Journal of Cleaner Production 233 (2019) 918–931

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Life-cycle impact and exergy based resource use assessment of torrefied and non-torrefied briquette use for heat and electricity generation

Sevda Alanya-Rosenbaum*, Richard D. Bergman

USDA Forest Service Forest Products Laboratory, 1 Gifford Pinchot Dr, Madison, WI, 53726, USA

A R T I C L E I N F O

Article history:
Received 10 April 2019
Received in revised form
24 May 2019
Accepted 26 May 2019
Available online 1 June 2019

Keywords:
Torrefaction
Wood briquettes
Life cycle assessment
Resource use assessment
Exergetic life cycle assessment
Bioenergy

A B S T R A C T

Forest residue biomass can be used as bioenergy feedstock, however, issues associated with its properties including low density and high moisture content constrains its valorization. Using mobile conversion technologies that can operate in remote areas and are capable of converting forest residues into high quality energy products can address the issues associated with its valorization for renewable energy production. This study evaluated environmental sustainability of using an integrated novel system of semi-mobile biomass conversion technologies (BCTs) to utilize low-value forest residue biomass as high value bioenergy products. A cradle-to-grave life cycle assessment (LCA) and resource use assessment on a unit-process level was conducted for two bio-products: nontorrefied briquettes (NTB) and torrefied briquettes (TOB). Their use for production of useful thermal energy in wood stoves for domestic heating and electricity at power plants were investigated along with their alternatives. The analyses were performed with SimaPro 8.5 using the DATASMART database. The impact assessment results showed a notable decrease in global warming (GW) impact when substituting fossil fuels with these two bio-products. Specifically, for domestic heating on an equivalent energy basis, a 50% substitution of propane with NTB and TOB showed GHG emission reductions of 46% and 41%, respectively. For electricity generation, 10% cofiring at coal power plant with NTB and TOB showed GHG emission reductions of 6% and 8%, respectively. For the TOB supply chain, a large portion of the GW impact of the came from the torrefaction process and followed by the drying process. This was due to the propane use in these processes. Comparative analysis showed that near-woods biomass conversion for TOB production instead of processing feedstock at an in-town facility with access to grid electricity found 48%–55% lower GW impact for both electricity and heat generation scenarios, respectively. Resourced footprint analysis showed that most exergy extraction from the natural environment came from the drying process for NTB supply chain. In the TOB product system, torrefaction was the major contributor.

1. Introduction

Bioenergy is considered a favorable alternative energy source during transition from fossil fuels to renewable energy to mitigate their adverse environmental impacts. Forest waste can be a viable option for biomass-based renewable energy considering the potential conflicts between land and water resource use of biomass for energy versus for food. In the United States (US), removal of post-harvest forest residues is encouraged to mitigate wildfire frequency and intensity, and spreading of pests and diseases. In the Northwest and Southeast US, frequent wildfires between 2008 and 2012 resulted in increased particulate matter (PM) levels posing risks to human health (Dennison et al., 2014; Fann et al., 2018; Giuntoli et al., 2015; Loeffler et al., 2010; USDA Forest Service, 2005). These adverse health impacts from poor air quality resulting from forest fires have a huge economic cost between 76 and 130 billion US dollars annually (Fann et al., 2018). Therefore, valorization of low-value forest residues as biofuels can be used to increase the supply of renewable energy to achieve a healthy natural environment, reduce fire risk, and ensure environmental sustainability.

Forest residues have been an underutilized resource and is quite abundant in the western US. Converting this resource to biofuel and

* Corresponding author.
E-mail addresses: sevda.alanya-rosenbaum@usda.gov (S. Alanya-Rosenbaum), richard.d.bergman@usda.gov (R.D. Bergman).

https://doi.org/10.1016/j.jclepro.2019.05.298
0959-6526/

bio-products offers a unique solution for certain problems facing our forests but also feeds into renewable energy efforts. Forest residues have been shown to be used as feedstock for higher-value bioproducts and can contribute to achieving broad national energy objectives (Jakes et al., 2016; Stokes et al., 2016). However, low bulk density and low energy density are major barriers to valorization of woody biomass residues as renewable energy, particularly forest residues. Thus, transportation tends to be a limiting economic factor when hauling woody biomass, as low bulk density results in high transportation costs (Giuntoli et al., 2015; Kylili et al., 2016; Ranta et al., 2016; Sahoo et al., 2019). Likewise, utilizing low-energy density material such as woody biomass makes it less favorable compared with fossil fuels. In this study, a novel near-woods system of integrated biomass conversion technologies with new timber harvesting operation techniques are suggested to overcome these barriers (Bergman et al., 2018). Applying this approach, transportation of high moisture content woody biomass from the forest is eliminated through field-drying and the fuel characteristics of the biomass is further improved through the processes of forced drying and densification. Although densification does increase the bulk density of biomass feedstock which reduces long-distance transportation costs, it remains an issue by contributing to more than half of the fuel cost (Goh et al., 2013). As an alternative technology, torrefaction, which is a thermal pretreatment process, can be used to achieve higher energy and bulk density. Proskurina et al. (2017) reported that the use of torrefaction technology resulted in a 9% decrease in supply chain costs resulting from higher bulk density. Another study showed that about 5% cost reduction was observed from transportation of torrefied product compared with white briquettes and torrefied wood has lower storage costs compared with wood biomass (Sahoo et al., 2018, 2019). In addition, the product is hydrophobic, has high energy and bulk density and increased grindability which makes it a suitable replacement fuel to coal because of its similar specifications (Nunes et al., 2014; Proskurina et al., 2017; Thran et al., 2016). Replacing coal with energy sources with lower environmental impacts has been a global priority for many countries to mitigate greenhouse gas (GHG) emissions and their resultant impact to climate change (Oberschelp et al., 2019).

In the US, the process of generating electricity is the largest source of CO_2 emissions representing 34% of the US GHG emissions (USEIA, 2018). The US Climate Alliance including seventeen states are committed to achieve at least 26–28% reduction in GHG emissions by 2025 compared with emission levels in 2005 in accordance with the Paris Agreement where Oregon has proposed to eliminate coal-fired power by 2035 (Milman, 2016). As a coal substitute, non-torrefied pellets can be cofired with cofiring ratios up to 10% without modifications and up to 30% with modifications (IRENA/IEA-ETSAP, 2013; Proskurina et al., 2017). Conversely, torrefied wood can replace coal in power plants up to 25% with no modification and 100% with minimal adjustments (Nunes et al., 2014; Proskurina et al., 2017). This makes torrefied wood a viable alternative to coal.

Life Cycle Assessment (LCA) is a widely accepted method used to quantify environmental impacts associated with a product or service taking into account the overall life-cycle. Several studies showed a decrease in GHG emissions from cofiring torrefied wood at coal power plants using LCA (Arteaga-Pérez et al., 2015; Kabir and Kumar, 2012; Thran et al., 2016; Tsalidis et al., 2014; Woytiuk et al., 2017). Most torrefaction LCA studies consider only GHG emissions thus were only partial LCAs. Simply put, these studies did not take into account the other impact categories that the torrefied wood production may have important contribution to. Moreover, previous studies argued that transportation cost and high bulk density are major barriers in post-harvest forest residue utilization. As mentioned, this work considers an integrated system of semimobile biomass conversion technologies to convert field-dried forest residues to non-torrefied briquettes (NTB) and torrefied briquettes (TOB) near where the timber harvest occurred (i.e., near-woods). Use of semimobile systems in remote areas were compared with nearby in-town operations with access to grid electricity. To the best of our knowledge, a complete resource use assessment has not yet been performed for a torrefied biomass supply chain. Therefore, an in-depth resource use assessment was performed using exergetic life cycle assessment (ELCA) to evaluate the resource footprint of these systems. Cumulative Exergy Extracted from the Environment (CEENE) method was used for natural resource accounting (Dewulf et al., 2007). The use of an exergy-based unit in ELCA allows for quantification of all resources, energy and non-energy flows, extracted from the natural environment using a single unit, MJex.

This research was part of a U.S. Department of Energy-funded Biomass Research and development Initiative project called Waste to Wisdom (WTW) (http://wastetowisdom. com/) (Bergman et al., 2018; Han et al., 2018) to investigate and solve the major limitations on recovery of forest residues, a by-product of timber harvest, into bioenergy products. The goal of this particular study was to investigate the potential environmental benefits of utilizing these forest residues using semimobile units for TOB and NTB production for different energy applications using LCA and ELCA.

2. Materials and methods

Life cycle impact assessment (LCIA) and ELCA tools were used for comprehensive environmental evaluation. Both environmental impacts and resource consumption associated with two energy carriers, NTB and TOB, were evaluated. The primary data collected during the WTW project, in which tests on the woody biomass feedstock logistics, near-woods biomass conversion, and product end use were conducted. In this study, LCA guidelines ISO 14040 and ISO 14044 were followed (ISO, 2006a, 2006b). The analysis were performed using SimaPro 8.5 LCA software package (PRé Consultants, 2017).

2.1. Scope

The scope of this LCA included cradle-to-grave life-cycle stages of near-woods production of TOB and NTB starting at procurement of post-harvest forest residues and ending at the use phase (i.e. combustion). Torrefied briquette and NTB supply chains consisted of feedstock procurement (processing, sorting and loading), hauling, feedstock preparation (chipping, screening, and drying), biomass conversion (densification and/or torrefaction), energy product distribution, and product use phase. Since the forest residues are considered as a waste product generated as a result of commercial harvest operations, harvesting processes were excluded from the system boundary. Two alternative uses of the solid biofuels produced were considered: generating thermal energy for domestic heating and generating electricity via cofiring at a coal-fired power plant. For comparison, the thermal energy production from propane for domestic heating and electricity production at coal-fired power plants were considered as the reference supply chains. In line with the reference systems selected, two functional units were defined: 1 MJ of useful heat produced for domestic heating and 1 kWh of electricity generated at a power plant.

