LIFE-CYCLE ASSESSMENT OF A DISTRIBUTED-SCALE THERMOCHEMICAL BIOENERGY CONVERSION SYSTEM[1]

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(Received January 2016)

Abstract. Expanding bioenergy production from woody biomass has the potential to decrease net greenhouse gas (GHG) emissions and improve the energy security of the United States. Science-based and internationally accepted life-cycle assessment (LCA) is an effective tool for policy makers to make scientifically informed decisions on expanding renewable energy production from newly developed bioenergy technologies. A distributed-scale high-temperature thermochemical conversion system, referred to as the Tucker renewable natural gas (RNG) unit, was evaluated for producing medium-energy synthesis gas (syngas) and biochar along with its waste from harvested woody biomass. Mass and energy balances, cumulative energy demand, and life-cycle inventory (LCI) flows were calculated based on operational data from a 1-h continuous run. Emissions data summarized from the cradle-to-gate LCI showed biomass and fossil CO_2 emissions of 0.159 and 0.534 kg, respectively, for each oven-dry (OD) kilogram of wood chips pyrolyzed. LCA, applied in accordance with International Organization for Standardization standards, was used to determine the potential environmental impacts. Total GHG was 0.595 kg CO_2 eq per OD kilogram of wood chips processed. Contributions to total GHG were 20.7% from upstream forest resource extraction and chip processing at sawmills and 77.6% from the thermochemical conversion process with propane combustion. The remaining 1.62% was from parasitic electricity operating the Tucker RNG unit. Quantifying global warming showed the carbon benefits (eg, low GHG emissions) along with the carbon hotspots from burning propane to maintain the endothermic reaction in the Tucker RNG unit. The use of low-energy syngas generated from what was originally a waste in the pyrolysis reaction to augment propane combustion would decrease GHG emissions (ie, fossil CO_2) by about 30.4%.

Keywords: Thermochemical pyrolysis conversion, syngas, biochar, woody biomass, life-cycle inventory (LCI), life-cycle assessment (LCA).

INTRODUCTION

There has been great demand on management of US western forests to decrease the threats from wild forest fires, insect and disease outbreak, and invasive species. Restoration treatments, including forest health thinning and regeneration harvest, have produced large amounts of woody biomass that can be used as feedstock for production of bioenergy or bioproducts. In addition, the decline of pulp and paper industries in the United States increases the need for application outlets for pulpwood logs and lumber mill residues. Producing bioenergy and bioproducts from such materials would contribute not only to achieving the broad US energy objectives, but also to decreasing greenhouse gas (GHG) emissions from fossil fuels, a major cause of climate

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change, according to the International Panel on Climate Change (IPCC 2014).

The US Department of Energy (DOE) and the US Department of Agriculture (USDA) are both strongly committed to expanding the role of biomass as an energy source. They envision a 30% replacement of the current US petroleum consumption with biofuels by 2030 (Perlack et al 2005). Biomass fuels and products are one way to decrease the need for oil and gasoline imports while supporting the growth of agriculture, forestry, and rural economies. Also, expanding biofuels and bioproduct production from biomass has the potential to decrease net GHG emissions and improve local economies and energy security. The 2007 Energy Independence and Security Act (EISA) sets aggressive goals for moving biofuels into the marketplace to decrease the nation's dependence on foreign sources of energy and decrease GHG emissions by increasing the supply of renewable fuels from 15 billion L in 2006 to 136 billion L by 2022, with 60 billion L of cellulosic biofuel (EISA 2007). Schnepf and Yacobucci (2013) defined cellulosic biofuel as renewable fuel derived from any cellulose, hemicellulose, or lignin source that has life-cycle GHG at least 60% less than the baseline life-cycle GHG from gasoline or diesel as transportation fuel for the year 2005. Decreasing GHG emissions and mitigation of climate change are the main driving forces for development and deployment of bioenergy systems. Many technologies are under development for bioenergy conversion from biomass feedstock. Life-cycle assessment (LCA) is a well-established and internationally accepted method for categorizing life-cycle GHG emissions from such technologies (ISO 2006a, b).

The use of LCA to evaluate the environmental impact from converting biomass to bioenergy, including liquid fuel, electricity, or transportation fuel, has been studied intensively in recent years (Jungbluth et al 2008; Cherubini and Stromman 2011; Sebastian et al 2011; Steubing et al 2011; Field et al 2013; Hertwich et al 2013; Pierobon et al 2014; Stephenson and MacKay 2014). Pierobon et al (2014) used radiative forcing analysis to evaluate the environmental impact of woody-biomass-based bioenergy conversion. Pierobon et al (2014) incorporated the dynamics of carbon sequestration, decomposition of residues, and biomass processing in the life-cycle analysis framework of bioenergy. They concluded that the adverse global warming (GW) impact associated with biomass collection and burning from industrial forests can be fully offset by the carbon sequestration during forest growth within about 18 yr. Stephenson and MacKay (2014) from the UK Department of Energy and Climate Change performed scenario analysis using North American woody biomass for UK's electricity in 2020. They found that the lowest GHG impact can be achieved using forest or mill residues or trees killed from natural disturbance as the feedstock that would otherwise be burned as waste (<100 kg CO_2 eq/MWh).

