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Using Life-Cycle Assessment to Evaluate Environmental Impacts of Briquette Production from Forest Residues

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Abstract

This report presents a life-cycle impact assessment analysis of near-woods processing of post-harvest forest residues into wood briquettes as an alternative to other fuels such as propane in residential heating systems. The study was part of the Waste to Wisdom project with a broader goal of evaluating the feasibility of using semimobile biomass conversion technologies to overcome the barriers of valorizing woody biomass residues for renewable energy and material production. The cradle-to-grave system boundary included feedstock procurement, hauling, feedstock preparation, production of briquetted biomass from forest residues, briquette transportation (distribution), and heat generation at the residential wood stove (use phase) life-cycle stages. The feedstock preparation stage contributed the most to the global warming (GW) impact of the near-woods wood briquette production supply chain. This was because of the drying process, which contributed 72% of the overall GW impact. Near-woods biomass conversion using wood gasifier as the power source was favorable compared with the other scenarios, which included diesel power and in-town processing of forest residues using grid electricity. The overall decrease in GW impact was 33%, after taking into account the avoided pile and burn emissions. Thus, substituting propane with wood briquettes in heating systems provided greenhouse gas reduction while aiding forest restoration activities.

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Keywords: bioenergy, biomass densification, briquette, post-harvest forest residues, life-cycle assessment

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Executive Summary

This study evaluates environmental sustainability of using post-harvest forest residues in the briquetting process, where biomass conversion takes place close to the harvest site, for solid biofuel production using the life-cycle assessment (LCA) tool. The objective was to assess and document life-cycle environmental impacts associated with briquetted biomass production from post-harvest forest residues and the use of briquetted biomass as a solid biofuel for domestic heating. This study was funded by the U.S. Department of Energy (DOE) and U.S. Department of Agriculture (USDA) through a Biomass Research and Development Initiative (BRDI) grant.

The scope of this LCA study covered a cradle-to-grave system boundary for the wood briquette production supply chain. The system boundary started at feedstock procurement (woody biomass collection) and included six life-cycle stages: feedstock procurement, hauling, feedstock preparation, production of briquetted biomass from forest residues, product transportation (distribution), and heat generation at the residential wood stove (use phase). The feedstock procurement stage included processing (delimbing), sorting, and loading. The feedstock preparation life-cycle stage, which is located at the near-woods processing site, included chipping, screening, and (propane-fueled forced) drying unit processes.

The operational data used in this study were developed by other subtasks under the Waste to Wisdom (WTW) project (www.wastetowisdom.com). Feedstock procurement and feedstock preparation data were based on field data collected and experimental studies performed in 2015 by Humboldt State University, Arcata, California, USA. The primary data for the briquetter relied on the operational runs of the 200-kg/h distributed-scale briquetting unit collected from the production site in Big Lagoon, California, USA, in 2015 near a major commercial harvesting site. This included data for the dryer and briquetting processes.

The cradle-to-grave LCA was performed using the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) v2.1 impact assessment method (USEPA 2012), and the system was modeled using the SimaPro 8.5 LCA software package (PRéConsultants bv, Amersfoort, the Netherlands). The functional unit in this study was defined as 1 MJ of useful thermal energy produced for domestic heating, including any efficiencies lost.

The results of the comparative analysis revealed that a notable reduction in global warming (GW) impact can be achieved by substituting wood briquettes produced from post-harvest forest residues using near-woods biomass conversion operation for propane. Although the post-harvest forest residues were field-dried to 20% moisture content (MC) before being collected, the contribution analysis showed that the drying unit process had the highest contribution to the overall GW impact, about 72% contribution, followed by other feedstock preparation processes: chipping and screening. Overall, most GW impact (about 82%) resulted from the feedstock preparation life-cycle stage. More specifically, propane consumption during the drying process was responsible for the large contribution of the drying process to the overall GW impact. Conversely, the contribution of densification (briquetting) and use phases were minor, about 1%. When alternative scenarios were considered, near-woods operation using wood gasifier power was identified to be the scenario with the best environmental performance. Not unexpectedly, sensitivity analysis showed that MC of the incoming feedstock used in the briquetter system was revealed to have a substantial effect on the resulting environmental impacts. This was caused by the greater heat demand for the dryer when high MC feedstock was used, which resulted in increased propane consumption. Thus, lowering the amount of force-drying would have the greatest influence on lowering environmental impacts, especially for greenhouse gas (GHG) mitigation efforts.

Definition of Goal and Scope

Study Goals

The aim of this study was to evaluate environmental sustainability of briquetting (densifying) post-harvest forest residues for solid biofuel production. A cradle-to-grave LCA was performed to assess the environmental sustainability of producing wood briquettes from forest residues near the point of harvesting logs (i.e., near-woods). The LCA analysis was performed at plant and unit process level in accordance with ISO 14040 and ISO 14044 LCA standards (ISO 2006a, 2006b).

Currently, there is growing demand for biomass-based renewable energy to decrease the use of fossil fuels and to mitigate GHG emissions (Tilman and others 2009, Lippke and others 2012, Jakes and others 2016). Therefore, this study was performed to evaluate the environmental footprint and to obtain more insight into the life-cycle impacts of producing wood briquettes as an alternative low-carbon energy source. To evaluate the environmental performance and competitiveness of the studied system, the briquette production system was evaluated against the propane production system for energy substitution. The wood briquettes from forest residues are designed to replace firewood in wood heating systems. This study was conducted with funding support from a BRDI grant, which is a collaborative initiative between DOE and USDA.

Intended Application

This study assessed and documented life-cycle environmental performance associated with the briquetted biomass production from post-harvest forest residues. Briquetting improves the quality of biomass allowing easier transportation and storage of the product compared with wood logs (Bergman and Zerbe 2008). In addition, briquettes have higher calorific value and volume density, have lower MC, and provide more consistent, efficient, and longer burn compared with wood logs (Canadian Biomass Magazine 2010, Grover and Mishra 1996). Briquettes made from biomass are a solid renewable energy source that can be burned in domestic hot water boilers and wood furnaces and stoves for space heating as an energy substitute for propane or cordwood (Roy and Corscadden 2012). Valorization of forest residues, which are a byproduct of commercial harvesting operations, for biofuel production may result in considerable environmental and economic benefits. Briquetting technology can be used for transformation of forest residues to a (solid) bioenergy carrier, which may be used to substitute for fossil fuels. This can allow for mitigation of GHG emissions. Therefore, the intended application of this study was to provide credited data and enhance knowledge about environmental aspects associated with conversion of forest residues to bioenergy carriers using a decentralized small-scale briquetting process at life-cycle level. The assessment also included comparison of wood briquette production with production of traditional fuel, i.e., propane, to demonstrate the environmental benefits that may be achieved through substitution of traditional energy sources. The results of this study may promote production of forest-based bioenergy using the briquetting process.

Motivation

The increase in demand for and consumption of energy resources, environmental sustainability initiations, and new policies to combat climate change are major drivers for establishing renewable energy sources (USEIA 2017b, IEA 2017). Energy consumption in the Organization for Economic Cooperation and Development (OECD) countries is expected to increase 9% between 2015 and 2040, whereas the expected increase is 41% in nonOECD countries (USEIA 2017b). Mitigation of GHG emissions and achieving energy independence via reducing the nation's dependence on fossil fuels are major challenges that can be overcome by adopting use of renewable energy sources (US Congress 2007).

Biomass is considered a promising feedstock for renewable energy production. Currently in the United States, the forest biomass, i.e., slash, resulting from commercial logging operations is often left on site to decay or is burned (USDOE 2011, USEPA 2007). In the United States, there is good potential for forest residues as wood waste to be utilized as a renewable energy source (Oswalt and others 2014). About 93 million dry metric tons of forest removals are generated in the United States annually, 73% of which is the result of logging residues (Smith and others 2009, USDOE 2011). According to the 2016 Billion-Ton Report baseline scenario (assuming moderate growth in housing starts and low growth in biomass for energy), about 84 million dry metric tons (93 million dry tons) of forest residues and whole-tree biomass from commercial timber harvesting and thinning operations will be available in 2022 at US$60 per dry metric ton (USDOE 2016). Also, increasing wildfire frequency and intensity are growing concerns, especially in the western United States, and forest residues left on site increase the risk of wildfires and spreading of diseases (USDA Forest Service 2005, Dennison and others 2014, Giuntoli and others 2015). Many forestland management agencies in the United States encourage biomass removal as a means to reduce fire hazard (Loeffler and others 2010). Potential benefits of removing forestry residues from public lands include reducing the risk of catastrophic fires and preventing diseases from spreading (USDA Forest Service 2005, Giuntoli and others 2015).

The motivation for undertaking this study was to evaluate environmental viability of valorization of post-harvest forest residues, in combination with a briquetter, to produce a bioenergy carrier. The use of forest residues as biomass feedstock has the potential to decrease fossil fuel dependence while eliminating fossil-fuel-based GHG emission. Moreover, this study aimed to support the national policy on GHG emission reductions and promote national energy security by investigating the viability of alternative renewable energy sources that may decrease dependence on fossil fuels (U.S. Senate 2005, U.S. Congress 2007).

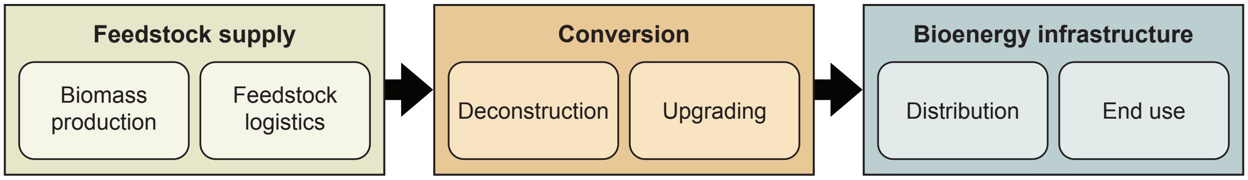

Figure 1. Biomass-to-bioenergy supply chain (USDOE 2014).