2.2. Description of the woody biomass energy product Systems investigated

The system boundaries covered the procurement, preparation, and biomass conversion of forest residues to TOB and NTB, and ended at the grave. The life-cycle level impacts associated with cradle-to-grave supply chain of TOB and NTB were quantified. A cradle-to-grave process flow diagram of TOB and NTB production supply chains are provided in Fig. 1. The biomass preparation and conversion processes were designed as semimobile units to operate near-woods so that biomass conversion occurs close to the biomass feedstock. Thus, units can be transported to other nearby harvest sites. This allows processing of the low-density forest residues closer to the primary landing, a cleared area where the trees are processed 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. Using the same feedstock to produce the biomass fuels, the Power Pallet-PP20 biomass gasifier by All Power Biomass gasification generator set (genset) with engine generator rated at 20 kWe was used for remote power generation (All Power Labs, 2016; Palmer et al., 2018).

2.2.1. Feedstock procurement

The feedstock procurement stage covers recovering pulp logs and tree tops left at the landing after commercial harvesting operations for biomass conversion. Collection of post-harvest residues after forest operations consists of the following activities: processing (delimbing), sorting, and loading along with hauling to the secondary landing (BCT site) (Kizha and Han, 2016). In order to improve the quality of the bioenergy product, tree tops and pulp logs were delimbed for biomass conversion to generate the forest residue feedstock. After air-drying in the forests about one year, the post-harvest residues were collected at the primary landing and loaded onto a dump truck for shuttling to the BCT site. Theoretical BCT sites were designated for five commercial harvest regions in the western US, which was located at the centroid of the watershed. Five scenario locations were used for the analysis: Port Angeles, Washington; Warm Springs, Lakeview, and Oakridge, Oregon, and Quincy, California. Hauling distance from the parcel to the theoretical remote BCT site was based on the weighted average of the five sites and their forest residue availability. The average transport distance traveled from the primary landing to the BCT site for the five locations investigated was 18.8 km (Oneil et al., 2017). Forest residues composed of pulp logs and processed tree tops were transported using mule train (truck with trailer) with a maximum capacity of about 25.9 tonnes.

2.2.2. Feedstock preparation

Feedstock preparation included chipping, screening and (forced) drying in order to achieve the specifications required for feedstock to be torrefied and/or briquetted into bioenergy products. Feedstock was sourced from a common hardwood species in the western US, tan oak (*Notholithocarpus densiflorus*) with a higher heating value (HHV) of 19.6 MJ/kg (dry basis). In this study, the logging slash, the by-product of timber harvesting and commonly referred to as forest residues was left in the forest for air-drying for one year before collection to a moisture content (MC) (wet basis) of 20 ± 3% (Kizha et al., 2018). Torrefaction and briquetting tests were performed using various feedstock moisture contents to identify the optimum MC for the highest quality product (Alanya-Rosenbaum and Bergman, 2016; Severy et al., 2018). As a result, the feedstock MC was further decreased from roughly 20% to 9.3% at the drying process before bioconversion. For the NTB product chain, propane was used to heat the dryer while torrefaction gas (torgas) was used in the TOB supply chain. Yet, because of the low energy content of the torgas, combustion was supplemented with propane fuel to initiate and maintain optimum combustion.

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) generated as a part of the WTW project (Bisson and Han, 2016). Details of forest operations model and the equipment used for feedstock preparation are provided in Oneil et al. (2017).

2.2.3. Woody biomass conversion

Torrefaction, a thermochemical conversion process is performed by heating the biomass feedstock in an oxygen-free environment to a temperature of approximately 200–300 °C (Tumuluru et al., 2011). In this project, torrefaction data came from a semimobile electrically-heated screw-type torrefaction unit (Biogreen, ETIA Group, Compiègne, France, and Norris Thermal Technologies, Tippecanoe, Indiana, USA), which processed about 0.5 tonnes of wood chips per hour. The small-scale torrefaction unit included condensation and filtration, which were used to remove contaminants from the gases released during 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. Bio-oil by-product generated, had a pH of about 2, was neutralized using sodium hydroxide (NaOH), and then disposed to a municipal sewage system. Torgas collected was assumed to be captured and combusted in order to provide heat for the drying process.

Torrefied and non-torrefied wood chips were densified into briquettes using a RUF lignum model briquetter that uses hydraulic cylinders for densification (RUF Briquetting Systems, Zaisertshofen, Germany) (RUF Briquetting Systems, 2016). The produced briquette had dimensions of 63 mm width by 150 mm length by 109 mm height. No binding agents were used in briquetting. The characteristics of the TOB and NTB fuel after biomass conversion are provided in Table 1.

2.2.4. Energy product use phase

Two pathways considered for the use (combustion) phase of

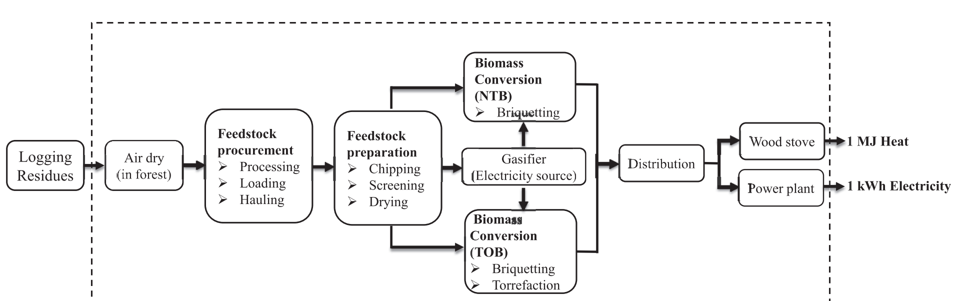

Fig. 1. Torrefied and non-torrefied briquette product systems process chain.

Table 1
Properties of torrefied briquette and non-torrefied briquette products.

Property	Value	
	TOB	NTB
Moisture Content, %, wb[a]	0.6%	8.3%
Ash Content, (%) db[b]	2.5%	3.4%
VM[c], %, db	71%	71%
HHV, MJ/kg db	23.0	19.6

[a] Wet basis.
[b] Dry basis.
[c] Volatile matter.

NTB and TOB produced were producing heat for domestic use from wood stove and electricity generation from a coal-fired power plant. Use phase data for domestic heating scenarios came from the combustion test results provided by Schatz Energy Research Center, (OMNI, 2017). 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). Overall stove efficiency of combusting TOB and NTB at the wood stove were 76% and 72%, respectively (OMNI, 2017).

Data for the use phase of the torrefied biomass at the power plant was retrieved from the data generated as a part of the Consortium for Advanced Wood-to-Energy Solutions (CAWES) project funded by the US Endowment for Forestry and Communities (Endowment), USDA Forest Service. The experimental data generated by Western Research Institute (WRI), 2017 for combusting torrefied briquettes at a power plant came from a 73 kW (250,000 Btu/hr) balanced-draft system. The system was designed to simulate a pulverized coal-fired utility boiler such as the Boardman power plant (WRI, 2017). The Power Plant Flexible Model (PPFM) model developed by the National Energy Technology Laboratory (NETL) provided the emission profiles for the coal-power plant and cofiring model (NETL, 2018). PPFM is an MS-Excel-based tool used to model coal combustion and biomass cofiring-based power generation. The data used in the model was based on a coal-fired power plant with a net plant efficiency of 34.1% operating with an 85% capacity factor, whereas cofiring with NTB resulted in 33.9% net efficiency (NETL, 2018).

2.2.5. Transportation

Besides the feedstock hauling mentioned above, transportation of materials to BCT sites and the final product to user (distribution) were included in the analysis. It was assumed that the briquettes were transported to the end-user in the closest town for use and tractor trailers fueled by diesel were used for transportation. The transportation distance of the product to the end-user for residential heating was about 90 km representing the average 2 h transport time calculated based on the road quality in the region (Oneil et al., 2017). Distribution to the power plant from BCT site was about 211 km based on 4 h travel time.

2.3. Alternative System configurations investigated

Scenario sensitivity analysis was performed using alternative system configurations for evaluation of effect on various changes in the supply chain on the resulting environmental impact. The influence of the remote power generation technology used was evaluated for a woody biomass gasifier generator set (genset) and diesel generator. The biomass gasifier genset was the reference scenario. In addition, the impact of transferring forest residues to an in-town facility instead of performing near-woods bioconversion was quantified. In-town scenarios used grid electricity as its power source. The effect of the moisture content of incoming feedstock was also examined as an alternative scenario. For the alternative scenario, it was assumed that the feedstock received was not air dried in the forest and had a 50% MC (wet basis) which was far wetter than the base-line. Another scenario considered the environmental savings from the avoided pile-and-burn emissions by converting forest residues to solid biofuel instead. To be conservative, it was assumed that only 50% of the forest residue was collected for energy products instead of burnt. The combustion emissions profile from pile-and-burn was adopted from Pierobon et al. (2014). For use phase of bioenergy products in power generation, different biomass co-firing ratios were investigated. The cofiring ratio for NTB was 10% by energy input because biomass cofire applications are generally limited to around 10% in most commercial applications (Agbor et al., 2014; Basu et al., 2011; Woytiuk et al., 2017). On the other hand, higher percentages were evaluated for TOB where even 100% substitution is feasible using torrefied biomass (Nhuchhen et al., 2014; Ndibe et al., 2015). These results highlighted the most critical set of model parameters to improve the interpretation of the environmental impacts found and if data quality required improvement (ISO, 2006b; Wei et al., 2015).

2.3.1. Description of the fossil based reference supply chains

The cradle-to-grave system boundary for the propane system consisted of the extraction of crude oil, propane production, distribution, and heat production at the residential furnace to be used for domestic heating. Propane combustion data was retrieved from Johnson (2012). Details of the propane reference system is provided in Alanya-Rosenbaum and Bergman (2016). Coal-power plant data was generated using PPFM model developed by NETL (NETL, 2018).