From a review on LCA for bioenergy systems, Cherubini and Stromman (2011) found that most studies concluded that a significant net decrease in GHG emissions and fossil fuel consumption is possible when bioenergy replaces fossil energy. Net GHG emissions from biomass-generated electricity are usually 5-10% of those from fossil-fuel-based electricity, and GHG emissions could be lower if the feedstock biomass is derived from residue streams such as logging slash and small-diameter trees. All the studies reviewed by Cherubini and Stromman (2011) assumed neutral climate impact from biomass combustion in terms of CO_2 emissions. Steubing et al (2011) conducted a cradle-to-grave LCA of a polygeneration unit that produced synthesis gas (syngas) for heat, electricity generation, and transportation fuel. They compared the results with the fossil-based system LCA. Their study showed environmental benefits in GW effects when syngas was substituted for fossil fuel, but these benefits were partially offset by other environmental effects related to human health and eutrophication. They considered syngas from wood used for transportation fuel as a promising technology in the light of growing demand for renewable transportation fuels. Field et al (2013) did a case study on a

Colorado regional coproduction of biochar and bioenergy from biomass residue feedstock. Their financial analysis suggested that the returns were generally greater when char was consumed for energy (biocoal) than when used for soil amendment (biochar), whereas biochar application had greater GHG mitigation value than did biocoal application.

The Biomass Research and Development Initiative (BRDI) was formed by USDA and DOE as an interagency program to support the development of a biomass-based industry in the United States for energy production and environmental protection. This study is a part of one BRDI project, which is conducting an integrated examination of biomass feedstock production, logistics, conversion, distribution, and end use focused on an advanced thermochemical conversion technology into existing forest industry operations (Miller et al 2014; Miller et al 2015).

The technology to be evaluated is a distributed-scale advanced biomass pyrolysis system, which will be referred to in this study as the Tucker (developed by Tucker Engineer Associates, Locust, NC) renewable natural gas (RNG) unit. The Tucker RNG unit uses high-temperature (>750°C) thermochemical conversion in an extremely low-oxygen environment (more explanation in the next section) to convert the feedstock from forest thinning and mill residues into syngas, which can be used for heat and electricity, and coproduct biochar for soil amendment or as a precursor in the manufacturing of activated carbon and other industrial carbon products. As a BRDI project goal, syngas-generated electricity is intended to be a substitute for a portion (marginal part) of grid electricity generated from fossil fuels, mostly natural gas and coal (USEIA 2015). The system was also specifically designed to generate a high-quality biochar to become activated carbon and not as a soil amendment, which is a less valued application than activated carbon.

For this study, we modeled the cradle-to-gate LCA of Tucker RNG technology for producing syngas and biochar from forest and sawmill residues and estimated the primary energy consumption and environmental impacts in a holistic life cycle starting from raw material extraction. In this study, pyrolysis and thermochemical conversion were used interchangeably because the operation of the Tucker RNG unit closely followed a pyrolysis process except for the production of bio-oil.

MATERIALS AND METHODS

The feedstock for the Tucker RNG unit was processed at Tricon Timber in St. Regis, MT. Tricon Timber is a processer of small-diameter logs in western Montana. The mill produces chips from the lumber production residues and from whole trees if harvested logs are not of quality high enough to be processed for lumber. The feedstock for the Tucker RNG unit was processed from under-used, small-diameter logs extracted from national forests with a mix of conifer species dominated by lodgepole pine (*Pinus contorta*), Douglas fir (*Pseudotsuga menziesii*), and ponderosa pine (*Pinus ponderosa*). The (micro) wood chips were processed to less than 12.7 mm long, cleaned of bark, and then dried in a sawdust dryer to ~8.19% MC as required by the Tucker RNG unit. Proximate and

Table 1. Properties of wood chip feedstock and biochar product.

	Wood chips (input)	Biochar (output)
Proximate (%)		
Moisture	8.19	1.84
Ash	0.36	3.97
Volatile	79.47	6.20
Fixed carbon	11.98	87.99
Total	100.0	100.0
MJ/kg (higher heating value)	18.12	32.22
MJ/kg (lower heating value)	16.72	
Ultimate (%)		
Moisture	8.19	1.84
Carbon	46.74	88.42
Hydrogen	5.56	1.51
Nitrogen	0.09	0.41
Sulfur	<0.01	0.01
Ash	0.36	3.97
Oxygen	39.06	3.84
Total	100.0	100.0

ultimate material analyses were conducted to quantify energy values, physical properties, and chemical compositions of the chips (Table 1).

Two primary products were produced from the Tucker RNG unit after pyrolyzation: medium-energy syngas and biochar. The Tucker RNG unit was designed to produce more syngas but less biochar. Therefore, the output percentages on a mass basis for syngas, biochar, and wastewater tar were 65%, 14%, and 21%, respectively. The medium-energy syngas was intended for use in electricity generation. The gas chromatography test on Tucker RNG syngas, shown in Table 2, provided the gas composition, gross heat, and net heat value of combustion. The coproduct biochar from the Tucker RNG unit was intended to be used as either soil amendment or a precursor for activated carbon. The same proximate and ultimate material analyses on biochar were conducted, and results are shown in Table 1.