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 and others 2010, USDOE 2016, USEIA 2017c). This study was part of a USDOE-funded BRDI project called Waste to Wisdom (www.wastetowisdom.com) in which the team performed an investigation of biomass feedstock logistics, near-woods product production, distribution, and end-use, focusing on integrating three biomass conversion systems that used post-harvest forest residues near the woods where the timber harvest occurred, hence the term near-woods (Han and others 2018, Bergman and others 2018). This study focused only on briquetting raw woody biomass.

Intended Audience

The results of this study are intended to be used in comparative assertions and disclosed to the public. Thus, this LCA study was subjected to third-party critical review (ISO 2006a, 2006b). Another intended audience is researchers working on LCA analysis of biomass conversion of forest residues. The results may also be interesting for professionals representing governmental interests related to decision-making in renewable energy policies. The removal of forest residues might be required in forest management practices to decrease fire risk (Loeffler and others 2010). The removal of biomass for biofuel production may be of interest to forestland managers because this may assist them to overcome costs associated with biomass fuel treatment for decreasing fire hazard.

This study presented an environmental evaluation of briquetted biomass production in the United States as a potential low-carbon solid biofuel product that could replace fossil fuels. This may help industries or residential energy users achieve GHG emission reductions. Furthermore, this study may also be of interest to consumers that have basic environmental concerns.

Scope of the Study

The scope of this LCA study covered cradle-to-grave feedstock procurement and preparation, hauling, production of briquetted biomass from forest residues, distribution, and heat generation from domestic heating systems. The system boundaries begin at the collection and biomass conversion of forest residues to briquetted biomass near the forest and end at the grave, i.e., combustion in a wood stove for space heating. The life-cycle level environmental impacts of briquetted biomass production from post-harvest forest residues were evaluated and compared with propane production from crude oil as the reference supply chain for heating fuel. An LCA for propane was constructed from peer-reviewed literature and other secondary sources. Forest residues are 100% wood; therefore, the terms forest residues and wood are used interchangeably in this report.

Functional Unit

The functional unit (FU) in LCA analyses can be defined in terms of system input or output depending on the goal of the study. It should be based on a unit that allows valid comparison of different alternatives. The FU in this study was defined as 1 MJ of useful thermal energy produced for residential heating. The FU included any efficiency loss to generate the 1 MJ of heat and was based on higher heating value (HHV). HHV is used to convert volume or mass basis of a fuel to its energy value. HHV represents the energy content of a fuel with the combustion products such as water vapor brought to 25 ºC, whereas lower heating value (LHV) omits the energy consumed to vaporize water held in the native energy form or produced during the combustion process. HHV (gross heat content) is the preferred method used in the United States (USEIA 2017a). The input and output flows were standardized based on the selected FU.

System Boundary

This study evaluated two functionally compatible energy carriers, i.e., briquetted (densified) biomass and propane, with different production processes by making use of the LCA tool. The typical life cycle of a biomass-to-bioenergy supply chain starts at biomass production and ends at the end user (Fig. 1).

The system boundary of the briquetter system investigated is provided in Figure 2. This study performed a cradle-to-grave LCA in which the life-cycle stages of briquetted biomass production included feedstock procurement, hauling, feedstock preparation (chipper, screener, and dryer), briquetting, distribution, and the use phase. The biomass feedstock supplied to the system was post-harvest forest residue, which is generated during commercial timber harvesting operations and treated as a waste product. Because forest residues are a waste product, which are typically left to decay or burnt on site, it was assumed that they do not have an environmental burden. Therefore,

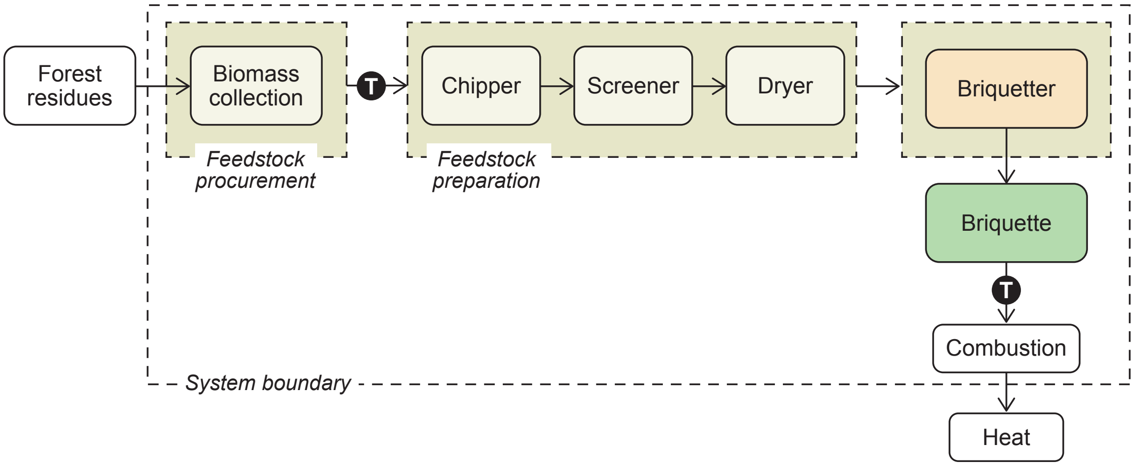

Figure 2. System boundary for briquetted biomass production supply chain (T, transportation).

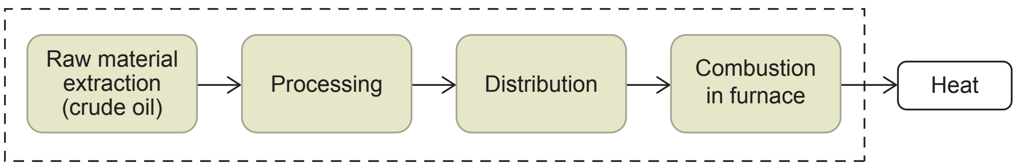

Figure 3. System boundary for propane production supply chain.

the cradle-to-grave system boundary does not include the previous life-cycle stages associated with harvesting and generation of forest residues. The cradle starts at the point of collection or extraction of post-harvest forest residues. Because of insufficient information on the briquetting technology investigated, manufacturing, maintenance, and disposal of equipment used in the system were considered outside the scope of the LCA. This is in line with the propane production system, which also excludes those elements.

The cradle-to-grave system boundary of the propane production system is provided in Figure 3. The system boundary starts at the extraction of crude oil and stops at the useful heat produced from the residential furnace for domestic heating purposes (Corma and others 2018, USEIA 2017c, LTS 2017, Johnson 2012).

In this study, various system configurations were analyzed to evaluate the effect of process variation and logistics on life-cycle impacts of the briquette production supply chain. The system description of briquetting plant processes along with the inputs and emissions to and from the system is provided in Figure 4.

The feedstock used in this study was obtained from commercial timber harvesting operations in the western United States, specifically Washington, Oregon, and California. Logging slash residues were used as the input biomass feedstock. These residues included tree tops, limbs, chunks, and branches, which are byproducts of commercial harvesting operations. The feedstock procurement stage (woody biomass collection) included processing (delimbing), sorting, and loading. All electricity and heat necessary for the remote system was generated on site using a wood gasifier and propane burner, respectively. The system components are described in the following sections in detail.

Feedstock Procurement

The biomass feedstock received was the waste from commercial timber harvesting operations and was composed of tree tops, limbs, branches, etc. Pulp logs made up part of the biomass feedstock because of the lack of nearby markets, which is not historically typical. In this study, the term logging slash was used when referring to forest residues. Because the logging slash was left in the forest for air-drying for 1 year before collection, it had an MC (wet basis) of 17% to 23% (Kizha and others 2018). At the feedstock procurement stage, this biomass feedstock was processed (delimbed) and sorted (Kizha and Han 2016). To improve the quality of the bioenergy product, tree tops and pulp logs were delimbed for further processing to generate the post-harvest forest residues. Branches were not used in biomass conversion. Then, the post-harvest residues were collected at the primary landing and loaded onto a dump truck for shuttling to the secondary landing (i.e., near-woods biomass conversion technology (BCT) site). Primary data from five commercial harvesting sites in the western United States were used for modeling the biomass procurement

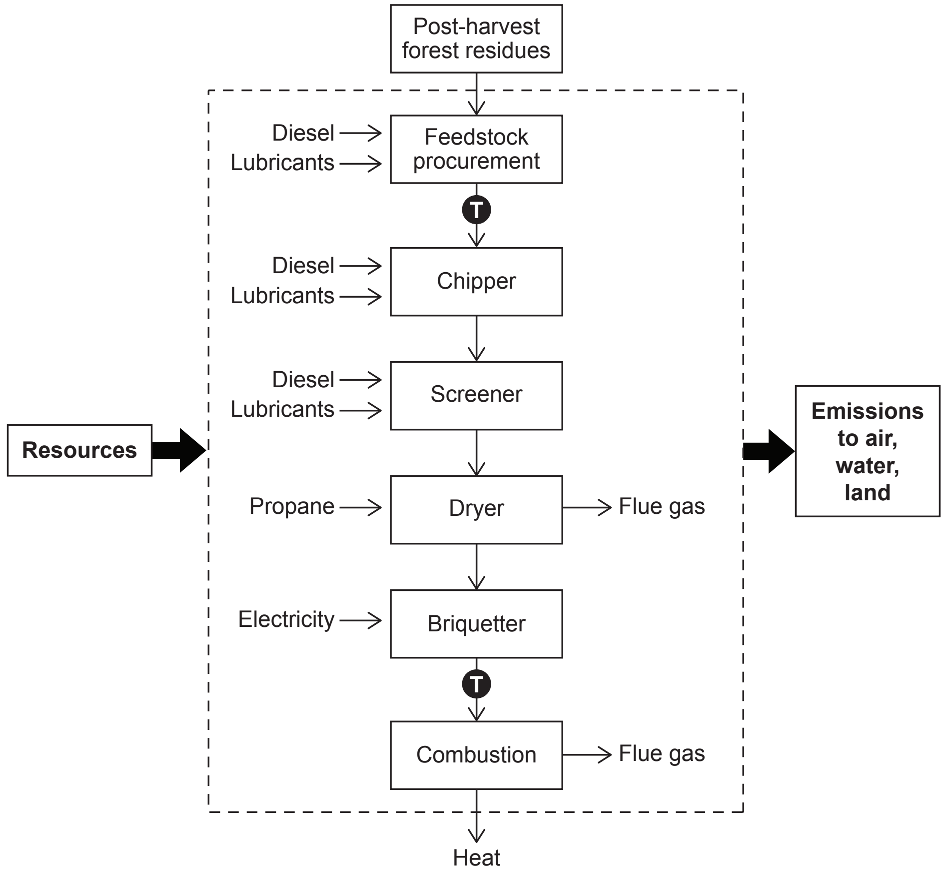

Figure 4. Cradle-to-grave process flow diagram of near-woods briquette production supply chain (T, transportation).

