ENVIRONMENTAL IMPACTS OF TORREFIED BRIQUETTE PRODUCTION FROM FOREST RESIDUES USING LIFE-CYCLE ASSESSMENT

Waste to Wisdom: Subtask 4.7.2

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EXECUTIVE SUMMARY

The goal of this study was to assess environmental sustainability of the 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, Forest Products Laboratory (FPL) 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 four main life-cycle stages: feedstock procurement, feedstock preparation, biomass conversion (torrefaction and briquetting) and heat generation at a residential wood stove (use phase). Feedstock procurement stage included processing (delimbing), sorting, and loading. Feedstock preparation stage included processes used to achieve the feedstock specifications required for 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 (http://wastetowisdom.com/). These data include feedstock procurement and preparation processes, torrefaction, densification (briquetting) and biomass gasification generator set (genset). Biomass collection and feedstock preparation data were based on field-based data and experimental studies, during 2015, performed by Humboldt State University. This includes 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, CA in 2016.

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 8.4 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 operation of forest residues. Two remote power generation technologies were taken into account: a biomass gasification genset and 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-wood processing of forest residues was by using on-site biomass gasification generation set (gen-set) for power.

• Near-woods operation using woody biomass gasification gen-set to meet the electricity demand of torrefaction, briquetter and dryer processes instead of diesel generator or in-town operation using grid electricity showed major reductions in greenhouse gas emissions. Near-woods operation using diesel power was proved to be the least favorable alternative.

• When non-renewable power source options are compared, using diesel power had a worse environmental performance, even though longer hauling distance for in-town operation resulted in higher global warming impact from hauling process.

• Global Warming impact was highly dependent on drying process and torgas management at TOB production. For better environmental performance, it is recommended to use the following: high-efficiency drying systems, field-dried feedstock with low MC, and efficient recovery systems by displacing propane with torgas especially in the drying process.

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1 DEFINITION OF GOAL AND SCOPE

1.1 Study Goals

The goal of this study is to assess environmental sustainability of the processing of forest residues near the point of harvesting logs (i.e. near-woods) as a feedstock in torrefied briquette (TOB) production. To quantify the impact of the TOB supply chain on the environment and address environmental impacts associated with each processes involved, a cradle-to-grave life-cycle assessment (LCA) was performed. The study was conducted with funding support from the Biomass Research and Development Initiative (BRDI) grant, which is a collaborative initiative between the U.S. Department of Energy (DOE) and U.S. Department of Agriculture (USDA).

The evaluation was performed at plant and unit process level in accordance with ISO14040 and ISO14044 LCA standards (ISO, 2006a; ISO, 2006b). The main function of torrefaction process was to generate a solid bio-based fuel that can be an alternative to non-renewable fossil fuels. To evaluate environmental performance and obtain more insight into the environmental competitiveness of torrefied wood as a bio-based fuel substitute, a comparison was made with a residential heating system using propane.

1.1.1 Intended application

This study assessed and documented the environmental burden and benefits associated with the 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 et al., 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 torrefaction process at life-cycle level. Torrefaction allows production of a renewable and carbon-neutral solid biomass energy resource (Hektor et al., 2016; Miner et al., 2014). Hence, the assessment also includes comparison of the torrefied wood production against use of traditional fuel, i.e. propane, for domestic heating to evaluate its environmental performance against traditional fossil energy sources. The results of this study may promote the production of forest-based bioenergy using torrefaction process.

1.1.2 Motivation

Today, the radical increase in demand 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 (U.S.), about 93 million dry tonnes of forest removals are generated annually 73% of which is 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). The forest residues resulting from commercial logging operations, which are often left on-site to decay or be burned, can potentially be utilized by biomass conversion technologies to produce biofuels (USDOE, 2011; USEPA, 2007). Overstocked forests increase wildfire risk. Forest thinnings and removal of post-harvest forest residues may help mitigation of wildfires (USFS, 2003; Giuntoli, et al., 2015). By use of 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 is 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 aims to support the national policy on GHG emission reductions and promotes national energy security by investigating the viability of alternative renewable energy sources that may reduce dependence on fossil fuels.

1.1.3 Intended audience

The results of this study are intended to be used in comparative assertions and disclosed to the public. Thus, this LCA study will be subject to third-party critical review. Other intended audiences include researchers working on LCA analysis of biomass conversion studies focusing on forest residues. The results may also be interesting for professionals representing governmental interests in administrative functions 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 et al., 2010). The results fostering the removal of biomass for biofuel production may be of interest to forest land managers as this may assist them to overcome costs associated with biomass fuel treatment for reducing fire hazards.

The final Clean Power Plan rule released by United States Environmental Protection Agency (US EPA) requires approximately 32 percent reduction in electricity sector carbon emissions from CO_2 emission levels in 2005 by 2030 (Ohio EPA, 2017). Torrefied wood has compatible properties to coal and can replace coal in power plants.

This study presents an environmental evaluation of torrefied wood production in the U.S. as a low-carbon biofuel product with the potential to replace coal in power plants or propane in residential heating systems. Further, this study will be of interest to consumers that have environmental concerns regarding their residential heating systems.

1.2 The Scope of the Study

The scope of this LCA included cradle-to-grave stages of feedstock procurement and preparation, near-woods production of TOB from post-harvest forest residues and its combustion in a domestic wood stove for heat generation. The system boundaries covered the procurement, preparation, and biomass conversion of forest residues to TOB and ends at the grave, i.e. combustion in the wood stove for residential space heating. The life-cycle level impacts of TOB production was evaluated and compared to 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. LCA for propane was constructed from peer-reviewed literature and other secondary sources.

1.2.1 Functional unit

The functional unit (FU) in LCA analysis 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 functional unit in this study was defined as 1 MJ of useful thermal energy produced for residential heating.

The functional unit includes any efficiency loss to generate the 1 MJ and was based on the higher heating values (HHV). HHVs are used to convert volume or mass basis of a fuel to its energy value. HHVs represents the energy content of a fuel with the combustion products such as water vapor brought to 25ºC (77ºF) while the 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).

1.2.2 System boundary

This study evaluated two energy carriers, i.e., torrefied briquette 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 biofuel is used for energy production (Figure 1).

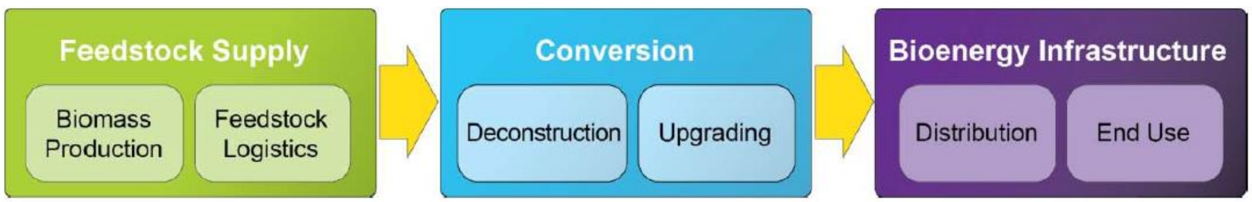

Figure 1 Biomass-to-bioenergy supply chain (USDOE, 2014)

The system boundary of the torrefaction system investigated is provided in Figure 2. The life cycle stages of a TOB production include feedstock procurement, feedstock preparation, biomass conversion, and use (combustion) phase. Feedstock preparation and biomass conversion processes occur at the BCT site. Disposal/beneficial use of the ash generated is left outside the scope of this study. In addition, disposal of ash would be hard to determine in rural areas as it is likely to be spread onto fields/woods. Due to insufficient 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 also in line with propane production system that excludes these elements.

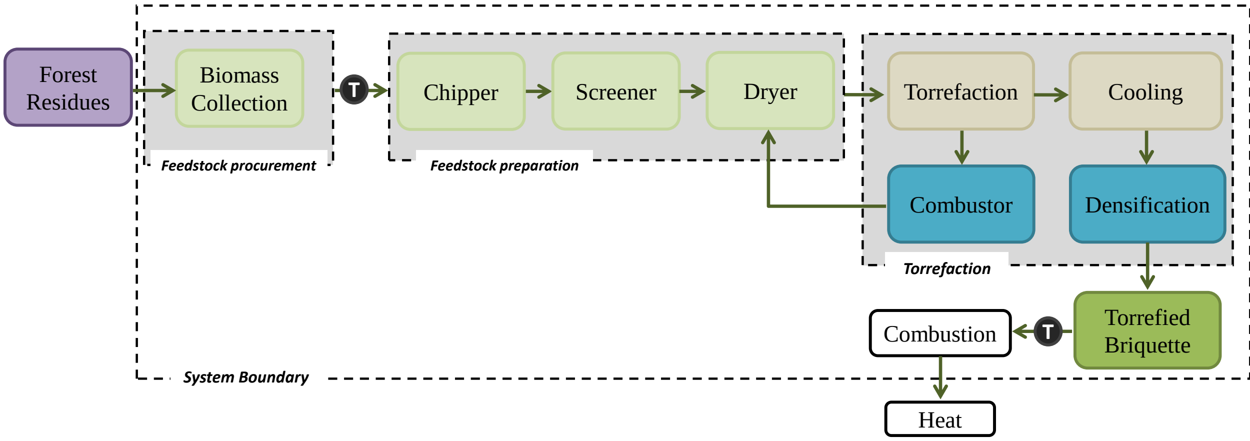

Figure 2 Cradle-to-grave system boundary for torrefied wood production supply chain

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 to be used for domestic heating.

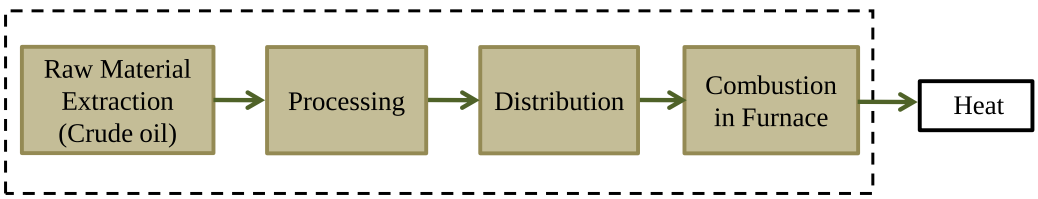

Figure 3 Cradle-to-grave system boundary for propane production supply chain

The torrefied briquette supply chain processes along with the inputs and emissions to and from the system is provided in Figure 4. Input biomass feedstock was post-harvest logging residues, which is a by-product of commercial harvesting operations. The field-dried feedstock was sourced from timber harvesting operations in the western U.S. from the following states: Washington, Oregon, and California.

