# Life-Cycle Inventory Analysis of Bioproducts from a Modular Advanced Biomass Pyrolysis System

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**Abstract**

Expanding bioenergy production has the potential to reduce net greenhouse gas (GHG) emissions and improve energy security. Science-based assessments of new bioenergy technologies are essential tools for policy makers dealing with expanding renewable energy production. Using life cycle inventory (LCI) analysis, this study evaluated a 200-$kW_e$ modular advanced biomass pyrolysis system, referred to as the Tucker renewable natural gas (RNG) unit. Similar to pyrolysis systems except no bio-oil is produced, the Tucker RNG unit converts forest and woody residues at high temperatures in an extremely low oxygen environment to synthesis gas (syngas) and biochar. Mass and energy balances, cumulative energy consumption, and LCI flows including environmental outputs were determined. Feedstock consumption for the Tucker RNG unit was estimated at 263 kg/h of whole-tree coniferous micro-chips at 8% moisture content. A 1-h system run test was done to collect production data and sample products. The Tucker RNG unit showed a net energy gain of 12.0 MJ/kg of dry chips from the system when excluding chip transportation. Consequentially, the system had a positive (over 1.0) fossil energy replacement ratio (FERR) of 2.54, which means 2.54 MJ of bioenergy products (syngas and biochar) were produced for every 1 MJ of fossil energy consumed in the system. Including chip transportation of 4,000 km, emission data summarized from the LCI flows through SimaPro modeling showed biomass and fossil $CO_2$ emissions of 0.43 g and 734 g, respectively, per kilogram of chips processed. The fossil $CO_2$ emission contributions were as follows: wood chip transportation (48.7%), propane combustion (50.2%) and electricity use (1.1%). A FERR of 2.54 shows, from a life cycle perspective, that the Tucker RNG unit has a net energy gain. Additionally, co-locating the Tucker RNG unit and the wood chip source would substantially lower GHG emissions while saving energy.

***Keywords***: Life-cycle inventory, biochar, syngas, pyrolysis, wood chips, modular, renewable natural gas

## Introduction

Biomass as feedstock for producing bioenergy and bioproducts has raised considerable attention. The U.S. Department of Energy and the U.S. Department of Agriculture are both strongly committed to expanding the role of biomass as an energy source (Perlack et al. 2005), and envision a 30% replacement of the current U.S. petroleum consumption with biofuels by 2030. Biomass fuels and products are one way to reduce the need for oil and gasoline imports while supporting the growth of agriculture, forestry, and rural economies. Also, expanding biofuels and bioproducts production from biomass has the potential to reduce net greenhouse gas (GHG) emissions and improve local economy and energy security. The 2007 Energy Independence and Security Act (EISA) sets aggressive goals for moving biofuels into the marketplace to reduce the nation's dependence on foreign sources of energy and reduce greenhouse gas emissions by increasing the supply of renewable fuels from 4 billion in 2006 to 36 billion gallons by 2022 with 16 billion gallons being cellulosic biofuel (EISA 2007). Cellulosic biofuel refers to renewable fuel derived from any cellulose, hemicellulose, or lignin sources and has life-cycle GHGs that are at least 60% less than the baseline life-cycle GHGs from gasoline or diesel as transportation fuel for the year 2005.

Our study determined the cumulative energy and environmental outputs from a 200-$kW_e$ modular advanced biomass pyrolysis system, which will be referred to in this paper as the Tucker renewable natural gas (RNG) unit. The system uses high temperature conversion (>750 °C) in an extremely low oxygen environment to convert forest thinning and mill residue feedstock into syngas for heat or biofuel and biochar for soil amendment or filtering products after activation. Eventually, the modular unit is expected to be integrated into existing forest industry operations and forest management to assist in environmental and economic sustainability measures. Because of its 20 dry tonne per day production and modular size, the Tucker RNG unit has the potential to be deployed at forest industry facilities of various sizes. Furthermore, the potential to produce high-value activated carbon from treatment residues and mill waste is highly desirable to mills that are unlikely to make investments in new conversion technologies that produce only heat and power.

