United States Department of Agriculture

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

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Forest Service | Forest Products Laboratory | General Technical Report FPL–GTR–263 | December 2018

Abstract

This report presents life-cycle impact assessment analysis of near-woods processing of post-harvest forest residues (a biomass raw material) into torrefied wood for bioenergy production. The study was part of the Waste to Wisdom project with a broader goal of evaluating the use semimobile biomass conversion technologies to optimize biomass logistics, thereby overcoming the barriers of valorizing woody biomass residues for renewable energy and material production. Cradle-to-grave analysis of the torrefied briquettes (TOB) supply chain included feedstock procurement, hauling, feedstock preparation and bioconversion (torrefaction and densification) stages, product transportation (distribution), and combustion of TOB in domestic wood stoves for heat generation. The results showed that a large portion of the global warming (GW) impact of the TOB supply chain resulted from the torrefaction process (59%) followed by the drying process with about 24% of the contribution. The large contribution of these processes resulted from propane use. Comparative analysis showed that 50% substitution of propane used in domestic heating with TOB resulted in a 41% decrease in GW impact. The near-woods operation resulted in a 55% lower GW impact compared with transporting the feedstock to an in-town facility with access to grid electricity.

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

December 2018

Alanya-Rosenbaum, Sevda; Bergman, Richard. 2018. Using life-cycle assessment to evaluate environmental impacts of torrefied briquette production from forest residues. General Technical Report FPL-GTR-263. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 24 p.

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The Forest Products Laboratory is maintained in cooperation with the University of Wisconsin.

Acknowledgments

This material is based on work supported by a grant from the U.S. Department of Energy under the Biomass Research and Development Initiative program: Award Number DE-EE0006297. This research was supported in part by an appointment to the USDA Forest Service Research Participation Program administered by the Oak Ridge Institute for Science and Education (ORISE) through an interagency agreement between the U.S. Department of Energy and the USDA Forest Service. ORISE is managed by Oak Ridge Associated Universities (ORAU) under DOE contract number DE-AC05-06OR23100. All opinions expressed in this report are the authors' and do not necessarily reflect the policies and views of USDA, DOE, or ORAU/ORISE.

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Executive Summary

The goal of this study was to assess environmental sustainability of near-woods processing of post-harvest forest residues as a feedstock in torrefied briquette (TOB) production and its use as biofuel for domestic heating. To quantify the impact associated with the torrefied briquette supply chain, USDA Forest Service, Forest Products Laboratory, scientists developed a cradle-to-gate life-cycle inventory (LCI) and performed a life-cycle assessment (LCA) analysis. The 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 included six main life-cycle stages: feedstock procurement, hauling, feedstock preparation, biomass conversion (torrefaction and briquetting), transportation (distribution), and heat generation at a residential wood stove (use phase). The feedstock procurement stage included processing (delimbing), sorting, and loading. The feedstock preparation stage included processes used to achieve the feedstock specifications required for the biomass conversion stage: chipping, screening, and drying of the feedstock. The operational data used in this study were developed by other subtasks under the Waste to Wisdom project (www.wastetowisdom.com). These data include feedstock procurement and preparation processes, torrefaction, densification (briquetting), and woody biomass gasification generator set (genset). Biomass collection and feedstock preparation data were based on field data and experimental studies performed by Humboldt State University (HSU) (Arcata, California, USA) in 2015. This included data for the dryer and briquetting processes. The primary data for the torrefaction and briquetting processes relied on operational runs of the demonstration-scale torrefaction unit at Samoa, California, USA, in 2016.

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. The system was modeled using the SimaPro 8.5 LCA software package. The data were normalized using the functional unit, which was defined as 1 MJ of useful thermal energy produced for residential heating.

Alternative system configurations were investigated at the cradle-to-grave level for evaluation of the effect of near-woods versus in-town processing of forest residues. Two remote power generation technologies were taken into account: a woody biomass gasification genset and a diesel generator. Effect of moisture content of incoming feedstock on the resulting impact was also investigated.

The following list shows the main conclusions of the study based on the life-cycle impact assessment results:

- Scenario analyses indicated that the most favorable scenario for near-woods processing of forest residues was using on-site woody biomass gasification genset for power.
- Near-woods operation using woody biomass gasification genset to meet the electricity demand of torrefaction, briquetter, and dryer processes showed major reductions in greenhouse gas (GHG) emissions compared with using a diesel generator or using grid electricity from in-town operations. Near-woods operation using diesel power was proven to be the least favorable alternative.
- When nonrenewable power source options were compared, diesel power had the worst environmental performance, even though longer hauling distances for in-town operations resulted in higher global warming impact from the hauling process.
- Global warming impact was highly dependent on drying process and torgas management at TOB production. For better environmental performance, the following are recommended: high-efficiency drying systems, field-dried feedstock with low moisture content (MC), and efficient recovery systems from displacing propane with torgas, especially in the drying process.

Definition of Goal and Scope

Study Goals

The goal of this study was to assess environmental sustainability of the processing of forest residues near the point of harvesting logs (i.e., near-woods) as a feedstock in TOB production. To quantify the impact of the TOB supply chain on the environment and to address environmental impacts associated with each process involved, a cradle-to-grave LCA was performed. The evaluation was performed at plant and unit process levels in accordance with ISO 14040 and ISO 14044 LCA standards (ISO 2006a, 2006b). The study was conducted with funding support from a BRDI grant, which is a collaborative initiative between the DOE and USDA.

The main function of the torrefaction process was to generate a solid biobased fuel that can be an alternative to nonrenewable fossil fuels. To evaluate environmental performance and obtain more insight into the environmental competitiveness of torrefied wood as a biobased fuel substitute, a comparison was made with a residential propane heating system.

Intended Application

This study assessed and documented the environmental burden and benefits associated with TOB production from forest residues at life-cycle level. Torrefaction is a promising technology for production of a sustainable energy carrier that can be used in existing infrastructure. Yet, its market penetration is still in the initial stages and information on its application is limited (Nhuchhen and others 2104). Therefore, the intended application of this study was to provide credited data and enhance our knowledge on environmental aspects associated with conversion of forest residues to bioenergy carriers using the torrefaction process at a life-cycle level. Torrefaction allows production of a renewable and carbon-neutral solid biomass energy resource (Hektor and others 2016, Miner and others 2014). Hence, the assessment also includes comparison of the torrefied wood production with use of traditional fuel, i.e., propane, for domestic heating to evaluate its environmental performance compared with traditional fossil energy sources. The results of this study may promote the production of forest-based bioenergy using the torrefaction process.

Motivation

Today, the radical increase in demand for and consumption of energy resources, environmental sustainability initiations, and new policies to combat climate change are major drivers for establishing new renewable energy sources (USEIA 2016). 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.

Currently in the United States, about 93 million dry metric tons of forest removals are generated annually, 73% of which are the result of logging residues (USDOE 2011). The forest removals represent the removed portion of standing timber, which include roundwood products, logging residues, and other removals from growing stock and other sources (USDOE 2011). Forest residues resulting from commercial logging operations, which are often left on site to decay or be burned, can potentially be used by biomass conversion technologies to produce biofuels (USDOE 2011, USEPA 2007). Overstocked forests increase wildfire risk. Forest thinning and removal of post-harvest forest residues may help mitigate wildfires (Giuntoli and others 2015, Loeffler and others 2017). With the torrefaction process, forest residues can be eliminated and converted to a high-quality renewable energy source that can replace fossil fuels.

The motivation for undertaking this study was to evaluate environmental viability of using post-harvest forest residues, in combination with a torrefaction process, to produce a high-quality bioenergy carrier. The use of forest residues as biomass feedstock has the potential to reduce fossil fuel dependence. 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 reduce dependence on fossil fuels.

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 subject to third-party critical review. 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 reduce fire risk (Loeffler and others 2010). Removal of biomass for biofuel production may be of interest to forest land managers because this may assist them to overcome costs associated with biomass fuel treatment for reducing fire hazards.

The final Clean Power Plan rule released by the U.S. Environmental Protection Agency (EPA) requires approximately 32% reduction in electricity sector carbon emissions by 2030 compared with CO_2 emission levels in 2005 (Ohio EPA 2015). Torrefied wood has properties that are comparable with coal and can replace coal in power plants.

This study presents an environmental evaluation of torrefied wood production in the United States as a low-carbon biofuel product with the potential to replace coal in power plants or propane in residential heating systems. Furthermore, this study will be of interest to consumers that

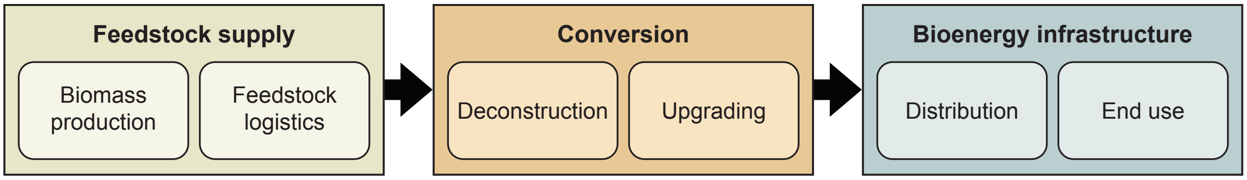

Figure 1. Biomass-to-bioenergy supply chain (USDOE 2014).