The waste-to-wisdom (WTW) project (http://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). 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 processes. The unit processes of biomass conversion system included torrefaction, cooling, and densification. Briquetting process was used for densification where torrefied biomass was densified into briquettes. All electricity and heat necessary for the system was generated on-site using either a biomass gasification generator set (genset) or a diesel power generator. The system components are described in detail here.

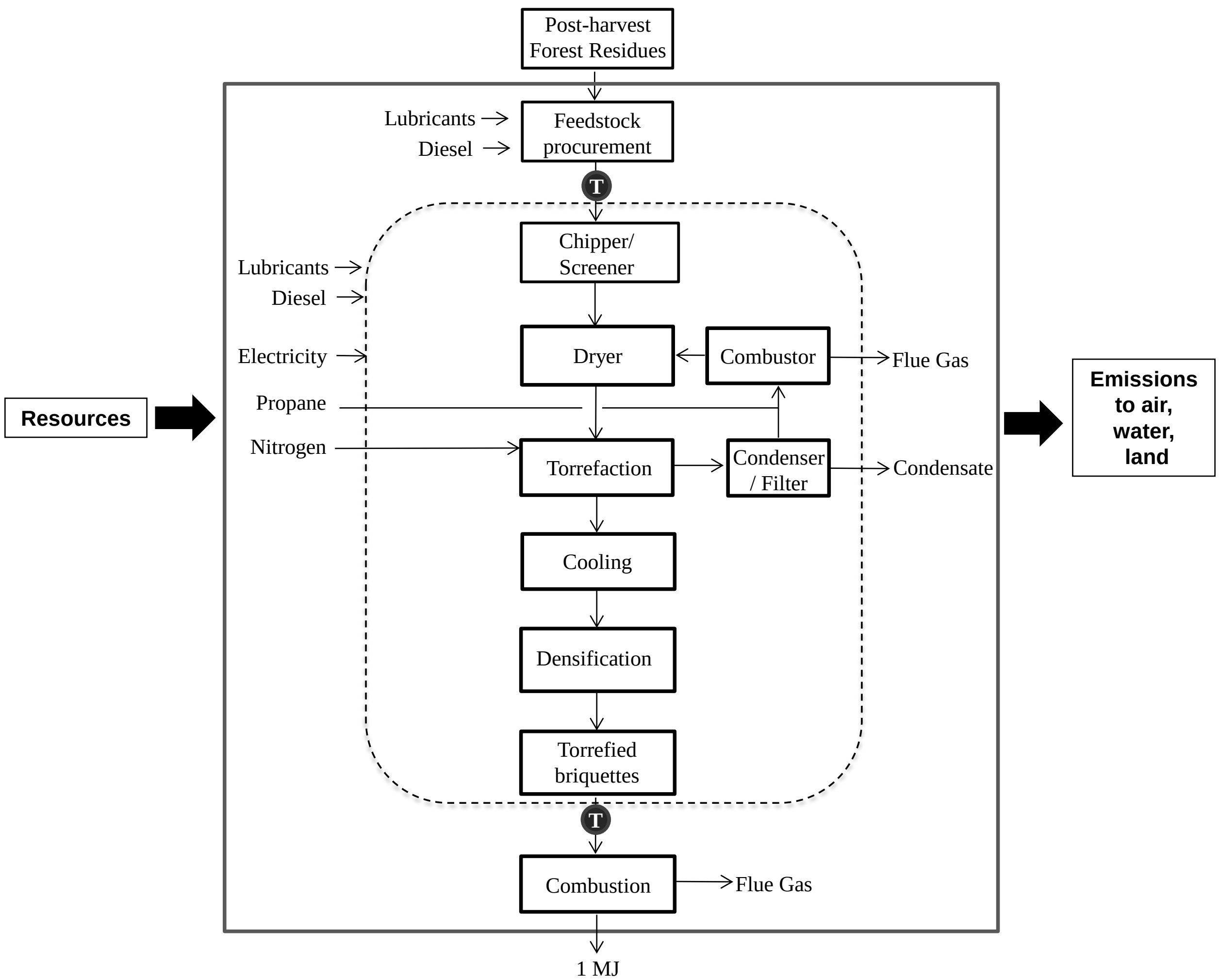

Figure 4 Cradle-to-grave process flow diagram of near-woods TOB production supply chain

1.2.2.1 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 a moisture content (wet basis) of 17-23% (Kizha et al., 2018). At feedstock procurement stage, this biomass feedstock was processed (delimbed) and sorted (Kizha and Han, 2016). In order 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. 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., near-woods biomass conversion technology (BCT) site). Primary data from five commercial harvesting sites in the western U.S. were used for modeling biomass procurement model: Port Angeles, WA; Warm Springs, OR; Oakridge, OR; Lakeview, OR; Quincy, CA. The average transport distance traveled from the primary landing to the BCT site for the five regions investigated was nearly 18.8 km (Oneil et al. 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 et al. 2017).

1.2.2.2 Feedstock Preparation

Feedstock preparation included chipping, screening and drying of the feedstock in order to achieve the specifications required for feedstock that can be torrefied and briquetted into bioenergy products. The lubricant consumption data for chipping equipment that consisted of hydraulic oils, general lubricants, and fuel consumption of chipper and screener were based on tests performed by Humboldt State University (HSU). These were generated as a part of the WTW project (Oneil 2017, Han Sup Han and Joel Bisson, personal communication, May 2016). Details of forest operations model and the equipment used for feedstock preparation are provided in Oneil et al. (2017).

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

Table 1 Properties of feedstock before torrefaction

Property	**Value**
Moisture Content, %, wb[a]	9.34%
Ash Content, (%) db[b]	3.4%
VM[c], %, db	81%
HHV, MJ/kg db	19.6

[a] wet basis
[b] dry basis
[c] volatile matter

1.2.2.3 Torrefaction

Torrefaction is a thermal pre-treatment process that adds value to the biofuel produced, given that the product is hydrophobic, has high energy and bulk density and increased grindability compared to non-thermally treated biomass. The biomass feedstock is heated in the absence or near-absence of an oxygen environment to a temperature of approximately 200-300°C (Tumuluru et al., 2011). These characteristics make it a suitable bioenergy carrier with specifications equivalent to coal (Nunes et al., 2014; Proskurina et al., 2017).

For the WTW project, a semi-mobile electrically-heated screw type demonstration-scale torrefaction, Biogreen (Norris Thermal Tech., IN, USA), process, which processed about 0.5 tonnes wood chips per hour was used. Piping and instrumentation diagram of the torrefaction unit used is provided in Figure 5. The reactor temperature was at about 275^{o}C and in order to provide the required inert conditions at the torrefaction process, nitrogen gas was introduced to the process for purging. Nitrogen used for purging was negligible since it was needed only at the start of the operation nitrogen and gas was shut off when the reactor reached a steady state temperature. As noted in Table 1, the moisture content of the biomass input was about 9%. Torrefaction unit included condensation and filtration, which were used to remove the contaminants from the gases released during torrefaction (torgas) that can potentially damage combustion equipment when torgas is utilized (i.e. propane burner or thermal oxidizer). The by-products of condensation and filtration units were condensate (bio-oil) and tar, respectively. Biooil by-product generated was acidic, had a pH of about 2, 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. Utilization 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.

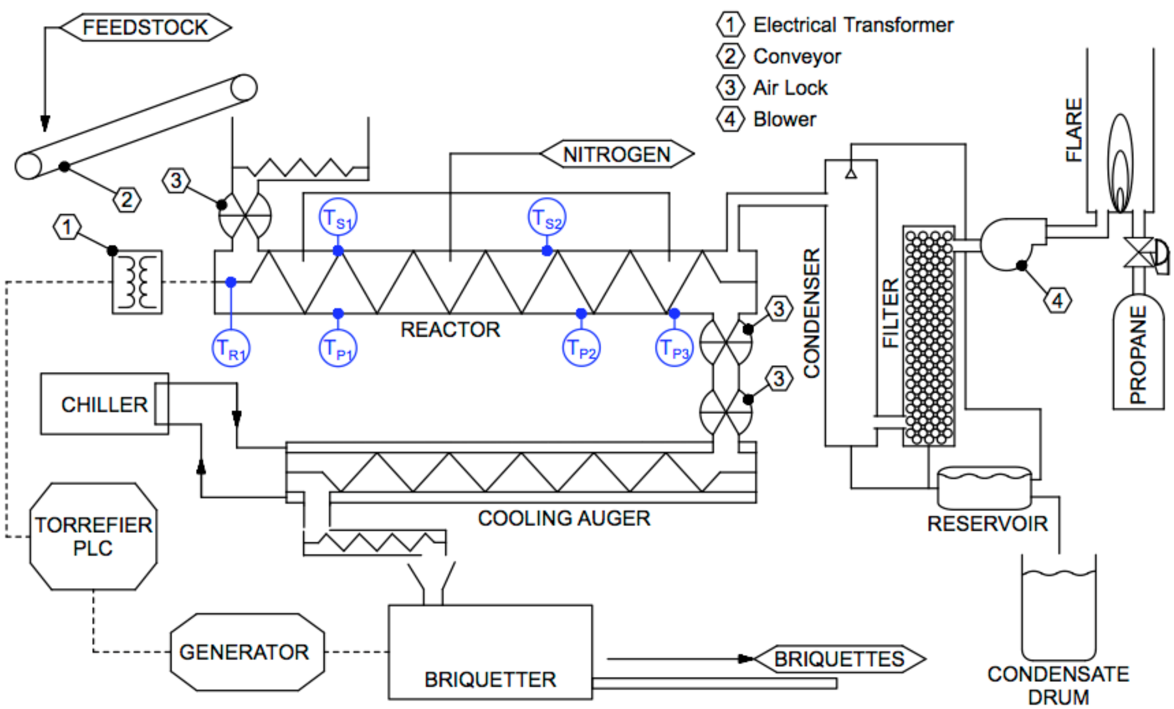

Figure 5 Norris Thermal Technologies torrefaction unit (Severy et al., 2018)

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

Table 2 Properties of feedstock after torrefaction and briquetting

Property	**Value**
Moisture Content, %, wb[a]	0.6%
Ash Content, (%) db[b]	2.5%
VM[c], %, db	71%
HHV, MJ/kg db	23.0

[a] wet basis
[b] dry basis
[c] volatile matter

1.2.2.4 Densification

Torrefied wood was densified into briquettes using a RUF lignum model briquetter (RUF Inc., 2017). Briquetter used hydraulic cylinders, which consumed electricity for compressing the feedstock (Figure 6). The torrefied wood chips were fed into a hopper, then transferred to a pressing chamber via screw conveyor. Finally, the compressed torrefied wood was ejected as finished briquette. Finished briquette dimensions were 63 mm wide by 150 mm long by 109 mm high (Mark Severy, personal communication, January 26, 2018). Binding agents may be used in densification process in order to improve binding characteristics. For the system under investigation no binder was used.