## Method

On a per production unit basis, the present study listed material flow, energy consumption, and emissions for the Tucker RNG unit production process. Primary data were collected from a 1-h continuous run of the Tucker RNG unit located in Locust, NC, using micro wood chips (<13 mm in the largest dimension) made and shipped from a lumber mill located in St. Regis, MO. Secondary data were collected according to CORRIM guidelines (CORRIM 2010) from peer-reviewed literature. Mass and energy balances for the system were then constructed using a spreadsheet algorithm. Energy present in the incoming feedstock was not considered in the analysis. With the material and energy inputs and reported emissions, the life-cycle inventory (LCI) model for of the Tucker system was built in SimaPro 8 to estimate the environmental outputs and cumulated energy consumption (PRé Consultants 2014). LCI can be thought of as a detailed mass and energy balance with all inputs and outputs accounted for.

**Scope.** The goal of this study was to find the emission profile and determine the mass and energy balances for the Tucker RNG unit using LCI analysis. To achieve this goal, we modeled the gate-

to-gate LCI for the Tucker RNG unit thermochemical process according to the ISO 14040 and 14044 standards (ISO 2006a; 2006b). In the analysis, the input gate begins with the chips leaving the lumber mill and being transported to the conversion site in North Carolina for processing. The trees chipped for feedstock were small-diameter logs 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 output gate is at the outlet of Tucker RNG unit with the two primary output products, syngas and biochar. Before feeding the Tucker RNG unit, the chips were re-dried to ~8% moisture content (MC) to remove the ambient moisture absorbed during transportation and storage. However, this re-drying process was not considered in the LCI modeling since the re-drying of the feedstock will not be necessary if the pyrolysis unit co-locates with a lumber mill, which is the configuration considered in this study.

Eventually, this analysis will become part of an our overall project goal that covers the cradle-to-grave environmental impact for the Tucker RNG unit from forest extraction to wood chip processing and transportation, to thermochemical conversion, to downstream products' transportation and end use. In addition, the LCI data developed in this project will help conduct a comparative life-cycle assessment (LCA) for secondary biobased products to their corresponding fossil fuel-based commercial products in terms of the cumulative energy consumption, air pollution, water pollution, solid waste production, and climate change impacts. These secondary products will include electricity generated from the synthesis gas (syngas) and activated carbon manufactured from the biochar. The primary data for developing the LCI model of the Tucker RNG unit were collected from a 1-h continuous run in March 2013 in Locus, NC. Secondary LCI data used in the study including electricity and natural gas as a proxy for propane have already been developed by previous LCI work. We were able to use these (secondary) LCI data because the developed data are found in the US LCI database (NREL 2014) as part of the LCA modeling software, SimaPro 8 (PRé Consultants 2014). The energy densities for the two gases were considered when inputting the data into the LCI model.

**Functional unit.** Functional unit is the reference unit used to quantify the environmental performance of a product system. It is also a reference related to the inputs and outputs. The functional unit for the present study is 1 kg of whole tree chips at 10% MC being processed in the Tucker RNG unit. Material flows, energy use, and emission data are standardized based on the functional unit within the system boundaries. The GHG emissions as well as other emissions and raw material consumption will be allocated based on the mass content of the two primary products from system; i.e., mass allocation.