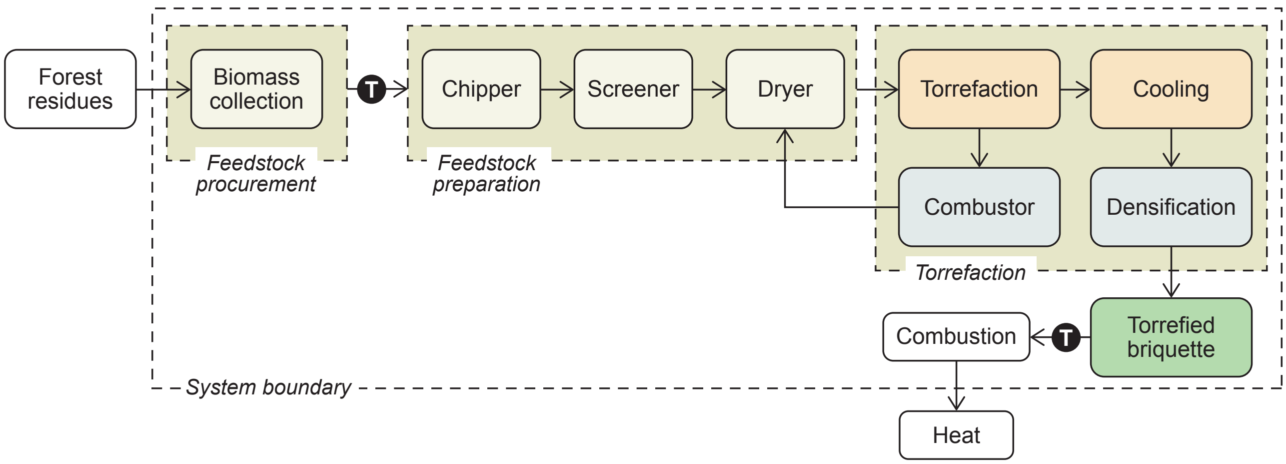

Figure 2. Cradle-to-grave system boundary for torrefied wood production supply chain (T, transportation).

have environmental concerns regarding their residential heating systems.

The Scope of the Study

The scope of this LCA included cradle-to-grave stages of feedstock procurement and preparation, hauling, near-woods production of TOB from post-harvest forest residues, distribution, and combustion of TOB in domestic wood stoves for heat generation. The system boundaries covered procurement, hauling, preparation, biomass conversion of forest residues to TOB, and distribution and ended at the grave, i.e., combustion in wood stoves for residential space heating. The life-cycle level impacts of TOB production were evaluated and compared with propane as a reference fossil fuel source. Propane is the most common fossil fuel energy source used in the studied area for domestic heating in rural areas. The heat production from propane for domestic heating was considered as the reference supply chain. The LCA for propane was constructed from peer-reviewed literature and other secondary sources.

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 includes any efficiency loss to generate the 1 MJ of heat and was based on the higher heating value (HHV). HHVs are used to convert volume or mass basis of a fuel to its energy value. HHVs represent the energy content of a fuel with the combustion products such as water vapor brought to 25 ºC, whereas lower heating value (LHV) ignores the energy produced by the combustion of hydrogen in fuel. HHV (gross heat content) is the preferred method used in the United States (USEIA 2017).

System Boundary

This study evaluated two energy carriers, torrefied briquettes and propane, with different production processes, by making use of the LCA tool. The life cycle of a biomass-to-bioenergy supply chain typically starts at the feedstock supply stage where biomass production occurs followed by biomass conversion. It ends at the user where the biofuel is used for energy production (Fig. 1).

The system boundary of the torrefaction system investigated is provided in Figure 2. The life-cycle stages of TOB production include feedstock procurement, feedstock preparation, biomass conversion, and use (combustion). Feedstock preparation and biomass conversion processes occurred at the biomass conversion technology (BCT) site. Disposal or beneficial use of the ash generated was left outside the scope of this study. In addition, disposal of ash would be hard to determine in rural areas because it is likely to be spread onto fields and woods. Because of insufficient

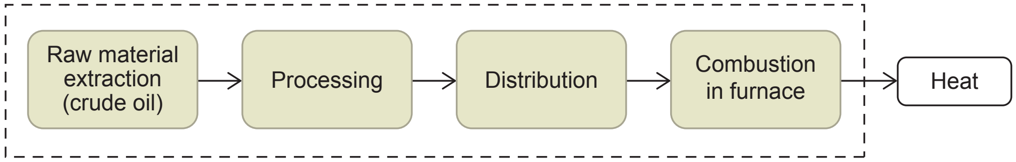

Figure 3. Cradle-to-grave system boundary for propane production supply chain.

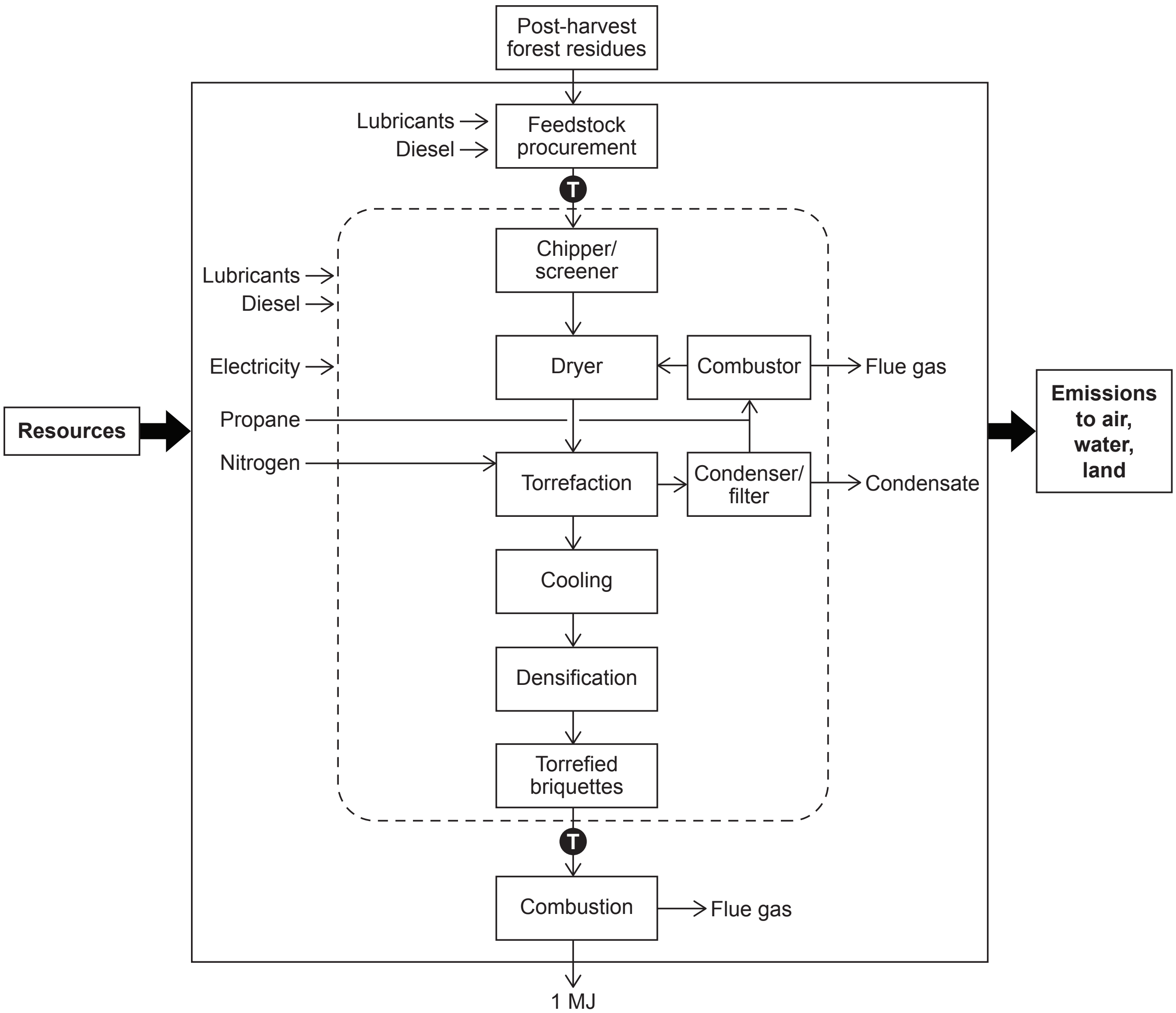

Figure 4. Cradle-to-grave process flow diagram of near-woods torrefied briquette production supply chain (T, transportation).

information on the torrefaction technology investigated, the manufacturing, maintenance, and disposal of equipment used in the system are considered outside the scope of this LCA, which is in line with the propane production system that also excludes these 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 ends at the useful heat produced at the residential furnace for domestic heating.