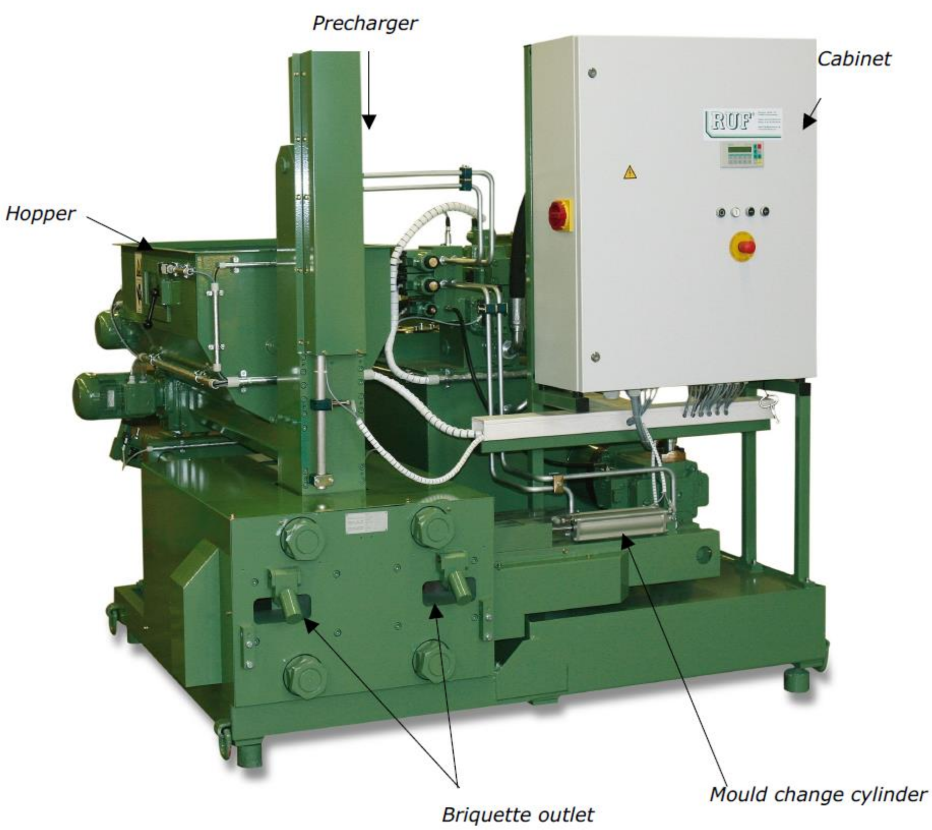

Figure 6 RUF200 Briquetter Machine (RUF Briquetting Systems, Germany)

1.2.2.5 Transportation

Transportation including raw materials and final product 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 et al. 2017). The transportation of TOB to end-user for residential heating was included in the inventory. It was assumed that the briquettes transported to the closest town for use and 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.

1.2.2.6 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, Humboldt State University. Each test was conducted in a freestanding non-EPA certified wood stove (Schrader Woodstove) using eight feet of single-walled stove pipe followed by eight feet 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).

1.2.2.7 Alternative System Configurations Investigated

Alternative system configurations were investigated at the cradle-to-grave level for evaluation of effect on various changes in the supply chain (Table 3). The torrefaction unit was designed to be a semi-mobile unit to perform near-forest operations so that biomass conversion occurs close to the source and can 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 biomass gasification genset and diesel generator. Using the same feedstock to produce the torrefied wood briquettes, the Power Pallet-PP20 biomass gasifier by All Power Biomass with engine generator rated at 20 kWe was tested for remote power generation (All Power Labs, 2015). The 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 considering 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 the moisture content of incoming feedstock was also examined. It was assumed that the feedstock received was not air dried in the forest and had a 50% moisture content – 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 et al. (2014).

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 hr travel distance) with grid power
S4	1 MJ Heat- in-town operation (4 hr travel distance) with grid power
S5	1 MJ Heat- 50% MC feedstock, near-woods operation with wood gasifier power
S6	1 MJ Heat- near-woods operation with wood gasifier power with pile & burn credit

1.2.3 Allocation procedure

Allocation is required for multi-output systems where two or more functions are delivered. The major product of the system under investigation was TOB while torgas was the co-product. Energy allocation was used for accounting for the burden between the torgas and torrefied chips. Mass allocation was used in the propane system model.

1.2.4 Assumptions and Limitations

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

Torrefaction is an emerging technology. Due to insufficient information on this technology, the manufacturing, maintenance and disposal of equipment used in the system are 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 was assumed to be combusted with 95% combustion efficiency (McNamee et al., 2016). In addition, the data on heat requirements at dryer process was not available through experimental runs performed, therefore it is retrieved from literature as 5 MJ/kg water removed (Adams et al., 2015). All mass and energy flows were accounted for in this study without applying cutoff criteria. The mass loss at densification process was negligible. Therefore it is assumed that there was no mass loss at the briquetter.

United States Environmental Protection Agency released a second draft of "Framework for Assessing Biogenic Carbon Dioxide 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. 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 is considered biogenic thus carbon-neutral, in line with 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) for combustion was used instead of DATASMART which is based on USLCI database because the literature source compares data from different databases, sources, evaluates the data, and provides an integrated dataset based on most reliable data available.

1.2.5 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 (OP) (kg chlorofluorocarbons-11-eq), and smog formation (kg O_3-eq), human health (CTU), respiratory effects (kg $PM_{2.5}$ eq), eco toxicity (CTU), and fossil depletion (MJ). Among the available methods for the life-cycle impact assessment (LCIA), the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) method was used in this study (Bare 2011; USEPA 2012). The system was modeled using SimaPro 8.4 LCA software package (PRé Consultants, 2017). TRACI is a mid-point level impact assessment model developed by the U.S. Environmental Protection Agency and is representative for the United States using 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, which requires more research to establish these impact categories since site specific data is required because of the unique properties of location, meteorology, and existing ecosystems (USEPA, 2012). Thus, these impact categories were also not taken into consideration in this study. Forest residues are generated as a byproduct of commercial harvesting operations and are considered a 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 don'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.

1.2.6 Data Quality

The data were collected in line with the data quality requirements addressed by ISO 14044 (2006b) to ensure quality and reliability. Details are provided in the following sections.

1.2.6.1 Geographical and Time-related coverage

Quantitative data on mass and energy flows of the demonstration-scale torrefaction system and forest operations data 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 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 US LCI database using U.S. ecoinvent processes using underlying Ecoinvent v.2.2 datasets (LTS, 2017; Pre Consultants, 2017; NREL, 2012). US LCI database is based on regional conditions and represent U.S. circumstances.

1.2.6.2 Precision

No variance can be calculated because the present study was based on a single dataset, not on an industry level. However, process-specific data were collected and analyzed wherever possible.

1.2.6.3 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 analysis were conducted to address completeness, consistency, and uncertainty issues relevant to the data used.

1.2.6.4 Representativeness

The torrefaction technology used is a current and representative technology, which is compatible 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^{o}C for increased energy density and decreased volatile mater and moisture content of product.

1.2.6.5 Reproducibility

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

1.2.6.6 Data sources

Feedstock procurement were obtained from Oneil et al. (2017). The data came from five commercial harvesting sites located in the western U.S.: Port Angeles, WA; Warm Springs, OR; Oakridge, OR; Lakeview, OR; and Quincy, CA. Average transport distance traveled from the primary landing to the BCT site and BCT site to closest town is based on the data derived from the operations in the five regions investigated. Feedstock preparation data were based on field-based data and experimental studies, year 2015, performed as a part of the WTW project (Bisson and Han, 2016; Kizha and Han, 2016; Kizha et al. 2018).

The primary data for the torrefaction processes relies on the operational runs of the demonstration-scale torrefaction unit. A semi-mobile electrically-heated screw type demonstration-scale torrefaction unit with 0.5 tonnes wood chips per hour processing capacity was used. All relevant quantitative data (i.e. input-output flows) associated with the unit processes were collected from the production site. These include data for the dryer, torrefaction, densification processes and biomass gasification gen-set. The data included input-output mass and energy flows, air emissions resulting from the torrefaction process and physical properties of the feedstock received by the systems and characteristics of the final product, i.e. torrefied briquette. 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).

1.2.6.7 Type of critical review

Due to the comparative nature of this study and its intention to be disclosed to the public, as required by ISO 14044 (2006b) 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, Post-doctoral research fellow.

The main aims of the review panel, as outlined by ISO 14044 (2006b), are: 1) to ensure that the methods are scientifically and technically valid and 2) consistent with ISO 14044 (2006b), 3) that the data are appropriate and reasonable in light of the goal of the study, 4) that the interpretations reflect the limitations and study goal, and 5) that the report is transparent and consistent.