2.4. Life cycle inventory

Data used for modelling was broken into two sections. One was for producing the wood chips, and the second was for converting the wood chips into the final products and their use. Table 2 shows the environmental input and output data for one bone-dry metric ton (BDT) of wood chips produced. Primary data for the feedstock procurement, feedstock preparation, biomass conversion and use phase were based on field-based data and experimental studies performed as a part of the WTW project (Bisson and Han, 2016; Kizha and Han, 2016; Kizha et al., 2018; Oneil et al., 2017; Severy et al., 2018). The secondary data such as supply of electricity and manufacturing, transport, and waste disposal came from DATASMART database and peer reviewed literature (Long Trail Sustainability, 2017). 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. The mass loss at the densification process was negligible. Therefore it is assumed that there was no mass loss at the briquetter. At the dryer, propane and torgas were assumed to be combusted with 95% combustion efficiency (McNamee et al., 2016). In addition, heat requirements of the drying process was assumed to be 5 MJ/kg of water removed (Adams et al., 2015). Volatile organic compound (VOC) emissions, which occur during air drying of the fresh biomass feedstock in forest floor and drying process were taken into account. It is assumed that 80% of the VOC emissions occurred in the forest and the rest, 20%, was emitted at the drying process. Since VOC emission data from tanoak were not available, white oak was used as proxy (Beakler et al., 2007).

The environmental inputs and outputs for woody biomass

Table 2
Cradle-to-gate input–output flow analysis for one bone-dry metric ton of wood chips.

Process	Units	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	km	18.77	Oneil et al. (2017)
Feedstock Preparation			
Chipper			
Diesel	L	0.5461	Oneil et al. (2017)
Lubricants	L	0.0098	Oneil et al. (2017)
Screener	L		
Diesel	L	1.5939	Oneil et al. (2017)
Lubricants	L	0.0287	Oneil et al. (2017)
Dryer			
Electricity	kWh	7.14	Process data
Propane	L	20.9	Engineering calculations
VOC[a]	g	2.13	Alanya-Rosenbaum et al. (2018)
Torgas	m^3	212	Process data
Waste heat	MJ	391	Engineering calculations

[a] Volatile organic compound.

conversion and product use phases are provided in Table 3. The data showed were for biomass conversion processes of torrefaction and briquetting (densification), distribution to user for domestic heating and to the power plant for electricity generation, and use phase at wood stove and at power plant. Use-phase data, including stack emissions from combustion of TOB that were obtained from WTW project combustion tests, were complemented by literature data. It was assumed that the briquettes were stored and sold in 15-kg-capacity plastic bags made from low-density polyethylene (LDPE) for domestic heating (Laschi et al., 2016). No packaging was used for the biofuel products distributed to the power plant.

2.5. Life cycle impact assessment modelling

For the life-cycle impact assessment (LCIA) the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) method was used (Bare, 2011; USEPA, 2012). TRACI method was used because it is developed for the US and is consistent with the US EPA regulations, guidelines and policies. All impact categories covered in the TRACI method were considered.

2.6. Sensitivity analysis

Sensitivity analysis was performed using both parameter and scenario-based uncertainty analysis. The parameter sensitivity was tested via contribution to the GW impact for 25% variation in key parameters including briquetter, torrefier and grinder electricity demand, product distribution and feedstock hauling distances,

Table 3
Input-output flows of non-torrefied briquette (NTB) and torrefied briquette (TOB) production and use.[a].

	Units	TOB	NTB	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				
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	0.0039	Operational data
Lubricants	ml/MJ TOB	0.0002	0.0002	Operational data
Packaging				
LDPE packaging	gr/BDT	0.632	0.686	Laschi et al. (2016)
Distribution to user	km	90	90	Oneil et al. (2017)
Distribution to power plant	km	211	211	Oneil et al. (2017)
Grinding	Wh/MJ briquette	5.393	17.989	Operational data
Combustion at wood stove (Use phase)				
CO	gr/MJ briquette	3.4756	5.0638	Operational data
NO_x	gr/MJ briquette	0.0277	0.0375	Operational data
SO_2	gr/MJ briquette	0.0079	0.0073	Khalil et al. (2013)
CH_4	gr/MJ briquette	0.0023	0.0039	Khalil et al. (2013)
VOC	gr/MJ briquette	0.7295	0.7638	Operational data
$PM_{2.5}$	gr/MJ briquette	0.0143	0.0354	Operational data
PM_{10}	gr/MJ briquette	0.1036	0.2175	Operational data
CO_2 (biogenic)	gr/MJ briquette	76.873	85.43	Operational data
Combustion at power plant (Use phase)				
CH_4	gr/MJ briquette	0.0003	–	Kabir and Kumar (2012)
N_2O	gr/MJ briquette	0.0021	–	Kabir and Kumar (2012)
CO	gr/MJ briquette	0.0021	–	Western Research Institute (WRI), 2017
VOC	gr/MJ briquette	0.0013	–	Kabir and Kumar (2012)
NO_x	gr/MJ briquette	0.0751	–	Western Research Institute (WRI), 2017
SO_2	gr/MJ briquette	0.0161	–	Western Research Institute (WRI), 2017
CO_2 biogenic	gr/MJ briquette	72.870	–	Western Research Institute (WRI), 2017
$PM_{2.5}$	gr/MJ briquette	0.0590	–	Yani et al., 2015
PM_{10}	gr/MJ briquette	0.2000	–	Yani et al., 20154

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

Table 4
Environmental performance of 1 MJ of useful heat produced from TOB and NTB.

Impact category	Unit	TOB at wood stove	NTB at wood stove
Ozone depletion	kg CFC-11 eq	1.64E-10	1.27E-11
Global warming	kg CO_2 eq	1.65E-02	7.44E-03
Smog	kg O_3 eq	7.44E-03	2.95E-03
Acidification	kg SO_2 eq	1.41E-04	9.04E-05
Eutrophication	kg N eq	1.26E-05	6.33E-06
Carcinogenics	CTUh	2.67E-10	1.15E-10
Non carcinogenics	CTUh	2.73E-09	1.14E-09
Respiratory effects	kg $PM_{2.5}$ eq	2.40E-05	5.30E-05
Ecotoxicity	CTUe	6.33E-02	2.91E-02

dryer propane requirement, and propane supplement used for torgas combustion.

Monte Carlo simulation is used to estimate the uncertainty of LCIA results associated with the LCI data and its effect on the LCIA. In this project, Monte Carlo analysis was performed by running 10,000 iterations at the 95% confidence interval within SimaPro software. Uncertainty ranges for unit processes were calculated based on the standard deviation from primary data. When standard deviation data were not available, the pedigree matrix algorithm available in SimaPro software was used. Data quality is of the highest importance when conducting environmental assessments such as LCA. Pedigree matrix is a procedure proposed by Weidema and Suhr Weidema and Wesnaes (1996) to assess data quality using five independent data quality indicators: reliability, completeness, temporal, geographical, and technological correlation. In pedigree method, uncertainty factors were calculated based on the scales selected for the pedigree quality indicators. Parameters used for uncertainty analysis are provided in the Appendix A Supplementary data.

2.7. Exergetic life cycle assessment

Cumulative Exergy Extraction from the Natural Environment (CEENE) method was used to evaluate the resource footprint by quantifying total amount of resources extracted from natural environment in exergy units (MJex) (Dewulf et al., 2007). CEENE method categorizes resource consumption under eight main resource use categories; fossil fuels, metal ores, nuclear energy, land occupation, renewable energy flows (wind, hydropower, solar), minerals and mineral aggregates, atmospheric resources, and water resources to calculate of the overall resource demand.

3. Results

3.1. Impact assessment of utilization of forest residues as fuel

The environmental LCIA results associated with generating heat and electricity from TOB and NTB are presented in Table 4 for nine impact categories. NTB showed better performance compared to TOB in domestic heat generation with an exception of the respiratory effects impact category. Higher environmental impact in the TOB supply chain was because of the additional processing required to produce TOB. Note that wood stove was used for the use phase to represent the available technology used today. Yet, combustion of the torrefied briquettes in wood stove was not efficient for using this biofuel. Using advanced stove appropriate for TOB combustion would likely lead to better environmental performance.

The global warming (GW) impact results per MJ of useful heat generated from propane furnace and propane system supplemented with heat generated through combustion of TOB and NTB at wood stove are presented in Fig. 2. Comparative results showed that a 50% substitution of heat from propane with NTB and TOB resulted in 46% and 41% reduction in GW, respectively. A large portion of the GW impact of the TOB supply chain resulted from torrefaction (59%) followed by the drying process (24%). This was due to propane used for torgas combustion. Torgas combustion was supplemented with propane for ignition and steady burn. This was necessary because torgas generated had low heating content. Even

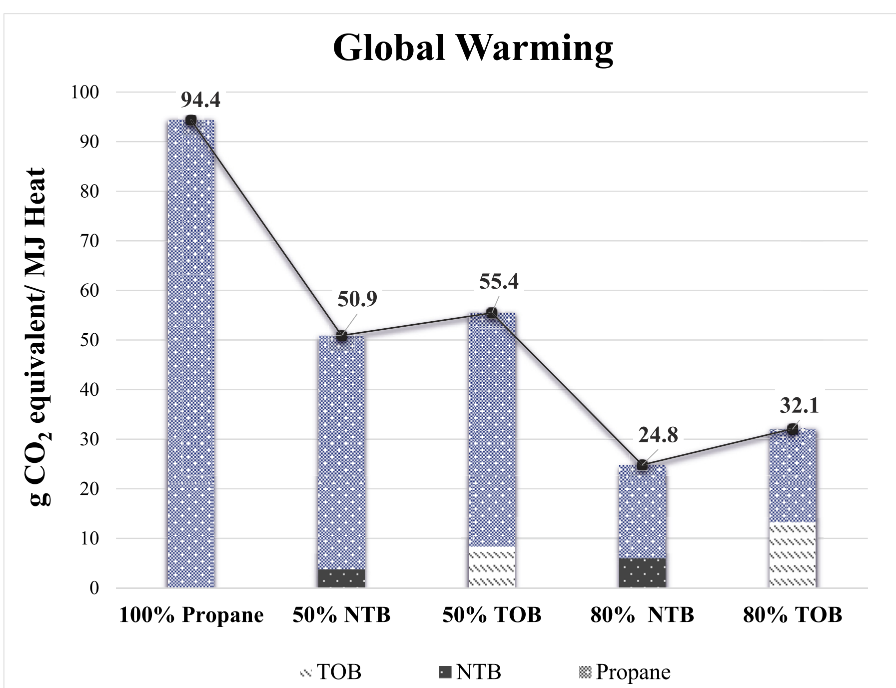

Fig. 2. Comparison of global warming impact results per megajoule of heat generated for domestic heating through a propane furnace (100% propane), a propane system supplemented by TOB and NTB (50% and 80%).