Figure 4 shows the torrefied briquette supply chain processes along with the inputs to and emissions from the system. Input biomass feedstock was post-harvest logging residue, which is a byproduct of commercial harvesting operations. The field-dried feedstock was sourced from timber harvesting operations in the western United States, specifically Washington, Oregon, and California.

The Waste to Wisdom (WTW) project (www.wastetowisdom.com) investigated integrated harvesting and near-woods biomass conversion of post-harvest forest residues to produce high-quality feedstock with low contamination and uniform-sized feedstock (Kizha and Han 2016, Bergman and others 2018, Han and others 2018). The feedstock procurement stage included biomass processing, sorting, and loading. Processed tree tops from integrated timber harvesting operations were used as feedstock biomass for the biomass conversion technology. Sorting and processing (delimbing) were used to generate processed tree tops. Feedstock preparation was performed to achieve necessary feedstock specifications for the biomass conversion process. This included chipping, screening, and drying. The unit processes of the biomass conversion system included torrefaction, cooling, and densification. In the briquetting process, torrefied biomass was densified into briquettes. All electricity and heat necessary for the system was generated on site using either a woody biomass gasification generator set (genset) or a diesel power generator. The system components are subsequently described in detail.

Feedstock Procurement

The biomass feedstock received was a waste product of commercial timber harvesting operations composed of tree tops, limbs, and branches. Pulp logs made up part of the biomass feedstock because of the lack of near-by markets, which is not historically typical. In this study, the term logging slash was used interchangeably when referring to forest residues. Because the logging slash was left in the forest for air-drying for one 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 post-harvest forest residues. In this study, 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., the near-woods BCT site). Primary data from five commercial harvesting sites in the western United States were used for modeling biomass procurement: Port Angeles, Washington; Warm Springs, Oregon; Oakridge, Oregon; Lakeview, Oregon; and Quincy, California. The average transport distance traveled from the primary landing to the BCT site for the five regions investigated was nearly 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 feedstock to be torrefied and briquetted into bioenergy products. The lubricant consumption data for chipping equipment, which consisted of hydraulic oils, general lubricants, and fuel

Table 1—Properties of feedstock before torrefaction

Property	Value
Moisture content (%) wb[a]	9.34
Ash content (%) db[b]	3.4
Volatile matter (%) db	81
Higher heating value (MJ/kg db)	19.6

[a]wb, wet basis.
[b]db, dry basis.

consumption of chipper and screener, were based on tests performed by HSU. These were generated as a part of the WTW project (Oneil and others 2017). Details of the forest operations model and the equipment used for feedstock preparation are provided in Oneil and others (2017).

In this study, feedstocks were sourced from Tanoak (*Notholithocarpus densiflorus*). Forced-drying was applied before the torrefaction process to decrease the MC of the biomass feedstock. The use of the dryer was based on the target MC of the biomass feedstock (Li and others 2012). Torrefaction tests were performed using various feedstock MCs to identify the optimum MC for the highest quality product (Severy and others 2018). The characteristics of the feedstock after the preparation stage are provided in Table 1.

Torrefaction

Torrefaction is a thermal pretreatment process that adds value to the biofuel produced, given that the product is hydrophobic, has high energy and bulk density, and has increased grindability compared with nonthermally treated biomass. The biomass feedstock is heated in a virtually oxygen-free environment to a temperature of approximately 200 to 300 °C (Tumuluru and others 2011). These characteristics make it a suitable bioenergy carrier with specifications equivalent to coal (Nunes and others 2014, Proskurina and others 2017).

For the WTW project, a semimobile, electrically heated, screw-type, demonstration-scale torrefaction process (Biogreen, ETIA Group, Compiègne, France, and Norris Thermal Technologies, Tippecanoe, Indiana, USA) was used, which processed about 0.5 metric tons wood chips per hour. A piping and instrumentation diagram of the torrefaction unit used is provided in Figure 5. The reactor temperature was at about 275 °C, and to provide the required inert conditions during the torrefaction process, nitrogen gas was introduced to the process for purging. Nitrogen used for purging was negligible because it was needed only at the start of the operation. Nitrogen and gas were shut off when the reactor reached a steady state temperature. As noted in Table 1, the MC of the biomass input was about 9%. The torrefaction unit included condensation and filtration, which were used to remove contaminants from the gases released during torrefaction (torgas), which can potentially damage combustion equipment when torgas is used (i.e., propane burner or

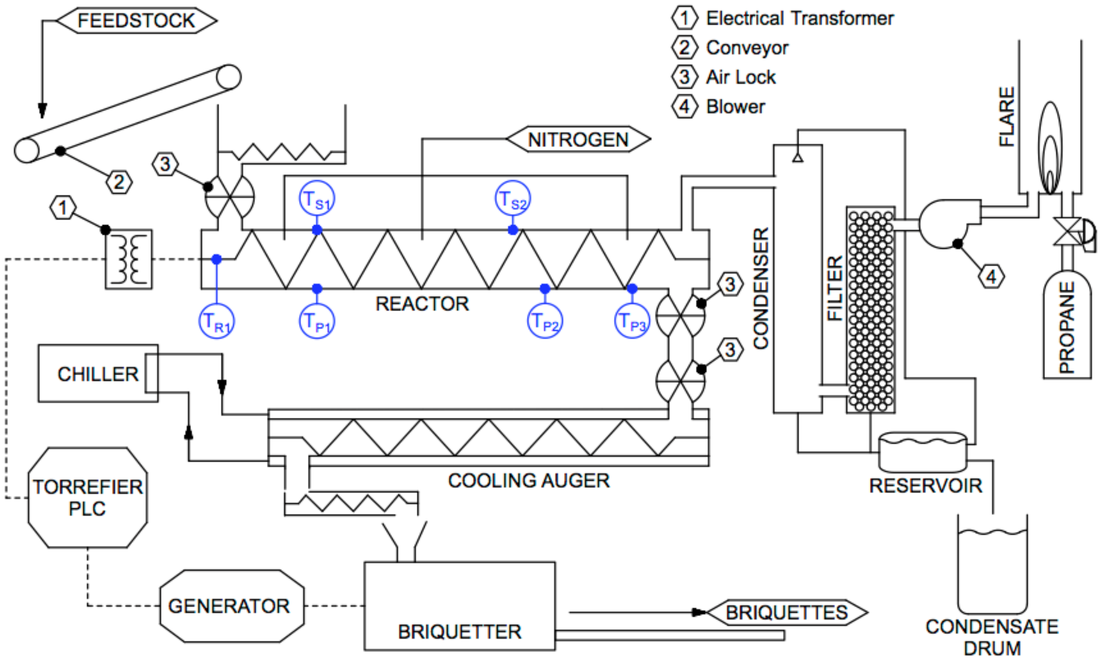

Figure 5. Biogreen torrefaction unit (Severy and others 2018).

Table 2—Properties of the torrefied briquette product

Property	Value
Moisture content (%) wb[a]	0.6
Ash content (%) db[b]	2.5
Volatile matter (%) db	71
Higher heating value (MJ/kg db)	23.0

[a]wb, wet basis.
[b]db, dry basis.

thermal oxidizer). The byproducts of condensation and filtration were condensate (bio-oil) and tar, respectively. The bio-oil generated was acidic (pH of about 2). It was neutralized using sodium hydroxide (NaOH) and disposed to a municipal sewage system. During the testing, the torgas generated at the torrefaction unit was flared. But, in the LCA analysis, torgas was assumed to be used to support dryer energy requirement. Because of the low energy content of the torgas, flaring was supplemented with propane fuel to initiate and maintain optimum combustion. In the LCA analysis, various scenarios were investigated to evaluate the environmental burden resulting from different applications. Use of torgas for thermal energy generation was one of the scenarios investigated. In this specific scenario, torgas was assumed to be combusted as a substitute for propane where its exhaust (flue) gases supplied heat for the dryer.

The characteristics of the TOB fuel after biomass conversion are provided in Table 2.

Densification

Torrefied wood was densified into briquettes using a RUF lignum model briquetter (RUF Briquetting Systems, Zaisertshofen, Germany) (RUF Briquetting Systems 2016). The briquetter used hydraulic cylinders, which consumed electricity, for compressing the feedstock (Fig. 6). The torrefied wood chips were fed into a hopper, then transferred to a pressing chamber via a screw conveyor. Finally, the compressed torrefied 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 process to improve binding characteristics. For the system under investigation, no binder was used.

