIS

Sensitivity analysis performed focused on the influence of variation in parameters on the GW impact. The results showed that feedstock moisture content and heat requirement at dryer were key parameters with large influence on GW at S1 (table 7). Effect on GW of variation in heating value of biomass used was also notably large because increasing HHV from 19 to 21.9 MJ/b.d. kg resulted in about 15% decrease in overall GW impact.

The effect of electricity consumption at briquetter process was minor. It is important to note that the S1 process used a wood gasifier to satisfy the electricity demand.

Yet, when S1 and S1a scenarios are compared, briquetter process has a higher share in the overall GW impact due to diesel consumption (fig. 4). Use of diesel power and grid

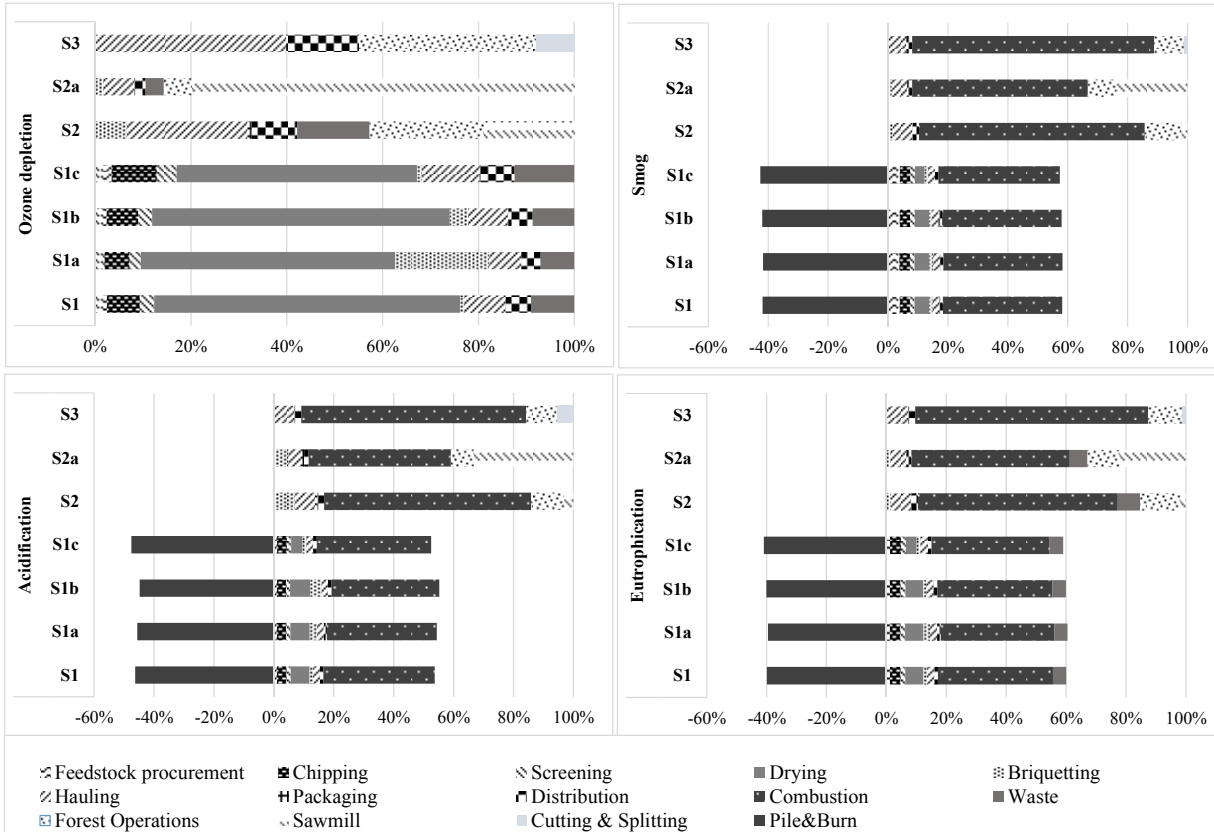


Figure 5. Process contribution to environmental impact per 1 MJ of thermal energy generated for domestic heating.