Table 5
Environmental impacts of heat generated for domestic heating at propane furnace in comparison to impacts from propane furnace supplemented with 50% of heat from NTB and TOB.

Impact category	Unit	Propane Furnace	Propane Supplemented by 50% NTB	% Change	Propane Supplemented by 50% TOB	% Change
Ozone depletion	kg CFC-11 eq	1.81E-10	9.70E-11	−46%	1.72E-10	−5%
Global warming	kg CO_2 eq	9.44E-02	5.09E-02	−46%	5.54E-02	−41%
Smog	kg O_3 eq	3.52E-03	3.23E-03	−8%	5.48E-03	56%
Acidification	kg SO_2 eq	1.94E-04	1.42E-04	−27%	1.68E-04	−14%
Eutrophication	kg N eq	3.11E-05	1.87E-05	−40%	2.19E-05	−30%
Carcinogenics	CTUh	1.64E-09	8.79E-10	−46%	9.55E-10	−42%
Non carcinogenics	CTU_h	1.62E-08	8.67E-09	−46%	9.47E-09	−42%
Respiratory effects	kg $PM_{2.5}$ eq	2.93E-06	2.80E-05	854%	1.34E-05	359%
Ecotoxicity	CTU_e	4.16E-01	2.23E-01	−46%	2.40E-01	−42%

though the torrefaction process used an electrically-heated screw system powered by wood gasifier genset, the GW impact was high compared with other processes because of the torgas combustion. Excess torgas was combusted to avoid VOC emissions. The dryer process was the highest contributor to GW impact, about 64% of the overall impact, in NTB supply chain.

Environmental impact assessment results associated with generating heat from propane furnace supplemented by TOB and NTB at wood stove are presented in Table 5 for the rest of the impact categories considered. TOB and NTB supplemented propane heating showed lower impact per useful thermal energy generated in most of the impact categories except respiratory effects for NTB supply chain. Particulate matter (PM) emissions have a high relative contribution to the respiratory effects impact category. Briquette combustion results in higher PM emissions, which were avoided when propane was used. Similarly, use of TOB performed better environmentally except for the respiratory effects and smog impact categories. Higher smog impact at TOB supply chain resulted from combustion phase. This might be due to TOB fuel properties where combustion of TOB at an existing wood stove may require adaptations to achieve better combustion characteristics because of its properties such as higher fixed carbon content (SECTOR, 2015).

Environmental impact assessment results associated with cofiring with TOB and NTB are presented in Fig. 3 and Fig. 4. Cofiring with biomass, leads to major reduction on the GW impact, while it reaches 82% when coal is completely substituted with TOB.

With the exception of ozone depletion potential, smog, eutrophication and ecotoxicity impact categories, electricity generation through cofiring with NTB and TOB led to a reduction in environmental impact in comparison to electricity generation from coal. For these impact categories, reductions for a 10% cofire ratio ranged 2–6% for NTB and 3–8% for TOB. Most ozone depletion potential in TOB cofiring resulted from the grinding (55%) process. It is followed by the torrefaction process (40%), due to NaOH used for neutralization of bio-oil before it is disposed to municipal sewer. Propane use in the torrefaction process was responsible for the higher

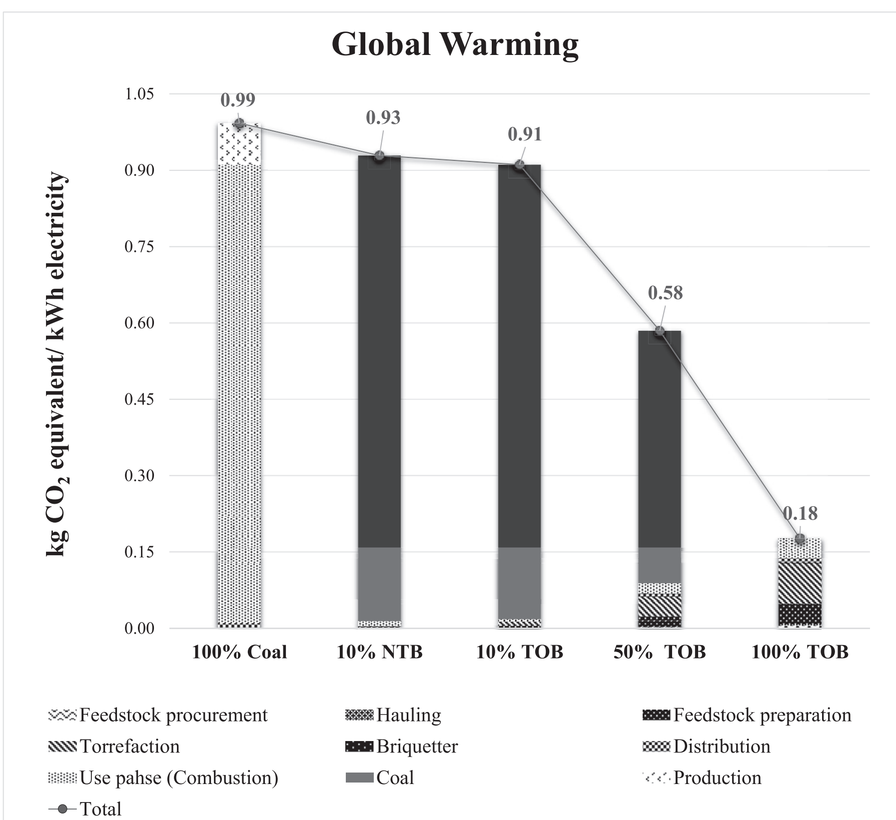

Fig. 3. Comparison of global warming impact per 1 kWh electricity generated from 100% coal, cofire with NTB (10%) and TOB (10%, 50% and 100%) at coal-fired power plant.

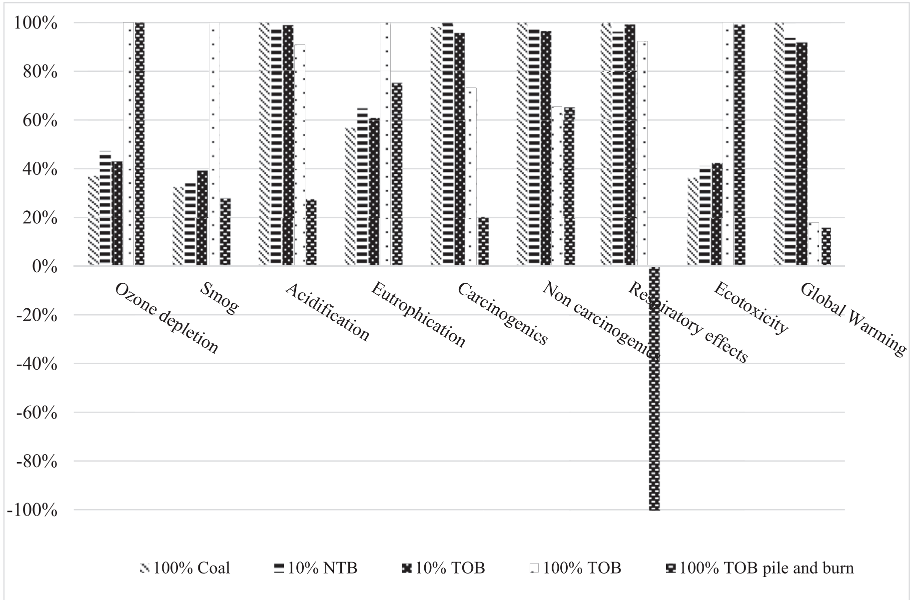

Fig. 4. Environmental impacts from cofiring with NTB and TOB for electricity generation at coal fired power plant.

eutrophication and ecotoxicity impacts, because combustion of torgas was supplemented with propane. The torrefaction process was the key player in most impact categories for TOB supply chain since it involved propane consumption. Substantial decrease in respiratory effects occurred when avoided pile-and-burn emissions were considered. This would be expected considering the consequences associated with uncontrolled burning (Fann et al., 2018; Reid et al., 2016).