Transportation

Transportation including that for raw materials and the final product (distribution) was considered in this study. Average transport distance traveled from the primary landing to the BCT site for the five regions investigated was 18.8 km (Oneil and others 2017). The transportation of TOB to end user for residential heating was included in the inventory. It was assumed that the briquettes were transported to the closest town for use and that tractor trailers fueled by diesel were used for transportation. As part of this study, transportation sensitivity analysis was conducted and results are shown in a later section. In addition, transportation of other materials from manufacturers to the BCT site were considered in this study.

Combustion

Use-phase data comes 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 freestanding

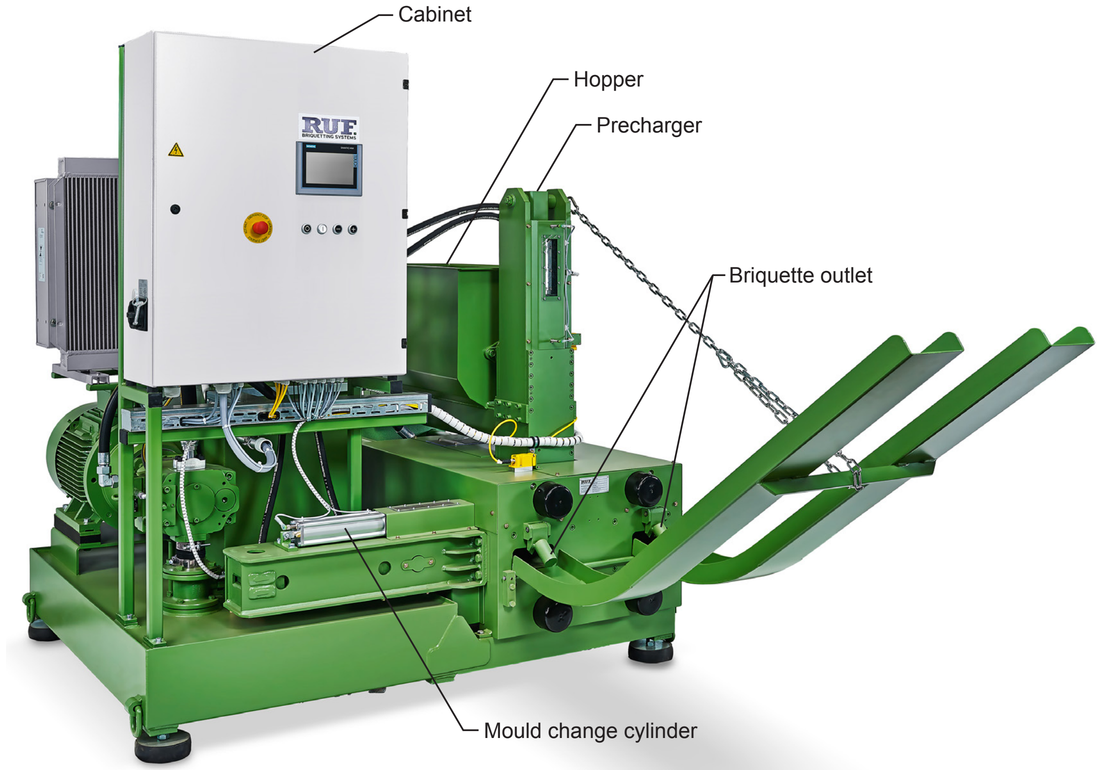

Figure 6. RUF briquetter machine (photo used with permission from RUF Briquetting Systems, Zaisertshofen, Germany).

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, near-woods operation with wood gasifier power with pile and burn credit

non-EPA-certified wood stove (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

Alternative system configurations were investigated at the cradle-to-grave level for evaluating the effect on various changes in the supply chain (Table 3). The torrefaction unit was designed to be a semimobile unit to perform near-woods operations, allowing biomass conversion to occur close to the source and allowing the unit to be transported between forest operation sites. This allows processing of the low-density forest residues closer to the primary landing before the high-density bioenergy product is shipped to the user. Near-woods processing required remote power generation because the selected BCT site had no access to grid electricity. Two remote power generation technologies were taken into account: a woody biomass gasification genset and a diesel generator. Using the same feedstock to produce the torrefied wood briquettes, the Power Pallet-PP20 biomass gasifier (All Power Labs, Berkeley, California, USA) (All Power Labs 2016) with an engine generator rated at 20 kWe was tested for remote power generation. The woody biomass gasifier genset was selected as the base case with a diesel power generator as the alternative scenario to investigate the effect of the power source used on the environmental impact results. Diesel was supplied by an on-site fuel tank to run the diesel generator. In addition, the impact of logistics on the results were evaluated with a scenario that considered transferring forest residues to an in-town facility where grid electricity was used for biomass conversion as opposed to the on-site operation. 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 as a result of 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 in which two or more functions are delivered. The major product of the system under investigation was TOB, whereas torgas was the coproduct. Energy allocation was used for accounting for the burden between the torgas and torrefied chips. Mass allocation was used in the propane system model.

Assumptions and Limitations

Volatile organic compound (VOC) emissions, which occur during drying of the fresh biomass feedstock, were taken into account. Because the biomass was field-dried and the MC was around 20% on a wet basis when received at the dryer unit, it was assumed that 20% of the VOC was emitted during the dryer and the rest, 80%, was emitted at the forest. Because exact emission VOC data from tanoak were not available, white oak was used as a proxy (Beakler and others 2007).

Torrefaction is an emerging technology. Because of insufficient information on this technology, the manufacturing, maintenance, and disposal of equipment used in the system were considered outside the scope of the LCA. For consistency, the propane production system excluded these elements as well.

At the use phase, propane and torgas were assumed to be combusted with 95% combustion efficiency (McNamee and others 2016). In addition, data on heat requirements at 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). All mass and energy flows were accounted for in this study without applying cutoff criteria. Mass loss at the densification process was negligible. Therefore, it was assumed that there was no mass loss at the briquetter.

EPA released a second draft of *Framework for Assessing Biogenic CO_2 Emissions from Stationary Sources* that provides an analytical methodology on the 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, 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.

For propane combustion data, a literature source (Johnson 2012) was used instead of DATASMART, which is based on the U.S. LCI Database, because the literature source compared data from different databases and sources, evaluated the data, and provided an integrated dataset based on the most reliable data available.

Life-Cycle Impact Assessment Methodology and Types of Impacts

For the life-cycle impact assessment (LCIA), the impact categories examined in this study include global warming (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). Among the available methods for the LCIA, the TRACI method was used in this study (Bare 2011, USEPA 2012). The system was modeled using the SimaPro 8.5 LCA software package (PRé Consultants 2017). TRACI is a midpoint-level impact assessment model developed by EPA and is representative for the United States with input parameters consistent with U.S. conditions. All impact categories covered in the TRACI method were considered in this study. 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, but they require more research to establish since site-specific data are required because of the unique properties of location, meteorology, and existing ecosystems (USEPA 2012). Thus, 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 waste. As mentioned, forest residues are commonly left on the forest floor to decay or cleared using pile-and-burn methods. For this reason, we didn't consider the growth of the tree that generates the forest residues within the system boundaries. Consequently, the authors did not evaluate the land use impacts.

Data Quality

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

Geographical and Time-Related Coverage

Quantitative data on mass and energy flows of the demonstration-scale torrefaction system and forest operations were based on the operational data of core processes for the years 2015 and 2016. The torrefaction unit was located and operated in northern California. The field data on the feedstock procurement stage were 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 using underlying Ecoinvent v.2.2 datasets (LTS 2017, PRé Consultants 2017, NREL 2012). The U.S. LCI database is based on regional conditions and represents U.S. circumstances.

Precision

No variance can be calculated because this study was based on a single dataset not on an industry level. However, process-specific data were collected and analyzed 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 TOB production 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 torrefaction technology used here is current and representative technology and creates a product that is comparable with other products in the market. The internal process of torrefying feedstock can be different depending on the technology used, but the final product is similar. Torrefaction is a thermochemical process that occurs in the following temperatures: 200 to 300 °C for increased energy density and decreased volatile matter and MC of the product.

Reproducibility

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

Data Sources

Feedstock procurement data were obtained from Oneil and others (2017). The data came from five commercial harvesting sites located in the western United States: Port Angeles, Washington; Warm Springs, Oregon; Oakridge, Oregon; Lakeview, Oregon; and Quincy, California. Average transport distance traveled from the primary landing to the BCT site and BCT site to the closest town was based on the data derived from the operations in the five regions investigated. Feedstock preparation data were based on field data and experimental studies performed as a part of the WTW project in 2015 (Bisson and Han 2016, Kizha and Han 2016, Kizha and others 2018).