Description of Processes

Feedstock processing. The feedstock processing included chipping, screening, and drying. An 812-kWe whole-tree chipper was run to chip low-quality logs. After whole-tree chipping, the chips went through a two-pass screener to select chips within the dimension limits of less than 12.7 mm long. A 108-kWe screener (BM&M Screening Solutions, Surrey, British Columbia, Canada) was running in conjunction with the mill's chipping operation. The feedstock chips were then dried to 8.19% MC (Table 1) in a triple-pass sawdust dryer. The sawdust dryer was fired by hog (wood) fuel. Data collected from Tricon Timber included material source, transportation of logs to the mill, and electricity and heat consumption at the mill for chipping and screening. Input data summarized in Table 3 were based on the Tucker RNG unit's feedstock hourly input rate of 263 kg/h. The feedstock chips had an MC of 12% after being equilibrated to the environment during transportation and storing in North Carolina before the pyrolysis.

Table 2. Gas composition and heating value for Tucker RNG syngas from gas chromatography.

Tucker RNG syngas		Volume (%)
Methane	CH_4	15.00
Ethylene	C_2H_4	3.70
Ethane	C_2H_6	1.10
Acetylene	C_2H_2	0.15
Propane	C_3H_8	0.56
Isobutane	C_4H_{10}	0.05
n-Butane	C_4H_{10}	0.23
Neopentane	C_5H_{12}	0.02
Isopentane	C_5H_{12}	0.03
n-Pentane	C_5H_{12}	0.03
Hexanes	C_6H_{14}	0.16
Heptanes	C_7H_{16}	0.44
Octanes	C_8H_{18}	0.33
Hydrogen	H_2	17.00
Oxygen	O_2	0.53
Nitrogen	N_2	1.70
Carbon dioxide	CO_2	11.00
Carbon monoxide	CO	48.00
Total		100.00
Gross heat of combustion (MJ/m^3)		19.70
Net heat of combustion (MJ/m^3)		18.30

Thermochemical conversion. The Tucker RNG unit is a distributed-scale thermochemical conversion system composed of active and passive sections (ie, chambers) shown in Fig 1. The Tucker RNG unit thermochemically converts forest or mill residues to syngas and biochar at a temperature between 760°C and 870°C in an extremely low-oxygen environment. Although the system does not typically displace atmospheric gasses using an inert sweep gas such as nitrogen, the system does minimize the introduction of atmosphere using a double air lock coupled with a feedstock compression system that expels interparticulate air from the feedstock before heating. Therefore, oxygen in the system is primarily a function of feedstock chemistry, which in the case of the wood feedstock used in this study is generally about 44% mass by dry weight (Bower et al 2007). The unit was engineered to maximize syngas output. Because the process is endothermic (requiring the absorption of heat), three propane burners fire to provide the initial heat to the active chamber. The residence time for biomass feedstock in the Tucker RNG unit is estimated at 3 min for the complete reaction (1.5 min in each of the two chambers).

An auger moved the dried feedstock through an air-locked system to the active section, in which

Table 3. Process inputs and energy flows for the 1-h thermochemical conversion run with 263 kg/h (12% MC) woody biomass.[a]

Energy sources	Material flows		Energy flows	
Flow into the system				
Chip processing at Tricon Timber		(unit)	(MJ)	(%)
Chipping (electricity)[b]	36.21	kWh	395.29	17.0
Screening (electricity)[b]	4.82	kWh	52.62	2.2
Drying (electricity)[b]	5.27	kWh	57.50	2.5
Drying (thermal energy)	0.18	OD kg	3.77	0.2
Truck transportation to Tricon Timber	75	miles	75.82	3.2
Railroad transportation to Tricon Timber	245	miles	21.34	0.9
Subtotal				26
Thermochemical conversion			(MJ)	(%)
Parasitic electricity[b]	2.87	kWh	31.31	1.3
Propane gas (thermal energy)	18.06	m^3	1707.55	72.8
Total			2345.2	100
Flow out of the system				
Products	(kg/h)	(%)	(MJ)[d]	
Syngas	172	82.5	3091	70.8
Biochar	36	17.5	1274	29.2
Total			4365	100
Net energy gain				
Per hour			2019.8	MJ/h
Per OD kg feedstock			8.6	MJ/OD kg

[a] 263.3 kg/h at 12% MC = 263.3/(1.12) = 235 OD kg/h.
[b] Electricity conversion efficiency is 33%. 3.6 MJ/kWh / 0.33 = 10.91 MJ/kWh.
[c] Propane higher heating value (HHV) values are taken from Channiwala and Parikh (2002) and propane gas density is 1.882 kg/m^3.
[d] HHV for syngas was measured by Natural Gas Analysis ASTM-D 1945/3588 by AirTechnology Lab, Inc. (Naperville, IL) on May 17, 2013. For the whole-tree chips, HHV for biochar was obtained from the Proximate test by Hazen Research, Inc. (Golden, CO), on May 16, 2013.

three propane burners provided continuous, active heating. Temperature in the active section was approximately 870°C. After the feedstock was mostly converted, the generated biochar, syngas, and residual heat were moved into the passive section, which did not have an active heat source but only the residual heat from the active section, which passed through three pipes connected between the two sections. After the biochar entered this section, it moved through two 3-m-long retorts for a total of 6 m. Additional conversion of higher molecular chain gases to methane occurred due to nickel embedded in the retort as a catalyst. The temperature measured at the entry of this section was approximately 760°C and was close to 510°C at the exit.