**Unit process.** Tucker RNG unit is a production-oriented advanced pyrolysis system comprised of two sections (i.e., chambers), Mable (active) and Ethyl (passive) (Figure 1). The system is engineered to maximize methane-rich syngas output in an extremely low oxygen reaction chamber at a temperature between 760 and 870 °C. The Mable section is heated by three propane burners providing continuous heating. When all the operating parameters are within the specified ranges and the system has stabilized, feedstock is fed in by an air-locked auger system to the Mable section. The injector feeding system is designed to prevent backflow from the Mable chamber as the system operates under a low-positive pressure. Temperature in Mable section is 870 °C. The gasified volatiles and solids generated from the feedstock leave Mable and enter into the Ethyl passive section (Figure 1), which operates at approximately 760 °C using the residual

heat from Mable section passed through the three pipes connected between the two sections. The feedstock entering Ethyl moves through two 3.0-m-long retorts for a total of 6 m of retort or condensing, whereby additional conversion of higher molecular chain gases to methane occurs from using a catalyst in the retort. The temperature measured at the entry of Ethyl is ~760 °C and ~510 °C at the exit of Ethyl. The residence time for the feedstock in the Tucker RNG unit is estimated at 3 minutes for the complete reaction (1.5 minutes/section).

Syngas leaving the passive section is cooled in a tar condenser. The tar condenser has twin screws to remove buildup of tar from the condensing caused by the cooling of the syngas. The tar condenser uses potable water for cooling. Water temperature and flow rate can be monitored during operations. The residual tars from the condenser are then augured back into a smaller retort inside the Mabel section to generate a low-Btu syngas that could be used to augment the propane gas currently used to heat the Mabel section. This occurs in conjunction with the production of the product syngas, a medium-Btu syngas. After cooling, the medium-Btu syngas goes through a misting chamber (Figure 1) that removes oil and tars before leaving the Tucker system for outside gas storage. The two primary products from the system, biochar and medium-Btu syngas are collected at separated outlets. The medium-Btu syngas is stored in a gas tank with very little compression although the syngas can be compressed to higher pressures as needed. After forced air cooling to remove heat from the biochar and thus prevent instantaneous combustion, the biochar is collected in a bin outside the building housing the Tucker RNG unit. The flue gas from the burning propane is emitted to the atmosphere without cooling or filtering.

**Project Limitations.** Human labor and the manufacturing LCA of the machinery and infrastructure were outside the system boundaries and therefore not modeled in this analysis.

**Cut-off Rules**. If the mass/energy of a flow is less 1% of the cumulative mass/energy of the model flow it may be excluded, provided its environmental relevance is minor. This analysis included all energy and mass flows for primary data.