3.1.1. LCIA of the scenarios investigated

The GW impact results per megajoule of heat generated from TOB through various scenarios was compared (Fig. 5). Analysis showed that the near-woods operation using a wood gasifier as the power source (S1) was the most favorable scenario, while remote operation using diesel power was the worst alternative scenario (S2). A 19% reduction in GW impact was achieved when the benefits from avoided pile-and-burn emission (S6) were taken into account. As suggested in this study, the near-woods operation had a higher environmental performance compared with in-town operation where feedstock was transported for 2-h (S3) or 4-h (S4) drive (maximum) to an in-town facility with access to grid electricity. The GW impact was 55% and 57% higher for S3 and S4 scenarios compared with S1, respectively. High feedstock MC scenario resulted in a 55% increase in total GW impact (S5) because of higher

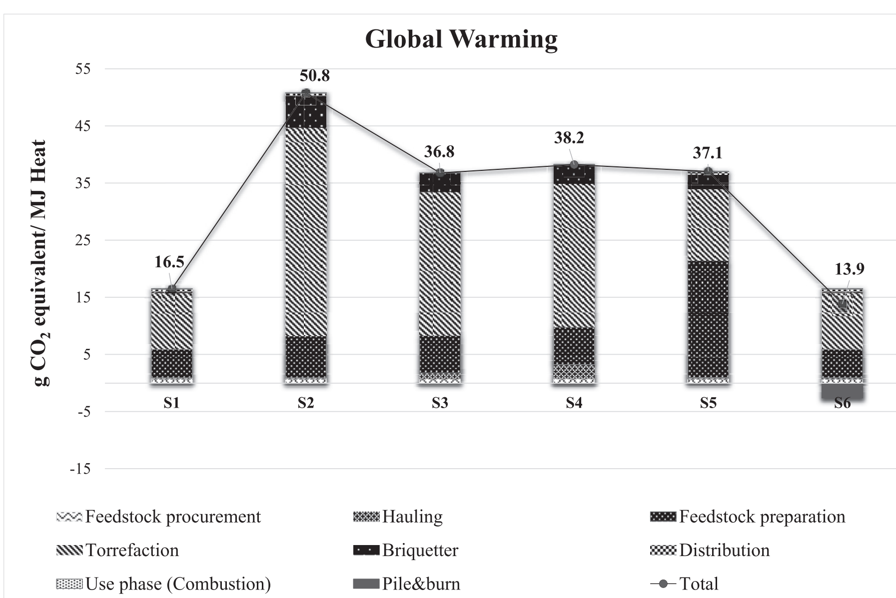

Fig. 5. Contribution of processes to overall global warming impact per megajoule of heat generated for six scenarios investigated. S1: near-woods operation with wood gasifier power; S2: near-woods operation with diesel power; S3: in-town operation (2-h travel distance) with grid power; S4: in-town operation (4-h travel distance) with grid power; S5: 50% moisture content feedstock, near-woods operation with wood gasifier power; S6: near-woods operation with wood gasifier power with pile-and-burn credit.

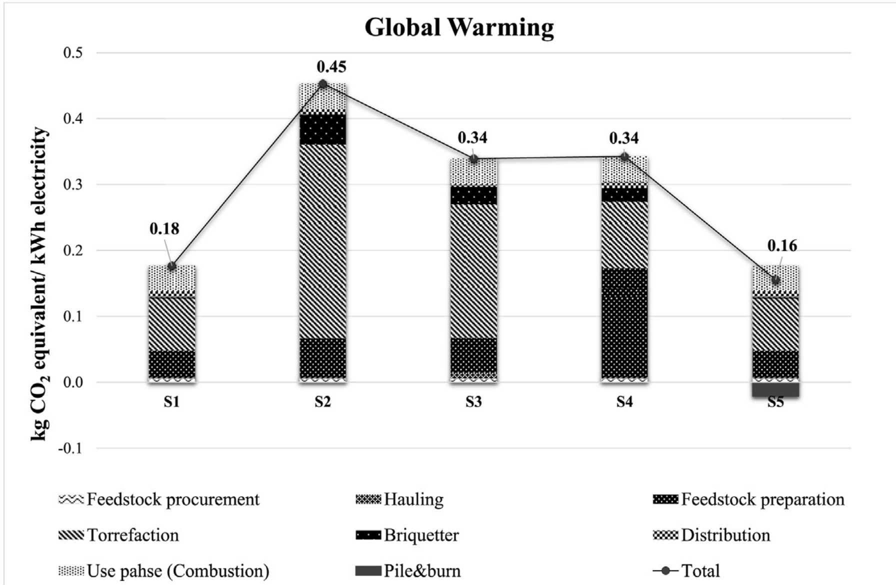

Fig. 6. Contribution of processes to overall global warming impact per 1 kWh of electricity generated for five scenarios investigated. S1: near-woods operation with wood gasifier power; S2: near-woods operation with diesel power; S3: in-town operation with grid power; S4: 50% MC feedstock, near-woods operation with wood gasifier power; S5: near-woods operation with wood gasifier power with pile-and-burn credit.

heat demand at the dryer. The S6 scenario had the lowest GW impact because it both used a wood gasifier gen-set in a near-wood operation and considered the GHG reduction from avoiding the pile and burning of 50% of the forest residues.

Fig. 6 shows the GW contribution of the various processes for a given scenario for generating electricity. For example, total GW impact of producing 1 kWh of electricity from TOB was nearly 180 g CO_2 eq. for the base scenario (S1) but improved by 14% reduction when pile-and-burn credits (S5) were taken into account. Analysis showed that near-woods operation using diesel power for a remote (off-grid) power generation source was the least favorable alternative (S2). Using diesel generator instead of wood gasifier gen-set for remote power generation resulted in 61% higher GHG emissions. Similarly, transporting feedstock maximum 2 h (S3) to an in-town facility with access to grid electricity for processing increased the GW impact by 48%. High feedstock MC scenario resulted in a 48% increase in total GW impact (S5), due to increased propane use for drying. Transporting feedstock to an in-town facility (S3) for processing increased global warming impact of hauling from 1.82 to 8.75 g CO_2 eq per kWh of electricity generated. Like S6 scenario above for producing heat, the S5 scenario for generating electricity had the lowest GW impact for the same two reasons.

Comparative results showed that the remote biomass conversion using gasifier genset was favorable for the rest of the impact categories over alternative options except for smog and respiratory impact categories (Fig. 7). Yet, when pile-and-burn credit was considered, it was the option with least environmental impact for processing forest residues in all impact categories. With respect to

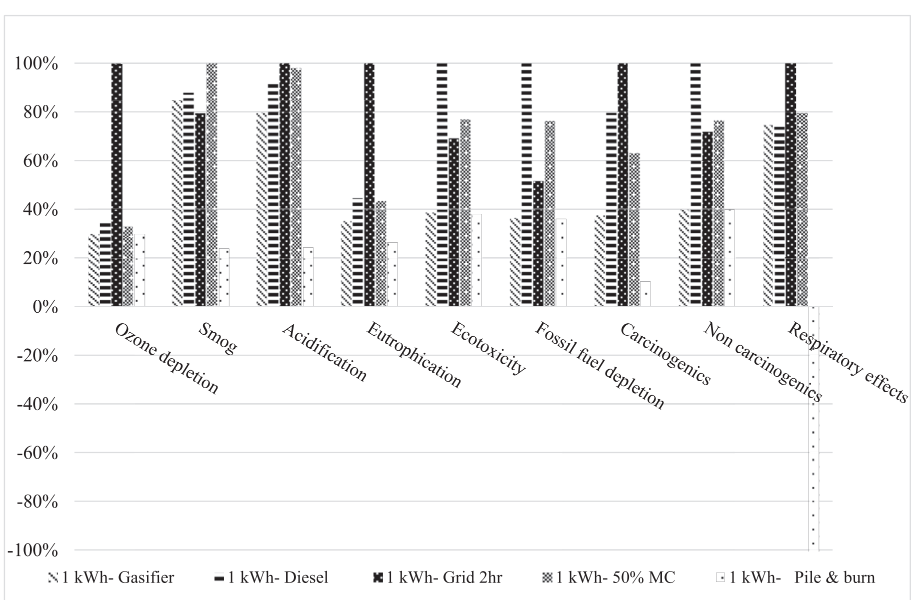

Fig. 7. Summary of the comparative life cycle impact assessment results for five scenarios for TOB production system for generating 1 kWh of electricity.

smog impact category the nitrogen oxide emission at use phase was the major contributor.

3.2. Resource footprint of utilization of forest residues

Fig. 8 shows the results of the comparative CEENE analysis for various fuels investigated. The total resource footprint of producing heat for domestic heating using TOB and NTB with a wood stove was about 0.23 and 0.10 MJex per MJ thermal heat generated, respectively. Use of renewable fuel generated through utilization of forest residues for domestic heating had a significant influence on the overall resource footprint, where use of NTB and TOB resulted in about 93% and 84% less exergy consumption, respectively. About 1.06 MJex reduction was achieved per kWh electricity generated through substitution of coal with TOB at a coal-fired plant for power generation.

The normalized results of the CEENE analysis are presented for all scenarios for the seven resource categories in Fig. 9. The contribution analysis showed that the torrefaction process in the domestic heating scenario accounted for a considerable share of the minerals, metal ores, water resources and land and biotic resources. This was mainly due to NaOH use for bio-oil neutralization which was unexpected. Similarly the torrefaction process was the second major contributor to these resource categories in the electricity generation from TOB in which the major contributor was the grinding process. Most exergy extraction at the use of NTB at the wood stove supply chain resulted from the dryer process due to propane consumed, followed by other feedstock preparation processes, screening and chipping.