Syngas leaving the passive section was cooled in a tar condenser. The tar condenser had twin screws to remove buildup of tar from condensing caused by the cooling of the syngas. The residual tars from the condenser could be then augured back into a smaller retort inside the active section to generate a low-energy syngas. This occurred in conjunction with the production of the product gas—medium-energy syngas. After cooling, the medium-energy syngas passed through a misting chamber that removed oil and tars before leaving the Tucker RNG unit for outside gas storage. The two primary products from the system, biochar and medium-energy syngas, were collected at separated outlets. The flue gas from burning propane was emitted to the air without cooling or filtering. The medium-energy syngas was stored in a gas tank with very little compression although the syngas could be compressed to higher pressures if needed.

Goal and Scope

The cradle-to-gate LCA of thermochemically converting woody biomass residue into bioenergy (ie, syngas) and bioproduct (biochar) by the

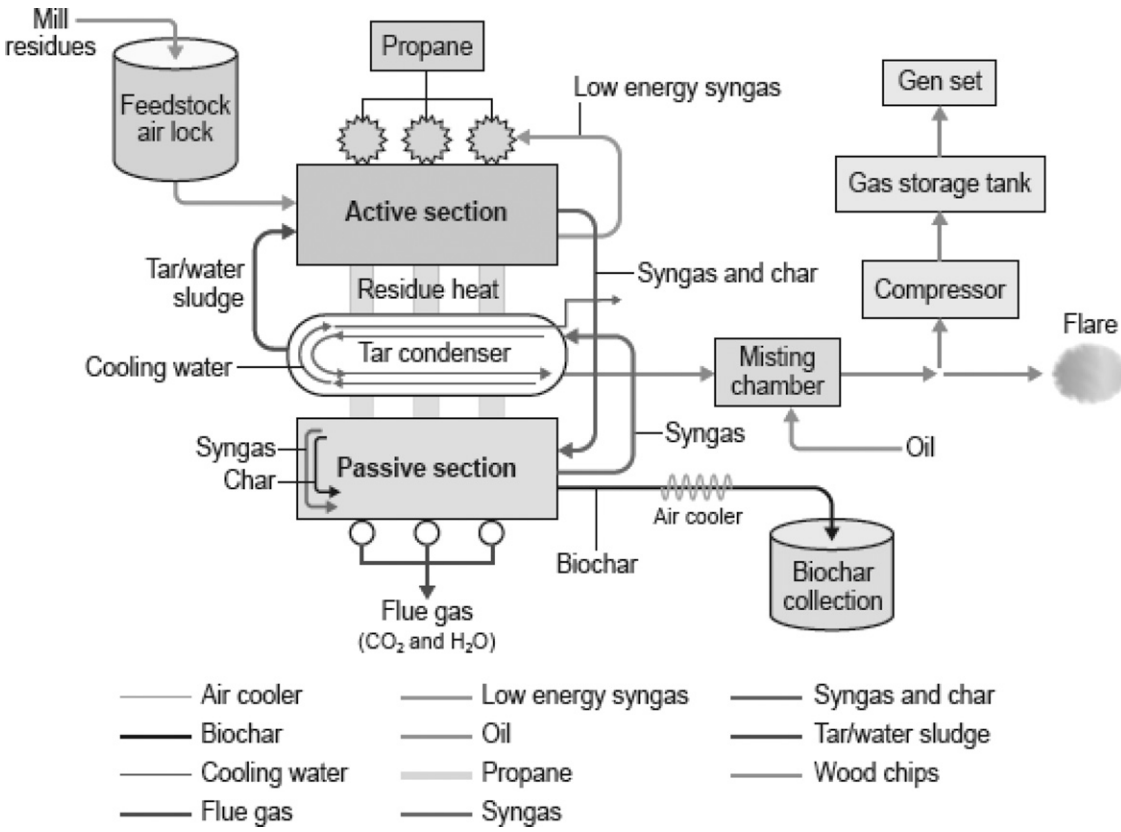

Figure 1. Tucker RNG unit process flow diagram.

Tucker RNG unit was conducted with a process-based modeling method. The goal was to quantify the primary energy consumption and environmental impacts. Therefore, the "environmental" hotspots of energy concentration in the processes can be identified and decreased.

The study scope covered the system from forest management, extraction of raw materials that included log harvesting and transportation to the processing site, feedstock processing of chipping, screening, and drying, and then finally to the generation of syngas and biochar from the thermochemical conversion system (Fig 2). From material and energy inputs and reported emissions, SimaPro 8 software (PRé Consultants, Amersfoort, the Netherlands) was used to model the estimates for raw material consumption and environmental outputs on a per-functional-unit basis (PRé Consultants 2015). Forest management and extraction of logs were modeled with secondary data from the US LCI database (NREL 2012). Feedstock processing and thermochemical conversion was modeled with primary data obtained from the observed operation. This was a cradle-to-gate LCA study, the gate being the syngas and biochar produced. The functional unit was 1 oven-dry (OD) kg wood chips (feedstock) pyrolyzed into syngas and biochar. Mass flow and energy use associated with the pyrolysis units were tracked.