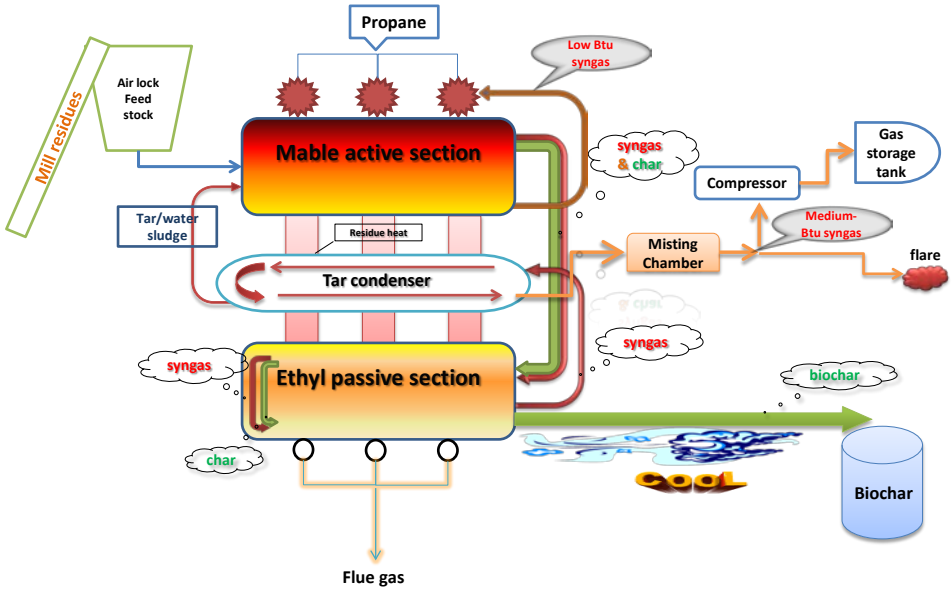


*Figure 1. Process flow diagram for Tucker advanced pyrolysis system.*

**System boundary.** Defining the system boundary selects the unit processes to be included in the system. Based on our goal to determine the cumulative energy consumption and emissions associated with the Tucker RNG unit, we drew our system boundary to include the entire conversion process within the Tucker RNG unit and the materials and energy inputs into the Tucker RNG unit. The thermochemical process includes feedstock conveyance, active reacting, passive reacting, condensing, tar cracking, cooling, collecting, and storing. Figure 2 shows the system boundary defined for this gate-to-gate LCI study. Transportation of the feedstock from the lumber mill to the Tucker RNG unit was not included when calculating the mass and energy balances of the Tucker RNG itself but was included when reporting air and water emissions.. Two system boundaries were considered. One, shown as solid line in Figure 2, is the cumulative system boundary including both on- and off-site emissions for all material and energy consumed by Tucker RNG unit. Fuel and electricity use for the converting process were included in the cumulative boundary to calculate the total emissions. The other (on-site) system boundary, shown as dotted line in Figure 2, covered emissions occurring only within the Tucker RNG unit. The off-site emissions include the grid electricity production, transportation of feedstock to the Tucker processing site, and fuels produced off-site but consumed onsite.