1.2.6.8 Value Choices

In this study, mid-point level impact assessment was performed using the TRACI 2.1 (Bare, 2011; USEPA, 2012) method. Mid-point level analysis was used to express results from the impact assessment where value judgments from weighting was avoided since 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 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 aggregates midpoint impacts under the three areas of protection: natural environment, human health, and natural resources. End point analysis allow presenting the results using a single score result, which allows easier interpretation and communication of LCA results with non-LCA 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 analysis leading higher uncertainties.

2 LIFE-CYCLE INVENTORY ANALYSIS

Cradle-to-grave system boundary of the TOB supply chain included feedstock procurement (processing, sorting and loading), feedstock preparation (chipping, screening and drying), biomass conversion (torrefaction and densification), and use phase (combustion at domestic wood stove). Biomass procurement and preparation data were provided under the WTW project a Biomass Research and Development Initiative. 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 conforms to ISO14040 and ISO14044 LCA standards (ISO 2006a, 2006b).

2.1 Cradle-to-grave LCI of Propane System

The cradle-to-grave system boundary begins at the extraction of crude oil and ends at the useful heat produced at the residential furnace to be used 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 DATASMART database where combustion data was retrieved from literature. Johnson (2012) evaluated the existing data sources for the residential heating systems using propane LCI and generated an integrated data set for the propane combustion emissions factors (Table 4).

Table 4 Propane combustion emission factors (Johnson, 2012)

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

2.2 Cradle-to-grave LCI of Torrefaction System

The cradle-to-grave LCI 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 in-woods field experiments. LCI for different life cycle stages are provided in the following section.

2.2.1 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 1 bone-dry tonne (BDT) of wood chips. Feedstock procurement stage along with hauling the forest residue were adopted from the forest operations model developed by Oneil et al. (2017). The Oneil et al. (2017) model was based on the operational data generated in year 2015 (Bisson and Han, 2016; Kizha and Han, 2016; Kizha et al. 2018).

Table 5 Cradle-to-gate input-output flow analysis for procuring material for 1 BDT of wood chips

Process	**Unit**	**Value**	**Source**
Feedstock Procurement			
Processing			
Diesel	L	1.0115	Oneil et al. 2017
Lubricants	L	0.0182	Oneil et al. 2017
Sorting			
Diesel	L	0.346	Oneil et al. 2017
Lubricants	L	0.006	Oneil et al. 2017
Loading			
Diesel	L	0.708	Oneil et al. 2017
Lubricants	L	0.013	Oneil et al. 2017
VOC	g	8.54	Alanya-Rosenbaum et al., 2018
Hauling			
Transportation	km	18.77	Oneil et al. 2017

2.2.2 Feedstock preparation

Gate-to-gate input and output flows of feedstock preparation including chipping, screening and drying processes are provided in Table 6. Screening and chipping data were adopted from the forest operations model developed by Oneil et al. (2017) and modeled based on the operational data generated in year 2015 (Bisson and Han, 2016; Kizha and Han, 2016; Kizha et al. 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 dryer process occurred from the belt conveyor used (Beltomatic, Norris Thermal Technologies, IN, USA). Drying process was modeled based on the operational data generated in year 2015.

Table 6 Cradle-to-gate input-output flow analysis for 1 BDT of wood chip

Process	**Unit**	**Value**	**Source**
Feedstock Preparation			
Chipper			
Diesel	L	0.5461	Oneil et al., 2017
Lubricants	L	0.0098	Oneil et al., 2017
Screener			
Diesel	L	1.5939	Oneil et al., 2017
Lubricants	L	0.0287	Oneil et al., 2017
Dryer			
Electricity	Wh	7.14	Alanya-Rosenbaum et al., 2018
Propane	L	20.9	Engineering calculations
VOC*	g	2.13	Alanya-Rosenbaum et al., 2018
Torgas	m^3	212	Process data
Waste heat	MJ	391	Engineering calculations

*Volatile organic carbon

Although the feedstock was left in the forest and field dried to 20±3% MC, feedstock was forced-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. Average feedstock MC after drying process was about 9.3%, which provided an optimum product (Severy et al, 2018). Process data for heat consumed in drying process were not available, therefore heat requirements at drying process was assumed to be 5 MJ/kg water removed (Adams et al., 2015). Torrefaction gases (torgas) were assumed to be combusted to provide heat for the dryer. Torgas was assumed =combusted with 95% combustion efficiency (McNamee et al., 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 volatile organic carbon (VOC) emissions, which was accounted for in the analysis. Assuming freshly-cut wood, this analysis on the conservative side tracked any VOC emitted during field drying of 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 et al. 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 the aged material. Milota (2013)concluded that only 10 to 20 percent of the total hydrocarbon emissions occur below 20% MC. In this study, it is assumed that 20% of the VOC emissions were emitted during forced drying where the rest (80%) were emitted at the forest during field drying.

2.2.3 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) and use phase. Use phase data including stack emissions from emissions from burning TOB that were obtained from WTW project combustion tests and data were complemented by literature data. Overall stove efficiency of burning TOB at the wood stove was 76%. It is assumed that the briquettes were stored and sold in 15 kg capacity plastic bags made from low-density polyethylene (LDPE) (Laschi et al., 2016).

Table 7 Input-output flows of torrefied briquette (TOB) production and use

Process	**Unit**	**Value**	**Source**
Biomass conversion			
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	gr/MJ torrefied chips	0.667	Operational data
Outputs			
Biooil	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	gr/BDT	0.632	Laschi et al., 2016
Distribution	km	90.200	Oneil et al., 2017
Combustion (Use			
CO_2 (biogenic)	gr/MJ TOB	76.873	Operational data
CH_4	gr/MJ TOB	0.002	Khalil et al., 2013
NO_x	gr/MJ TOB	0.028	Operational data
CO	gr/MJ TOB	3.476	Operational data
VOC	gr/MJ TOB	0.730	Operational data
SO_2	gr/MJ TOB	0.008	Khalil et al., 2013
$PM_{2.5}$	gr/MJ TOB	0.014	Operational data
PM_{10}	gr/MJ TOB	0.104	Operational data

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.

Table 8 Flue gas composition of torgas combustion

Process	Unit	Value	Source
Torgas Combustion			
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 et al., 2016

2.3 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 Table 9 and Table 10. Total primary energy used to produce 1 MJ of heat from TOB at domestic wood stove was 1.34 MJ (Table 9). Majority of the primary energy consumption was from wood fuel with about 82.7% contribution to overall primary energy consumption. This was due to high electricity consumption in torrefaction process, 75.2% contribution, where the power source used was a wood gasifier. Contribution of other renewable energy sources to total primary energy use was minor. Most of the fossil energy was derived from propane and diesel consumption during torgas combustion and transportation respectively, which is captured as crude oil as the primary energy source before conversion (Table 10). Non-renewable material resource use was minor (less than about 10^{-6} MJ).

Table 9 Cumulative primary energy consumption per 1 MJ of thermal energy generated for domestic heating from combusting torrefied briquette (TOB)

Fuel	**Percent**	**Total**	**Feedstock procurement**	**Feedstock preparation**	**Torrefaction**	**Densification**	**Transportation**	**Use phase (Combustion)**	**Packaging**
		(MJ/MJ heat)							
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 percent		100%	0.8%	10.0%	75.2%	13.4%	0.6%	0.0%	0.0%

Table 10 Resources and waste generated per 1 MJ of thermal energy generated for domestic heating from combusting torrefied briquette (TOB)

Total Primary Energy Consumption	**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
Non-renewable 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
Non-renewable 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									
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

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

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

Fuel	Percent	Total	Production	Transportation	Combustion
		(MJ/MJ heat)			
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 percent		100%	99.9%	0.1%	0.0%

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

Total Primary Energy Consumption	**Unit**	**Total**	**Production**	**Transportation**	**Combustion**
Total Primary Energy Consumption	MJ	1.46E+00	1.46E+00	8.80E-04	0.00E+00
Non-renewable fossil	MJ	1.44E+00	1.44E+00	9.01E-05	0.00E+00
Non-renewable 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					
Non-renewable 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

3 LIFE-CYCLE IMPACT ASSESSMENT

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

3.1 Cradle-to-grave LCA results of torrefied briquette supply chain

Environmental impact assessment results associated with generating heat from wood briquettes at wood stove are presented in Table 13 for ten impact categories: global warming (GW), acidification, eutrophication, ozone depletion (OD), smog formation, human health (carcinogenics and non-carcinogenics), respiratory effects, eco toxicity (CTU), and fossil depletion (MJ). The results presented here are for the same conditions where the demonstration-scale system was operated near-woods where torrefaction and briquetting occur at BCT site close to feedstock source and powered using wood gasifier gen-set as the base scenario. The drying process was heated by a portion of torgas combustion- 31%. The remaining torgas was flared at torrefaction unit. Propane was used to achieve ignition and complete combustion of torgas, which caused torrefaction process having the highest impacts for OD, GW, eutrophication, carcinogenics, non-carcinogenics, ecotoxicity, and fossil fuel depletion category.