RESULTS AND DISCUSSION

Material and Energy Flow

Primary data were collected from a whole-tree chipping operation and the 1-h continuous run of the Tucker RNG unit. Feedstock consumption for the Tucker RNG unit was recorded at

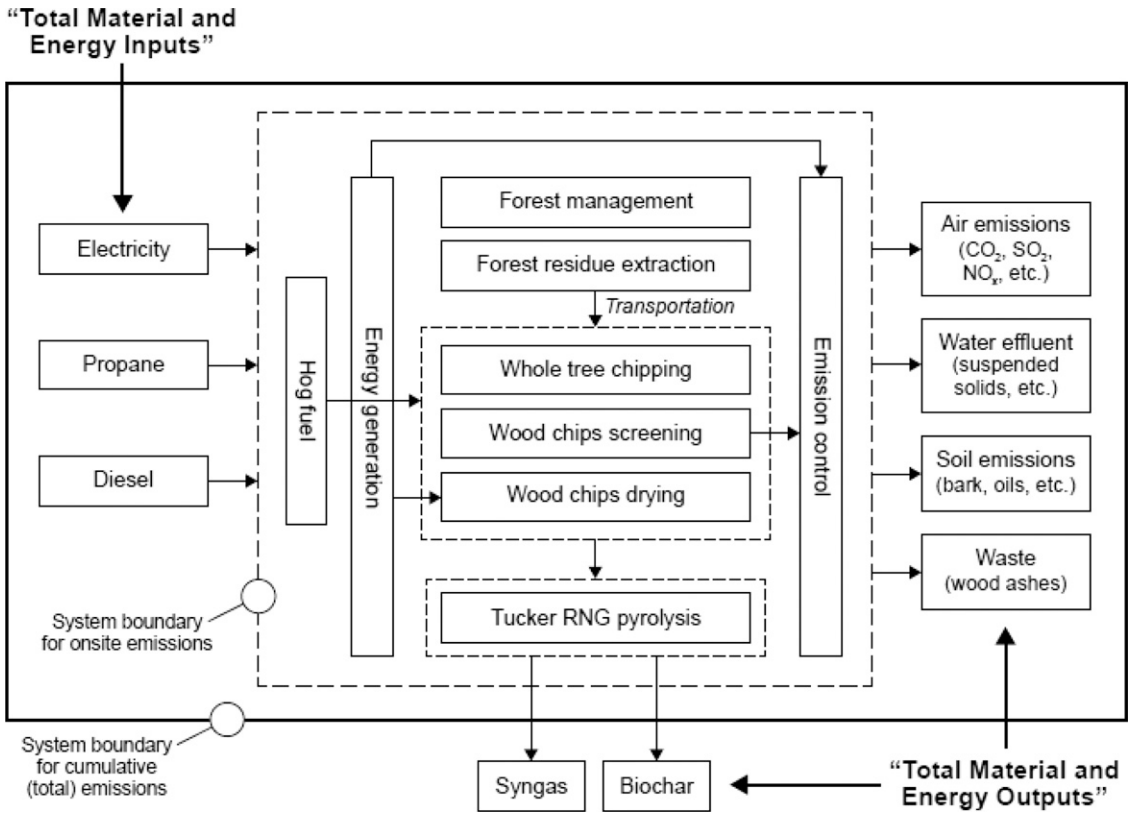

Figure 2. Cradle-to-gate system boundary for the Tucker RNG unit.

263 kg/h of whole-tree coniferous microchips at 12% MC. Feedstock processing and transportation energy use was based on the 1-h feedstock consumption. Electricity and propane usage for the Tucker pyrolysis process were recorded for the 1-h continuous run and are shown in Table 3. Output includes two primary products, syngas and biochar, along with some waste tar sludge. Deducting the waste tar sludge, the output product ratio was 4.7:1 (syngas to biochar) based on mass value and was 2.4:1 if based on energy values of the two.

Net energy gain is one way to calculate the energy efficiency of a new technology. In this study, we calculated the energy gain based on the bioenergy output to the fossil energy consumed for feedstock processing and the thermochemical conversion process. For the Tucker RNG unit, a net energy gain of 8.6 MJ/OD kg chips was calculated within the boundary system considered (Table 3). Energy efficiency is an important parameter to investigate, and this can be done using LCI flows. Fossil energy replacement ratio (FERR) is one of the indicators for the efficiency of a bioenergy system. FERR is defined as the ratio of bioenergy output from the system to fossil energy input to the system (Geottemoeller and Geottemoeller 2007). Using input and output values from Table 3, there were 9.98 MJ/OD kg (2345 MJ/235 OD kg = 9.98 MJ/OD kg) of fossil energy input to the system, whereas 18.57 MJ/OD kg (4365 MJ/235 OD kg = 18.57 MJ/OD kg) of bioenergy were produced. Therefore, the system had a positive (greater than 1.0) FERR of 1.86, which means 1.86 MJ of bioenergy products (syngas and biochar) were produced for every 1 MJ of fossil energy consumed in the process within the defined boundary. An FERR of 1.86, from a