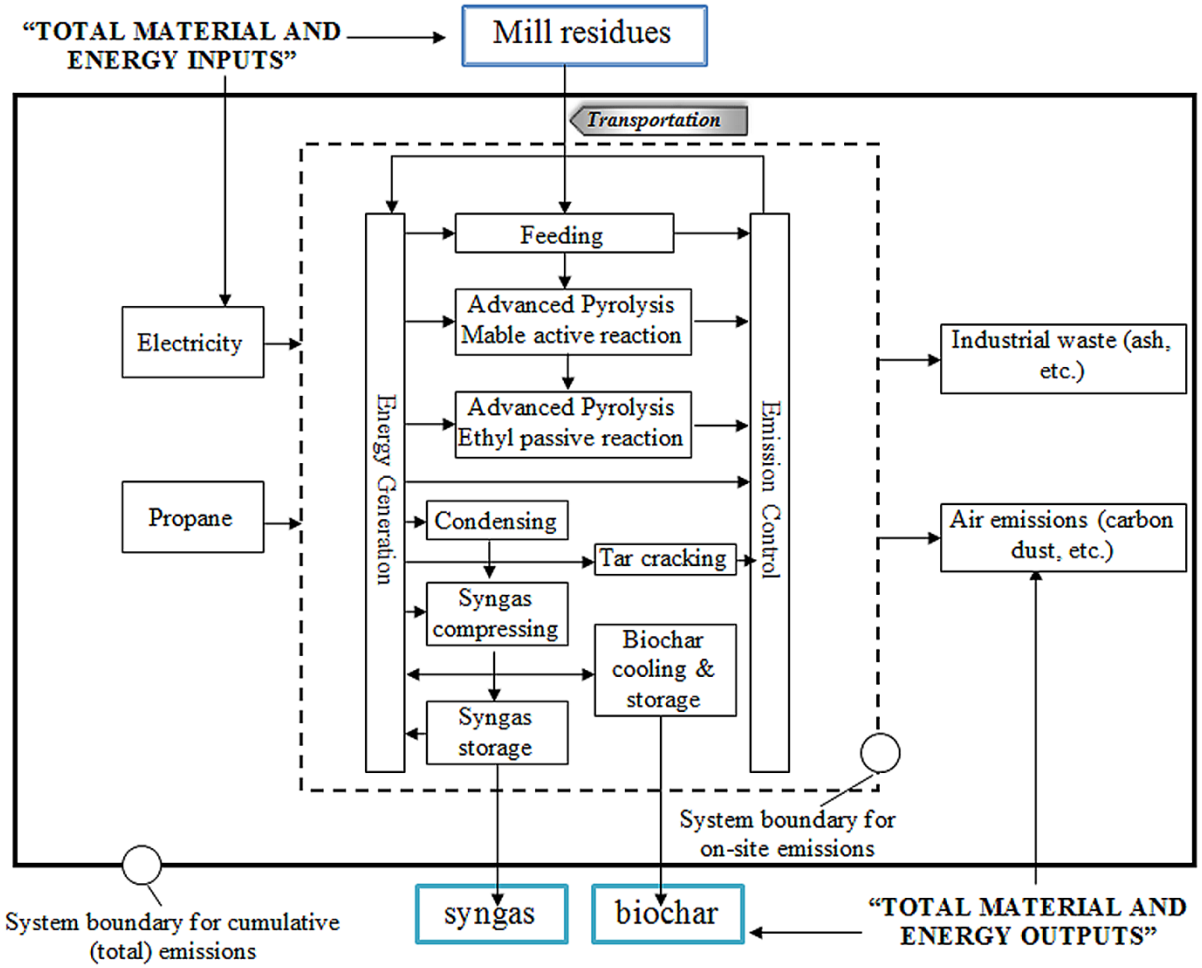


*Figure 2. System boundaries for Tucker renewable natural gas unit.*

## Results and Discussion

The Tucker RNG unit is a modular, high-temperature pyrolysis system capable of converting multiple organic feedstocks into medium-BTU gas and biochar. For our study, the biomass feedstock was from whole trees chipped at a lumber mill in Montana, dried to ~10% MC, and shipped to North Carolina. In this analysis, wood chip transportation was not included in the inputs and outputs of the Tucker RNG unit and not for the net energy gain calculation as well. However, wood chip transportation was included when reporting cumulative energy consumption and environmental outputs.

The energy and mass balances account for the energy and mass flowing across the system boundary. This includes the parasitic loads to operate the input feeder, augers, and fans. Table 1 provides the mass and energy inputs into the Tucker system within a 1-h continuous operation. The feeding system on the Tucker RNG unit operated at 263 kg/h for wood chips. During the 1-h run, a computer monitored flow for propane, product (syngas) gas, and flue gas, pressure of product gas, temperatures at various locations, and power consumption by various electrical components. Table 1 shows the propane consumption and electricity use calculated during the 1-h run.

*Table 1. Inputs into the Tucker advanced pyrolysis unit for 1-h operation.*

**MASS and ENERGY INPUTS**

| Source | Mass (kg) | Energy (MJ/kg) | Total Energy (MJ) | Percent (%) |
|---|---|---|---|---|
| Feedstock | 263 | 18.41 [(1)] | 4,850 | 72.0 |
| Propane | 36.4 | 51.83 [(2)] | 1,880 | 28.0 |
| Total thermal Input | | | 6,730 | 100 |
| **Parasitic** | | | | |
| Electrical power | 2.87 kWh | 3.6 (MJ/kWh) [(2)] | 10.3 | |

[(1)] As measured from wood chips with 8.19% moisture (wt).

[(2)] Propane and electricity unit energy HHV values are taken from Franklin Database. http://www.fal.com/lifecycle.htm.

Table 2 gives the mass and energy outputs from the system after the 1-h run. Heat loss to the atmosphere was not measured and is accounted for by the difference in energy in and out. Samples of biochar and syngas were collected to conduct the analysis for the constituents and chemical energy content. The ASTM-D3588 standard test was conducted on the syngas to obtain the heat of combustion value of 522 Btu/ft$^3$. It was then converted to 18.0 MJ/kg based on the conversion factor and syngas density calculated from the gas chromatography test (ASTM-D1945) for gas constituents. The proximate analysis was performed on the feedstock and solid product biochar to determine the fixed carbon, volatile matter, and moisture and ash percentages. Then the ultimate analysis was done to provide the composition in percentage weight of the major components in the feedstock and biochar, such as carbon, hydrogen and oxygen, as well as sulfur and nitrogen after complete combustion of the samples. The high heating value (HHV) of the feedstock and biochar shown in Tables 1 and 2 were from the proximate and ultimate analysis.