model: Port Angeles, Washington; Warm Springs, Oregon; Oakridge, Oregon; Lakeview, Oregon; Quincy, California. Average transport distance traveled from the primary landing to the BCT site for the five regions investigated was about 18.8 km (Oneil and others 2017). Transport distance, lubricant, and fuel consumption for the processing, sorting, and loading data were from field experiments performed as a part of the WTW project (Kizha and Han 2016, Oneil and others 2017).

Feedstock Preparation

Feedstock preparation included chipping, screening, and drying to achieve the specifications required for briquetting into bioenergy products. The lubricant consumption data for hydraulic oils, general lubricants, and fuel consumption of chipper and screener were based on the tests performed by Humboldt State University (HSU), which were generated as a part of the WTW project (Oneil and others 2017).

In this study, a variety of feedstocks were tested for certain characteristics for the WTW project. Feedstocks used were sourced from Redwood (*Sequoioideae*), Douglas-fir (*Pseudotsuga menziesii*), Tanoak (*Lithocarpus densiflorus*), and mixed conifer species. The characteristics of the feedstock used for biomass conversion are provided in Table 1.

Densification (Briquetting)

Wood chips were densified into briquettes using an RUF200 model briquetter (RUF Briquetting Systems, Zaisertshofen, Germany). The briquetter used hydraulic cylinders for compressing the feedstock and had a capacity of 200 kg feedstock per hour. The woody biomass feedstock was fed into a hopper, then transferred to a pressing chamber via a screw conveyor (Fig. 5). Finally, the compressed wood was ejected as finished briquettes. Finished briquette dimensions were 63 mm wide by 150 mm long by 109 mm high (Severy 2018). Binding agents may be used in the densification (briquetting) phase to improve binding characteristics. For the system under investigation, no binder addition occurred. The characteristics of the briquette fuel produced after biomass conversion are provided in Table 2.

Transportation

Environmental burdens resulting from transportation of materials from the harvesting site (distribution) and from manufacturers to the briquetting site were considered in this study. The briquetter was located in Big Lagoon, California, USA, and transportation of briquettes to the end-user for residential heating was included in the inventory. It was assumed that the briquettes produced for use in the closest town were transported via tractor trailer fueled by diesel.

Table 1—Properties of feedstock used for bioconversion

Sample ID	Type	Moisture content (%)	Bulk density (kg/m^3)
S1	Redwood, chip, medium[a]	6.5	—
S2	Douglas-fir, chip, small[b]	6.3	187.07
S3	Douglas-fir, chip, medium	6.3	174.46
S4	Tanoak, chip, small	4.2	194.47
S5	Tanoak, chip, medium	6.5	196.07
S6	Conifer, chip, medium	6.9	180.92

[a]Medium chips: 0.75 to 2 in.
[b]Small chips: ≤0.75 in.

Table 2—Properties of briquettes produced

Property	Value[a]
Moisture content (%) wb[b]	6.13 (15.60)
Average density (kg/m^3)	861.67 (8.07)
Energy density (MJ/kg) HHV[c]	17.78 (1.89)
Durability (%)	95.98 (2.11)

[a]Coefficient of variation (%) values are provided in parentheses.
[b]wb, wet basis.
[c]HHV, higher heating value.

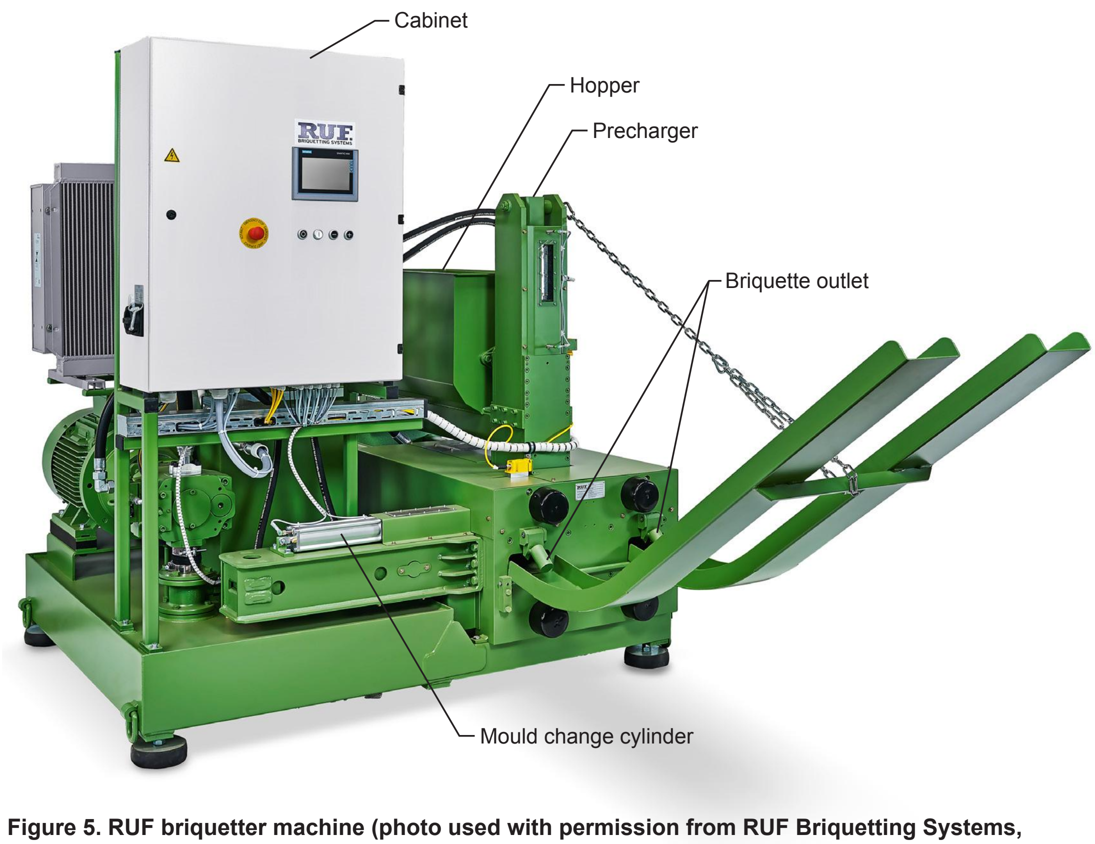

Figure 5. RUF briquetter machine (photo used with permission from RUF Briquetting Systems, Zaisertshofen, Germany).

Table 3—A review of the scenarios investigated

Scenario	Description
S0	Propane production system
S1	1 MJ heat, near-woods operation with wood gasifier power
S2	1 MJ heat, near-woods operation with diesel power
S3	1 MJ heat, in-town operation (2-h travel distance) with grid power
S4	1 MJ heat, in-town operation (4-h travel distance) with grid power
S5	1 MJ heat, 50% moisture content feedstock, near-woods operation with wood gasifier power
S6	1 MJ heat, 50% moisture content feedstock, in-town operation (2-h travel distance) with grid power
S7	1 MJ heat, near-woods operation with wood gasifier power with pile and burn credit

Additionally, environmental impact resulting from the 18.8-km weighted-average transportation of biomass feedstock to the briquetting site was taken into account. Transportation tends to be a limiting economic factor when hauling woody biomass but not a limiting environmental factor (Giuntoli and others 2015, Ranta and others 2016, Kylili and others 2016).

Combustion

Use-phase data came from the combustion tests conducted to simulate the use phase of the briquettes produced. Test results were provided by Schatz Energy Research Center, HSU. Each test was conducted in a typical freestanding wood stove that was not U.S. Environmental Protection Agency (EPA) certified (Schrader Woodstoves, Harrisburg, Pennsylvania, USA) using 2.4 m of single-walled stove pipe followed by 2.4 m of insulated double-walled chimney pipe to replicate residential installation. Burn tests were performed by modifying EPA Method 28 – Certification and Auditing of Wood Heaters (USEPA 2017).

Alternative System Configurations Investigated

In this study, alternative system configurations were investigated at the cradle-to-grave level (Table 3). The effects of logistical options, such as locating the BCT site at a remote location close to the harvest site or close to town with access to grid electricity, were investigated.