life-cycle perspective, shows that the Tucker RNG unit has a net energy gain. This included fossil energy for the chip production and the pyrolysis converting processing (Table 3). When only considering the Tucker RNG unit pyrolysis converting process, an FERR of 2.54 was calculated previously in the study (Bergman and Gu 2014). Other research has shown support of such efficiency for bioenergy conversion over fossil fuel operations. Zaimes et al (2015) reported the Energy Return on Investment (EROI; fuel energy output/life cycle energy in) for miscanthus and switchgrass converted into liquid transportation biofuel from 1.5 to 2.6 MJ/MJ. Gaunt and Lehmann (2008) showed a net energy gain for a slow pyrolysis-based bioenergy system for biochar and energy production. They found an energy yield as syngas of 2-7 MJ/MJ when biochar is retained for soil amendment and an increase energy yield to 3-9 MJ/MJ when biochar is used as an energy source instead. When compared with the production of ethanol from corn, the corresponding energy yield was between 0.7 and 2.2 MJ/MJ according to Patzek and Pimentel (2005) and Metzger (2006). Steele et al (2012) reported an EROI of 2 for cradle-to-grave production and use of bio-oil derived from southern pine whole-tree chips.

LCI Data

With the LCA method, the LCI phase measures all the raw materials and energy inputs for producing syngas and biochar from 1 kg of OD wood chips within the defined system boundary. The cumulated energy calculation and emission profiles included forest resource extraction and transportation of logs, chip production at the mill, and pyrolysis processing with the Tucker RNG unit. Results are presented in Tables 4-6.

Cumulative Energy Demand

The total cumulative energy demand (CED) calculated by the inventory from the model was 13.9 MJ/OD kg of the feedstock within the boundary defined. The results in Table 4 show that propane use for heating during the conversion was the highest energy component with about 52% of the total CED, followed by drying with wood fuel, which was 27%. Propane gas was modeled using natural gas as a proxy in SimaPro. Table 5 reorganizes the energy categories into nonrenewable fossil or nuclear and renewable biomass or others. Nonrenewable fossil fuel contributed 72% and renewable biomass energy contributed 27% of the total CED.

Emissions to air, water, and soil are summarized in Table 6. Total fossil CO_2 emissions were about 0.534 kg for every 1 OD kg of woody biomass pyrolyzed, whereas the total biogenic CO_2 emission was 0.159 kg/OD kg of woody biomass. All other emissions came from transportation, whole-tree chipping operation, and off-site electricity generation being consumed on site.

Table 4. Cradle-to-gate CED for producing syngas and biochar from pyrolyzing 1 OD kg whole-tree chips.

			Higher heating values		Energy	
Substance	Unit	Total	MJ/m^3	MJ/kg	MJ/OD kg	%
Natural gas (proxy for propane)	m^3	0.1898	38.4		7.288	52.42
Wood fuel, OD basis	kg	0.180		20.9	3.759	27.04
Natural gas	m^3	0.028	38.4		1.090	7.84
Crude oil	kg	0.0094		45.5	0.426	3.06
Coal	kg	0.046		26.4	1.219	8.77
Electricity usage	MJ	0.00014			0.00014	0.001
Nuclear energy	kg	3.66E-07		33,2000	0.12	0.87
Biomass energy	MJ	0.000116			0.00012	0.0008
Hydro energy	MJ	0.000077			0.00008	0.0006
Wind energy	MJ	0.000004			0.000004	0.00003
Total					13.90	100

Table 5. CED per 1 OD kg whole-tree chips by renewable and nonrenewable sources.

Substance	Unit	Energy	
		MJ/OD kg	%
Nonrenewable fossil	MJ	10.02	72.09
Nonrenewable nuclear	MJ	0.12	0.87
Renewable, biomass	MJ	3.76	27.04
Renewable (solar, wind, and hydropower)	MJ	0.00008	0.0014
Total		13.90	100

Life-Cycle Impact Assessment

Life-cycle impact assessment (LCIA) integrates the LCI data to quantify the magnitude and significance of potential environmental impacts of a product through its whole life cycle. The environmental impacts were modeled using SimaPro 8 (PRé Consultants 2015) and the tool for the reduction and assessment of chemical and other environmental impacts (TRACI) 2.1 impact method (Bare 2011). TRACI facilitates the characterization of environmental stressors that have potential effects, including ozone depletion, GW, acidification, eutrophication, tropospheric ozone (smog) formation, ecotoxicity, human health criteria related effects, human health cancer effects, and human health noncancer effects. Fossil fuel depletion was tracked separately through the impact measure, CED. Environmental performance results from TRACI 2.1 for the syngas and biochar produced from pyrolyzing 1 OD kg of woody biomass feedstock are provided in Table 7 for each of the nine categories.

Table 6. LCI flows for the Tucker RNG unit pyrolyzing 1 OD kg of whole-tree chips.