*Table 2. Outputs from the Tucker advanced pyrolysis unit of 1-h run.*

**MASS and ENERGY OUTPUTS**

| Source | Mass (kg) | Mass (%) | Energy [3] (MJ/kg) | Total Energy (MJ) | Percent |
|---|---|---|---|---|---|
| Syngas | 172 | 65.4 | 18.0 | 3,090 | 64.1 |
| Tar, oil/water | 54.3 | 20.6 | 10.5 | 572 | 11.9 |
| Biochar | 36.4 | 13.8 | 31.7 | 1,160 | 24.0 |
| Total | 263 | 99.8 | | 4,820 | 100.0 |

[3] Unit energy values for biochar and tar oil/water were obtained from the proximate and ultimate analysis, syngas unit energy value obtained from ASTM–D1945/3588 standard tests.

Net energy gain or energy balance is calculated as the difference between the energy contents in the output products and the fossil fuel energy consumed to produce the products. The total output energy in Table 2 from Tucker RNG unit is 4,820 MJ. To produce this amount of bioenergy, it required a total of 1,890 MJ of fossil fuels (propane and electricity) as shown in Table 1. This gives a net energy gain of 2,930 MJ for the total input feedstock of 263 kg, as shown in Table 3. Converting to 1 oven-dry kg (OD-kg) feedstock of wood chips to be processed by the Tucker RNG unit into syngas and biochar, the net energy gain is 12.0 MJ/OD kg chips (Table 3). Fossil Energy Replacement Ratio (FERR) is defined as the ratio of bioenergy output from the system over the fossil energy input into the system. For the Tucker RNG unit, the FERR is 2.54, which means for every 1 MJ of fossil fuel input into the system, there is 2.54 MJ of bioenergy output produced. This indicates 1.54 times more MJs are available in the bioenergy produced than in the fossil fuels that went into producing these bioenergy products. Therefore, on the basis of fossil energy inputs, using propane and grid electricity is an effective use of a finite energy resource.

*Table 3. Net energy gain from Tucker RNG unit pyrolysis process.*

**NET ENERGY CALCULATION**

| Total energy gain | Unit net energy gain | Fossil energy input into the system | Bioenergy output from the system | Fossil energy replacement ratio |
|---|---|---|---|---|
| (MJ) | (MJ/OD kg) | (MJ/OD kg) | (MJ/OD kg) | (MJ/MJ) |
| **2,920** | **12.0** | **7.79** | **19.8** | **2.54** |

Other research has shown support of such efficiency for bioenergy conversion over fossil fuel operations. Zaimes and others (2013) reported the Energy Return on Investment (EROI = fuel energy output/life cycle energy in) for miscanthus and switchgrass to convert into biofuel for bioelectricity use at about 2.5 to 4.5 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. The avoided emissions are between 2 and 5 times greater when biochar is applied to agricultural land than used solely for fossil energy offsets. To compare with the production of ethanol from corn, the corresponding energy yield is about 0.7–2.2 MJ/MJ according to Patzek (2005) and Metzger (2006). Steele and others (2012) reported an EROI of 2 for cradle-to-grave production and use of bio-oil derived from southern pine whole tree chips.