Table 13 Environmental performance of 1 MJ of thermal energy generated for domestic heating from combusting TOB

Impact category	Unit	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
Non carcinogenics	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

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

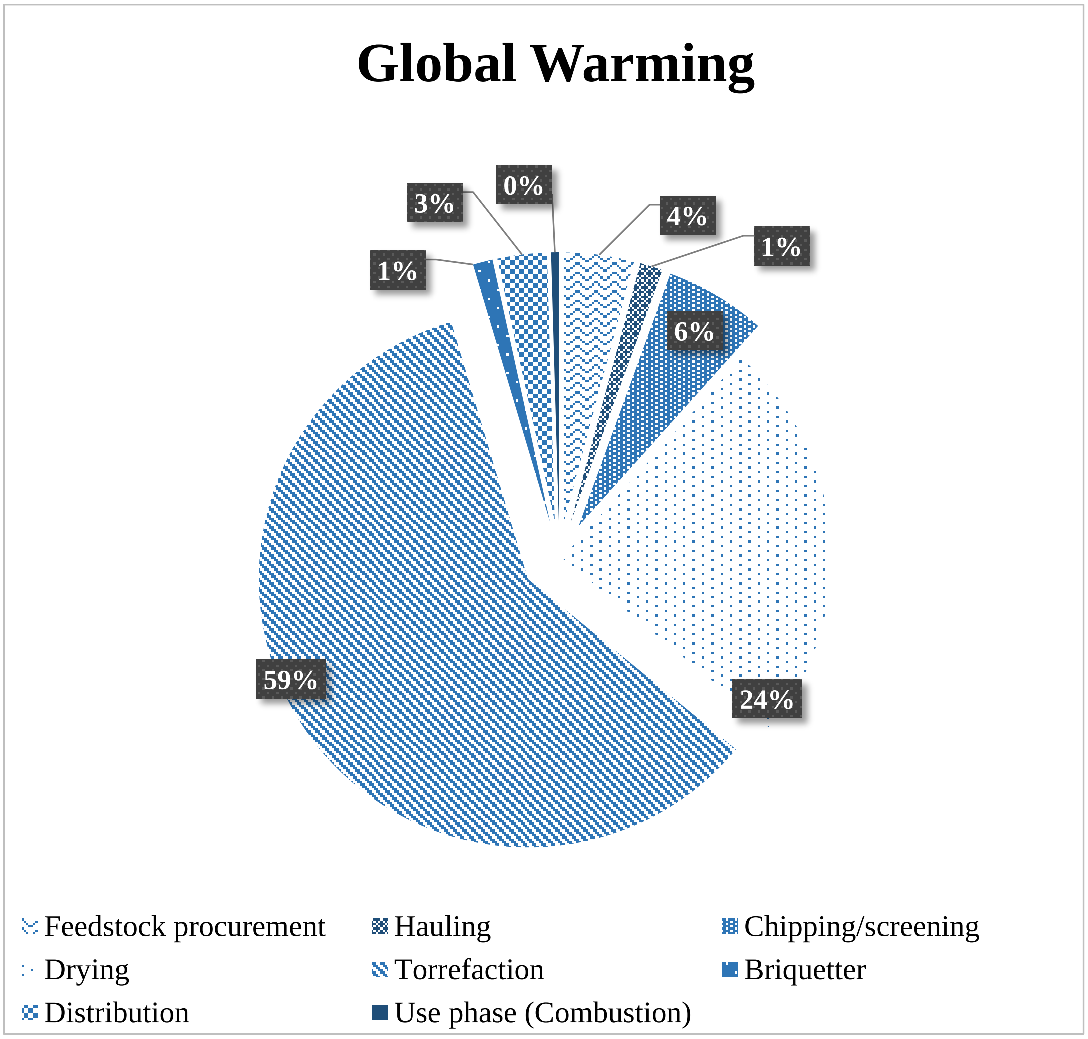

Figure 7 Processes contribution to the overall global warming impact for TOB production system

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

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

Impact category	Unit	Production	Distribution	Use phase (Combustion)
Ozone depletion	kg CFC-11 eq	1.81E-10	1.27E-13	0.00E+00
Global warming	kg CO2 eq	1.62E-02	7.65E-05	7.81E-02
Smog	kg O3 eq	2.05E-03	1.96E-05	1.45E-03
Acidification	kg SO2 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
Non carcinogenics	CTUh	1.62E-08	1.13E-11	0.00E+00
Respiratory effects	kg PM2.5 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

Comparison of the GW impact results per MJ of heat generated through various scenarios was performed. 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 heat from propane with torrefied wood briquettes result in 41% and 66% reduction in the GW impact, respectively.

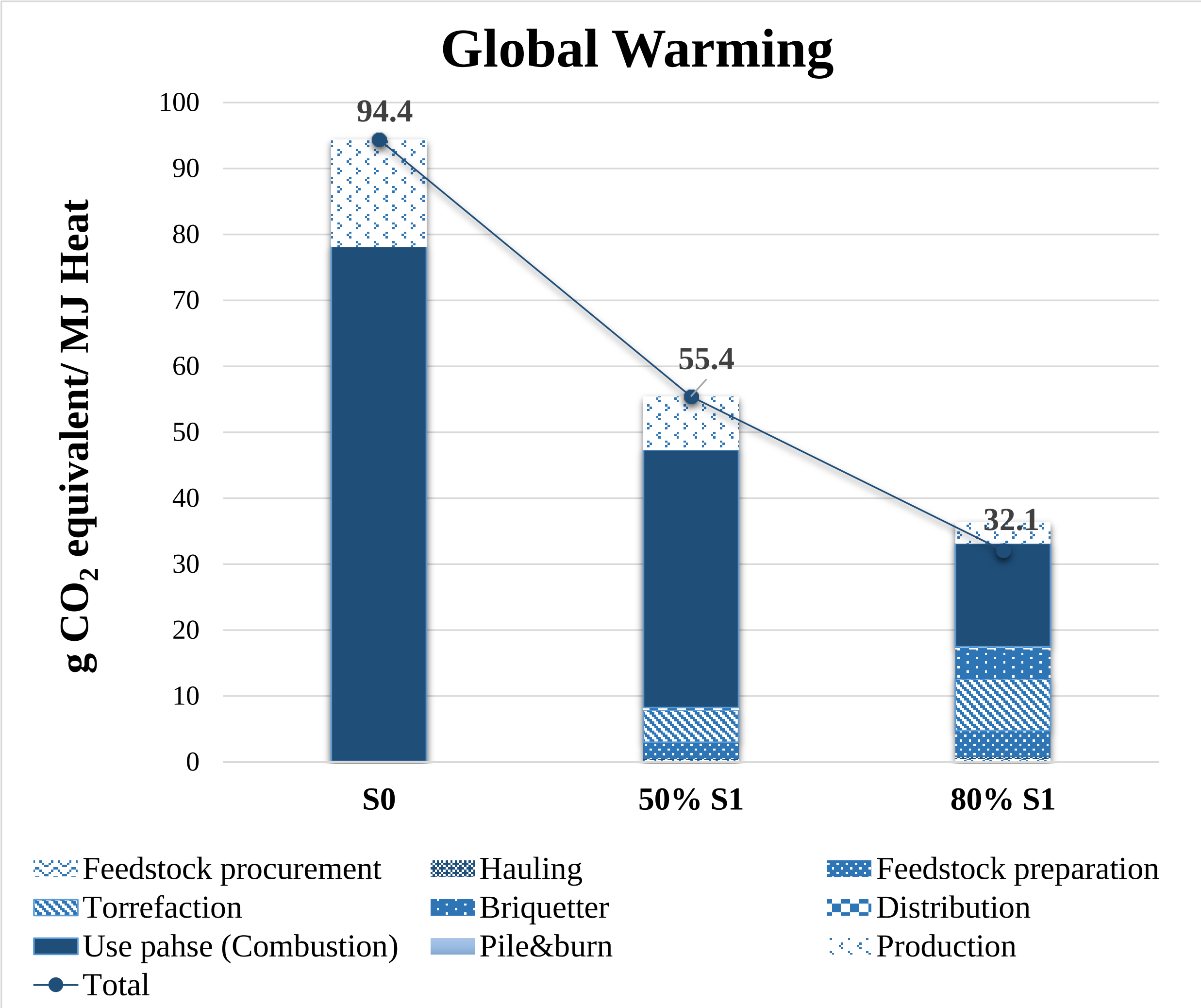

Figure 8 Comparison of the GW impact results per MJ of heat generated through propane furnace, Scenario 0 (S0), and propane system supplemented with TOB, Scenario 1 (S1)

3.1.1 Alternative System Configurations LCA

Results of the comparative analysis of alternative scenarios investigated for the GW impact are provided in Figure 9. Total GW impact of producing 1 MJ of heat from TOB combustion at wood stove was nearly 17 g CO_2 eq. for the base scenario (S1). Analysis showed that near-woods operation using diesel power for remote (off-grid) power generation source was the least favorable alternative scenario (S2). Using diesel generator instead of wood gasifier gen-set for remote power generation resulted in 308% higher GHG emissions. Similarly, biomass conversion of forest residues close to biomass source using gasifier genset instead of transporting feedstock maximum

2 hour (S3) or 4 hour (S4) drive 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), due to increased propane consumption at dryer process. Using feedstock with higher MC resulted in 6% increase in global warming impact of hauling process. Higher propane consumption was due to increased torgas use and additional propane requirements due to higher heat demand at dryer. This shifted environmental burden from torrefaction process to feedstock preparation stage, mainly drying process, because more torgas was used in drying process and torgas combustion itself requires support by propane. In S1, some portion of the torgas was used to generate heat for the dryer while the remaining was flared at the torrefaction process. In S5, total torgas produced was used in drying process instead of flaring at torrefaction process. Accounting for the benefits of heat generation through controlled burn compared to pile and burn (S6) resulted in a 19% decrease in resulting GW impact.