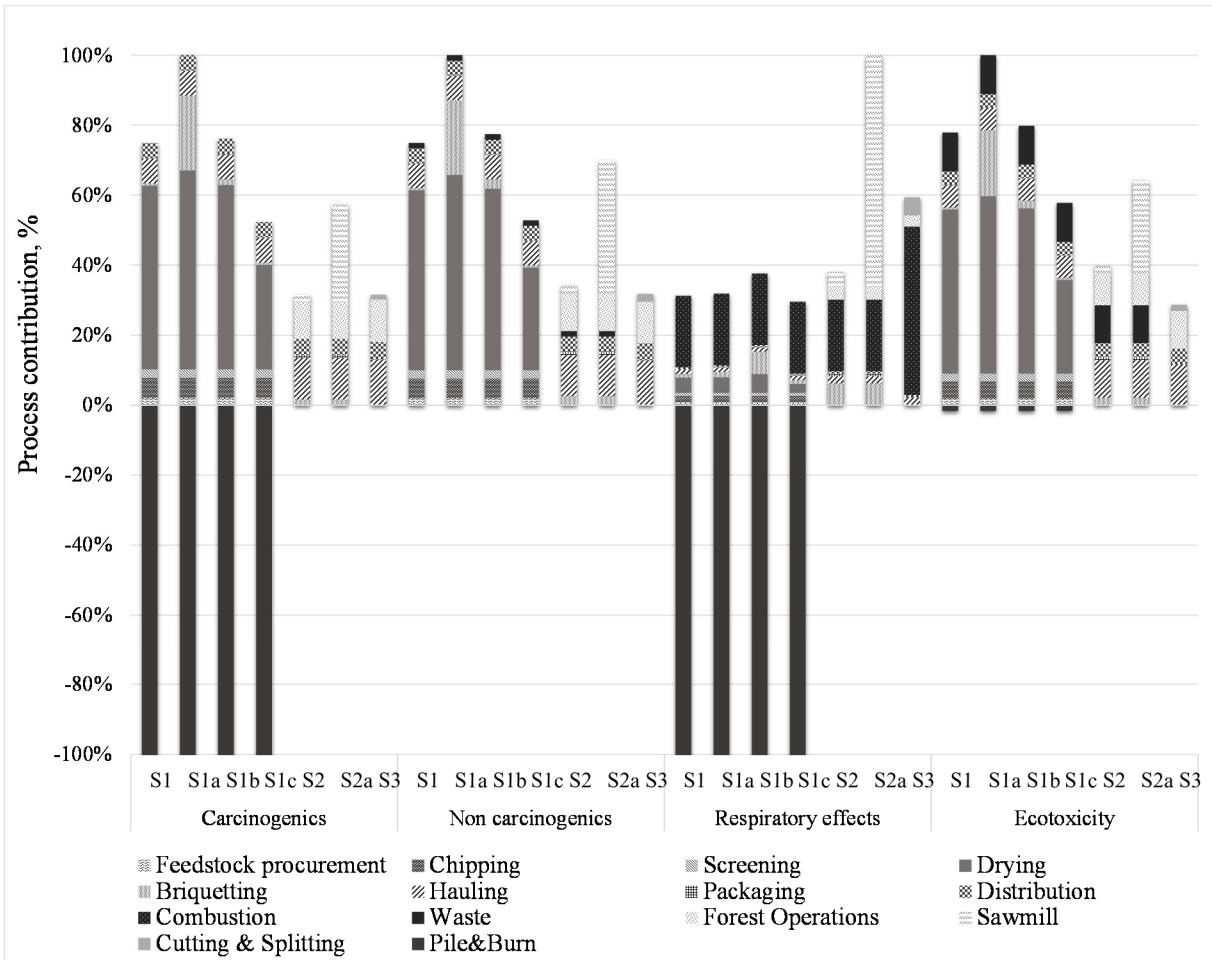


Figure 6. Cradle-to-grave toxicity resulting from generating 1 MJ of thermal output for the scenarios investigated.

electricity at briquetter and dryer processes resulted in 45% and 21% increases in GW impact, respectively. Therefore, selecting a low-GHG electricity source such as wood gas offers substantial environmental benefits.