Gate-to-gate LCI model for 1-kg wood chips processed in Tucker RNG unit was constructed in the SimaPro 8 LCA modeling software (PRé 2014). Table 4 shows the cumulative energy consumption within the system boundary (Figure 2) from the input gate of wood chips leaving

the lumber mill to the output gate of bioenergy (syngas) and bioproduct (biochar) produced from Tucker RNG unit. A total of 12.6 MJ was consumed for 1-kg of feedstock thermochemical conversion. We used natural gas as a proxy in SimaPro for modeling the gas phase of propane combustion to generate heat for the endothermic reaction. This is the closest approximation within the U.S. LCI database for propane combustion reaction. About 59% of the energy was used to heat up the active reaction chamber to the high temperature of 870 °C. Crude oil provided almost 38% of the cumulative energy needed and was primary due to chip transportation. Chip transportation is included in our system boundary (Figure 2). For this study, feedstock was transported 4,000 km as part of the larger project examining feedstock from the Rocky Mountain region. This transportation distance is only used for this initial study and model set up. The model can be easily updated with any transportation distance and integration. A more realistic deployment of the system would be closer to the feedstock supply, potentially co-located at the sawmill, which would eliminate the energy use and GHG emissions from chip transportation.

*Table 4. Cumulative energy calculated from the SimaPro LCI modeling for 1-kg of wood chips.*

| | | Mass allocation | | | NG HHV | HHV | Energy | |
|---|---|---|---|---|---|---|---|---|
| **Substance** | **Unit** | **Syngas** | **Biochar** | **Total** | **(MJ/m^3)** | **(MJ/kg)** | **(MJ)** | **(%)** |
| Coal, 26.4 MJ per kg | kg | 0.00962 | 0.00204 | 0.0117 | | 26.2 | 0.305 | 2.4 |
| Gas, natural/m3 | m3 | 0.16048 | 0.03397 | 0.1945 | 38.4 | | 7.462 | 59.2 |
| Uranium oxide, 332 GJ per kg, in ore | kg | 2.12E-07 | 4.48E-08 | 2.56E-07 | | 332,000 | 0.085 | 0.7 |
| Oil, crude | kg | 0.08605 | 0.01822 | 1.04E-01 | | 45.5 | 4.744 | 37.7 |
| **Total** | | | | | | | **12.60** | 100 |

Table 5 allocates the environmental outputs from 1 kg of the feedstock processing to the two primary products – syngas and biochar based on their mass allocation. Emission data summarized through SimaPro modeling for biogenic and fossil carbon dioxide were 0.43 g and 735 g, respectively, per kilogram of chips used. The total air emission from the system is 747 g/kg of wood chips, of which 98% is fossil $CO_2$ emitted primarily from fossil fuel use in the heating of the reaction chamber and transportation of the feedstock. From the SimaPro model analysis output, we also identified the process contribution to the total fossil $CO_2$ emissions , chips transportation (48.7%), propane combustion (50.2%), and electricity use (1.1%). Biogenic $CO_2$ is extremely low because no biomass is consumed on-site to aid in the thermochemical conversion process. In addition, the release of biogenic $CO_2$ to the atmosphere from burning woody biomass is considered to be equal to the $CO_2$ absorption by forest regrowth. Therefore, as long as the forest carbon growth is equal or greater than the forest carbon lost through sustainable harvesting practices, burning woody biomass is assumed to be carbon neutral. Suspended solids (unspecified) and chloride generated the highest emissions to water at 45.4 and 35.6 g/kg of wood chips, respectively (see Table 5). Suspended solids (unspecified) and chloride are released during the extraction and production of fossil fuels. Although these environmental outputs are indirect, they are still accounted for, which is standard LCA practice.

*Table 5. Environmental outputs from thermochemical conversion of one oven-dry kg of wood chips.*