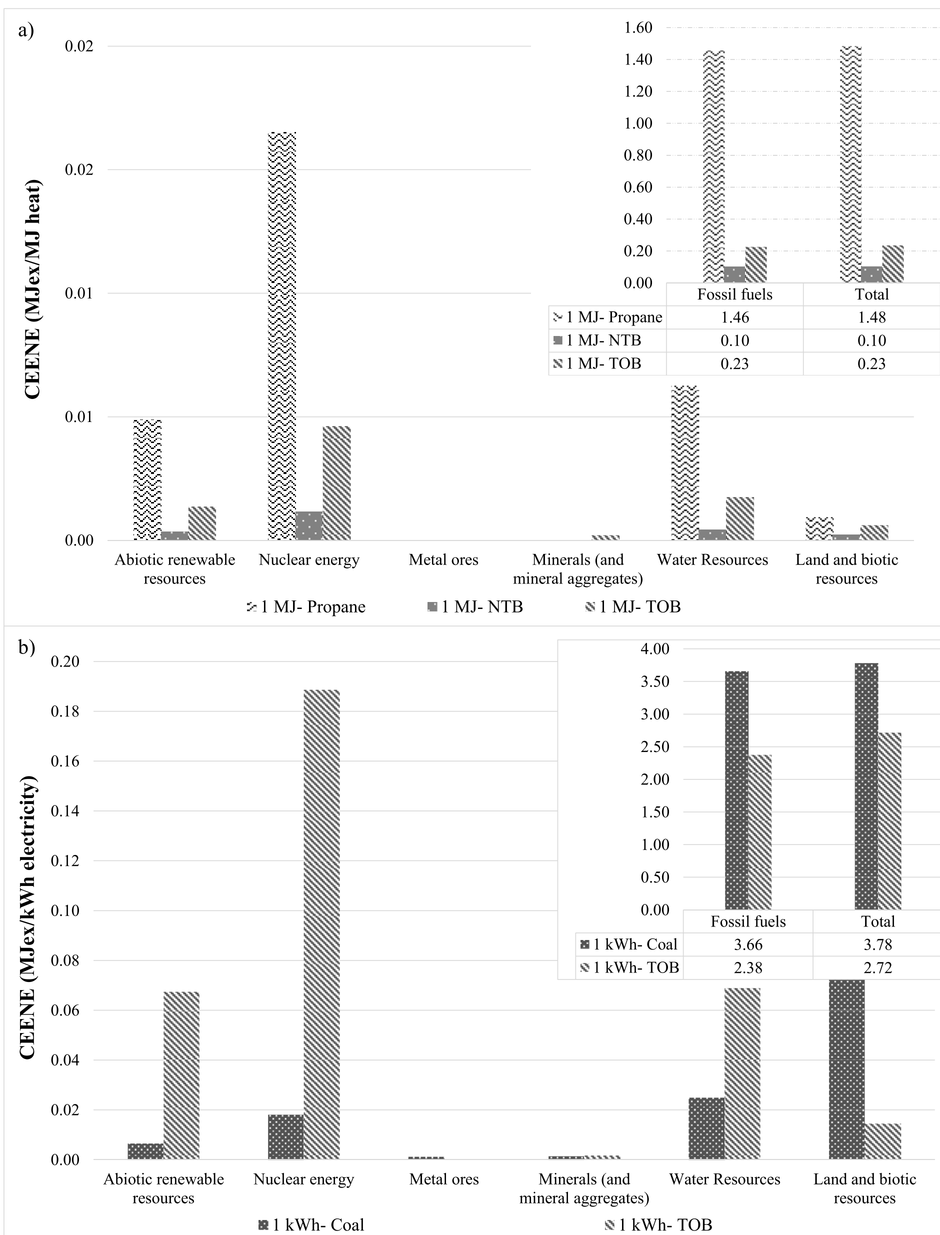

Fig. 8. Results of the comparative CEENE analysis for; a: per 1 MJ of heat generated for domestic heating from propane, NTB and TOB; b: 1 kWh of electricity generated from coal and TOB at power plant.

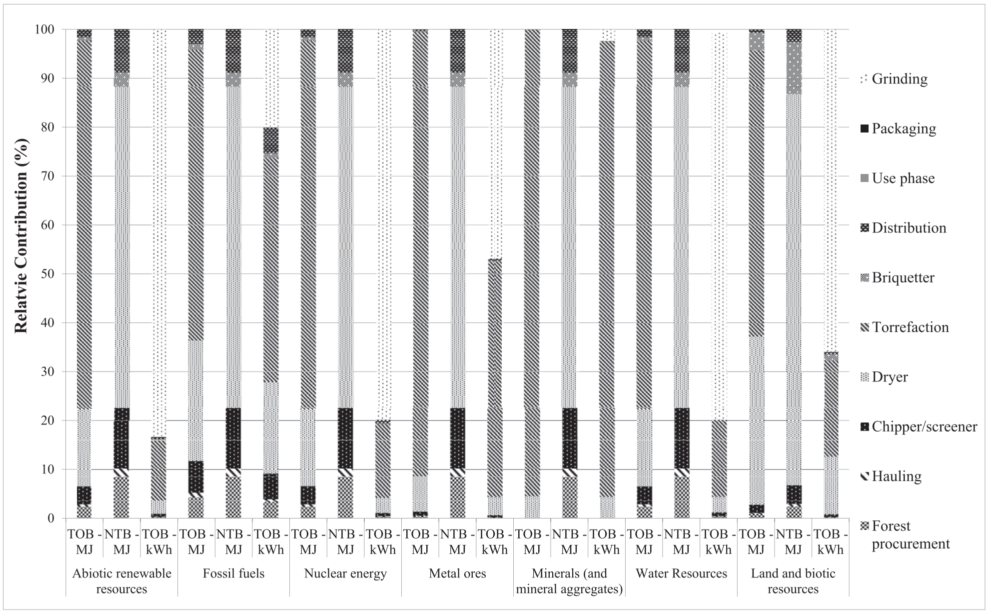

Fig. 9. A relative contribution of unit processes to seven resource categories for heat generated from combustion of TOB and NTB at wood stove, and electricity production form TOB at power plant (%).

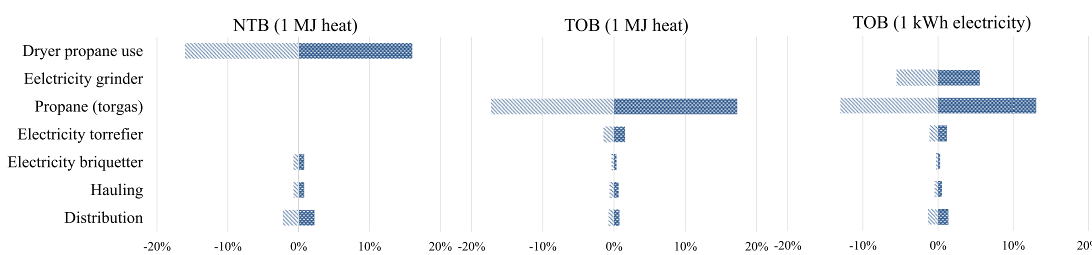

Fig. 10. Sensitivity of key parameters on global warming impact.

3.3. Sensitivity analysis

Parameter based sensitivity analysis was performed where the sensitivity of the GW impact was examined for 25% variation in key parameters including: briquetter and torrefier electricity demand, product distribution and feedstock hauling distances, grinder electricity use, dryer propane use and propane supplement used for torgas combustion (Fig. 10). Sensitivity analysis showed that propane supplement used for torgas combustion was a key parameter with large influence on variation in the GW impact at the torrefaction supply chain. Propane consumption at the dryer was influential on the resulting GW impact at NTB supply chain, while the GW was not sensitive to other parameters.

Fig. 11 shows the 95% confidence intervals from the Monte Carlo analyses on the ten impact categories. The error bars suggest that a large degree of uncertainty was introduced into the eutrophication and carcinogenic impact scores of the use of TOB at the power plant. Nontorrefied briquette product system had higher uncertainty in the respiratory effects impact. Global warming impact scores showed relatively lower uncertainty interval compared with other impact scores.

Monte Carlo analysis results showing the effect of the LCI on the GW impact are presented in Fig. 12. The results showed that NTB for the wood stove scenario had a lower GW potential compared with TOB at the wood stove, where the 90% confidence interval of GW impact was expected to be 6.9–8.1 g CO_2 eq/MJ heat and the 25th to the 75th percentile were between 7.2 and 7.7 CO_2 eq/MJ heat. In almost 100% of the cases, all the impact scores for the NTB scenario except for the respiratory effects were lower compared with TOB scenario (Fig. 12c). In 88% of the cases, the respiratory effects score was higher for NTB scenario, meaning that it was almost certain that the TOB scenario had a lower score in this impact category.

4. Conclusions

The environmental impacts and the resource footprint of NTB and TOB production from post-harvest forest residues from timber harvesting were quantified using cradle-to-grave LCA and exergetic LCA. Consistent with previous studies use of NTB and TOB for substitution of their fossil alternatives resulted in increased environmental performance, particularly in GW impact (Arteaga-Pérez et al., 2015; Kabir and Kumar, 2012; Thran et al., 2016; Tsalidis et al., 2014; Woytiuk et al., 2017). In addition, it is shown that reduction in overall resource footprint was achieved. Therefore, production of NTB and TOB ought not to be limited because of the environmental performance has shown.

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, different remote power sources, feedstock MC and pile-and-burn credits on the GW scores. The torrefaction process used an electrically-heated screw system, therefore in-town scenarios using grid electricity, which

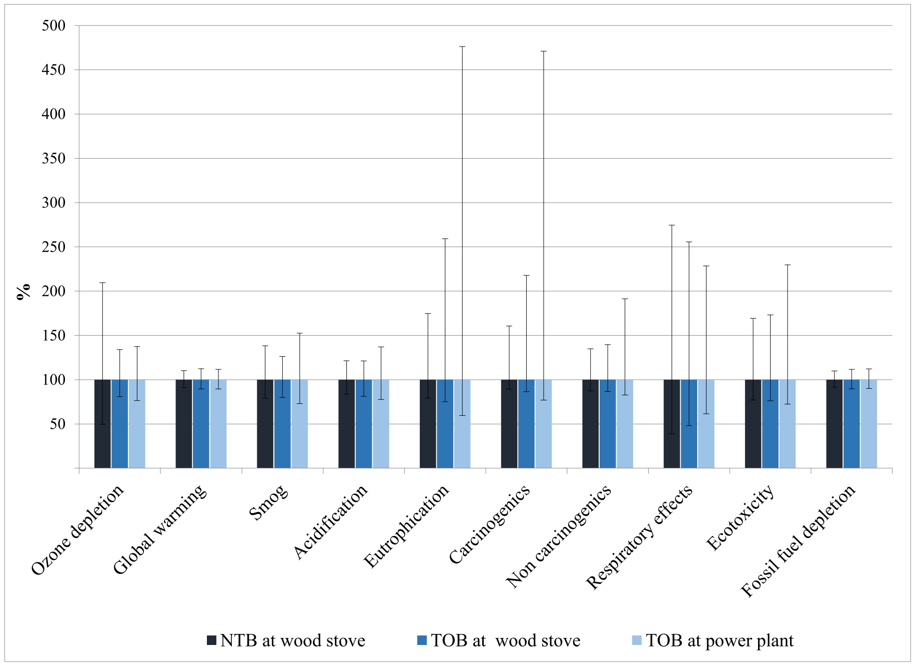

Fig. 11. Effect of parameter uncertainty on environmental impact assessment results for the ten impact categories for heat generation from NTB and TOB at stove and electricity generation from TOB at power plant. Results from the Monte Carlo simulations are for 95% confidence interval.