The primary data for the torrefaction processes rely on the operational runs of the demonstration-scale torrefaction unit. A semimobile electrically heated screw-type demonstration-scale torrefaction unit with 0.5 metric tons wood chips per hour processing capacity was used. All relevant quantitative data (input–output flows) associated with the unit processes were collected from the production site. These include data for the dryer, torrefaction, densification processes, and woody biomass gasification genset. The data included input–output mass and energy flows, air emissions resulting from the torrefaction process, physical properties of the feedstock received by the systems, and characteristics of the final product, i.e., torrefied briquettes. Secondary data such as supply of electricity, manufacturing of the chemicals, transport, and waste disposal came from the 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 (Vancouver, British Columbia, Canada), and Shaobo Liang, PhD, Postdoctoral Research Fellow, USDA Forest Service, Forest Products Laboratory.

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

Value Choices

In this study, 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. 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. The endpoint-level impact assessment analysis aggregates midpoint impacts under the three areas of protection: natural environment, human health, and natural resources. Endpoint analysis allows the results to be presented using a single score result, which allows easier interpretation and communication of LCA results with nonLCA experts and comparison of the environmental impact of different products or scenarios. The optional weighting step based on value choices allows for obtaining a single score result of LCA analysis, yet it introduces more assumptions to the analysis, leading to greater uncertainties.

Life-Cycle Inventory Analysis

Cradle-to-grave system boundary of the TOB supply chain included feedstock procurement (processing, sorting, and loading), hauling, feedstock preparation (chipping, screening, and drying), biomass conversion (torrefaction and densification), transportation (distribution), and the use phase (combustion at domestic wood stoves). Biomass procurement and preparation 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 TOB 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 for the propane system began at the extraction of crude oil and ended at the useful heat produced at the residential furnace for domestic heating. The propane product system included four major life-cycle stages: crude oil extraction, propane production, distribution, and use phase. Crude oil extraction, propane production, and distribution data came from the DATASMART database for which combustion data were retrieved from literature. Johnson (2012) evaluated the existing data sources for residential heating systems that use propane and generated an integrated data set for propane combustion emission factors (Table 4).

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

The cradle-to-grave LCI for the torrefaction system was developed using all the primary data related to the inputs and outputs of the processes included in the system boundary. Data were obtained by on-site measurements at the torrefaction plant near-woods field experiments. LCI for different life-cycle stages are provided in the following section.

Table 4—Propane combustion emission factors (Johnson 2012)

Emissions[a]	Value (mg/MJ)
CH_4	1.03
CO	8.86
CO_2, fossil	63,111
N_2O	0.11
NO_x	47.00
PM_{10}	0.33
SO_2	0.19
NMVOC	1.72

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

Feedstock Procurement

Table 5 shows the cradle-to-gate input and output flows for feedstock procurement including processing (delimbing), sorting, and loading along with hauling for one bone-dry metric ton (BDT) of wood chips. The feedstock procurement stage along with hauling the forest residue were adopted from the forest operations model developed by Oneil and others (2017). The Oneil and others (2017) model was based on the operational data generated in 2015 (Bisson and Han 2016, Kizha and Han 2016, Kizha and others 2018).

Feedstock Preparation

Gate-to-gate input and output flows of feedstock preparation including chipping, screening, and drying are provided in Table 6. Screening and chipping data were adopted from the forest operations model developed by Oneil and others (2017) and were modeled based on the operational data generated in 2015 (Bisson and Han 2016, Kizha and Han 2016, Kizha and others 2018).

Thermal energy required for drying the input biomass was provided from torgas, which was supplemented by propane fuel for ignition and continuous combustion. About 31% of the torgas generated at the torrefaction unit was directed to the dryer as heat supply. Electricity consumption in the dryer process occurred from the belt conveyor (Beltomatic, Norris Thermal Technologies). The drying process was modeled based on the operational data generated in 2015.

Although the feedstock was left in the forest and field-dried to 20±3% MC, feedstock was force-dried using torgas and propane before torrefaction to achieve the desired product quality. A value below 25% MC was suggested by the manufacturer for desired product quality. However, average feedstock MC after the drying process was about 9.3%, which provided an optimum product (Severy and others 2018). Process data for heat consumed in the drying process were not available. Therefore, heat requirements of the drying process were assumed to be 5 MJ/kg water removed (Adams and others 2015). Torrefaction gases (torgas) were assumed to be combusted to provide heat for the dryer and were also assumed to have 95% combustion efficiency (McNamee and others 2016). Heating content of torgas after the condensation stage was about 3.7±0.03 kJ/L, and its combustion was supplemented by propane to start ignition and maintain effective combustion.

Drying wood results in VOC emissions, which was accounted for in the analysis. Assuming freshly cut wood, this analysis conservatively tracked any VOCs emitted during field-drying of the forest residues as well as

Table 5—Cradle-to-gate input–output flow analysis for procuring material for one bone-dry metric ton of wood chips

Category	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	g	8.54	Alanya-Rosenbaum and others 2018
Hauling			
Transportation	km	18.77	Oneil and others 2017

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

Category	Unit	Value	Source
Feedstock procurement			
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	Wh	7.14	Alanya-Rosenbaum and others 2018
Propane	L	20.9	Engineering calculations
Volatile organic compounds	g	2.13	Alanya-Rosenbaum and others 2018
Torgas	m^3	212	Process data
Waste heat	MJ	391	Engineering calculations

during the forced-drying. It would be expected that VOCs emitted during field-drying, because they occur at lower concentrations and for 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 Milota (2013), emission levels mainly depend on the species and are higher for drying fresh woody biomass compared with drying aged material. Milota (2013) 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 forced-drying, whereas the rest (80%) were emitted in the forest during field-drying.

Biomass Conversion and Use Phases

The material and energy inputs and outputs for TOB production and use phases are provided in Table 7. The data were provided for biomass conversion processes: torrefaction and briquetting (densification), along with the use phase. Use-phase data, including stack emissions from burning TOB that were obtained from the WTW project combustion tests and data, were complemented by literature data. Overall, efficiency of burning TOB in the wood stove was 76%. It was assumed that the briquettes were stored and sold in 15-kg-capacity plastic bags made from low-density polyethylene (LDPE) (Laschi and others 2016).

Table 7—Input–output flows of torrefied briquette (TOB) production and use[a]

Category	Unit	Value	Source
Torrefaction			
Inputs			
Dry wood chip	kg db/MJ torrefied chips	0.063	Operational data
Lubricants	mL/MJ torrefied chips	0.002	Operational data
Electricity	kWh/MJ torrefied chips	0.019	Operational data
NaOH	g/MJ torrefied chips	0.667	Operational data
Outputs			
Bio-oil	L/MJ torrefied chips	0.011	Operational data
Torgas	m^3/MJ torrefied chips	0.043	Operational data
Briquetter			
Electricity	kWh/MJ TOB	0.0037	Operational data
Lubricants	mL/MJ TOB	0.00019	Operational data
Packaging			
LDPE packaging	g/BDT	0.632	Laschi and others 2016
Distribution			
Distribution	km	90.200	Oneil and others 2017
Combustion (use phase)			
CO_2 (biogenic)	g/MJ TOB	76.873	Operational data
CH_4	g/MJ TOB	0.002	Khalil and others 2013
NO_x	g/MJ TOB	0.028	Operational data
CO	g/MJ TOB	3.476	Operational data
VOC	g/MJ TOB	0.730	Operational data
SO_2	g/MJ TOB	0.008	Khalil and others 2013
$PM_{2.5}$	g/MJ TOB	0.014	Operational data
PM_{10}	g/MJ TOB	0.104	Operational data

[a]LDPE, low-density polyethylene; BDT, bone-dry ton; VOC, volatile organic compounds; PM, particulate matter.

Table 8 presents the concentration of compounds in the flue gas generated as a result of torgas combustion. Torgas combustion was supplemented by propane to start ignition and maintain combustion.

Life-Cycle Inventory Analysis

The results of the LCI analysis per 1 MJ of thermal energy generated for domestic heating from combusting TOB are presented in Tables 9 and 10. Total primary energy used to produce 1 MJ of heat from TOB at a domestic wood stove was 1.34 MJ (Table 9). The majority of the overall primary energy consumption was from wood fuel with about 82.7% contribution. This was caused by high electricity consumption in the torrefaction process, 75.2% contribution, in which the power source used was a wood gasifier genset. Contribution of other renewable energy sources to total primary energy was minor. Most of the fossil energy was derived from propane and diesel consumption during torgas combustion and transportation, respectively, which was captured as crude oil as the primary energy source before conversion (Table 10). Nonrenewable material resource use was minor (less than about 10^{-6} MJ).

