GATE-TO-GATE LIFE CYCLE INVENTORY ANALYSIS OF TORREFYING POST-HARVEST LOGGING RESIDUES

Waste to Wisdom: Subtask 4.7.4

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ABSTRACT

In the United States (U.S.), nearly 93 million dry tonnes of forest removals are generated annually, 73% of which is the result of logging residues. Today, biomass is considered a promising feedstock for renewable energy production and utilization of forest residues for energy production may be a favorable alternative to decrease fossil fuel use in U.S. Through the life-cycle assessment method, identifying environmental 'hotspots' or areas of environmental concern of new bioenergy technology can guide future development. This paper documented the gate-to-gate life cycle inventory developed for bioconversion of post-harvest forest logging residues to bioenergy product using torrefaction technology. The functional unit in this study was defined as 1 MJ of energy delivered by the torrefaction system. The system boundary of the torrefaction system analyzed included feedstock preparation, drying, torrefaction, and cooling unit processes. All the primary data related to the inputs and outputs of the processes were obtained by on-site measurements while secondary data were derived from peer reviewed literature and LCI databases like the US LCI Database.

The results showed that the cumulative energy consumption for production of 1 MJ of torrefied wood range between 0.66-0.85 MJ/MJ. Torrefaction process had the largest share in overall energy consumption, which was attributed to high electricity consumption. Similarly, majority of the fossil carbon emissions came from torrefaction process due to electricity consumption.

Keywords: life cycle inventory, bioenergy, torrefaction, biomass conversion

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INTRODUCTION

In the United States (US) greenhouse gas (GHG) emission resulting from the electric power industry was about 30% of the total GHG emissions in 2014 (US Environmental Protection Agency [EPA] 2016). At the global level, there is an increase in environmental sustainability initiations and new policies to combat climate change due to increasing global environmental concerns. Mitigation of GHG emissions and achieving energy independence via reducing dependence on fossil fuels are major challenges that can be overcome by adopting use of renewable energy sources. Therefore, today, there is a high demand for establishing renewable energy sources.

Forest (logging) residues are low value byproducts of timber operations that are often underutilized. In the western US, forest residues are generally left in the woods to decay or piled and burned in prescribed fire. Currently, there is a rising interest in biomass as a renewable energy source due to its carbon neutral nature where forest residues, as a waste product, can be a valuable resource for energy production. However there are economical and environmental burdens of utilization of forest residues due its processing and transportation. Its bulk density and high moisture content are still a barrier in their beneficial use. Therefore, there are many studies developing and investigating emerging technologies that can be used for the conversion of residual forest waste to useful and high quality energy products in an environmentally and economically sound way. One emerging thermochemical conversion technology that is used for transformation of forest residues to renewable energy products is torrefaction process. Co-firing biomass at coal-fired power plants is currently a common method used for mitigation of GHG emission resulting from power plants. However, the co-firing ratios are limited when untreated biomass is used where torrefied wood can increase co-firing ratio from 5-10% to 80% (Nhuchhen et al. 2104). The main function of torrefaction process is to generate a bio-based fuel that can be an alternative to non-renewable fossil fuels. Thus, utilization of forest residues for production of torrefied wood results in a high quality biofuel that can replace coal and ultimately decrease the greenhouse gas (GHG) emissions.

Torrefaction process allows conversion of logging residues to a high quality energy carrier that can replace coal in existing coal-fired plants. Yet, it is necessary to evaluate the environmental viability of emerging technologies in order to provide environmentally sustainable solutions. For environmental evaluation, data availability and accuracy are crucial. Life cycle assessment (LCA) is a powerful and common tool that is used to quantify environmental impacts associated with a product or a service at life cycle level. A major step of LCA is developing the life cycle inventory (LCI) data. This study developed a gate-to-gate LCI of pilot scale torrefaction study based on various system parameters and feedstocks. The LCI of torrefied wood production from various post-harvest residues was documented in this paper. The data provided in this paper may be used for environmental burden and benefits associated with the torrefied wood production from forest residues at life-cycle level.