CONCLUSION

Utilizing post-harvest timber residues as solid bioenergy products are preferred on an environmental performance basis than piling and burning the material. This study presented the application of LCA for evaluating the environmental performance of various biomass product systems in the PNW region along with an alternative fossil fuel system, propane.

As for impacts related to forest management activities, using forest residues as an energy source versus pile-and-burning shows a notable environmental advantage. The results are consistent with Springsteen et al. (2011) and Ganguly et al. (2018). As a caveat, not every region in the United States has the same wildfire issue or performs pile and burn after harvesting as does the western United States. For example, it is more common in the Midwestern United States to leave forest residues in place (Scott Bove, personal communication, October 2016). Therefore, forest residues left to decay would not result in an impact reduction as noticeable as with pile-and-burning, and it would occur over a longer period as the wood decays.

The life-cycle impact from combustion of briquetted forest residue for domestic heating proved to be a promising biomass fuel alternative, particularly in smog, ACD, and EUT impact categories. Global warming impact of producing 1 MJ of useful thermal energy generated from combusting briquette appeared to be most advantageous energy product system when a more efficient dryer system was used, 3.97 g CO₂eq, because briquetting forest residues was dominated by propane consumption in the drying process. Sensitivity analysis showed that decreasing or increasing the dryer heat requirement had a notable influence on the GW impact. Therefore, use of high-efficiency dryer systems and

Table 7. Sensitivity of key parameters on Global Warming Impact.

Parameter	Parameter Increase (%)	GW Impact (kg CO ₂ eq)	GW Impact Base Value (kg CO ₂ eq)	GW Impact Change (%)
Electricity use (briquetter)	25	6.59E-03	6.57E-03	+0.3%
Dryer heat requirement	25	7.91E-03	6.57E-03	+16.9%
Hauling distance	25	6.75E-03	6.57E-03	+2.6%
Distribution distance	25	6.70E-03	6.57E-03	+1.9%
Moisture content of biomass feedstock	50	1.22E-02	6.57E-03	+45.9%
HHV of biomass feedstock	15	5.72E-03	6.57E-03	-14.8%

running the briquetter system with lower moisture content feedstock would have crucial impact on the overall system sustainability, with substantial reduction in life-cycle GW impact. Yet, in this study, relatively higher heat requirement was used for the dryer process, which resulted in higher overall impact at S1 than might be found in future operations given more familiarity of the operators with the forest residue briquette system. Furthermore, it should be noted that the firewood stove used in this study was assumed to be an advanced wood stove with 76% efficiency, whereas conventional firewood stove efficiency ranges between 50% and 65% (CMHC, 2010; Cespi et al., 2014). Consequentially, lower performance combustion systems would increase all life-cycle impacts for any energy product system.

Biomass energy product systems tend to show better environmental performance than their fossil fuel alternative. In this study, the LCA analysis revealed that substitution of propane with biomass-based fuel results in substantial benefits for all impact categories. The analysis of using diesel and wood gasifier in a generator onsite or grid electricity to power briquette production stage showed that using diesel power and grid electricity resulted in 45% and 21% increases in GW impact, respectively, compared to the use of an onsite gasifier powering a generator.

Allocating environmental impacts is a complex issue when using the LCA tool for multi-product systems. For sawdust briquette production and given the results showing large variation in environmental impacts from use of different allocation methods, it is recommended that results should be presented for both allocation methods when dealing with wood manufacturing systems. This would allow better evaluation and comparison of wood biomass bioenergy systems, where system expansion is not possible.

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