Table 8—Flue gas composition of torgas combustion

Category	Unit	Value	Source
Inputs			
Torgas	L	1	Operational data
Propane	L	9.9E–05	Operational data
Outputs			
CO_2 (biogenic)	mg	1,654	Operational data/ engineering calculations
CH_4	mg	0.0836	Operational data/ engineering calculations
C_2H_6	mg	0.0412	Operational data/ engineering calculations
C_3H_8	mg	0.0282	Operational data/ engineering calculations
NO_x	mg	0.0503	Nanou and others 2016

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

		Primary energy consumption (MJ/MJ heat)							
Fuel	Percentage	Total	Feedstock procurement	Feedstock preparation	Torrefaction	Densification	Transportation	Use phase (combustion)	Packaging
Renewable fuel use									
Wood fuel	82.7	1.11E+00	0.00E+00	6.36E–02	8.67E–01	1.76E–01	0.00E+00	0.00E+00	0.00E+00
Nonrenewable fuel use									
Gas, natural, in ground	1.4	1.84E–02	4.54E–04	3.53E–03	1.39E–02	1.25E–04	3.84E–04	0.00E+00	2.28E–06
Coal, in ground	1.0	1.31E–02	3.01E–04	2.38E–03	1.01E–02	8.19E–05	2.56E–04	0.00E+00	9.86E–08
Oil, crude, in ground	14.6	1.95E–01	9.27E–03	6.38E–02	1.11E–01	2.52E–03	7.88E–03	0.00E+00	4.98E–07
Uranium	0.3	3.75E–03	9.30E–05	7.22E–04	2.83E–03	2.53E–05	7.90E–05	0.00E+00	3.05E–08
Renewable energy sources									
Hydro	<1.0	4.87E–04	1.21E–05	9.38E–05	3.67E–04	3.28E–06	1.03E–05	0.00E+00	3.96E–09
Wind	<1.0	1.89E–04	4.69E–06	3.64E–05	1.43E–04	1.27E–06	3.98E–06	0.00E+00	1.54E–09
Solar	<1.0	2.89E–06	7.05E–08	5.50E–07	2.19E–06	1.92E–08	5.99E–08	0.00E+00	2.47E–11
Geothermal	<1.0	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Total	100.0	1.34E+00	1.01E–02	1.34E–01	1.01E+00	1.79E–01	8.61E–03	0.00E+00	2.91E–06
Total, by percentage		100	0.8	10.0	75.2	13.4	0.6	0.0	0.0

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

Resources and waste	Unit	Total	Feedstock procurement	Feedstock preparation	Torrefaction	Densification	Transportation	Use phase (combustion)	Packaging
Total primary energy consumption	MJ	1.34E+00	1.01E–02	1.34E–01	1.01E+00	1.79E–01	8.61E–03	0.00E+00	2.91E–06
Nonrenewable fossil	MJ	2.26E–01	1.00E–02	6.97E–02	1.35E–01	2.73E–03	8.52E–03	0.00E+00	2.88E–06
Nonrenewable nuclear	MJ	3.75E–03	9.30E–05	7.22E–04	2.83E–03	2.53E–05	7.90E–05	0.00E+00	3.05E–08
Renewable (solar, wind, hydroelectric, and geothermal)	MJ	6.79E–04	1.68E–05	1.31E–04	5.12E–04	4.58E–06	1.43E–05	0.00E+00	5.52E–09
Renewable (biomass)	MJ	1.11E+00	0.00E+00	6.36E–02	8.67E–01	1.76E–01	0.00E+00	0.00E+00	0.00E+00
Material resources consumption (nonfuel resources)									
Renewable materials	kg	1.16E–01	1.03E–01	7.61E–04	1.04E–02	2.10E–03	1.32E–07	0.00E+00	0.00E+00
Fresh water	L	3.01E–03	7.42E–05	5.77E–04	2.28E–03	2.01E–05	6.30E–05	0.00E+00	0.00E+00
Waste generated									
Solid waste	kg	3.60E–08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.60E–08

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

		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 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

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 TRACI v2.1 are documented in this section. The cradle-to-grave assessment analyzed environmental impacts associated with TOB production supply chain and compared with a fossil fuel alternative (i.e., propane). In addition, the effects of alternative scenarios with different power sources, logistics, and feedstock properties on the impact results were evaluated.

Cradle-to-Grave Life-Cycle Assessment Results of Torrefied Briquette Supply Chain

The environmental impact assessment results associated with generating heat from wood briquettes at 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 here are for the same conditions in which the demonstration-scale system was operated near the woods and torrefaction and briquetting occurred at the BCT site close to the feedstock source and was powered using a wood gasifier genset as the base scenario. The drying process was heated by a portion of the torgas combustion (31%). The remaining torgas was flared at the torrefaction unit. Propane was used to achieve ignition and complete combustion of torgas, which caused the torrefaction process to have the highest impacts for the categories of OD, GW, eutrophication, carcinogenics, noncarcinogenics, ecotoxicity, and fossil fuel depletion.

Process contributions to the overall GW impact for the TOB supply chain are presented in Figure 7. Contribution analysis revealed that a large portion of the GW impact resulted from torrefaction and drying processes with 59% and 24% contributions, respectively. As expected, the high contribution of these processes resulted from propane use. In the base scenario, torgas was used to provide heat to the drying process. Yet, because of the low energy content of torgas, combustion was supplemented with propane for ignition and steady burn.

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

The GW impact results per megajoule of heat generated through various scenarios was compared. These scenarios included propane furnace, Scenario 0 (S0), and propane system supplemented with TOB at two different percentages. Scenario 1 (S1) is presented in Figure 8. Comparative data showed that 50% and 80% substitution of propane with torrefied wood briquettes resulted in 41% and 66% reduction in GW impact, respectively.

Alternative System Configurations Life-Cycle Assessment

Results of the comparative analysis of alternative scenarios investigated for GW impact are provided in Figure 9. Total GW impact of producing 1 MJ of heat from TOB combustion at a wood stove was nearly 17 g CO_2 eq. for the base scenario (S1). Analysis showed that near-woods operation using diesel power as the remote (off-grid) power generation source was the least favorable alternative scenario (S2). Using a diesel generator instead of a wood gasifier genset for remote power generation resulted in 308% higher GHG emissions. Similarly, biomass conversion of forest residues close to the biomass source using gasifier genset instead of transporting the feedstock a 2-hour (S3) or 4-hour (S4) drive (maximum) to an in-town facility with access to grid electricity decreased the GW impact by 55% and 57%, respectively. High feedstock MC scenario resulted in a 55% increase in total GW impact (S5), because of increased propane consumption at the dryer process. Using feedstock with higher MC resulted in a 6% increase in GW impact of the hauling process. Higher propane consumption was caused by increased torgas use and additional propane requirements because of higher heat demand at the dryer. In S1, some portion of the torgas was used to generate heat for the dryer, whereas the remaining was flared at the torrefaction process. In S5, total torgas produced was used in the drying process instead of flaring at the torrefaction process. This shifted environmental burden from the torrefaction process to the feedstock preparation stage, mainly the drying process, because more torgas was used in the drying process and torgas combustion itself requires support by propane. Accounting for the benefits of heat generation through controlled burn compared with pile and burn (S6) resulted in a 19% decrease in resulting GW impact.

The effects of using different power sources, for meeting the electricity demand for the dryer, briquetter, and torrefaction processes, on the resulting environmental impact is presented in Figure 10. Comparative results are presented for OD, smog, acidification, eutrophication, and fossil fuel depletion impact assessment categories. The results of the analysis revealed that, at the cradle-to-grave level, using wood-gasifier-based power generation improved the environmental performance of the system compared with diesel electricity and grid electricity in all impact categories except smog. The difference was notable in the OD and eutrophication impact categories.

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

Impact category	Unit[a]	Feedstock procurement	Hauling	Chipping/ screening	Drying	Torrefaction	Briquetter	Distribution	Combustion	Packaging
Ozone depletion	kg CFC-11 eq	1.26E–12	2.51E–13	1.83E–12	1.31E–11	1.46E–10	3.42E–13	8.17E–13	0.00E+00	8.02E–16
Global warming	kg CO_2 eq	6.89E–04	2.26E–04	1.00E–03	4.02E–03	9.82E–03	1.96E–04	4.89E–04	7.57E–05	8.02E–08
Smog	kg O_3 eq	2.98E–04	3.64E–05	4.29E–04	3.24E–04	1.46E–03	1.99E–04	7.80E–05	4.61E–03	2.31E–09
Acidification	kg SO_2 eq	9.07E–06	1.20E–06	1.32E–05	1.33E–05	5.87E–05	7.18E–06	2.70E–06	3.59E–05	1.69E–10
Eutrophication	kg N eq	6.97E–07	9.90E–08	1.01E–06	1.62E–06	6.85E–06	4.30E–07	2.51E–07	1.61E–06	5.72E–10
Carcinogenics	CTUh	1.15E–11	2.28E–12	1.67E–11	6.31E–11	1.63E–10	3.11E–12	7.41E–12	0.00E+00	1.05E–15
Noncarcinogenics	CTUh	1.13E–10	2.25E–11	1.64E–10	6.27E–10	1.70E–09	3.06E–11	7.31E–11	0.00E+00	2.86E–14
Respiratory effects	kg $PM_{2.5}$ eq	1.79E–07	1.84E–08	2.61E–07	2.70E–07	1.63E–06	2.18E–07	4.17E–08	2.13E–05	6.81E–12
Ecotoxicity	CTUe	2.88E–03	5.77E–04	4.20E–03	1.58E–02	3.72E–02	7.83E–04	1.88E–03	0.00E+00	3.34E–06
Fossil fuel depletion	MJ surplus	1.33E–03	2.66E–04	1.94E–03	7.28E–03	1.72E–02	3.61E–04	8.65E–04	0.00E+00	3.76E–07