In addition, alternative options for the electricity source were compared. The briquetter unit was considered to be a mobile unit for near-woods operations because it can easily be transported between forest operation sites. This allows processing of the forest residues closer to the primary landing before the bioenergy product is shipped to the user. Two remote power generation technologies were taken into account: a woody biomass gasification generator set and a diesel generator set. These were compared with a local grid electricity mix that was used when biomass conversion operations took place in town instead of close to the harvest site. These two alternatives showed that as distance increased from the point of harvesting, speed increased because the type of transportation could be on-road versus off-road (i.e., in the forest). The off-road transportation was the same for both scenarios. For the two in-town scenarios, distribution distance of briquettes was not taken into consideration because the biomass conversion operation took place close to users. Power Pallet-PP20 biomass gasifier (All Power Labs, Berkeley, California, USA) with an engine generator rated at 20 kWe was tested for remote power generation (All Power Labs 2016). The power source used in the base scenario was a woody biomass gasifier generator set (genset), and as an alternative scenario, a diesel power generator was investigated to evaluate the effect of the power source used on the environmental impact results. In addition, the effect on the results was evaluated from a scenario of transferring forest residues to an in-town facility where grid electricity was used as opposed to an on-site operation for biomass conversion. The effect of MC of incoming feedstock was also examined. It was assumed that the feedstock received was not air-dried in the forest and had 50% MC – wet basis (MC_{wb}).

A scenario considering the environmental credit from avoided pile-and-burn emissions resulting from converting forest residues to solid biofuel was also analyzed. It was assumed that only 50% of the residue was burnt. The combustion emissions profile from pile and burn was adopted from Pierobon and others (2014).

Allocation Procedure

Allocation is required for multi-output systems where two or more functions are delivered. The only product of the system under investigation was briquetted biomass. For this reason, allocation was not required in the densification process. For the other life-cycle phases including multifunctional processes such as the screening process, mass allocation was used in line with the North American Structural and Architectural Wood Products product category rule, which suggests use of economic allocation when the difference in revenues is more than 10% (FPInnovations 2015). In this case, differences between the economic values of the products were less than 10%. Mass allocation was used in the propane system model. Thus, the allocation approach was consistent between the two product systems.

Assumptions and Limitations

Wood is composed of many compounds in addition to its solid components, including volatile organic compounds (VOCs). VOCs are considered hazardous air pollutants. VOC emissions from wood occur when it is freshly cut. In this study, VOC emissions that occurred during drying of the fresh biomass feedstock were taken into account. Because the biomass was field-dried to a MC of about 20% on a wet basis, it was assumed, when the biomass was received at the dryer unit, that 20% of the VOCs were emitted during drying, whereas the remaining 80% had been emitted in the forest. In addition, the data on heat requirement during the dryer process were not available through experimental runs performed. Therefore, it was retrieved from literature as 5 MJ/kg water removed (Adams and others 2015). Tracking material flow was important for verifying mass balance of product systems. Mass loss during the densification process was negligible. Therefore, it was assumed that there was no mass loss at the briquetter.

The EPA released a second draft of *Framework for Assessing Biogenic CO_2 Emissions from Stationary Sources* that provides an analytical methodology on evaluation of net atmospheric contribution of biogenic carbon dioxide (CO_2) emissions from production, processing, and use of biogenic material at stationary sources (USEPA 2015). Yet, accounting for emissions of biogenic CO_2 from stationary sources is still under evaluation. In this study, CO_2 emissions from woody biomass in the system under investigation was considered biogenic and thus carbon neutral, which is in line with the Intergovernmental Panel on Climate Change (IPCC) approach (IPCC 2006, 2014). Regardless, biogenic CO_2 emissions were reported along with fossil GHG emissions.

Life-Cycle Impact Assessment Method and Types of Impacts

For the life-cycle impact assessment (LCIA), the impact categories examined in this study included GW (kg CO_2-eq), acidification (kg SO_2-eq), eutrophication (kg N-eq), ozone depletion (OD) (kg chlorofluorocarbons-11-eq), smog formation (kg O_3-eq), human health (CTUh), respiratory effects (kg $PM_{2.5}$ eq), ecotoxicity (CTUe), and fossil fuel depletion (MJ). All impact categories covered in the TRACI method were considered in this study (Bare 2011, USEPA 2012). Resource depletion categories including water scarcity, land occupation, and land transformation are not included in the TRACI method. These categories are listed for future inclusion, and more research will be required to establish them. Site-specific data are required because of the unique properties of location, meteorology, and existing ecosystems (USEPA 2012). Therefore, these impact categories were not taken into consideration in this study. Forest residues are generated as a byproduct of commercial harvesting operations and are considered to be waste. As mentioned earlier, forest residues are commonly left on the forest floor to decay or cleared using the pile-and-burn method. For this reason, we did not consider the growth of the tree that generates the forest residues to be within the system boundaries. Consequently, we did not evaluate the land-use impacts.

Among the available methods for LCIA, TRACI was used in this study (Bare 2011). TRACI is a midpoint level impact assessment model developed by the EPA and is specifically representative for the United States using input parameters consistent with U.S. conditions. LCIA results are relative expressions and do not predict impacts on category endpoints or the exceeding of thresholds, safety margins, or risks.

Data Quality

The data were collected in line with the data quality criteria addressed by ISO 14044 to ensure quality and reliability. The details are provided in the following sections.

Geographical and Time-Related Coverage

Quantitative data on mass and energy flows of the briquetting system were based on the operational data of core processes in the year 2015. The unit was located and operated in northern California, USA. Woody biomass collection and feedstock preparation data were obtained from field-based data and experimental studies, in 2015, performed as a part of the WTW project (Bisson and Han 2016, Kizha and Han 2016). The field data on the feedstock procurement stage was based on forest operations in three western states: Washington, Oregon, and California. Secondary data were derived from peer-reviewed literature and LCI databases including the DATASMART database, which is an integrated database complementing the U.S. LCI Database using U.S. ecoinvent processes from the Ecoinvent v.2.2 data set (LTS 2017, PRé Consultants 2017, NREL 2012). The U.S. LCI Database is based on regional conditions and represents U.S. circumstances.

Precision

Variance could not be calculated because this study was based on a single data set, not on an industry level. However, process-specific data were provided wherever possible.

Completeness, Consistency, and Uncertainty

The quality of the data used in the analyses is crucial to accurately represent the systems investigated. Therefore, mass and energy balances for the briquetter were developed based on field data to assure reliability of the data used. In addition, sensitivity and scenario analyses were conducted to address completeness, consistency, and uncertainty issues relevant to the data used.

Representativeness

The briquetting technology used is current and representative, and the product it produces is compatible with other products in the market. The internal process (mechanical and hydraulic presses) and inputs (binding agents) can be different depending on the technology and feedstock used, but the final product is the same.

Reproducibility

The method used, the input and output data, and the LCI generated in this study were provided in detail to allow other LCA practitioners to reproduce the results presented in this study.

Data Sources

Feedstock procurement and preparation data were obtained from Oneil and others (2017) and were based on field data and experimental studies performed as part of the WTW project (Bisson and Han 2016, Kizha and Han 2016, Kizha and others 2018). The primary data for the briquetter relied on the operational runs of the mobile briquetting unit. All relevant quantitative data (input–output flows) associated with the unit processes were collected from the production site in Big Lagoon, California. This included operational data for the dryer and briquetting processes. These data included input–output mass and energy flows and physical properties of the feedstock received by the systems and characteristics of the final product, briquetted biomass. The secondary data such as supply of electricity, manufacturing of the chemicals, transport, and waste disposal came from DATASMART database and peer-reviewed literature (LTS 2017).

Type of Critical Review

Because of the comparative nature of this study and its intention to be disclosed to the public, as required by ISO 14044, a critical review was conducted by a panel of experts. The review panel for this study was composed of two LCA experts: James Salazar, M.S., Principal of Coldstream Consulting, and Shaobo Liang, PhD, Postdoctoral Research Fellow, USDA Forest Service, Forest Products Laboratory.

The main aims of the review panel, as outlined by ISO 14044, were to ensure that (1) the methods were scientifically and technically valid, (2) the methods were consistent with ISO 14044, (3) the data were appropriate and reasonable in light of the goal of the study, (4) the interpretations reflected the limitations, and (5) the report is transparent and consistent.

Value Choices

In this study, only the midpoint level impact assessment was performed using the TRACI 2.1 method (Bare 2011, USEPA 2012). Midpoint level analysis was used to express results from the impact assessment. Thus, value judgments from weighting were avoided because impact category results were neither ranked based on their importance nor aggregated to obtain a single score.

Although not considered for this study, endpoint results can be performed at the inventory stage or obtained by aggregation of midpoint level impact category results by assigning numerical weighting factors based on their importance. Endpoint-level impact assessment analysis combines midpoint impacts under the three areas of protection: natural environment, human health, and natural resources. Endpoint analysis allows the results to be presented with a single-score result, which allows easier interpretation and communication of LCA results with nonLCA experts and easier comparison of the environmental impact of different products or scenarios. The optional weighting step based on value choices allows a single-score result of the LCA analysis, yet it introduces more assumptions to the analysis, leading to more uncertainties.

Life-Cycle Inventory Analysis

The cradle-to-grave system boundary of the briquetting plant includes feedstock procurement (processing such as delimbing, sorting, and loading), feedstock preparation (chipping, screening, and drying), briquetting (densification) of forest residues, product transportation, and combustion of the briquettes in wood stoves for domestic heating. Biomass procurement data were provided by the WTW project. All relevant material and energy flows associated with the unit processes included in the cradle-to-grave system boundary of briquette production were collected to develop a cradle-to-grave LCI. The study conformed to ISO 14040 and ISO 14044 LCA standards.

Cradle-to-Grave Life-Cycle Inventory of the Propane System

The cradle-to-grave system boundary starts at the extraction of crude oil and stops at the useful heat produced at the residential furnace used for domestic heating. The propane product system includes four major life-cycle stages: crude oil extraction, propane production, propane distribution, and propane use. Crude oil extraction, propane production, and propane distribution data came from DATASMART database in which combustion data were retrieved from literature (LTS 2017, Johnson 2012). Johnson (2012) evaluated the existing data sources for residential heating systems using propane LCI and generated integrated data for propane combustion emission factors (Table 4).