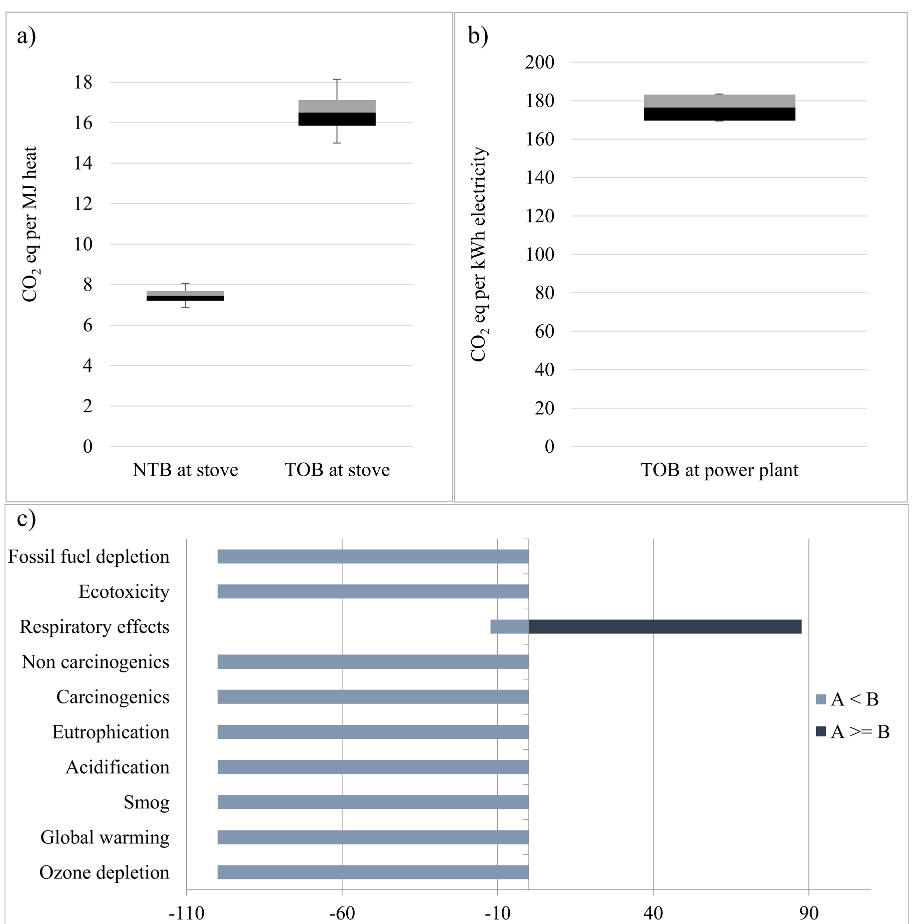

Fig. 12. Monte Carlo results from heat generation from NTB (a) and TOB (b) at stove and electricity generation from TOB at power plant for the GW impact category. Upper and lower borders of the box plot represent the 25th and 75th percentiles with error bars representing the 5th and 90th percentiles. Uncertainty comparison between 1 MJ of heat generation from NTB and TOB at wood stove scenarios per impact category (c).

was mainly based on fossil fuel resources, had higher GW impact compared with near-woods operation. Near-wood operations for processing forest residues using a wood gasifier genset would be the preferred environmental choice.

Global warming impact was highly dependent on the drying process at NTB product system and torgas management and drying at the TOB product system. The low heating content of the torgas itself required torgas combustion to be aided by propane, which increased the environmental impacts associated with propane use. One reason for this was the separation of bio-oil from the torgas resulting in decreased torgas heating content. In addition to decreasing the heating value of torgas, disposal of bio-oil also generated additional environmental burden for the product system. For better environmental performance 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 are recommended. In addition, eliminating the condensation step and burning torgas without separating bio-oil would likely yield better overall environmental performance. Obviously, these listed process improvements for this novel integrated system of semimobile biomass conversion technologies to produce energy products would occur if the technology itself moved into the commercial stage.

Acknowledgments

This material is based upon work supported by a grant from the US 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 through an interagency agreement between the US.Department of Energy and the US Department of Agriculture Forest Service. ORISE is managed by Oak Ridge Associated Universities (ORAU) under DOE contract number DE-AC05-06OR23100. All opinions expressed in this paper are the author's and do not necessarily reflect the policies and views of USDA, DOE, or ORAU/ORISE.

We thank Matt Krumenauer, Vice President Special Projects US Endowment for Forestry and Communities, and Wayne Lei, Chief Technical Officer at Oregon Torrefaction and Nico Wibisono from Western Research Institute, for data acquisition on use of torrefied wood at power plants. We would also like to show our gratitude to Arne Jacobson, Mark Severy, Anthony J. Eggink, Kyle Palmer from Schatz Energy Research Center and Elaine Oneil from University of Washington for their assistance.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2019.05.298.

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. https://doi.org/10.1016/j.apenergy.2014.11.002.

Agbor, E., Zhang, A., Kumar, A., 2014. A review of biomass co-firing in North America. Renew. Sustain. Energy Rev. 40, 930–943. https://doi.org/10.1016/j.rser.2014.07.19.

Alanya-Rosenbaum, S., Bergman, R., 2016. Gate-to-gate life cycle inventory analysis of torrefying post-harvest logging residues. In: Proceedings of the Forest Products Society 70th International Convention, (Pp. 1-8). Portland, OR.

Alanya-Rosenbaum, S., Bergman, R., Ganguly, I., Pierobon, F., 2018. A comparative life-cycle assessment of briquetting logging residues and lumber manufacturing coproducts in western United States. Appl. Eng. Agric. 34 (1), 11–24. https://doi.org/10.13031/aea.12378.

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

Arteaga-Pérez, L., Vega, M., Rodríguez, L., Flores, M., Zaror, C., Ledón, Y., 2015. Life-Cycle Assessment of coal–biomass based electricity in Chile: focus on using raw vs torrefied wood. Energy Sustain. Dev. 29, 81–90. https://doi.org/10.1016/j.esd.2015.10.004.

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), 687–696. https://doi.org/10.1007/s10098-010-0338-9.

Basu, P., Butler, J., Leon, M., 2011. Biomass co-firing options on the emission reduction and electricity generation costs in coal-fired power plants. Renew. Energy 36, 282–288. https://doi.org/10.1016/j.renene.2010.06.039.

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

Bergman, Rick, Berry, Michael, Bilek, E.M., Ted), Bowers, Tait, Eastin, Ivan, Ganguly, Indroneil, Han, Han-Sup, Hirth, Kolby, Jacobson, Arne, Karp, Steve, Oneil, Elaine, Page-Dumroese, Deborah, S., Pierobon, Francesca, Puettmann, Maureen, Rawlings, Craig, Rosenbaum, Sevda Alanya, Sahoo, Kamalakanta, Sasatani, Daisuke, Sessions, John, Sifford, Cody, Waddell, Tom, 2018. Waste to Wisdom: utilizing forest residues for the production of bioenergy and biobased products. Final Report: Biomass Research and Development Initiative Program Award Number DE-EE0006297. U.S. Department of Energy, Washington, DC, p. 65.

Bisson, J., Han, H., 2016. Quality of feedstock produced from sorted forest residues. Am. J. Biomass Bioenergy 5, 81–97. https://doi.org/10.7726/ajbb.2016.1007.

Consultants, PRé, 2017. SimaPro 8 Life-Cycle Assessment Software Package. Version 8. Plotter 12. Retrieved January 15, 2017, from. www.pre.nl/.

Dennison, P., Brewer, S., Arnold, J., Moritz, M., 2014. Large Wildfire Trends in the Western United States, 1984–2011, vol. 41, pp. 2928–2933. https://doi.org/10.1002/2014GL059576.

Dewulf, J., Bösch, M., De Meester, B., Van der Vorst, G., Van Langenhove, H., Hellweg, S., Huijbregts, M., 2007. Cumulative exergy extraction from the natural environment (CEENE): a comprehensive life cycle impact assessment method for resource accounting. Environ. Sci. Technol. 41, 8477–8483. https://doi.org/10.1021/es0711415.

Fann, N., Alman, B., Broome, R., Morgan, G., Johnston, F., Pouliot, G., Rapplod, A., 2018. The health impacts and economic value of wildland fire episodes in the US: 2008–2012. Sci. Total Environ. 610–611, 802–809. https://doi.org/10.1016/j.scitotenv.2017.08.024.

Giuntoli, J., Caserini, S., Marelli, L., Baxter, D., Agostini, A., 2015. Domestic heating from forest logging residues: environmental risks and benefits. J. Clean. Prod. 99, 206–216. https://doi.org/10.1016/j.jclepro.2015.03.025.