GOAL AND SCOPE

Goal

Torrefaction is a promising technology for production of a sustainable energy carrier. 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 that can be used to enhance knowledge on environmental aspects associated with conversion of forest residues to bioenergy carriers using torrefaction process at life-cycle level.

The goal of this study was to develop life cycle inventory (LCI) that will allow environmental sustainability assessment of the processing of post-harvest forest residues as a biomass raw material in torrefied wood production. Thus, to quantify the impact of the torrefied wood production on environment and address environmental impacts associated with the technology, LCI development is necessary.

Scope

The scope of this study considered gate-to-gate torrefaction plant that included feedstock preparation (chipping and screening), drying, torrefying, and cooling of torrefied wood from post-harvest forest residues. The analysis began at the plant (i.e. old sawmill site) with physical conversion phase of forest residues to the cooling of the torrefied wood phase that ended at the plant gate out. The upstream feedstock procurement and downstream use phases of the torrefied wood produced were left outside the system.

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. The functional unit in this study was defined as 1 MJ of energy delivered by the torrefaction system. The input and output flows were standardized based on the selected functional unit.

METHOD

This study assessed and documented the LCI of torrefied wood chip from forest residues. Life cycle inventories were developed for various feedstocks torrefied using a pilot-scale torrefaction unit. In addition to testing various feedstocks, the data from runs tested different torrefaction operation parameters to evaluate the effect of process variation on life-cycle level environmental performance. In this study, the experimental runs were performed using an electrically-heated screw type pilot-scale torrefaction unit, Biogreen (Norris Thermal Tech., IN, USA). The Schatz Energy Research Center (SERC) located at Humboldt State University performed the production runs under 'Waste to Wisdom' project, a Biomass Research and Development Initiative (http://wastetowisdom.com/). The tests were performed, in Big Logoon, CA in July 2015 on an old sawmill site.

All relevant material and energy flows associated with the unit processes included in the gate-to-gate system boundary of torrefied wood production were collected to develop a gate-to-gate LCI. The study was undertaken to conform with ISO14040 and ISO14044 LCA standards (ISO 2006a, 2006b).

Definition of System Boundary

The system description of torrefaction plant processes along with the inputs and emissions to and from the system is provided in Figure 1. All operations evaluated occurred on-site. Input biomass feedstock was post-harvest logging residues, i.e., tree tops, limbs, chunks and branches which was a by-product of commercial harvesting operations. Feedstock was obtained from timber harvesting operations in Western U.S. from the following states, i.e., Washington, Oregon and California. The system boundary began at the feedstock preparation phase and stopped with the torrefied wood at the plant gate. The system boundary included feedstock preparation of chipping and screening and drying. The unit processes of torrefaction system include torrefaction and cooling. The system components are described in the following sections in detail.