| Substance | Unit | Mass allocation | | Sum | Percent |
|---|---|---|---|---|---|
| | | Syngas | Biochar | | |
| **Air emission** | | | | | |
| Carbon monoxide, fossil | g | 1.782 | 0.377 | 2.160 | 0.289 |
| Carbon dioxide, biogenic | g | 0.358 | 0.076 | 0.434 | 0.058 |
| **Carbon dioxide, fossil** | **g** | **606.203** | **128.333** | **734.54** | **98.351** |
| Formaldehyde | g | 0.000 | 0.000 | 2.42E-04 | 0.000 |
| Methane | g | 1.749 | 0.370 | 2.119 | 0.284 |
| Methane, fossil | g | 0.233 | 0.049 | 0.283 | 0.038 |
| Mercury | g | 1.05E-06 | 2.22E-07 | 0.000 | 0.000 |
| Nitrogen oxides | g | 2.308 | 0.489 | 2.797 | 0.374 |
| NMVOC, non-methane volatile organic compounds, unspecified origin | g | 0.170 | 0.036 | 0.206 | 0.028 |
| Particulates, > 2.5 um, and < 10um | g | 0.055 | 0.012 | 0.067 | 0.009 |
| Particulates, unspecified | g | 0.034 | 0.007 | 0.041 | 0.006 |
| Sulfur monoxide | g | 0.289 | 0.061 | 0.350 | 0.047 |
| **Sulfur dioxide** | **g** | **2.923** | **0.619** | **3.542** | **0.474** |
| VOC, volatile organic compounds | g | 0.197 | 0.042 | 0.239 | 0.032 |
| **Total** | | | | 746.86 | |
| **Water effluents** | | | | | |
| **Suspended solids, unspecified** | **g** | **37.449** | **7.928** | **45.377** | **46.694** |
| **Chloride** | **g** | **29.414** | **6.227** | **35.641** | **36.675** |
| Chloride | g | 8.295 | 1.756 | 10.051 | 10.343 |
| Sodium | g | 2.617 | 0.554 | 3.171 | 3.263 |
| Calcium | g | 0.546 | 0.116 | 0.662 | 0.681 |
| Lithium | g | 0.520 | 0.110 | 0.630 | 0.649 |
| Barium | g | 0.512 | 0.108 | 0.620 | 0.638 |
| **Total** | | | | 97.18 | |

## Conclusion

The Tucker RNG unit and other new bioenergy systems show a net energy gain. Based on our analysis of converting 1-kg dry wood chips from whole tree chips into bioenergy products, the Tucker pyrolysis unit produces 2.54 MJ of bioenergy for every 1 MJ of fossil fuel energy inputted into the system. Therefore, the Tucker RNG unit is an energy efficient system and thus will help in providing renewable energy at a distributed scale. In addition, the unit has the potential to assist lumber mills and other manufacturing facilities to manage biomass byproducts and convert them into useful co-products.

New bioenergy systems are becoming important to mitigate climate change impacts by lowering GHG emissions per unit of energy output. As for GHGs, $CO_2$ is of primary concern. For the Tucker RNG unit, fossil $CO_2$ was the major air emission and was primarily from burning propane to maintain the endothermic reaction and from burning diesel fuel for chip transportation. Co-locating bioenergy systems to the feedstock source or replacing the propane with syngas or by redesigning the bioenergy system to burn wood will substantially reduce fossil $CO_2$ and thus lower GHG emissions. As for biogenic $CO_2$, with the biochar and syngas thermally converted from biomass, the energy values of these two products are roughly related to their carbon contents. Release of this energy by combustion is considered renewable and is largely carbon neutral except for the fossil fuel consumed in their production. If the carbon in the biochar is not burned but rather used as a soil amendment or activated for use in filtering application, the carbon can be equated to the $CO_2$ sequestered over the long term in soils or

landfills. In addition, some energy generated by bioenergy systems (e.g., the Tucker RNG unit) is currently being lost as waste heat. That energy can substitute for fossil fuel energy, especially in feedstock drying. This will further avoid fossil $CO_2$ emissions in the process. The sum of these effects could provide an even greater reduction of GHG emission than shown in the present study.

For future research, the authors will look at the associated environmental impacts upstream at material resources extraction and downstream at secondary conversion to higher value products of electricity and activated carbon. The authors will also look to characterize the system in its first commercial deployment, which is currently being installed in Charlotte, NC.

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