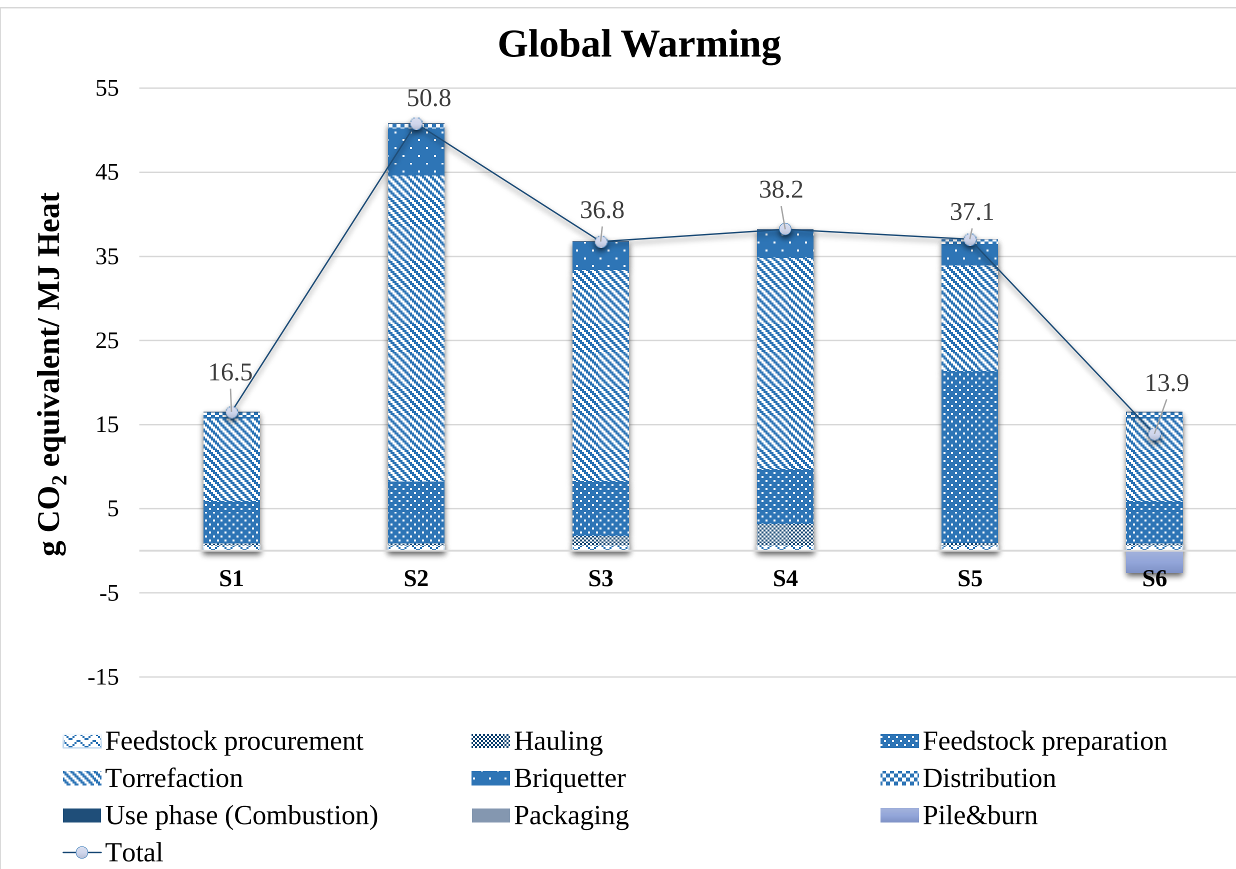

Figure 9 Processes contribution to overall global warming impact per 1 MJ of thermal energy generated for six scenarios investigated. S1: 1 MJ Heat- near-woods operation with wood gasifier power; S2: 1 MJ Heat- near-woods operation with diesel power; S3: 1 MJ Heat- in-town operation (2 hr travel distance) with grid

power; S4: 1 MJ Heat- in-town operation (4 hr travel distance) with grid power, S5: 1 MJ Heat- 50% MC feedstock, near-woods operation with wood gasifier power; S6: 1 MJ Heat- near-woods operation with wood gasifier power with pile & burn credit

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

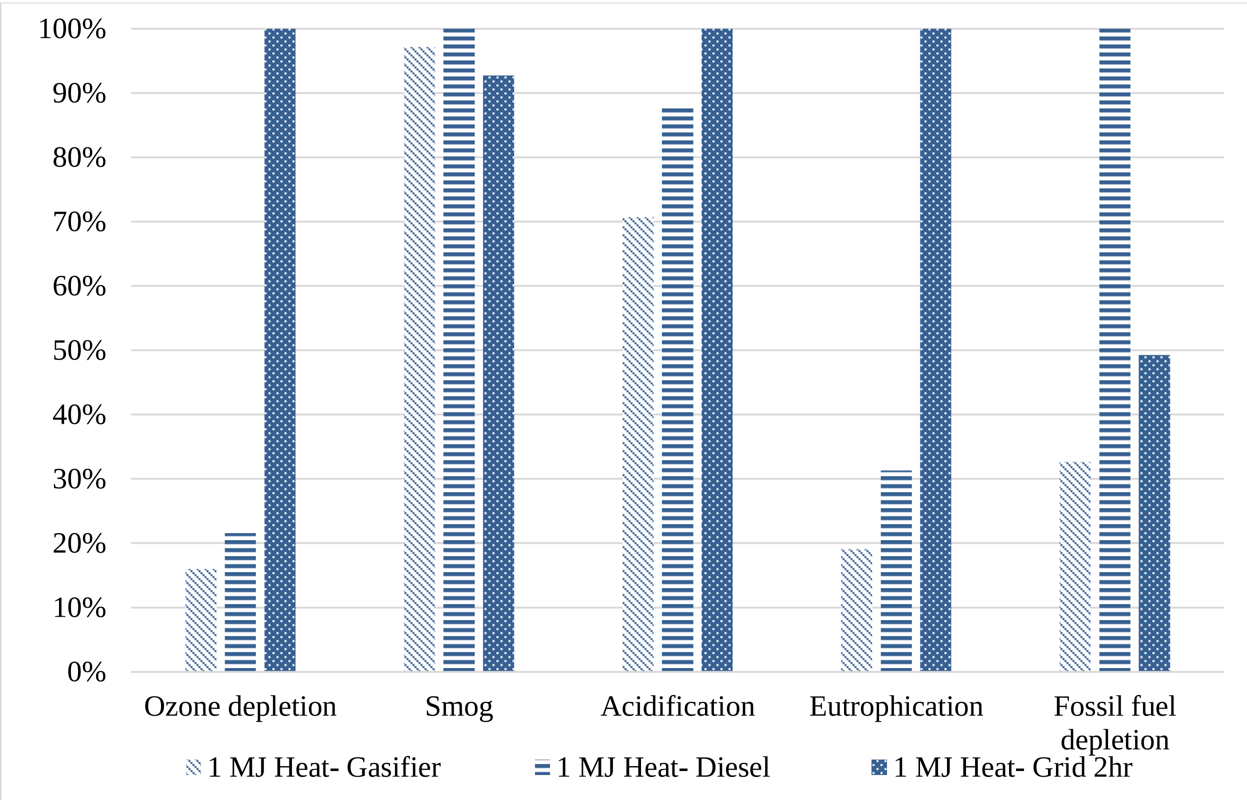

Figure 10 Summary of the comparative LCIA results for three power sources (grid, diesel and gasifier electricity) for TOB production system

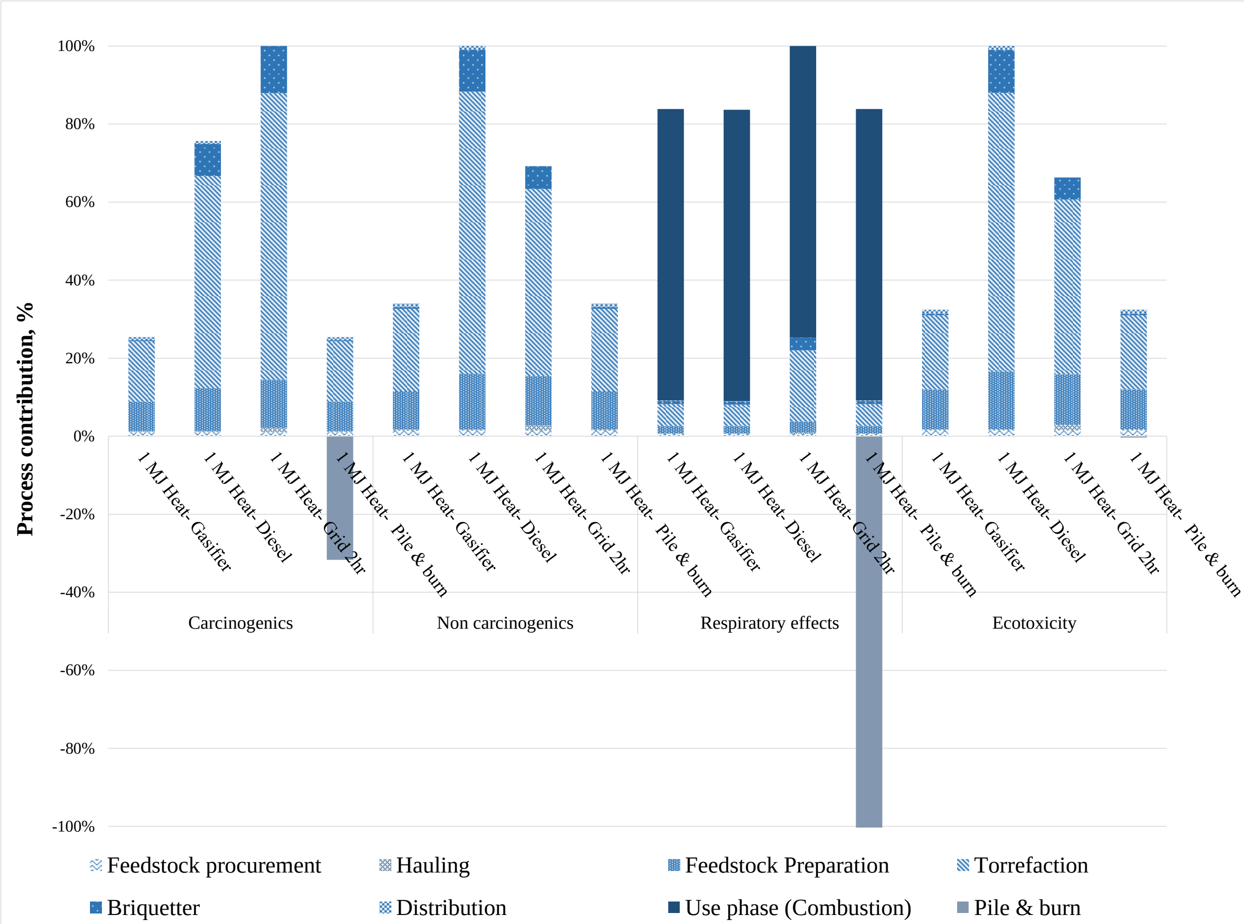

Figure 11 presents the toxicity impact category results: human health (carcinogenics and non-carcinogenics), respiratory effects and, eco toxicity (CTU). Using wood gasifier as power source for near-woods operation, showed better performance compared to diesel and grid electricity alternatives for toxicity 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 respiratory effects impact category particularly in respiratory effects category mainly due to avoided particulate matter (PM) emissions.