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

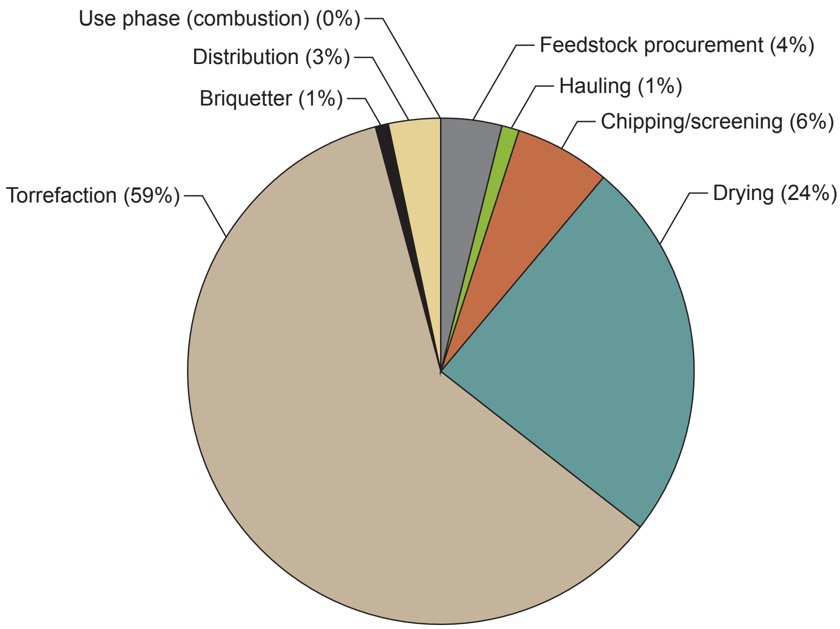

Figure 7. Contribution of processes to the overall global warming impact of the torrefied briquette production system.

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.

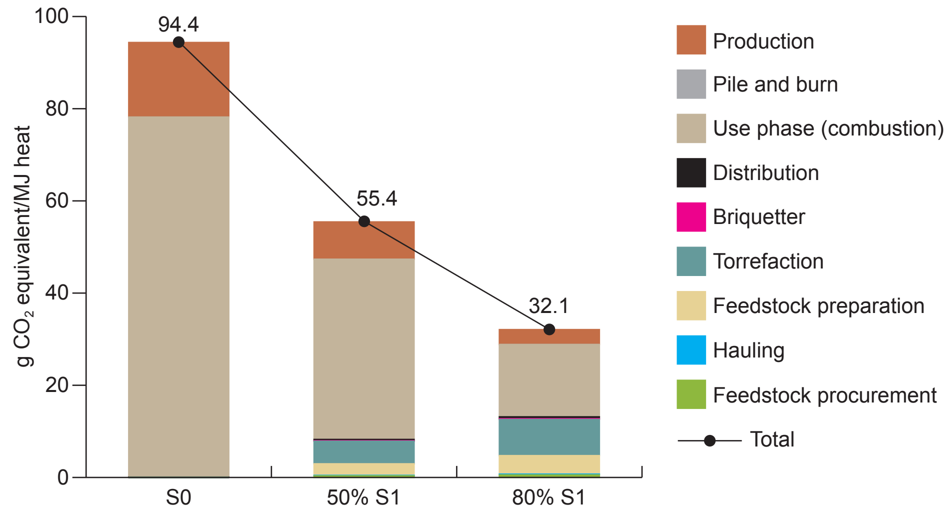

Figure 8. Comparison of the global warming impact results per megajoule of heat generated through a propane furnace, Scenario 0 (S0), and a propane system supplemented with torrefied briquettes (50% and 80%), Scenario 1 (S1).

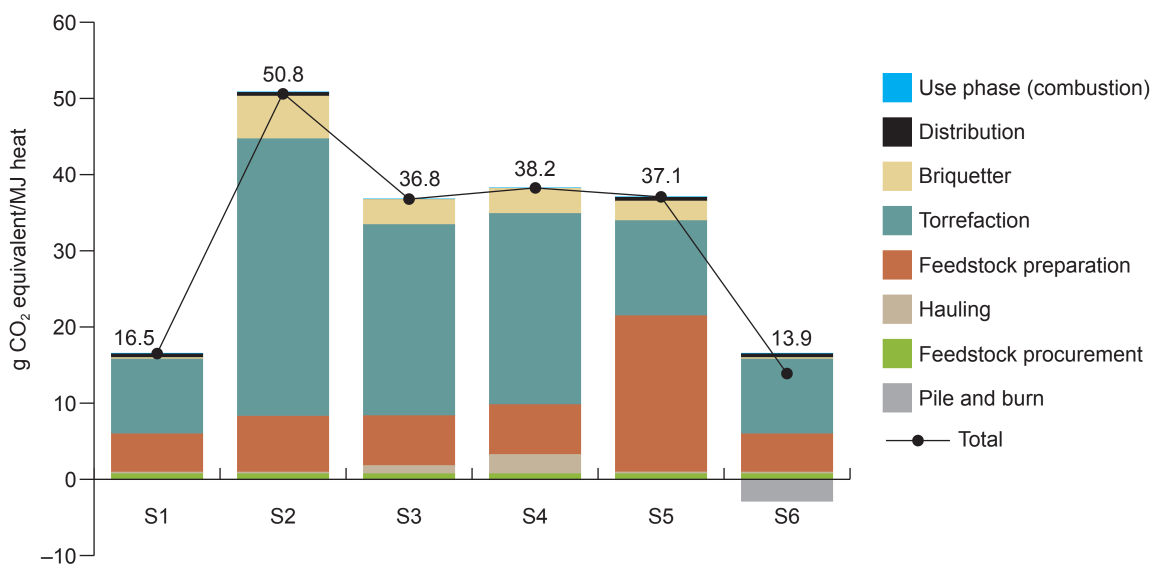

Figure 9. Contribution of processes to overall global warming impact per megajoule of thermal energy generated for six scenarios investigated. S1: 1 MJ heat, near-woods operation with wood gasifier power; S2: 1 MJ heat, near-woods operation with diesel power; S3: 1 MJ heat, in-town operation (2-h travel distance) with grid power; S4: 1 MJ heat, in-town operation (4-h travel distance) with grid power; S5: 1 MJ heat, 50% moisture content feedstock, near-woods operation with wood gasifier power; S6: 1 MJ heat, near-woods operation with wood gasifier power with pile-and-burn credit.

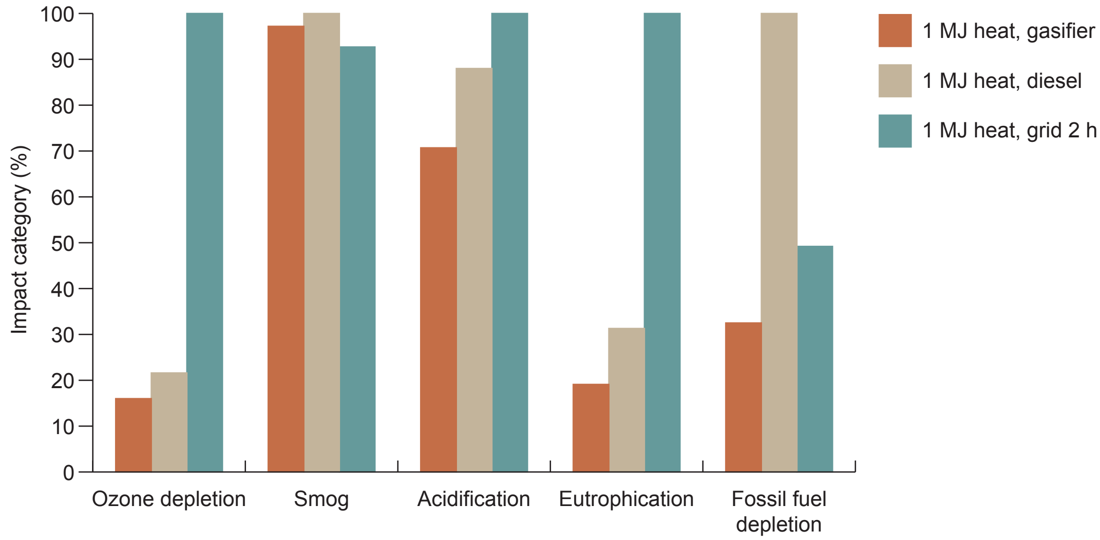

Figure 10. Summary of comparative life-cycle impact assessment results for three power sources (grid, diesel, and gasifier electricity) for the torrefied briquette production system.

