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Comparative Life-Cycle Assessment of Biochar Activated Carbon and Synthesis Gas Electricity with Commercially Available Alternatives

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Abstract

This report presents a compilation of research conducted on the life-cycle assessment analysis for processing raw material woody biomass into biochar activated carbon (AC) and synthesis gas (syngas) for electricity production. The study was part of the United States Department of Agriculture Biomass Research and Development Initiative project with a broader goal of an integrated assessment of biomass feedstock production, logistics, conversion, distribution, and end use focused on a novel thermochemical conversion system using woody biomass feedstocks. Cradle-to-grave analysis of the syngas electricity supply chain included upstream processes of the feedstock procurement and preparation life-cycle stages, core process of the thermochemical conversion (woody biomass carbonization) stage, and then downstream processes with syngas storage and combustion (use) at the generator for electricity production. Cradle-to-gate analysis of the biochar AC supply chain included upstream processes of feedstock procurement and preparation, the core process of thermochemical conversion (woody biomass carbonization), and then the downstream process of steam activation of the biochar into high-grade AC. The results of the comparative analysis revealed that a notable decrease in the global warming impact can be achieved through substitution of coal AC with biochar AC. Greenhouse gas (GHG) emissions were 39% lower for the biochar AC system compared with the coal AC system. However, GHG emissions were higher for syngas electricity than for electricity from natural gas when biochar sequestration effect was not accounted for, but this was reversed when the sequestration effect was accounted for. The primary driver of GHG emissions for both bioproducts was the thermochemical conversion stage (the core process) because carbonization required propane to fuel the endothermic reaction. The second greatest source of GHG emissions for biochar AC was the steam activation process. An alternative scenario using low-energy syngas generated from the carbonization stage (not currently being done) showed that displacing propane decreased GHG emissions substantially. Therefore, optimization of the supply chain would probably improve all environmental impacts for the two bioproducts analyzed.

Keywords: LCA, GHG emissions, life-cycle analysis, bioproducts, biochar, electricity, forest residues, coal

Contents

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Comparative Life-Cycle Assessment of Biochar Activated Carbon and Synthesis Gas Electricity with Commercially Available Alternatives

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Executive Summary

This report is a compilation of research conducted on the life-cycle assessment of processing the raw material woody biomass into biochar activated carbon (AC) and synthesis gas (syngas) for electricity production. This study used the life-cycle assessment (LCA) tool to evaluate the environmental sustainability of using woody biomass for electricity and AC production. The objective was to assess and document at the life-cycle level the environmental impacts associated with synthesis gas (syngas) electricity and biochar AC production from whole-tree chips and their use as substitutes for grid electricity and coal AC, respectively. The study was funded by the U.S. Department of Agriculture (USDA) and U.S. Department of Energy (DOE) through a Biomass Research and Development Initiative (BRDI) grant. The main drive of this project was to produce a high-quality and highly consistent AC as a replacement for coal AC with syngas electricity a secondary driver because, if this could be done, AC would command a far higher price in the current market. This report compiles previous research on the environmental impacts associated with thermochemical conversion (carbonization), synthesis gas (syngas) electricity production, and biochar AC to meet the critical review requirements of a comparative analysis that will be provided for public disclosure.

The scope of this LCA study covered the cradle-to-grave system boundary for syngas electricity and the cradle-to-gate system boundary for biochar AC production supply chains. For syngas electricity, the system boundary started upstream with feedstock procurement and preparation life-cycle stages, the core was the thermochemical conversion (woody biomass carbonization) stage, and then downstream was syngas storage and combustion (use stage) at the generator for electricity production. For biochar AC, the system boundary started upstream with feedstock procurement and preparation, the core was the thermochemical conversion, and then downstream was steam activation of the biochar into high-grade AC. The feedstock procurement and preparation life-cycle stage included forest harvesting activities, whole-tree chipping, the screening process, and the drying unit process. For both product supply chains, the upstream and the core processes were the same. The pathways differed after the two primary products were produced, with syngas combusted into electricity and biochar converted into AC.