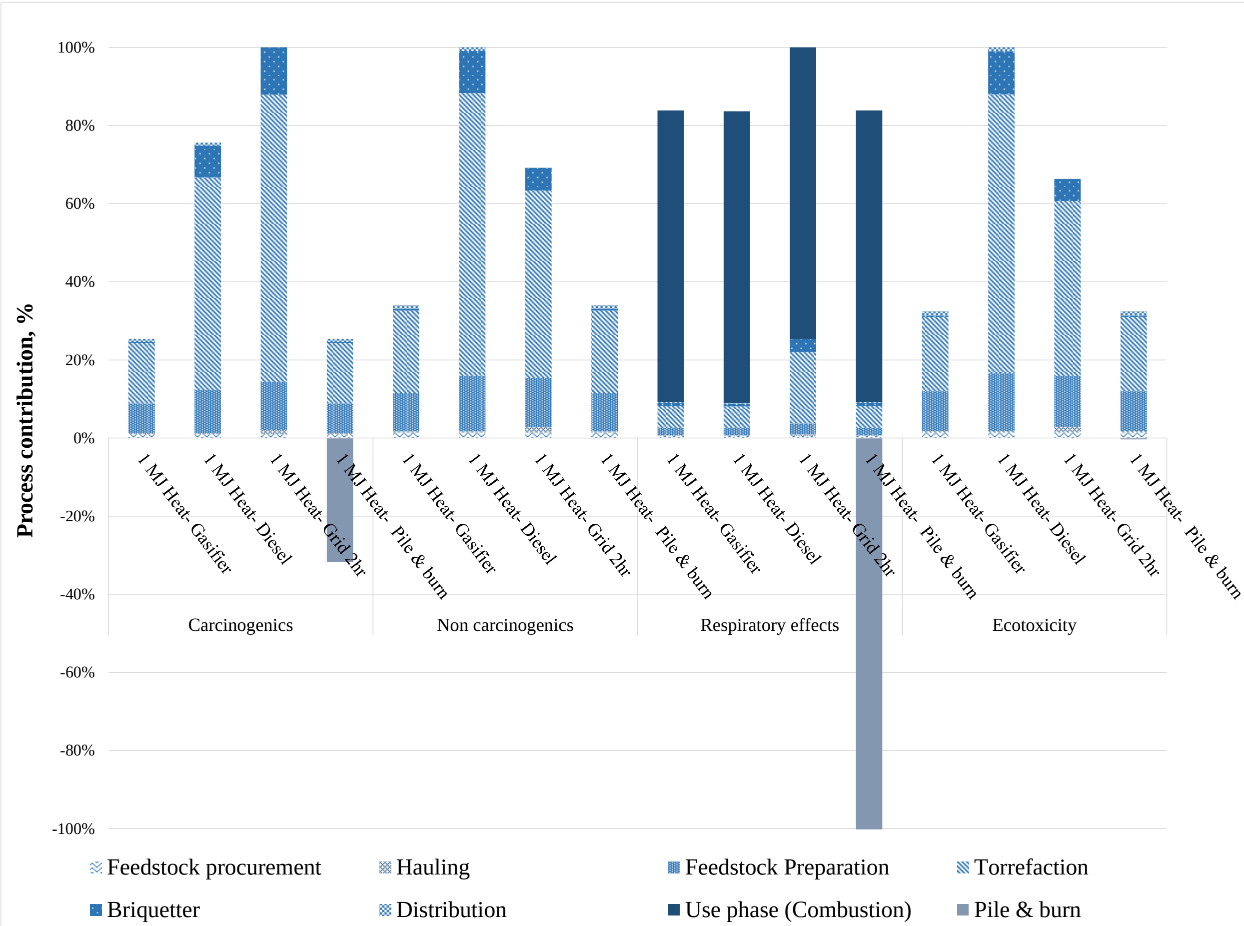

Figure 11 The toxicity impact category results for generating 1 MJ of thermal output for the Scenarios investigated

4 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 mid-point 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.

4.1 Completeness, Sensitivity, and Consistency Checks

Results of the parameter based sensitivity analysis are presented in

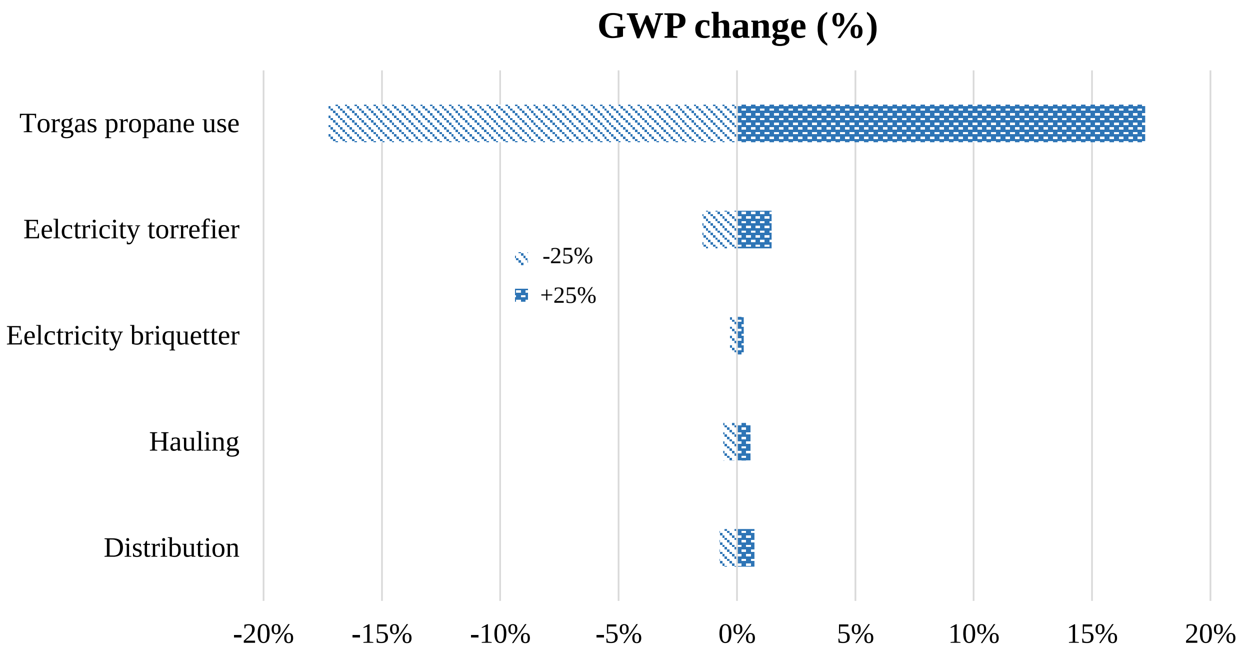

Figure 12. The sensitivity of the GW impact was examined for 25% variation in key parameters including briquetter and torrefier electricity demand, distribution and hauling distances, and propane supplement used for torgas combustion. Sensitivity analysis performed showed that propane supplement was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

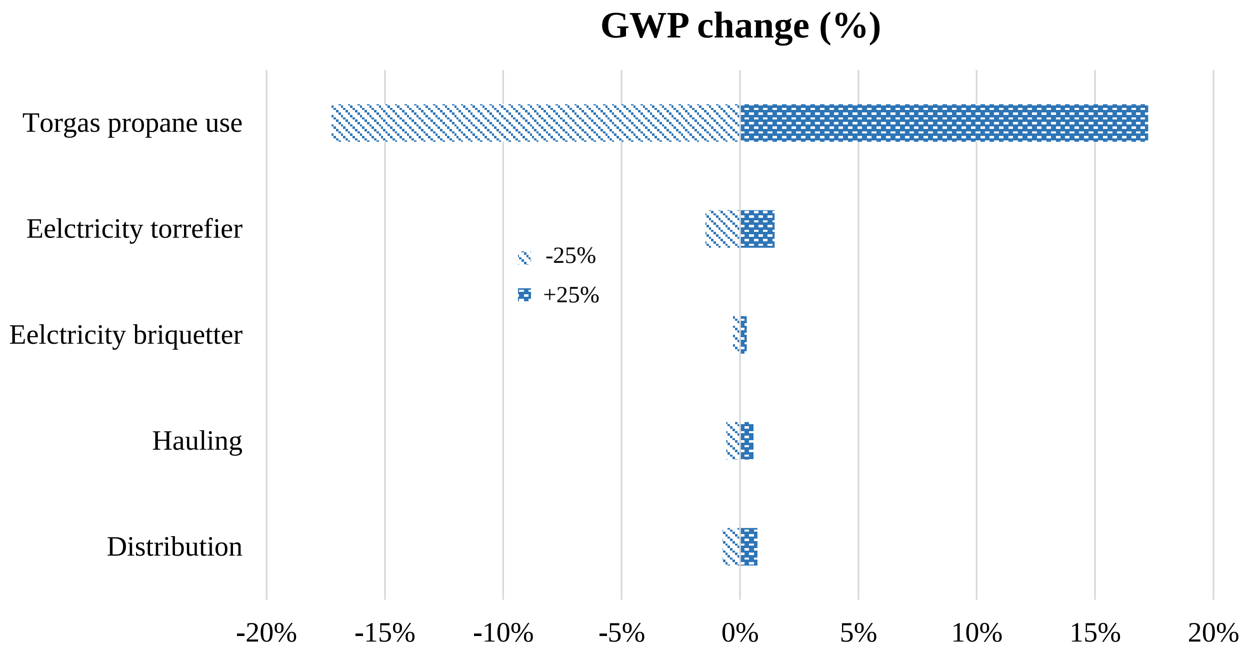

Figure 12 Sensitivity of key parameters on global warming impact

4.2 Conclusions, Limitations, and Recommendations

This study provides a comprehensive cradle-to-grave LCA of the TOB production supply chain investigating the environmental performance of utilizing post-harvest forest residues with torrefaction and briquetting processes for biofuel production. Use of torrefied briquettes for energy production compared to use 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 et al., 2015).

Near-woods bioenergy production systems using power from on-site wood gasifier showed better environmental performance than their fossil fuel alternatives; on-site diesel and in-town grid electricity. For remote power generation, GHG emissions were about three times lower when a biomass gasifier genset was substituted for a diesel generator. In-town operation with grid electricity supply was a better option compared to remote operation using a diesel generator. Utilization of post-harvest residues as biofuel as opposed to the typical pile and burning practice shows a notable environmental advantage in GW and toxicity impact categories. The data on heat requirement at dryer process was not available, therefore it is retrieved from literature adopting a conservative approach. As the sensitivity analysis revealed, drying parameters has a high influence on the impact assessment results. Therefore, drying data that rely on operational runs would improve the quality of the analysis.