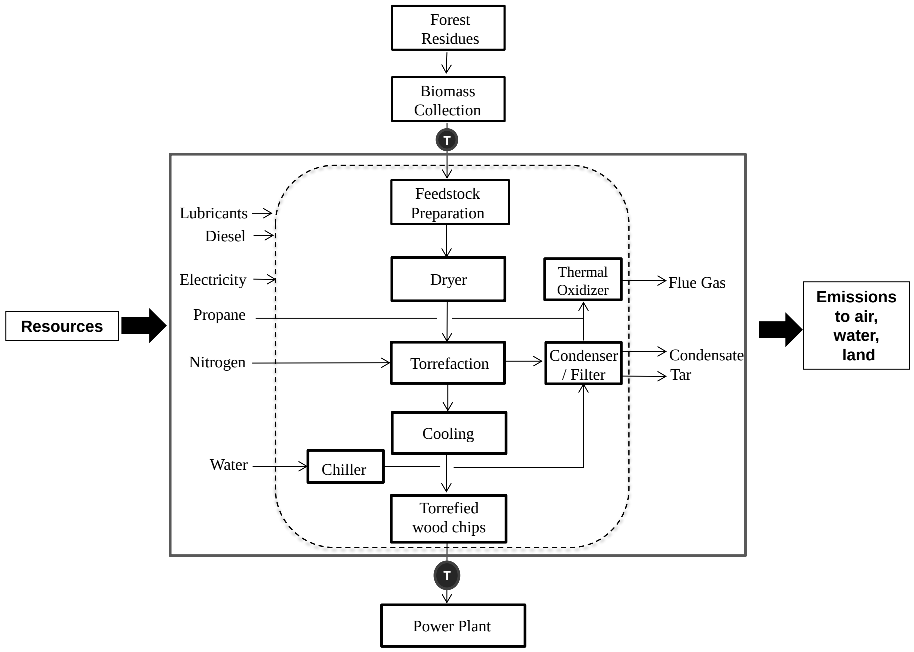

Figure 1. Gate-to-gate system boundary and process flow diagram of torrefied biomass production.

Unit Processes

Feedstock preparation. The biomass feedstock received by the system was a waste product of commercial harvesting operations composed of tree tops, limbs, branches, etc. The slash (logging) input had moisture content (MC: wet-basis) of 17-23%, which was left in the forest for 1-year before collection (Han-Sup Han, Joel Bisson, personal communication, May 2016). Feedstock preparation included chipping and screening of the feedstock to achieve good quality feedstock to be processed in the torrefaction unit. Lubricant consumption of chipping equipment that consisted of hydraulic oils and general lubricants came from literature (Johnson et al. 2012). The fuel consumption of chipper and screener were based on the tests performed by Humboldt State University (Han Sup Han and Joel Bisson, personal communication, May 2016).

In this study, data from three different of feedstocks were used. Four of the feedstocks samples analyzed were sourced from Douglas fir (*Pseudotsuga menziesii*). The other two types were hardwood slash of an unspecified species, and tanoak (*Notholithocarpus densiflorus*). The feedstock characteristics are provided in Table 1.

Table 1. Feedstock characteristics and overview of torrefaction process test parameters.

	DF 1	DF 2	DF 3	DF 4	HWS	TK
	Doug fir	**Doug fir**	**Doug fir**	**Doug fir**	**Hardwood slash**	**Tanoak**
MC, in (%)	4.6%	3.7%	11.6%	11.6%	6.8%	11.6%
MC, out (%)	0.8%	0.8%	0.7%	0.8%	0.4%	1.2%
Feedstock (g/min)	0.63	0.52	0.49	0.57	0.50	0.52
Residence Time (min)	8.00	6.0	6.00	8.00	6.00	6.00
Temperature (^oC)	350.00	350.00	350.00	350.00	350.00	400.00

Drying. Forced drying was applied before torrefaction process in order to decrease the moisture content of the biomass feedstock. The use of dryer was based on the incoming moisture content (MC) of the biomass feedstock. Drying was required if the MC of the incoming feedstock was higher than 20% for better system efficiency (Nunes et al., 2014). Thermal energy required for drying the input biomass was provided from a thermal oxidizer using propane as fuel. Electricity consumption in dryer process occurred from the belt conveyor used (Beltomatic, Norris Thermal Technologies, IN, USA).

Drying wood results in volatile organic carbon (VOC) emissions, which were accounted for in the analysis. The VOC emission data were derived from secondary data sources (Milota and Mosher 2008; Milota 2013), which was based on freshly-cut wood. Assuming freshly-cut wood, this conservative analysis tracked any VOCs emitted during field drying of the forest as well as during forced drying. It would be expected that VOCs emitted during field drying would be less harmful to the environment both because they occur at lower concentrations and over a longer period than during force drying.