Cradle-to-Grave Life-Cycle Inventory of the Briquetting System

All primary data related to the inputs and outputs of the processes were obtained by on-site measurements at the near-woods briquetter plant. The field experiments were performed in Big Lagoon, California, in 2015 on an old sawmill site using seven feedstock samples from four different species and two different chip sizes. The characteristics of the briquettes produced from seven

Table 4—Propane combustion emission factors (Johnson 2012)

Compound[a]	Emissions (mg/kWh)
CH_4	3.7
CO	31.9
CO_2, fossil	227,200
N_2O	0.4
NO_x	169.2
PM_{10}	1.2
SO_x	0.7
NMVOC	6.2

[a]PM, particulate matter; NMVOC, nonmethane volatile organic compound.

Table 5—Properties of briquettes produced using the feedstock tested for analysis

ID	Type	Average briquette mass (kg)	Average density (kg/m^3)	Moisture content (%)	Durability (%)
S1	Redwood, chip, small[a]	0.73	897.9	NA[b]	79
S2	Redwood, chip, medium[c]	0.70	831.0	8.1	97
S3	Douglas-fir, chip, small	0.81	930.1	6.6	97
S4	Douglas-fir, chip, medium	0.74	862.6	5.7	96
S5	Tanoak, chip, small	0.79	943.7	5.1	98
S6	Tanoak, chip, medium	0.77	753.7	7.5	93
S7	Conifer, chip, medium	0.75	848.8	6.7	95

[a]Small chips: ≤0.75 in.
[b]Data not available.
[c]Medium chips: 0.75 to 2 in.

different feedstocks are provided in Table 5. The material and energy inputs and outputs for production of 1 MJ of energy from wood briquettes are provided in the following sections.

Feedstock Procurement

Table 6 shows the cradle-to-gate input and output flows for feedstock procurement processes along with hauling for 1 bone-dry metric ton (BDT) of wood chips. Feedstock procurement processes and hauling were adopted from the forest operations model developed by Oneil and others (2017). The model by Oneil and others (2017) was based on the operational data generated in 2015 (Bisson and Han 2016, Kizha and Han 2016, Kizha and others 2018). The feedstock procurement stage includes woody biomass collection, sorting, and delimbing as well as the loading and transportation of the collected forest residues to the BCT site using a dump truck.

Feedstock Preparation

Gate-to-gate input and output flows of feedstock preparation including chipping, screening, and drying processes are provided in Table 7. Screening and chipping data were adopted from the forest operations model developed by Oneil and others (2017).

Forced-drying was applied before the briquetting process to decrease the MC of the biomass feedstock. Thermal energy required for forced-drying the input biomass was provided from a thermal oxidizer using propane as fuel. Electricity consumption in the dryer process came from the belt conveyor used (Beltomatic, Norris Thermal Technologies, Tippecanoe, Indiana, USA). The use of the dryer was based on the MC of the incoming biomass feedstock. For better system efficiency, forced-drying was required if the MC of the incoming feedstock was higher than 15% (Nemeth and others 2012). Although the feedstock was left in the forest and field-dried to 20±3% MC, feedstock was force-dried before the briquetting process to decrease the MC below 15%. Biomass conversion tests were performed using various feedstock MCs to identify the optimum MC, which for average feedstock after the drying process was about 6.13±0.96% for the experimental runs with high-quality product. Thermal energy required for forced-drying of the input biomass was provided from propane fuel. Heat requirement of the drying process was assumed to be 5 MJ/kg water removed, and system efficiency was 80% (Adams and others 2015).

Table 6—Cradle-to-gate input–output flow analysis for feedstock procurement of one bone-dry metric ton of wood chips

Process	Unit	Value	Source
Feedstock procurement			
Processing			
Diesel	L	1.0115	Oneil and others 2017
Lubricants	L	0.0182	Oneil and others 2017
Sorting			
Diesel	L	0.346	Oneil and others 2017
Lubricants	L	0.006	Oneil and others 2017
Loading			
Diesel	L	0.708	Oneil and others 2017
Lubricants	L	0.013	Oneil and others 2017
Volatile organic compounds	kg	0.696	Alanya-Rosenbaum and others 2018
Hauling			
Transportation	km	18.77	Oneil and others 2017

Table 7—Gate-to-gate input–output flow analysis for feedstock preparation of one bone-dry metric ton of wood chips

Process	Unit	Value	Source
Chipper			
Diesel	L	0.5461	Oneil and others 2017
Lubricants	L	0.0098	Oneil and others 2017
Screener			
Diesel	L	1.5939	Oneil and others 2017
Lubricants	L	0.0287	Oneil and others 2017
Dryer			
Electricity	kWh	7.14	Alanya-Rosenbaum and others 2018
Propane	L	44.4	Engineering calculations
Volatile organic compounds	g	174	Alanya-Rosenbaum and others 2018
Waste heat	MJ	491	Engineering calculations

Drying wood results in VOC emissions, which were accounted for in the analysis. This analysis assumed freshly cut wood to be on the conservative side and tracked any VOCs emitted during field-drying in the forest as well as during forced-drying. It would be expected that VOCs emitted during field-drying, because they occur at lower concentrations and over a far longer period, would be less harmful to the environment. The VOC emission data were derived from literature for the species used in this study (Beakler and others 2007, Milota and Lavery 1998, Milota and Mosher 2008, Milota 2013). According to the Milota (2013) findings, emission levels mainly depend on the species and are higher for drying fresh woody biomass than for drying aged material. He concluded that only 10% to 20% of total hydrocarbon emissions occur below 20% MC. In this study, it was assumed that 20% of the VOC emissions were emitted during the drying process, whereas the rest (80%) were emitted in the forest during field-drying.

Densification and Use Phases

Table 8 shows the environmental inputs and outputs for the densification and use phases. It is assumed that the briquettes were stored and sold in 15-kg-capacity plastic bags with low-density polyethylene (LDPE) (Laschi and others 2016). Overall efficiency of the wood stove was about 72%. Stack emissions from burning briquettes were obtained from WTW project combustion tests and were complemented by literature data.

Results of Life-Cycle Inventory Analysis

The results of the LCI analysis per 1 MJ of thermal energy generated for domestic heating from combusting wood briquettes are presented in Tables 9 and 10. Table 9 presents the cradle-to-grave primary energy consumption and contribution of different fuel sources to the briquette production supply chain. Total primary energy use was

Table 8—Environmental input and output flows for densification and use phases for a briquetting system

Process	Unit	Value	Source
Densification phase			
Briquetter			
Electricity	kWh/BDT[a]	33.8	Alanya-Rosenbaum and others 2018
Lubricants	mL/BDT	4.99	Alanya-Rosenbaum and others 2018
Packaging			
LDPE[b] packaging	g/BDT	0.67	Laschi and others 2016
Distribution	km	90.2	Oneil and others 2017
Use phase			
Combustion			
CO_2 (biogenic)	g/MJ input	85.43	Operational data
CH_4	g/MJ input	0.004	Khalil and others 2013
NO_x	g/MJ input	0.038	Operational data
CO	g/MJ input	5.064	Operational data
Volatile organic compounds	g/MJ input	0.764	Operational data
SO_2	g/MJ input	0.007	Khalil and others 2013
$PM_{2.5}$[c]	g/MJ input	0.035	Operational data
PM_{10}	g/MJ input	0.217	Operational data

[a]BDT, bone-dry metric ton.
[b]LDPE, low-density polyethylene.
[c]PM, particulate matter.

Table 9—Cumulative primary energy consumption per 1 MJ of thermal energy generated for domestic heating from combusting wood briquettes

		Primary energy consumption (MJ/MJ heat)					
Fuel	Percentage	Total	Feedstock procurement	Feedstock preparation	Densification	Transportation	Use phase (combustion)
Renewable fuel use							
Wood fuel	45.8	1.08E–01	0.00E+00	1.88E–02	8.92E–02	0.00E+00	0.00E+00
Nonrenewable fuel use							
Gas, natural, in ground	2.4	5.74E–03	4.00E–04	4.80E–03	6.60E–05	4.76E–04	0.00E+00
Coal, in ground	1.6	3.80E–03	2.65E–04	3.18E–03	4.19E–05	3.17E–04	0.00E+00
Oil, crude, in ground	49.6	1.17E–01	8.17E–03	9.77E–02	1.29E–03	9.78E–03	0.00E+00
Uranium	0.5	1.17E–03	8.20E–05	9.82E–04	1.30E–05	9.80E–05	0.00E+00
Renewable energy sources							
Hydro	<1.0	1.42E–04	2.13E–06	1.14E–04	1.06E–05	1.55E–05	0.00E+00
Wind	<1.0	5.92E–05	4.13E–06	4.94E–05	6.52E–07	4.93E–06	0.00E+00
Solar	<1.0	8.90E–07	6.21E–08	7.44E–07	9.82E–09	7.42E–08	0.00E+00
Geothermal	<1.0	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Total	100.0	2.36E–01	8.92E–03	1.26E–01	9.06E–02	1.07E–02	0.00E+00
Total, by percentage		100	3.8	53.3	38.4	4.5	0.0

Table 10—Resources consumed and waste generated per 1 MJ of thermal energy generated for domestic heating from combusting wood briquettes

Resources and waste	Unit	Total	Feedstock procurement	Feedstock preparation	Densification	Transportation	Use phase (combustion)
Total primary energy consumption	MJ	2.36E–01	8.92E–03	1.26E–01	9.06E–02	1.07E–02	0.00E+00
Nonrenewable fossil	MJ	1.26E–01	8.84E–03	1.06E–01	1.39E–03	1.06E–02	0.00E+00
Nonrenewable nuclear	MJ	1.17E–03	8.20E–05	9.82E–04	1.30E–05	9.80E–05	0.00E+00
Renewable (solar, wind, hydroelectric, and geothermal)	MJ	2.02E–04	6.32E–06	1.64E–04	1.13E–05	2.05E–05	0.00E+00
Renewable (biomass)	MJ	1.08E–01	0.00E+00	1.88E–02	8.92E–02	0.00E+00	0.00E+00
Material resources consumption (nonfuel resources)							
Renewable materials	kg	9.22E–02	9.09E–02	2.27E–04	1.07E–03	1.63E–07	0.00E+00
Fresh water	L	9.36E–04	6.54E–05	7.83E–04	1.03E–05	7.81E–05	0.00E+00
Waste generated							
Solid waste	kg	4.87E–08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.87E–08

0.236 MJ per MJ heat generated. The feedstock preparation stage was responsible for the majority of primary energy with about 53% contribution, followed by the densification stage (38%). Type of primary energy source used was dominated by wood fuel and crude oil. Most wood fuel was used for electricity production during the densification process, followed by feedstock preparation. This was caused by the wood-gasifier-based electricity consumption in these processes. Most of the fossil energy was from propane and diesel consumption during drying and transportation, respectively, which is extracted as crude oil from the ground as the primary energy source before conversion. The contribution of other renewable energy sources to total energy consumption, including geothermal, solar, hydro, and wind, was minor because of the lower renewable source in the electricity grid used in propane production.