Results indicate that the GW impact was highly dependent on torgas management at torrefaction process and heat demand in drying processes. This was mainly due to 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 biooil to improve the heating content of torgas. In addition separating bio-oil brings additional environmental burden to the system since 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 increase the environmental performance. Use of high-efficiency dryer systems, using field-dried feedstock with lower MC and efficient recovery of torgas are crucial.

4.3 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, Post-doctoral research fellow.

5 REFERENCES

Adams, P., Shirley, J., & McManus, M. (2015). Comparative cradle-to-gate life cycle assessment of wood pellet production with torrefaction. *Appl. Energy, 138,* 367–380. doi:10.1016/j.apenergy.2014.11.002

Alanya-Rosenbaum, S., Bergman, R., Ganguly, I., & Pierobon, F. (2017). A comparative life-cycle assessment of briquetting logging residues and lumber manufacturing coproducts in Western United States. *Applied Engineering in Agriculture, In press*.

All Power Labs. (2016, December 1). Retrieved from http://www.allpowerlabs.com/products/product-overview

Bare, J. (2011). TRACI 2.0: The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts 2.0. *Clean Technologies and Environ. Policy, 13*(5), 687–96. doi:10.1007/s10098-010-0338-9

Beakler, B., Blankenhorn, P., Brown, N., Scholl, M., & Stover, L. (2007). Quantification of the VOCs released during kiln-drying oak and white oak lumber. *Forest Prod. J., 57*(11), 27-32.

Bisson, J., & Han, H. (2016). Quality of Feedstock Produced from Sorted Forest Residues. *American Journal of Biomass and Bioenergy, 5,* 81-97. doi:10.7726/ajbb.2016.1007

Giuntoli, J., Caserini, S., Marelli, L., Baxter, D., & Agostini, A. (2015). Domestic heating from forest logging residues: environmental risks and benefits. *J. of Cleaner Production, 99*, 206-216. doi:10.1016/j.jclepro.2015.03.025

Hektor, B., Backeus, S., & Anderson, K. (2016). Carbon balance for wood production from sustainably managed forests. *Biomass and Bioenergy, 93*, 1-5.

Intergovernmental Panel on Climate Change (IPCC). (2006). *Task Force on National Greenhouse Gas Inventories.*

Intergovernmental Panel on Climate Change (IPCC). (2014). *Contribution of working groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change.*

Geneva, Switzerland: Page 151 in RK Pachauri and LA Meyer, eds. Core Writing Team. Climate change 2014: Synthesis report. IPCC.

ISO. (2006a). *ISO 14040: Environmental management—life-cycle assessment—principles and framework.* Geneva, Switzerland: International Organization for Standardization.

ISO. (2006b). *ISO 14044: Environmental management—life-cycle assessment—requirements and guidelines.* Geneva, Switzerland: International Organization for Standardization.

Johnson, E. (2012). Carbon footprints of heating oil and LPG heating systems. *Environmental Impact Assessment Review, 35*, 11–22. doi:10.1016/j.eiar.2012.01.004

Kizha, A., & Han, H. (2016). Processing and sorting forest residues: Cost, productivity and managerial impacts. *Biomass and Bioenergy*, *93*, 97-106. doi:10.1016/j.biombioe.2016.06.021.

Kizha, A., Han, H., Paulson, J., & Koirala, A. (2018). Strategies for Reducing Moisture Content in Forest Residues at the Harvest Site. *34*(1), 25-33. doi:10.13031/aea.12427

Laschi, A., Marchi, E., & S. (2016). Environmental performance of wood pellets' production through life cycle analysis. *Energy, 103*, 469-480. doi:10.1016/j.energy.2016.02.165.

Li, H., Chen, Q., & Zhang, X. (2012). Evaluation of a biomass drying process using waste heat from process industries: A case study. *Applied Thermal Engineering, 35*, 71-81.

Loeffler, D., Brandt, J., Morgan, T., & Jones, G. (2010). *Forestry-based biomass economic and financial information and tools: An annotated bibliography*. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Long Trail Sustainability (LTS). (2017, August 15). DATASMART Life Cycle Inventory. Retrieved from https://ltsexperts.com/wp-content/uploads/2017/06/DATASMART-End-User-Licence-Agreement_May-2017.pdf

Majer, S., Nebel, E., Gawor, M., Schipfer, F., Kranzl, L., Meyer, M., . . . Chand, T. (2015). *Production of Solid Sustainable Energy Carriers from Biomass by Means of Torrefaction. Deliverable No. D9.8.* SECTOR Project.

McNamee, P., Adams, P., McManus, M., Dooley, B., Darvell, L., Williams, A., & Jones, J. (2016). An assessment of the torrefaction of North American pine and life cycle greenhouse gas emissions. *Energy Conversion and Management, 113*, 177–188. doi:http://dx.doi.org/10.1016/j.enconman.2016.01.006

Milota , M. (2013). Emissions from Biomass in a Rotary Dryer. *Forest Prod. J., 63*(5/6), 155–161. doi:10.13073/FPJ-D-13-00052

Milota , M., & Mosher, P. (2008). Emissions of hazardous air pollutants from lumber drying. *Forest Prod. J., 58*(7/8), 50–55.

Milota, M., & Lavery , M. (1998). VOC emissions from Douglas-Fir lumber dried in commercial and laboratory kilns. *Western Dry Kiln Association Proceedings*, (pp. 91-108).

Miner, R., Abt, R., Bowyer, J., Buford, M., Malmsheimer, R., O'Laughlin, J., . . . Skog, K. (2014). Forest carbon accounting considerations in US bioenergy policy. *J. For., 112*(6), 591-606.

Nanou, P., Carbo, M., & Kiel, J. (2016). Detailed mapping of the mass and energy balance of a continuous biomass torrefaction plant. *Biomass and Bioenergy, 89*, 67e77. doi:10.1016/j.biombioe.2016.02.012

National Renewable Energy Laboratory (NREL). (2012). Life Cycle Inventory Database. National Renewable Energy Laboratory. Retrieved January 15, 2017, from www.lcacommons.gov/nrel/search

Nhuchhen, D., Basu, P., & Acharya, B. (2014). A Comprehensive Review on Biomass Torrefaction. *Int. J. of Renewable Energy & Biofuels, 2014*, 1-56. doi:10.5171/2014.506376

Nunes, L., Matias, J., & Catalão, J. (2014). A review on torrefied biomass pellets as a sustainable alternative to coal in power generation. *Renew. Sustain. Energy. Rev., 40*, 153–160. doi:10.1016/j.rser.2014.07.181

Ohio EPA. (2015). U.S. EPA's Clean Power Plan- 111(d) Rules. (O. EPA, Ed.) Columbus, OH, USA. Retrieved 08 22, 2017, from http://epa.ohio.gov/dapc/111drule.aspx

Oneil, E., Comnick, J., Rogers, L., & Puettmann, M. (2017). *Life cycle assessment of forest residue recovery for small scale bioenergy systems.* Final Report. Consortium for Research on Renewable Industrial Materials.

PRé Consultants. (2017). *SimaPro 8 Life-Cycle assessment software package, Version 8. Plotter 12*. Retrieved January 15, 2017, from www.pre.nl/

Proskurina, S., Heinimo, J., Schipfer, F., & Vakkilainen, E. (2017). Biomass for industrial applications: The role of torrefaction. *Renewable Energy*, *111*, 265-274.

RUF Inc. (2017). *RUF Briquetting Systems*. Retrieved December 15, 2016, from https://www.ruf-briquetter.com/content/documents/29682-RUF-Wood-Bi-Fold-Broc-No-crops.pdf.

Severy, M., Chamberlin, C., & Jacobson, A. (2018). Analysis of Process and Products from Mobile Biomass Torrefaction and Briquetting Demonstration Plant. *Applied Engineering in Agriculture. ASABE special collection publication (In review)*. doi:10.13031/aea.12376

Tumuluru, J., Wright, J., Hess, J., & Kenney, K. (2011). A review of biomass densification systems to develop uniform feedstock commodities for bioenergy application. *Biofuels, Bioprod. Bioref.*, *5*, 683–707.

U.S. Department of Energy (USDOE). (2011). *Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry.* Oak Ridge, TN: Oak Ridge National Laboratory.

U.S. Department of Energy (USDOE). (2014). *Biomass Multi-Year Program Plan.* Washington D.C.: Office of the Biomass Program, Energy Efficiency and Renewable Energy.

U.S. Department of Energy (USDOE). (2016). *2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy, Volume 1: Economic Availability of Feedstocks.* Oak Ridge, TN: M. H. Langholtz, B. J. Stokes, and L. M. Eaton, ORNL/TM-2016/160. Oak Ridge National Laboratory.

U.S. Energy Information Administration (USEIA). (2016). *International Energy Outlook 2016.* Washington, DC: U.S. Department of Energy.

U.S. Energy Information Administration (USEIA). (2017). Biomass and waste fuels made up 2% of total U.S. electricity generation in 2016. U.S. Energy Information Administration. Retrieved from https://www.eia.gov/todayinenergy/detail.php?id=33872

U.S. Energy Information Administration (USEIA). (2017). Heat Content. Retrieved December 4, 2017, from https://www.eia.gov/tools/glossary/index.php?id=H#heat_cont.

U.S. Environmental Protection Agency (USEPA). (2007). *Biomass Combined Heat and Power Catalog of Technologies.* Washington, D.C. : Combined Heat and Power Partnership.

U.S. Environmental Protection Agency (USEPA). (2012). *Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) TRACI version 2.1 User's Guide.* Cincinnati, OH: Office of Research and Development.

U.S. Environmental Protection Agency (USEPA). (2017). Method 28 – Certification and Auditing of Wood Heaters. Retrieved September 9, 2016, from https://www.epa.gov/emc/method-28-certification-and-auditing-wood-heaters