Substance	Unit	Mass allocation (82.5/17.5%)		
		Tucker RNG syngas	Tucker RNG biochar	Total
Air emission				
Carbon dioxide, fossil	g	440.04	93.51	533.55
Carbon dioxide, biogenic	g	131.29	27.90	159.19
Sulfur dioxide	g	3.64	0.77	4.41
Methane	g	1.76	0.37	2.13
Nitrogen oxides	g	1.00	0.21	1.22
Carbon monoxide, fossil	g	0.46	0.10	0.56
Carbon monoxide	g	0.40	0.09	0.49
Particulates, >2.5 um and <10 um	g	0.37	0.08	0.45
Methane, fossil	g	0.25	0.05	0.30
VOC	g	0.13	0.03	0.15
Water effluent				
Suspended solids, unspecified	g	27.04	5.75	32.78
Chloride	g	21.56	4.58	26.14
Sodium	g	6.08	1.29	7.37
Calcium	g	1.92	0.41	2.33
BOD5	g	1.40	0.30	1.70
Lithium	g	0.61	0.13	0.74
Magnesium	g	0.38	0.08	0.45
Barium	g	0.20	0.04	0.24
COD	g	0.17	0.04	0.21
Soil emission				
Bark	g	1.189	0.253	1.442
Oils, unspecified	g	3.00E-04	6.38E-05	3.64E-04
Iron	g	2.98E-06	6.33E-07	3.61E-06
Calcium	g	2.10E-07	4.46E-08	2.55E-07
Carbon	g	1.85E-07	3.94E-08	2.25E-07
Chloride	g	1.33E-07	2.82E-08	1.61E-07
Waste				
Wood ashes	g	6.54	1.39	7.93

BOD, biological oxygen demand; COD, chemical oxygen demand; VOC, volatile organic compounds.

Table 7. Cradle-to-gate LCIA for the Tucker RNG unit pyrolyzing 1 OD kg of whole-tree chips.

Impact category	Unit	Syngas	Biochar	Total
Ozone depletion	kg CFC-11 eq	2.20E-08	4.67E-09	2.66E-08
GW	kg CO_2 eq	0.491	0.104	0.595
Smog	kg O_3 eq	0.026	0.005	0.0312
Acidification	kg SO_2 eq	0.004	0.001	0.005
Eutrophication	kg N eq	1.30E-04	2.76E-05	1.58E-04
Carcinogenics	CTUh	3.46E-08	7.35E-09	4.19E-08
Noncarcinogenics	CTUh	3.06E-08	6.50E-09	3.71E-08
Respiratory effects	kg $PM_{2.5}$ eq	3.14E-04	6.67E-05	3.81E-04
Ecotoxicity	CTUe	0.593	0.126	0.719

CFC, chlorofluorocarbons; CO_2, carbon dioxide; CTU, comparative toxicity unit; N, nitrogen; O_3, ozone; $PM_{2.5}$, particulate matter less 2.5 microns; SO_2, sulfur dioxide.

The total impact for each category was allocated to the syngas and biochar based on the mass percentage of the two products minus the waste tar sludge (82.5/17.5%). The total GW within the studied system boundary is calculated at 0.595 kg CO_2 eq for 1 OD kg of woody biomass processed with the Tucker RNG technology. Roberts et al (2010) provided their LCA results on GW for stover and switchgrass pyrolyzed for syngas heat and biochar. Before considering the carbon emissions decrease from biochar carbon sequestration and fossil fuel replacement, their GW for the process emission of the entire system was between 0.1 and 1 kg CO_2 eq per 1 kg OD feedstock. Steubing et al (2011) provided a GW impact value for wood gasified syngas to be used as heat or electricity. Their processes did not include wood growth and the chipping process. They reported 0.35 kg CO_2 eq for each 1 m^3 of syngas produced within their systems. In our system, 1 kg OD wood chips produced 0.676 m^3 syngas, and the GW for our study was 0.88 kg CO_2 eq per 1 m^3 of syngas produced. Therefore, the thermochemical conversion system in this study is comparable with other studies found in the literature for the GW report.

Analysis for contributions to the GW impact from processes was examined too and is shown in Table 8. Among total CO_2 eq emission, 20.7% was from the upstream operation of feedstock processing and 77.6% was from Tucker RNG unit pyrolysis processing, mainly from propane combustion, and only 1.62% was from the on-site electricity use during pyrolysis.

Alternative Scenario Analysis

In the outputs from the Tucker RNG unit, there was waste tar sludge generated that can be thermally converted into a useable low-energy syngas. If recycled back to the active section of the Tucker RNG unit, it was estimated to be able to substitute 30% of propane usage based on the heating value calculated. Including this substitution would make a substantial change in the

Table 8. Contributions from process and resources to the life-cycle impacts of pyrolyzing 1 OD kg of whole-tree chips.

Impact category	Unit	Total	Feedstock processing	%	Thermal heating	%	Electricity use	%
Ozone depletion	kg CFC-11 eq	2.66E-08	2.66E-08	100.0	3.31E-13	0.00	1.65E-13	0.0
GW	kg CO_2 eq	0.595	0.123	20.7	0.462	77.6	9.65E-03	1.6
Smog	kg O_3 eq	0.031	0.021	65.9	0.010	32.1	6.40E-04	2.1
Acidification	kg SO_2 eq	0.005	0.001	24.7	0.004	73.7	8.37E-05	1.6
Eutrophication	kg N eq	1.58E-04	1.18E-04	74.7	3.87E-05	24.6	1.18E-06	0.8
Carcinogenics	CTUh	4.19E-08	4.00E-08	95.3	1.94E-09	4.6	1.21E-11	0.03
Noncarcinogenics	CTUh	3.71E-08	1.17E-08	31.4	2.52E-08	67.9	2.54E-10	0.7
Respiratory effects	kg PM2.5 eq	3.81E-04	1.43E-04	37.7	2.33E-04	61.2	4.18E-06	1.1
Ecotoxicity	CTUe	0.719	0.098	13.6	0.619	86.1	0.003	0.4

CFC, chlorofluorocarbons; CO_2, carbon dioxide; CTU, comparative toxicity unit; N, nitrogen; O_3, ozone; $PM_{2.5}$, particulate matter less 2.5 microns; SO_2, sulfur dioxide.