Goh, C., Junginger, M., Bradley, D., Hektor, B., Wild, M., Deutmeyer, M., Schouwenberg, P.P., Hess, R., Tumuluru, J.S., Bradburn, K., 2013. Low Cost, Long Distance Biomass Supply Chains. Report for IEA Bioenergy Task 40. Utrecht, NL.

Han, H.-S., Jacobson, A., Bilek, E., Sessions, J., 2018. Waste to wisdom: utilizing forest residues for the production of bioenergy and biobased products. Appl. Eng. Agric. 34 (1), 5–10. https://doi.org/10.13031/aea.12774.

IRENA/IEA-ETSAP, 2013. Biomass Co-firing in Coal Power Plants. Technology-Policy Brief E21.

ISO, 2006a. ISO 14040: Environmental Management—Life-Cycle Assessment—Principles and Framework. International Organization for Standardization, Geneva, Switzerland.

ISO, 2006b. ISO 14044: Environmental Management—Life-Cycle Assessment—Requirements and Guidelines. International Organization for Standardization, Geneva, Switzerland.

Jakes, J., Arzola, X., Bergman, R., Ciesielski, P., Hunt, C., Rhabar, N., Tshabalala, M., Wiedenhoeft, A.C., Zelinka, S., 2016. Not just lumber – utilizing wood in the sustainable future of materials, chemicals, and fuels. JOM 68 (9), 2395–2404.

Johnson, E., 2012. Carbon footprints of heating oil and LPG heating systems. Environ. Impact Assess. Rev. 35, 11–22. https://doi.org/10.1016/j.eiar.2012.01.004.

Kabir, M., Kumar, A., 2012. Comparison of the energy and environmental performances of nine biomass/coal co-firing pathways. Bioresour. Technol. 122, 394–405. https://doi.org/10.1016/j.biortech.2012.07.106.

Khalil, K., Bach, Q., Skreiberg, O., Tran, K., 2013. Performance of a residential pellet combustor operating on raw and torrefied spruce and spruce-derived residues. Energy Fuels 27, 4760–4769. https://doi.org/10.1021/ef400595f.

Kizha, A., Han, H., 2016. Processing and sorting forest residues: cost, productivity and managerial impacts. Biomass Bioenergy 93, 97–106. https://doi.org/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. https://doi.org/10.13031/aea.12427.

Kylili, A., Christoforou, E., Fokaides, P., 2016. Environmental evaluation of biomass pelleting using life cycle assessment. Biomass Bioenergy 84, 107–117. https://doi.org/10.1016/j.biombioe.2015.11.018.

Laschi, A., Marchi, E., S, 2016. Environmental performance of wood pellets' production through life cycle analysis. Energy 103, 469–480. https://doi.org/10.1016/j.energy.2016.02.165.

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. DATASMART life cycle inventory. Retrieved from. https://ltsexperts.com/wp-content/uploads/2017/06/DATASMART-End-User-Licence-Agreement_May-2017.pdf.

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 Convers. Manag. 113, 177–188. https://doi.org/10.1016/j.enconman.2016.01.006.

Milman, O., 2016. Oregon Becomes First State to Pass Law to Completely Eliminate Coal-Fired Power. Retrieved December 27, 2018, from. https://www.theguardian.com/environment/2016/mar/03/oregon-coal-climate-law-kate-brown.

Ndibe, C., Maier, J., Scheffknecht, G., 2015. Combustion, cofiring and emissions characteristics of torrefied biomass in a drop tube reactor. Biomass Bioenergy 79, 105–115. https://doi.org/10.1016/j.biombioe.2015.05.010.

NETL, 2018. April 15). Power Plant Flexible Model. Retrieved from. https://www.netl.doe.gov/research/energy-analysis/search-publications/vuedetails?id=785.

Nhuchhen, D., Basu, P., Acharya, B., 2014. A comprehensive review on biomass torrefaction. Int. J. Renew. Energy Biofuels 1–56. https://doi.org/10.5171/2014.506376, 2014.

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. https://doi.org/10.1016/j.rser.2014.07.181.

Oberschelp, C., Pfister, S., Raptis, C., Hellweg, S., 2019. Global emission hotspots of coal power generation. Nat. Sustain. 2 (2), 113–121. https://doi.org/10.1038/s41893-019-0221-6.

OMNI, 2017. Comparative Fuels Study Radiant Heat, Air Emissions and Efficiency of Formed Raw Biomass Briquettes and Torrefied Briquettes. OMNI Test Laboratories, Inc, Portland, OR.

Oneil, E., Comnick, J., Rogers, L., Puettmann, M., 2017. Waste to Wisdom: Integrating Feedstock Supply, Fire Risk and Life Cycle Assessment into a Wood to Energy Framework. Final Report. Consortium for Research on Renewable Industrial Materials.

Palmer, K., Severy, M., Chamberlin, C., Eggink, A., Jacobson, A., 2018. Performance analysis of a biomass gasifier genset at varying operating conditions. Appl. Eng. Agric. 34 (1), 135–143. https://doi.org/10.13031/aea.12414.

Pierobon, F., Ganguly, I., Anfodillo, T., Eastin, I., 2014. Evaluation of environmental impacts of harvest residue-based bioenergy using radiative forcing analysis. For. Chron. 90 (5), 577–585. https://doi.org/10.5558/tfc2014-120.

Proskurina, S., Heinimo, J., Schipfer, F., Vakkilainen, E., 2017. Biomass for industrial applications: the role of torrefaction. Renew. Energy 111, 265–274. https://doi.org/10.1016/j.renene.2017.04.015.

Ranta, T., Föhr, J., Soininen, H., 2016. Evaluation of a pilot-scale wood torrefcaction plant based on pellet properties and Finnish market economics. Int. J. Energy Environ. 7 (2), 159–168.

Reid, C., Brauer, M., Johnston, F., Jerrett, M., Balmes, J., Elliott, C., 2016. Critical review of health impacts of wildfire smoke exposure. Environ. Health Perspect. 124 (9), 1334–1343. https://doi.org/10.1289/ehp.1409277.

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

Sahoo, K., Bilek, E., Mani, S., 2018. Techno-economic and environmental assessments of storing woodchips and pellets for bioenergy applications. Renew. Sustain. Energy Rev. 98, 27–39. https://doi.org/10.1016/j.rser.2018.08.055.

Sahoo, K., Bilek, E., Bergman, R., Mani, S., 2019. Techno-economic analysis of producing solid biofuels and biochar from forest residues using portable systems. Appl. Energy 235, 578–590. https://doi.org/10.1016/j.apenergy.2018.10.076.

SECTOR, 2015. Production of Solid Sustainable Energy Carriers from Biomass by Means of Torrefaction. Deliverable No. D10.3. Brussels.

Severy, M., Chamberlin, C., Jacobson, A., 2018. Analysis of process and products from mobile biomass torrefaction and briquetting demonstration plant. Appl. Eng. Agric. ASABE Spec. Collect. Publ. 34 (1), 85–98. https://doi.org/10.13031/aea.12376.

Stokes, B., Rials, T., Johnson, L., Abt, K., Nepal, P., Skog, K.E., Abt, R.C., He, L., English, B., 2016. Chapter 3 - at the roadside: forest resources. 2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy, Volume 1: Economic Availability of Feedstock. ORNL/TM-2016/160. Oak Ridge National Laboratory. U.S. Department of Energy, Oak Ridge.

Thran, D., Witt, J., Schaubach, K., Kiel, J., Carbo, M., Maier, J., Ndibe, C., Koppejan, J., Alakangas, E., Majer, S., Schipfer, F., 2016. Moving torrefaction towards market introduction e Technical improvements and economic-environmental assessment along the overall torrefaction supply chain through the SECTOR project. Biomass Bioenergy 89, 184–200. https://doi.org/10.1016/j.biombioe.2016.03.004.

Tsalidis, G., Joshi, Y., Korevaar, G., Jong, W., 2014. Life cycle assessment of direct co-firing of torrefied and/or pelletised woody biomass with coal in The Netherlands. J. Clean. Prod. 81, 168e177. https://doi.org/10.1016/j.jclepro.2014.06.049.

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. https://doi.org/10.1002/bbb.324.

USDA Forest Service, 2005. A strategic assessment of forest biomass and fuel reduction treatments in western states. Gen. Tech. Rep. RMRS-GTR-149. U.S, Fort Collins, CO.

USEIA, 2018. How much of U.S. carbon dioxide emissions are associated with electricity generation? Retrieved January 29, 2019, from. https://www.eia.gov/tools/faqs/faq.php?id=77&t=11.

USEPA, 2012. Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) TRACI Version 2.1 User's Guide. Office of Research and Development, Cincinnati, OH.

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

Wei, W., Pyrene, L., Thierry, F., Nicolas, D., Philippe, R., Jean-Denis, M., 2015. How to conduct a proper sensitivity analysis in life cycle assessment: taking into account correlations within LCI data and interactions within the LCA calculation model. Environ. Sci. Technol. 49 (1), 377–385. https://doi.org/10.1021/es502128k.

Weidema, B., Wesnaes, M., 1996. Data quality management for life cycle inventories—an example of using data quality indicators. J. Clean. Prod. 4, 167–174.

Western Research Institute (WRI), 2017. Combustion Evaluation of Torrefied Biomass for Heat and Power Generation. Laramie, WY.

Woytiuk, K., Sanscartier, D., Amichev, B., Campbell, W., Rees, K., 2017. Life-cycle assessment of torrefied coppice willow co-firing with lignite coal in an existing pulverized coal boiler. Biofuels Bioprod. Bioref. 11, 830–846. https://doi.org/10.1002/bbb.1788.

Yani, S., Gao, X., Wu, H., 2015. Emission of inorganic PM10 from the combustion of torrefied biomass under pulverized-fuel conditions. Energy Fuels 29, 800–807. https://doi.org/10.1021/ef5023237.