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 not thermally treated biomass. These characteristics make it a suitable bioenergy carrier for coal substitution. The biomass feedstock is heated in the absence or near-absence of oxygen environment to a temperature of approximately 200-300°C (Tumuluru et al., 2011).

In this study, the torrefaction process occurred at atmospheric pressure and nitrogen gas was introduced to the process to provide the required inert conditions. Overview of the system parameters of the pilot scale torrefaction tests are provided in Table 1. A cooling process lowered the temperature of the torrefied wood product leaving the torrefier at elevated temperatures. This was required to prevent spontaneous combustion when the freshly-torrefied wood left the system and was exposed to oxygen. After torrefaction process, the torrefied wood chips were cooled using a loop type of water cooling that recirculates cooling water. Nitrogen purge occurred occasionally where the torrefied biomass exited the system to prevent fire risk.

The torrefaction gas (tor-gas) generated during torrefaction is generally utilized for thermal energy. In this study, the tor-gas was not utilized and was combusted in the thermal oxidizer before released to environment. Before the tor-gas was combusted, condensation and filtration took place to remove contaminants that could potentially damage the thermal oxidizer. In addition, a fiberglass filter was used to capture particles in the tor-gas. The by-products of condensation and filtration units were condensate (bio-oil) and tar, respectively. Both by-products were disposed as hazardous waste.

Data Sources

The primary data for the torrefaction processes relied on the operational runs of the pilot–scale torrefaction unit. All relevant quantitative data, i.e. input-output flows, associated with the unit processes were collected from the production site including data for the feedstock preparation, dryer and torrefaction processes. This data includes 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 product, i.e. torrefied chips. The background data of processes, such as generation of electricity and production and combustion emissions of fuels, manufacturing of the chemicals, and disposal of waste products were derived from peer reviewed literature and LCI databases including the US LCI Database (National Renewable Energy Laboratory [NREL] 2012). Natural gas was used a proxy for propane gas. The data collected were normalized using the selected functional unit, i.e.1 MJ of energy delivered in torrefied biomass. The consistency and accuracy of the data used in systems analysis was crucial. Therefore, a mass balance was performed for data validation to verify the input-output data and consistency of the set of inputs and outputs.

Due to insufficient information on the technology investigated, the manufacturing, maintenance and disposal of equipment used in the system were considered outside the scope of the study. The feedstock procurement and use (combustion) phases of the torrefied biomass were not included in the system boundary. The cooling in torrefaction unit was performed via a loop type of cooling that recirculated the cooling water from a large stationary. Since there was not accurate information of water loss per functional unit, the water consumption and wastewater handling were not taken into account in this study. The nitrogen purged to the system was negligible therefore was not included in the analysis.

In the torrefaction process, tor-gas combustion emissions mainly composed of water and CO_2, where NO_x emission were negligible due to low process temperatures and low nitrogen content of the lignocellulosic biomass (Ciolkosz and Wallace 2011). The same for sulfur-based emissions. Because of the lack of emission data and since the thermal oxidizer was used for combustion of tor-gas it was assumed after condensation and combustion only biogenic carbon dioxide emissions occurred.

RESULTS & DISCUSSIONS

Life cycle inventory analysis

The material and energy inputs and outputs for production of 1 MJ of energy per torrefied wood produced is provided in Table 2. The data presented the material and energy flows for six different feedstock runs; four Douglas fir, one (unspecified) hardwood slash, and one tanoak, two different temperatures (350 and 400^{o}C) and two residence time (6 and 8 minutes).

Table 2. Gate-to-gate material and energy flow analysis of 1 MJ of energy in torrefied wood.