Table 10 also provides values for the energy and material resource consumption. Total fossil energy use was 0.13 MJ/MJ heat, used mainly for force-drying of wood chips to desired MC. Total renewable energy was 0.11 MJ/MJ heat coming primarily from the biomass gasifier. Nonrenewable material resources were minor (less than about 10^{-6}). Solid waste generated consisted of packaging waste.

The results of the LCI analysis per 1 MJ of thermal energy generated for domestic heating from combusting propane are presented in Tables 11 and 12. Total primary energy used to produce 1 MJ of heat was 1.46 MJ. The majority of primary energy consumption was from crude oil with about 91.4% contribution.

Life-Cycle Impact Assessment

The results of the LCIA performed using the TRACI v2.1 method are documented in this section. Cradle-to-grave assessment analyzed environmental impacts associated with the wood briquette production supply chain and compared them with a fossil fuel alternative, i.e., propane. In addition, the effect of alternative scenarios considering different power sources, logistics, and feedstock properties on the impact results were evaluated using cradle-to-grave analysis.

Cradle-to-Grave Life-Cycle Analysis Results

Environmental impact assessment results associated with generating heat from wood briquettes in wood stoves are presented in Table 13 for 10 impact categories: GW, acidification, eutrophication, OD, smog formation, human health (carcinogenics and noncarcinogenics), respiratory effects, ecotoxicity, and fossil fuel depletion. The results presented were for the original scenario tested, in which the briquetter was operated near the woods close to the feedstock source and powered using a biomass gasifier. The drying process had the greatest impact in the GW, smog, carcinogenics, noncarcinogenics, ecotoxicity, and fossil fuel depletion categories.

Environmental impact assessment results associated with generating heat at the propane furnace are presented in Table 14. The production stage was responsible for the majority of the impact for all impact categories except GW, followed by the combustion stage. Contribution of the distribution stage to overall impact was minor.

Table 11—Cumulative primary energy consumption per 1 MJ of thermal energy generated at propane furnace for domestic heating from combusting propane

		Primary energy consumption (MJ/MJ heat)			
Fuel	Percentage	Total	Production	Transportation	Combustion
Renewable fuel use					
Wood fuel	0.0	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Nonrenewable fuel use					
Gas, natural, in ground	4.5	6.51E–02	6.51E–02	4.56E–05	0.00E+00
Coal, in ground	3.0	4.34E–02	4.33E–02	4.45E–05	0.00E+00
Oil, crude, in ground	91.4	1.34E+00	1.34E+00	9.44E–10	0.00E+00
Uranium	1.0	1.42E–02	1.34E–02	7.89E–04	0.00E+00
Renewable energy sources					
Hydro	<1.0	1.74E–03	1.74E–03	1.22E–06	0.00E+00
Wind	<1.0	6.75E–04	6.75E–04	4.72E–07	0.00E+00
Solar	<1.0	1.02E–05	1.01E–05	7.11E–09	0.00E+00
Geothermal	<1.0	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Total	100.0	1.46E+00	1.46E+00	8.80E–04	0.00E+00
Total, by percentage		100	99.9	0.1	0.0

Table 12—Resources consumed and waste generated per 1 MJ of thermal energy generated at the propane furnace for domestic heating

Resources and waste	Unit	Total	Production	Transportation	Combustion
Total primary energy consumption	MJ	1.46E+00	1.46E+00	8.80E–04	0.00E+00
Nonrenewable fossil	MJ	1.44E+00	1.44E+00	9.01E–05	0.00E+00
Nonrenewable nuclear	MJ	1.42E–02	1.34E–02	7.89E–04	0.00E+00
Renewable (solar, wind, hydroelectric, and geothermal)	MJ	2.43E–03	2.42E–03	1.70E–06	0.00E+00
Renewable (biomass)	MJ	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Material resources consumption (nonfuel resources)					
Nonrenewable materials	kg	4.29E–05	4.28E–05	3.00E–08	0.00E+00
Renewable materials	kg	2.24E–05	2.23E–05	1.56E–08	0.00E+00
Fresh water	L	1.07E–02	1.07E–02	7.48E–06	0.00E+00
Waste generated					
Solid waste	kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table 13—Environmental performance of 1 MJ of thermal energy generated for domestic heating from combusting wood briquettes

Impact category	Unit[a]	Feedstock procurement	Hauling	Chipping/ screening	Drying	Briquetter	Packaging	Distribution	Use phase
Ozone depletion	kg CFC-11 eq	1.11E–12	2.22E–13	1.61E–12	1.17E–11	1.75E–13	1.08E–15	1.10E–12	0.00E+00
Global warming	kg CO_2 eq	6.08E–04	1.99E–04	8.84E–04	6.70E–03	9.93E–05	1.08E–07	6.61E–04	1.24E–04
Smog	kg O_3 eq	4.87E–04	3.21E–05	3.78E–04	4.06E–04	1.01E–04	3.12E–09	1.05E–04	1.70E–03
Acidification	kg SO_2 eq	8.00E–06	1.05E–06	1.16E–05	1.64E–05	3.64E–06	2.29E–10	3.65E–06	4.67E–05
Eutrophication	kg N eq	6.14E–07	8.73E–08	8.94E–07	2.24E–06	2.19E–07	7.72E–10	3.38E–07	2.34E–06
Carcinogenics	CTUh	1.01E–11	2.01E–12	1.47E–11	1.06E–10	1.59E–12	1.42E–15	1.00E–11	0.00E+00
Noncarcinogenics	CTUh	9.93E–11	1.98E–11	1.44E–10	1.04E–09	1.56E–11	3.86E–14	9.87E–11	0.00E+00
Respiratory effects	kg $PM_{2.5}$ eq	1.58E–07	1.62E–08	2.30E–07	2.95E–07	1.11E–07	9.19E–12	5.63E–08	5.21E–05
Ecotoxicity	CTUe	2.54E–03	5.08E–04	3.70E–03	2.67E–02	4.00E–04	4.51E–06	2.53E–03	0.00E+00
Fossil fuel depletion	MJ surplus	1.17E–03	2.35E–04	1.71E–03	1.23E–02	1.85E–04	5.08E–07	1.17E–03	0.00E+00

[a]CFC, chlorofluorocarbons; CTUh, comparative toxicity units humans; PM, particulate matter; CTUe, comparative toxicity units ecotoxicity.

Table 14—Environmental performance of 1 MJ of thermal energy generated for domestic heating from propane combustion

Impact category	Unit[a]	Production	Distribution	Combustion
Ozone depletion	kg CFC-11 eq	1.81E–10	1.27E–13	0.00E+00
Global warming	kg CO_2 eq	1.62E–02	7.65E–05	7.81E–02
Smog	kg O_3 eq	2.05E–03	1.96E–05	1.45E–03
Acidification	kg SO_2 eq	1.52E–04	7.24E–07	4.09E–05
Eutrophication	kg N eq	2.85E–05	5.22E–08	2.57E–06
Carcinogenics	CTUh	1.64E–09	1.15E–12	0.00E+00
Noncarcinogenics	CTUh	1.62E–08	1.13E–11	0.00E+00
Respiratory effects	kg $PM_{2.5}$ eq	2.39E–06	1.08E–08	5.32E–07
Ecotoxicity	CTUe	4.16E–01	2.91E–04	0.00E+00
Fossil fuel depletion	MJ surplus	1.92E–01	1.34E–04	0.00E+00

[a]CFC, chlorofluorocarbons; CTUh, comparative toxicity units humans; PM, particulate matter; CTUe, comparative toxicity units ecotoxicity.

Comparison of the GW impact results per megajoule of heat generated from propane and wood briquettes and the contribution percentages of the different processes to the overall impact for the wood briquette supply chain are presented in Figures 6 and 7. Wood briquette production was performed as a near-woods operation using wood-fueled gasifier power. Environmental impacts associated with domestic heat generated through a propane furnace and a propane system supplemented with a wood furnace using briquette fuel were compared. Comparative data showed that 50% and 80% substitution of heat from propane with wood briquettes resulted in 45% and 72% reduction in the GW impact, respectively.

The contribution analysis revealed that a large portion of the GW impact resulted from drying processes (72%), with chipping and screening following. The large contribution of the drying process resulted from the propane used for heat generation for forced-drying. Converesly, contribution of densification (briquetting) and use phases were minor and the use phase for the propane scenario was the major contributor to GW impact that resulted from fossil-fuel-based GHG emissions (i.e., propane combustion emissions).