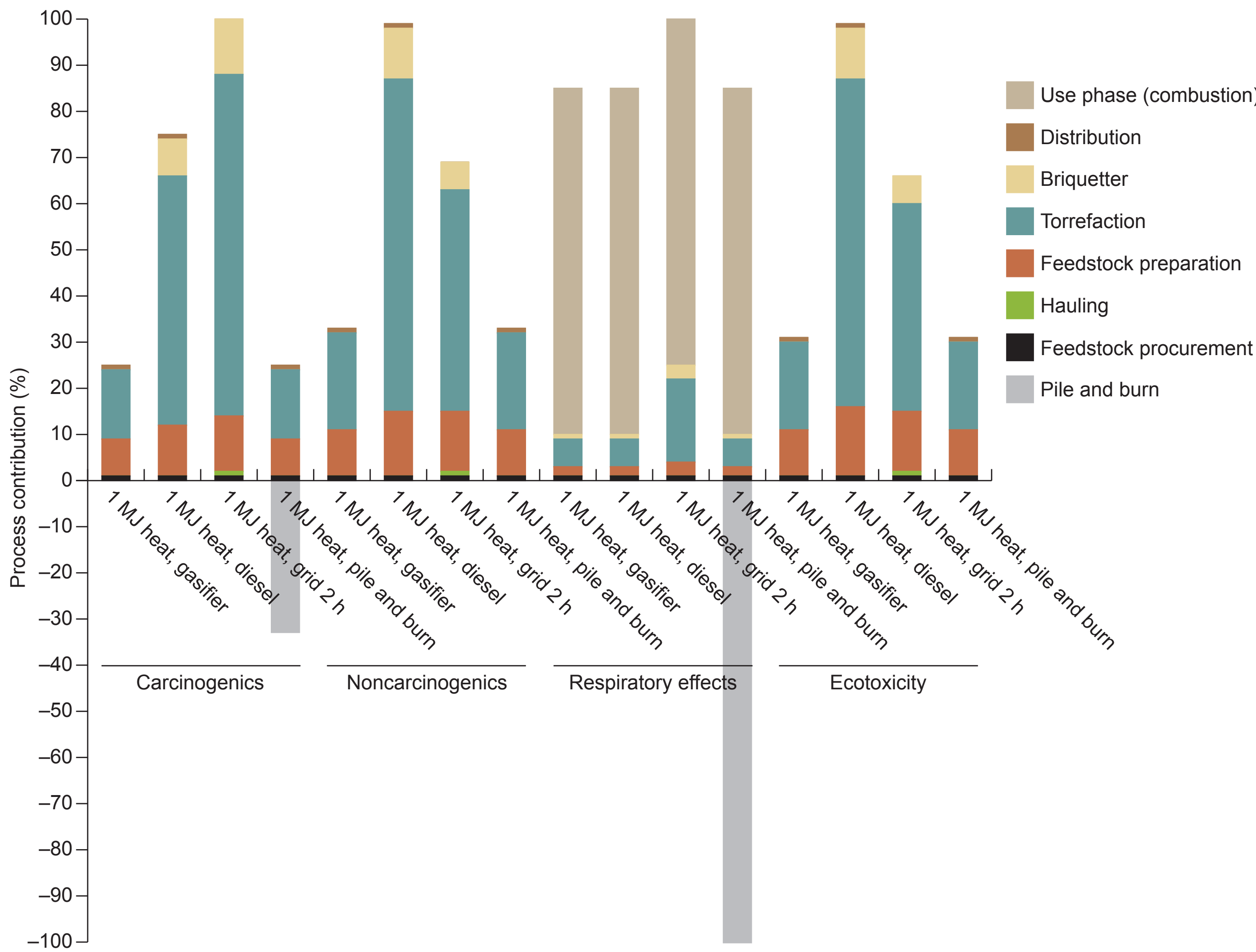

Figure 11. The toxicity impact category results for generating 1 MJ of thermal output for the scenarios investigated.

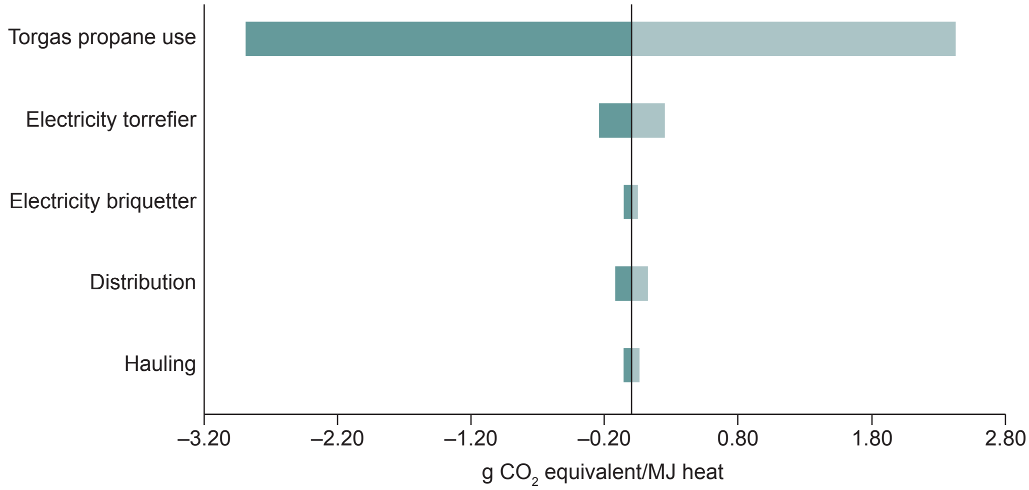

Figure 12. Sensitivity of key parameters on global warming impact.

Figure 11 presents the toxicity impact category results: human health (carcinogenics and noncarcinogenics), respiratory effects, and ecotoxicity. Using a wood gasifier as the power source for near-woods operation showed better performance compared with diesel and grid electricity alternatives for toxicity impact categories. Pile-and-burn credits resulted in substantial benefits particularly in human health impact categories. Environmental benefits of the avoided pile-and-burn emissions were notable in the respiratory effects impact category, mainly because of avoided particulate matter emissions.

Life-Cycle Interpretation

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

Completeness, Sensitivity, and Consistency Checks

Results of the parameter-based sensitivity analysis are presented in Figure 12. The sensitivity of the GW impact was examined for 25% variation in key parameters including briquetter and torrefier electricity demand, distribution and hauling distances, and propane supplement used for torgas combustion. The sensitivity analysis performed showed that propane supplement was a key parameter with great influence on variation in the GW impact, followed by electricity consumption of the torrefaction process. This reveals the importance of dryer heat requirement and energy consumption data to decrease the uncertainty resulting from parameters used.

Conclusions, Limitations, and Recommendations

This study provides a comprehensive cradle-to-grave LCA of the TOB production supply chain investigating the environmental performance of using post-harvest forest residues with torrefaction and briquetting processes for biofuel production. Using torrefied briquettes for energy production instead of fossil fuel alternatives was revealed to be preferable for GHG emission reduction. Major benefits were observed consistent with recent studies investigating the use of torrefied wood as a substitute for natural gas for heat production and coal for electricity production (Majer and others 2015).

Near-woods bioenergy production systems using power from an on-site wood gasifier genset showed better environmental performance than did the fossil fuel alternatives (on-site diesel and in-town grid electricity). For remote power generation, GHG emissions were about three times lower when a woody biomass gasifier genset was substituted for a diesel generator. In-town operation with grid electricity supply was a better option compared with remote operation using a diesel generator. Use of post-harvest residues as biofuel as opposed to the typical pile-and-burn practice showed a notable environmental advantage in GW and toxicity impact categories. Data on heat requirements at 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.

Results indicated that GW impact was highly dependent on torgas management in the torrefaction process and on heat demand in the drying processes. This was mainly because of the low energy content of torgas, which required use of propane as a supplement for continuous combustion. Therefore, effective torgas management at torrefaction is crucial to decrease the GW impact of the TOB supply chain. This may include burning torgas without separating bio-oil to improve the heating content of torgas. In addition, separating bio-oil brings additional environmental burden to the system because it is disposed to sewage systems and not beneficially used. In addition, recovery of torgas to supply heat demand of the torrefaction process instead of using electric heating may also improve the environmental performance. Use of high-efficiency dryer systems, using field-dried feedstock with lower MC, and efficient recovery of torgas are crucial.

External Review

The external review process is 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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