Process	**Unit**	**DF 1**	**DF 2**	**DF 3**	**DF 4**	**HWS**	**TK**
Feedstock Preparation							
Diesel/ chipper	ml	0.162	0.167	0.130	0.134	0.133	0.143
Diesel/ Screen	ml	0.135	0.140	0.109	0.112	0.111	0.119
Lubricants	mg	1.362	1.405	1.096	1.125	1.122	1.198
Dryer							
Propane	L	0.004	0.004	0.002	0.002	0.003	0.002
Electricity	Wh	0.435	0.448	0.350	0.359	0.358	0.382
VOC emission	mg	7.723	7.968	6.212	6.377	6.362	6.795
Waste Heat emission	MJ	0.038	0.041	0.018	0.018	0.027	0.019
Torrefaction							
Wood Chips	dry kg	0.071	0.073	0.057	0.059	0.059	0.063
Electricity	Wh	76.605	60.649	63.080	64.403	62.646	75.637
Nitrogen	cm3	37.884	35.049	31.772	37.218	30.312	32.561
Bio-oil	g	3.006	2.331	7.129	7.296	4.061	7.623

For the torrefaction process, electricity ran through the screws to maintain the required torrefaction temperature. At the dryer unit, electricity was used for the belt conveyor, which is negligible compared to electricity consumption at torrefaction unit. The total electricity consumption at the plant ranged between 61-77 Wh/MJ of torrefied wood (Table 3).

Table 3 Gate-to-gate on-site energy inputs for production of 1 MJ of energy in torrefied wood.

		Feedstock					
Fuel		**DF 1**	**DF 2**	**DF 3**	**DF 4**	**HW**	**TK**
Electricity	Wh	77.04	61.09	63.43	64.76	63.00	76.02
Diesel	ml	0.297	0.307	0.239	0.245	0.245	0.261
Propane	ml	3.609	3.906	1.709	1.758	2.601	1.857

Primary energy consumption and cumulative primary energy consumption (CPEC) for the gate-to-gate production of torrefied wood is provided in Table 4. Natural gas had a high contribution to the primary energy use for all samples with a share of above 44%. Other primary energy sources include coal and uranium oxide, which were used in electricity production. The contribution of feedstock preparation to crude oil consumption was about 50% for sample DF-3 where a similar trend was observed for the processing of other samples, and the rest was attributed to torrefaction process. Cumulative primary energy consumption for production of 1 MJ torrefied wood range between 0.66-0.85 MJ/MJ. The contribution of renewable energy sources, i.e. hydro, solar, geothermal and wind were negligible.

Table 4 Primary energy consumption per 1 MJ of energy in torrefied wood.

Fuel	**DF 1**	**DF 2**	**DF 3**	**DF 4**	**HW**	**TK**
Wood fuel	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Gas, natural, in ground	47.8%	49.6%	45.2%	45.3%	47.1%	44.9%
Coal, in ground	38.1%	36.4%	40.0%	39.9%	38.6%	40.3%
Oil, crude, in ground	3.0%	3.4%	3.1%	3.1%	3.1%	3.0%
Uranium oxide, in ore	11.1%	10.7%	11.7%	11.7%	11.3%	11.8%
Renewables	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Cumulative (MJ/MJ)	8.45E-01	7.02E-01	6.63E-01	6.77E-01	6.82E-01	7.87E-01

The major plant level air emissions inventory resulting from torrefaction plant are presented in Table 5. Majority (about 88% for DF-1 run) of the fossil carbon emissions came from torrefaction process and the rest was from drying process. The emissions resulting from biomass preparation were negligible. At torrefaction process fossil CO_2 emissions were due to high electricity consumption.