Alternative System Configurations Life-Cycle Impact Assessment

The LCIA results of alternative scenarios considered are evaluated in this section. The GW impact resulting from different scenarios and the process contribution to the overall impact are presented in Figure 8. When effect of using different power sources to support dryer and briquetter processes on the overall GW impact were compared at cradle-to-grave level, gasifier power (S1) generation outperformed diesel electricity (S2) and grid electricity (S3) scenarios. Displacing diesel-based power

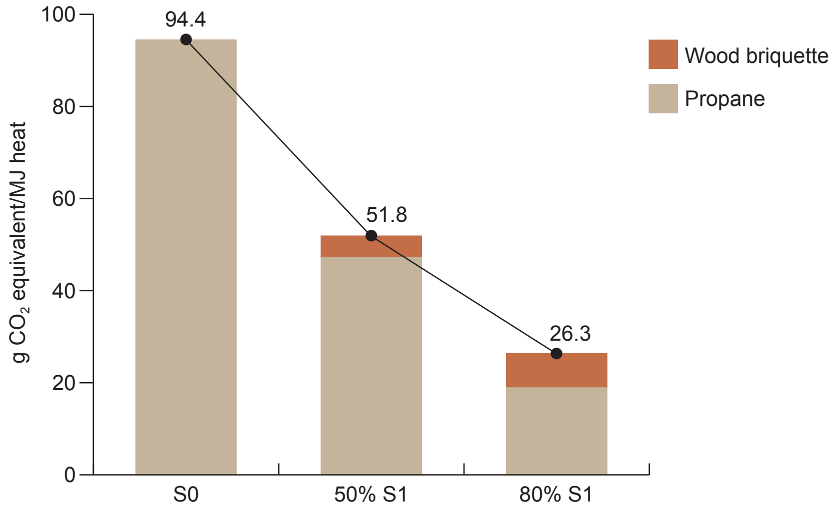

Figure 6. Comparison of global warming per 1 MJ of thermal energy generated for domestic heating from 100% propane (S0), propane system supplemented with 50% of the heat generated from a wood stove burning wood briquettes (S0+S1), and propane system supplemented with 80% of the heat generated from a wood stove burning wood briquettes (S0+S1).

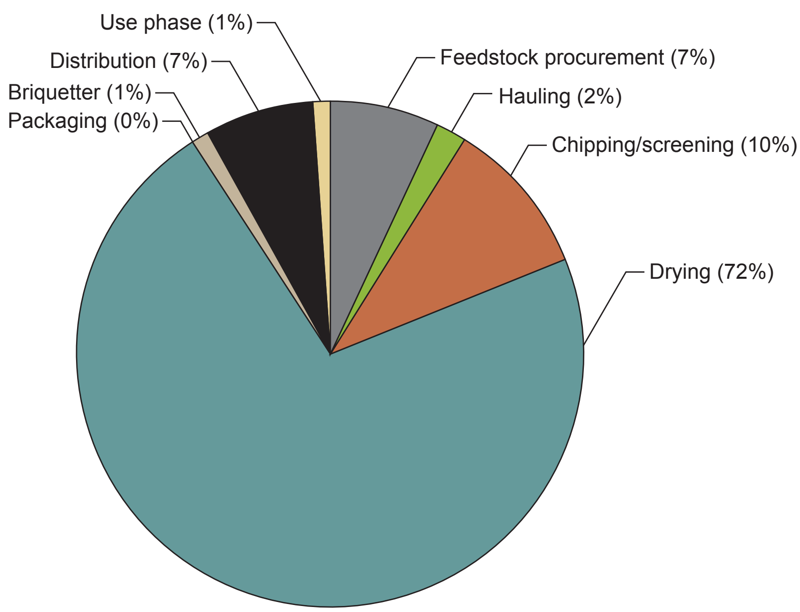

Figure 7. Contribution of processes to overall global warming impact for the wood briquette production system per 1 MJ of thermal energy generated by the wood stove.

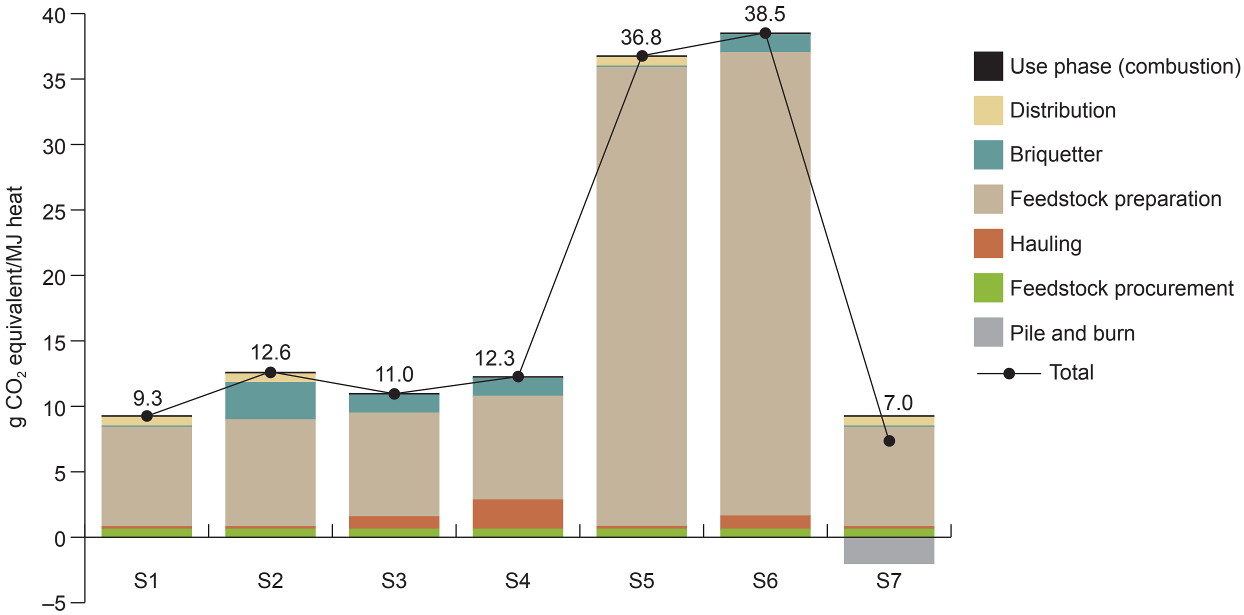

Figure 8. Contribution of processes to overall global warming impact per 1 MJ of thermal energy generated for seven scenarios investigated. S1: 1 MJ heat, near-woods operation with wood gasifier power; S2: 1 MJ heat, near-woods operation with diesel power; S3: 1 MJ heat, in-town operation (2-h travel distance) with grid power; S4: 1 MJ heat, in-town operation (4-h travel distance) with grid power; S5: 1 MJ heat, 50% MC feedstock, near-woods operation with wood gasifier power; S6: 1 MJ heat, 50% MC feedstock, in-town operation (2-h travel distance) with grid power; S7: 1 MJ heat, near-woods operation with wood gasifier power with pile and burn credit.

and grid power generation with gasifier power resulted in a 26% and 15% decrease, respectively, in GW impact. Grid power access scenarios, S3 and S4, are in-town operation scenarios for which the feedstock was hauled to town before the biomass preparation and biomass conversion processes occurred. Two different distances were evaluated to investigate the effect of hauling distance on the results when the biomass feedstock was processed in town. In these scenarios, an increase in the contribution of hauling to the overall impact was observed with longer transportation of feedstock. The contribution of hauling to GW impact increased from 2% to 9% when feedstock was transported to town with a limitation of 2-h travel distance (S3) before biomass conversion, whereas it increased to 18% when travel distance was assumed to be 4 h. The increase in hauling distance resulted in 1.7 g CO_2 equivalent increase in GW impact per megajoule heat generated for 2-h hauling. Scenario analysis also showed that use of feedstock with high MC, 50% in this case, was the least favorable of the alternative scenarios (S5, S6). For near-woods operations, using green post-harvest residues (with 50% MC) instead of air-dried feedstock with around 20% MC resulted in about four times higher GHG emissions. This was caused by increased propane consumption to meet the dryer heat demand. About 33% GHG reduction occurred with conversion of the post-harvest forest residues to briquettes for heat generation mainly because of avoided methane emissions from pile and burning (S7).

The effect of using different power sources for meeting the electricity demand for the dryer and briquetter processes on the impact was investigated and presented for OD, smog, acidification, eutrophication, and fossil fuel impact assessment categories (Fig. 9). The results of the analysis revealed that, at the cradle-to-grave level, using on-site wood gasifier power generation improved the environmental performance of the system compared with on-site diesel electricity and grid electricity in all impact categories except for smog impact. The difference was notable in the OD impact category for which displacing diesel power generation and electricity with a gasifier resulted in 26% and 47% decreases, respectively.

Pile and burn credits resulted in substantial benefits particularly in the human health impact categories (Fig. 10). Environmental benefits of the avoided pile-and-burn emissions were notable in the carcinogenic and respiratory effects impact categories. The respiratory effects impact category was dominated by emissions from use phase, whereas the major contributor to the rest of the human health impact categories was drying process because of the propane consumed.