Table 9. Change in environmental impacts if recycling the low-energy product gas to augment propane gas consumption.

		Substitute 30% of propane with low-butane product gas				
Impact category	Unit	Tucker RNG syngas	Tucker RNG biochar	Total[a]	Total[b]	Reduction %
Ozone depletion	kg CFC-11 eq	2.197E-08	4.669E-09	2.66E-08	2.66E-08	0.0
GW	kg CO_2 eq	0.376	0.080	0.456	0.595	30.4
Smog	kg O_3 eq	0.023	0.005	0.028	0.031	10.6
Acidification	kg SO_2 eq	0.003	0.001	0.004	0.005	28.4
Eutrophication	kg N eq	1.20E-04	2.56E-05	1.46E-04	1.58E-04	8.0
Carcinogenics	CTUh	3.41E-08	7.24E-09	4.13E-08	4.19E-08	1.4
Noncarcinogenics	CTUh	2.44E-08	5.18E-09	2.95E-08	3.71E-08	25.6
Respiratory effects	kg PM2.5 eq	2.56E-04	5.45E-05	3.11E-04	3.81E-04	22.5
Ecotoxicity	CTUe	0.440	0.093	0.533	0.719	34.8

CFC, chlorofluorocarbons; CO_2, carbon dioxide; CTU, comparative toxicity unit; N, nitrogen; O_3, ozone; $PM_{2.5}$, particulate matter less 2.5 microns; SO_2, sulfur dioxide.

[a] Total refers to the total impacts when 30% propane is considered to be substituted by the system's self-produced low-energy gas product.

[b] Total refers to the total impacts when no propane is considered to be substituted by the system's self-produced low-energy gas product.

impact assessment results. Prediction for the decrease in each impact category was calculated by the model, and results are shown in Table 9. In Table 9, "Total[b]" is the total impact if there is no propane substitution from the tar sludge, whereas "Total[a]" is the decreased total impact from substituting 30% propane heating with the tar sludge produced by the system itself. With 30% decrease of propane use in the pyrolysis process, most environmental impacts showed significant improvement. The GW impact decreased about 30.4% from its no waste recycling scenario. Other impact decreases are presented in Table 9 for different interests in human health or ecotoxicity.

CONCLUSIONS

Using the internationally accepted assessment method LCA, this study evaluated the bioenergy products produced from a modular advanced biomass pyrolysis system, referred to as the Tucker RNG unit. Similar to other pyrolysis systems, except no bio-oil is produced, the Tucker RNG unit converts forest or mill residues at high temperatures in an extremely low-oxygen environment to syngas and biochar. Mass and energy balances, cumulative energy consumption, LCI flows, and environmental impacts were determined. Feedstock consumption for the Tucker RNG unit was estimated at 263 kg/h of whole-tree coniferous microchips at 12% MC. The Tucker RNG unit showed a net energy gain of 8.6 MJ/OD kg chips from the system within the boundary system considered. Consequentially, the system had a positive (greater than 1.0) FERR of 1.86, which means 1.86 MJ of bioenergy products (syngas and biochar) were produced for every 1 MJ of fossil energy consumed in the system. An FERR of 1.88 shows that, from a life-cycle perspective, the Tucker RNG unit has a net bioenergy gain.

Environmental impacts from cradle-to-gate for the Tucker RNG unit bioenergy product were examined with SimaPro 8 using the TRACI method. The calculation included forest extraction and transportation of logs, chip production at the mill, and pyrolysis processing with the Tucker RNG unit. The impact was allocated based on the mass percentage of the two primary output products syngas (82.5%) and biochar (17.5%) from the conversion process. Emission data summarized from the LCI cradle-to-gate flows through SimaPro modeling showed biomass and fossil CO_2 emissions of 159 and 534 g, respectively, for each kilogram of OD chips pyrolyzed. GW or GHG emission contributions were 20.7% from upstream forest extraction and chip processing at the mill, 77.6% from pyrolysis process with propane combustion, and only 1.62% from on-site electricity use. Quantifying GWP showed the carbon hotspots coming from burning propane to maintain the endothermic reaction in the Tucker RNG unit. If possible,

reapplying the low-energy syngas from the tar sludge, a waste product from the process, to supplement propane usage would decrease GHG emissions (ie, fossil CO_2) by about 30.4%.

ACKNOWLEDGMENT

This project was supported by the Agriculture and Food Research Initiative, Biomass Research and Development Initiative, competitive grant no. 2011-10006-30357 from the USDA National Institute of Food and Agriculture.

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