Table 5 Gate-to-gate air emissions per 1 MJ of energy in torrefied biomass

Air Emission	**Unit**	**DF 1**	**DF 2**	**DF 3**	**DF 4**	**HW**	**TK**
Heat, waste	MJ	1.21E-01	1.05E-01	2.15E-01	2.20E-01	1.40E-01	2.30E-01
Carbon dioxide, fossil	kg	5.11E-02	4.20E-02	4.88E-02	4.99E-02	4.42E-02	5.65E-02
Carbon dioxide, biogenic	kg	4.58E-04	3.64E-04	3.77E-04	3.85E-04	3.74E-04	4.52E-04
Sulfur dioxide	kg	3.46E-04	2.87E-04	2.70E-04	2.76E-04	2.79E-04	3.21E-04
Methane	kg	1.37E-04	1.15E-04	1.05E-04	1.07E-04	1.10E-04	1.24E-04
Nitrogen oxides	kg	1.08E-04	9.13E-05	8.83E-05	9.03E-05	8.87E-05	1.04E-04
Carbon monoxide, fossil	kg	2.84E-05	2.48E-05	2.29E-05	2.34E-05	2.32E-05	2.67E-05
Particulates, unspecified	kg	1.78E-05	1.41E-05	1.46E-05	1.49E-05	1.45E-05	1.75E-05
VOC[a]	kg	1.51E-05	1.44E-05	1.18E-05	1.21E-05	1.23E-05	1.33E-05
Methane, fossil	kg	1.52E-05	1.321E-05	1.15E-05	1.17E-05	1.22E-05	1.35E-05

[a] Volatile organic compounds

CONCLUSION

This study was based on preliminary tests for various feedstocks and test conditions of producing torrefied wood chips from post-harvest logging residues. As mentioned earlier, the tor-gas generated in the torrefaction process was not utilized within the system, which would be generally the case in a commercial operation. It would be expected that greater utilization of tor-gas would substantially lower this fossil energy use and CO_2 emissions.

Future work will include upscale torrefier using a closed loop system combusting tor-gas for thermal energy that will allow better assessment of propane consumption and tor-gas utilization. In addition, the analysis will be performed to evaluate using diesel and synthesis gas in a generator on-site to evaluate the change in environmental performance.

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REFERENCES

USEPA. 2016. https://www3.epa.gov/climatechange/ghgemissions/sources.html. Accessed August 1, 2015.

Nhuchhen, D.R., P. Basu, and B. Acharya. 2014. A Comprehensive Review on Biomass Torrefaction. *International Journal of Renewable Energy & Biofuels*. Vol. 2014 (2014), Article ID 506376.

Norris Thermal Tech. 2016. http://www.biogreen-energy.com/overview/processes/

ISO. 2006a. Environmental management—life-cycle assessment—requirements and guidelines. ISO 14044. International Organization for Standardization, Geneva, Switzerland. 46 pp.

ISO. 2006b. Environmental management—life-cycle assessment—principles and framework. ISO 14040. International Organization for Standardization, Geneva, Switzerland. 20 pp.
Han, S.K., H. Han-Sup, and J.A. Bisson. 2015. Effects of Grate Size on Grinding Productivity, Fuel Consumption, and Particle Size Distribution. *Forest Prod. J.* 65(5/6):209–216.

Johnson, L., B. Lippke, and E. Oneil. 2012. Modeling Biomass Collection and Woods Processing Life-Cycle Analysis. *Forest Prod. J*. 62(4):258–272.

Nunes, L., J. Matias, and J. Catalão. 2014. A review on torrefied biomass pellets as a sustainable alternative to coal in power generation. *Renew. Sustain. Energy. Rev.* 40:153–60.

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

Milota M. 2013. Emissions from Biomass in a Rotary Dryer. *Forest Prod. J.* 63(5/6):155–161.

Tumuluru, J. S., C.T. Wright, J. R. Hess, and K.L. Kenney. 2011. A Review of Biomass Densification Systems to Develop Uniform Feedstock Commodities for Bioenergy Application. *Biofuel, Bioproducts, & Biorefinery.* 5:683-707.

NREL. 2012. U.S. Life-cycle inventory database project. National Renewable Energy Laboratory. www.lcacommons.gov/nrel/search. Accessed March 16, 2016.

Ciolkosz, D., and R. Wallace. 2011. A review of torrefaction for bioenergy feedstock production. *Biofuels, Bioprod. Bioref.* 5:317–329.