Life-Cycle Interpretation

The interpretation section evaluates results for the LCI or the LCIA, or both, in line with the defined goal and scope. The midpoint analysis results are presented and discussed

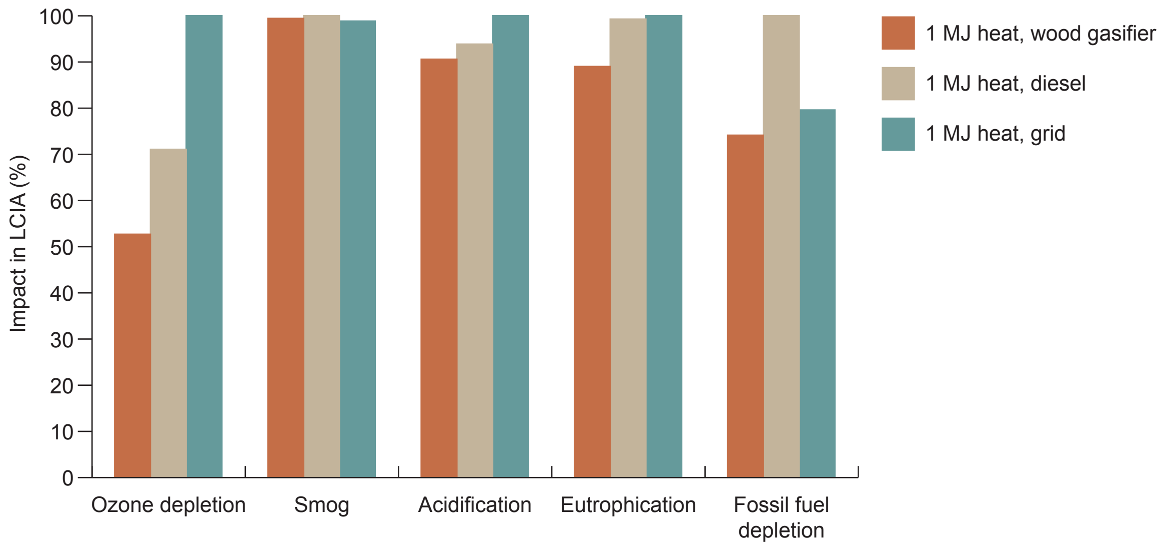

Figure 9. Summary of the comparative life-cycle impact assessment (LCIA) results for three power sources (grid, diesel, and gasifier electricity) for the briquetter system.

in the previous section, which included scenario analysis. In this part of the report, results from the additional parameter-based sensitivity analysis are addressed as part of the interpretation. Additional components include conclusions, limitations, and recommendations.

A parameter-based sensitivity analysis was conducted in addition to the scenario analysis performed in this section. The sensitivity of the GW impact was examined using key parameters including briquetter electricity demand, dryer propane consumption, and distribution and hauling distances. The effect of 25% variation of these parameters on the resulting GW impact is presented in Figure 11. Key parameters that had great influence on the impact assessment results were investigated through sensitivity analysis. The performed sensitivity analysis showed that dryer propane consumption was a key parameter with great influence on variation in the GW impact. Distribution distance also had some influence on the impact. This reveals the importance of dryer heat requirement and energy consumption data to decrease the uncertainty resulting from parameters used. Similarly, scenario analysis showed that the MC of the incoming feedstock had notable effect on the resulting environmental impact.

Conclusions, Limitations, and Recommendations

This study provided a comprehensive cradle-to-grave LCA of the wood briquette production supply chain. The environmental performance of using post-harvest forest residues in a near-woods briquetting process for solid biofuel production was investigated. Briquetting occurred near the point of harvesting to decrease transporting distance of the forest residues. Results indicated that the GW impact was highly dependent on drying process efficiency during wood briquette production; therefore, use of high-efficiency dryer systems is crucial to improve environmental performance of the supply chain. Using field-dried feedstock with lower MC resulted in considerable decrease of GW impact, which showed the importance of developing and using different techniques for decreasing the MC of biomass feedstock, such as air-drying. Alternatively, use of biomass as a fuel source for the drying system can be investigated to examine its effect on the overall environmental impact of the system, which may mitigate the GW impact of the drying process. Data on heat requirements of the dryer process were not available; therefore, data were retrieved from literature using a conservative approach. As the sensitivity analysis revealed, drying parameters had a great influence on the impact assessment results. Therefore, drying data that rely on operational runs would improve the quality of the analysis.

Substitution of fossil fuel products with renewable energy products consistently shows GHG emission reduction potential (Panwar and others 2011, Ellabban and others 2014, Baul and others 2017, Gustavsson and others 2017). In particular, this study showed that substituting wood briquettes produced from widely available forest residues for propane for domestic heating reduced GHG emissions. In addition, for remote power generation, GHG emissions were lower when a biomass gasifier genset was substituted for a diesel generator. When in-town grid electricity was used at 2-h distance instead of near-woods bioenergy production systems using power from an on-site wood gasifier, the GW impact increased by 15%. Using post-harvest residues as biofuel instead of using the typical pile and burn approach notably lowered resulting environmental impact.

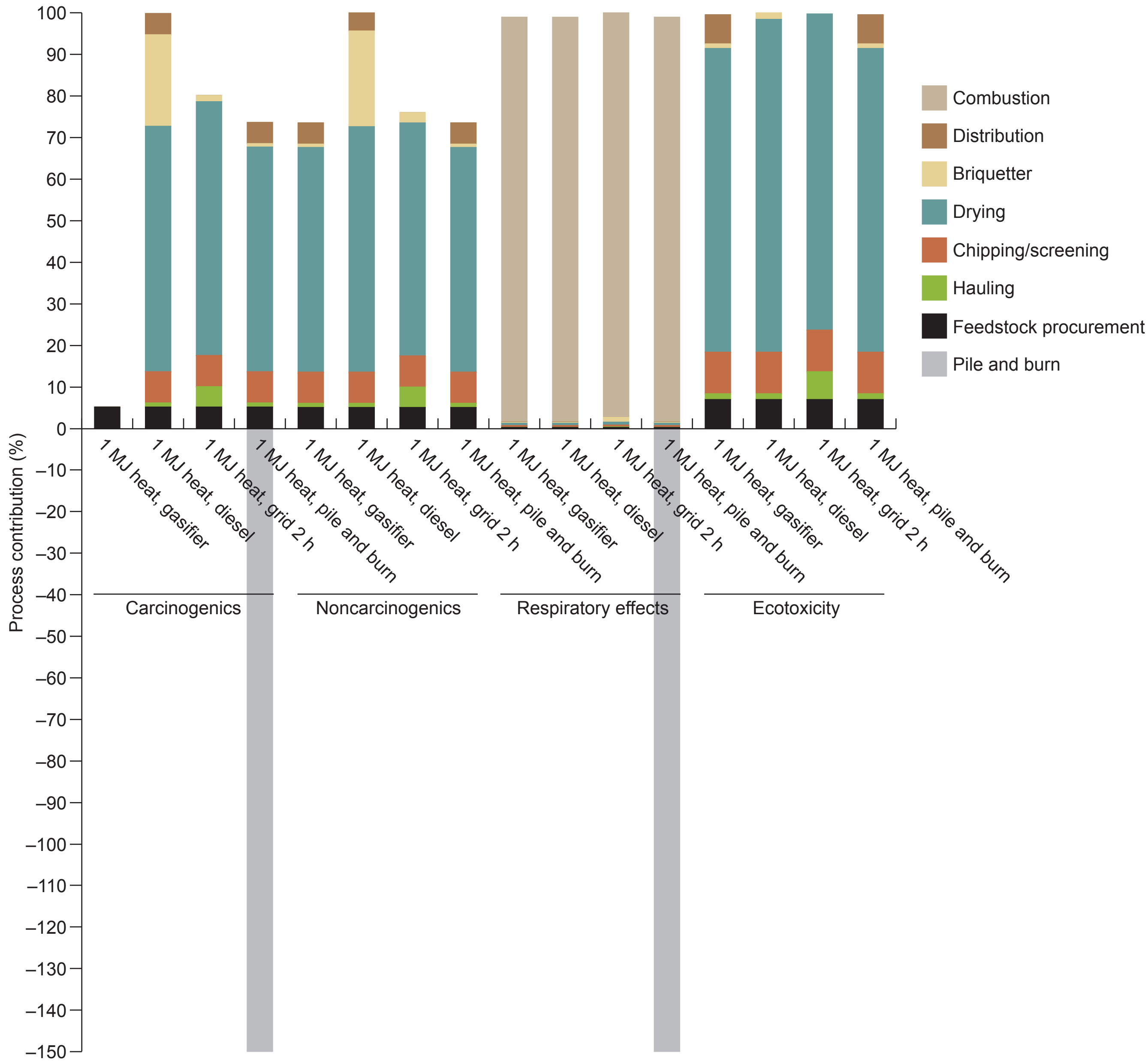

Figure 10. The toxicity impact category results for generating 1 MJ of thermal output for the scenarios investigated.

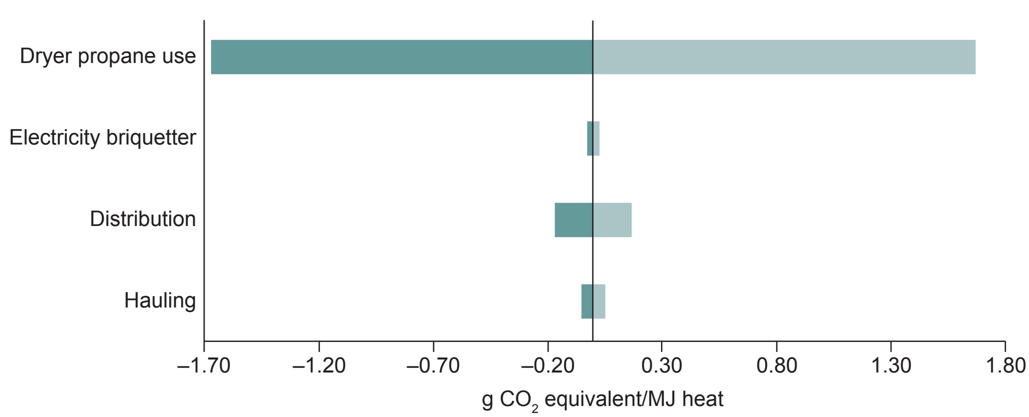

Figure 11. Sensitivity of key parameters on global warming impact.

External Review

The external review process was intended to ensure consistency between the completed LCA and the principals and requirements of the international standards on LCA (ISO 2006a). The independent external review was performed by James Salazar, M.S., Principal of Coldstream Consulting, and Shaobo Liang, PhD, Postdoctoral Research Fellow, USDA Forest Service, Forest Products Laboratory.

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