The operational data used in this study were collected at various points along the entire process. Primary (source) data were collected during forest harvesting, whole-tree chipping, screening, drying, woody biomass carbonization, and steam activation of biochar. To provide an integrated analysis, the output of the woody biomass carbonization unit, referred to as the Tucker renewable natural gas (RNG) system (Tucker Engineering, Inc., Round Rock, Texas, USA), at 33.3 kg/h through engineering analysis was matched to the input of a commercial rotary calciner, which is used for steam activation. Thus, the entire system hypothetically could be installed at a wood product production facility such as a sawmill from which operational data were collected.

LCA was performed using the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) v2.1 impact assessment method, and the system was modeled using the SimaPro 8 LCA software package. Depending on what product system was being evaluated, functional units (FU) were determined to provide a mechanism for comparing environmental performances between competing products. The FU for the electricity system was 1 kWh of electricity generated, whereas the FU for the AC LCA was 1 kg of AC produced. The primary focus of these analyses was on greenhouse gas (GHG) emissions and primary energy consumption, although all ten TRACI impact categories were reported.

The authors evaluated and reported the LCA results for the two final products separately. The results of the comparative analysis revealed that a notable decrease in the global

warming (GW) impact can be achieved through substitution of coal AC with biochar AC. In addition, when the biochar carbon sequestration effect was accounted for, GHG emissions were substantially lower for syngas electricity generation than for natural gas electricity generation. Because this system was based on novel technology, some scenarios could result in improved environmental performance. One such scenario involved the use of low-energy syngas generated from the carbonization stage. The associated tars were collected and converted to a syngas to substitute the propane combusted for the woody biomass carbonization stage. In this scenario, GHG emissions decreased by 41%.

A primary driver of GHG emissions for both bioproducts was the thermochemical conversion stage (the core process) because carbonization required propane, a fossil fuel, to fuel the endothermic reaction and to keep and maintain the correct temperature in the two reaction chambers. For the syngas electricity supply chain, most of the GW impact (about 60%) resulted from the core (thermochemical conversion) life-cycle stage. For the biochar AC, most of the GW impact (about 50%) resulted from the upstream (steam activation) life-cycle stage. More specifically, the propane consumption was responsible for the high contribution of carbonization to the overall GW impact. The resulting environmental impact of substituting natural gas with syngas from the Tucker RNG at the activation process was investigated. Replacing natural gas with syngas decreased GHG emissions by 11%. Given that the whole system was based on novel technology, the continual strive for resource and energy efficiencies will provide improved environmental as well as economic performance.

Study Goal

Large volumes of woody biomass (dead or alive) can intensify wildfire severity but alternatively can be used as feedstock for high-value bioproducts (Tilman and others 2009, Lippke and others 2012, Jakes and others 2016). New distributed-scale bioenergy systems using woody biomass from western U.S. forests are being developed and studied. This study evaluated the life-cycle environmental impacts of products derived from a novel woody biomass thermochemical conversion (carbonization) system referred to as the Tucker renewable natural gas (RNG) unit using life-cycle assessment (LCA). This LCA was conducted with funding support from the USDA - National Institute of Food and Agriculture (NIFA) BRDI in accordance with ISO 14040 (ISO 2006a) and ISO 14044 (ISO 2006b) standards. The following products were evaluated: (1) electricity derived from burning syngas (the primary gaseous product) and (2) AC for filtering applications from biochar (the primary solid product).

Using an attributional unit process-based LCA method and allocating life-cycle inventory flows by mass, this study estimated critical environmental impacts including cumulative energy demand and climate change impacts of bioproducts derived from the Tucker RNG unit along with other various impact categories. The primary goal was to quantify net energy and GHG emissions for syngas electricity and biochar AC per FU, then make comparisons to commercially available alternative products derived from fossil fuels such as natural gas and coal. The purpose was to estimate how much fossil fuel consumption and associated fossil GHG emissions could be avoided by using renewable resources (such as woody biomass) in the production of syngas electricity and biochar AC.

Intended Application

The project, "Integration of Biofuels and Bioproducts Production into Forest Products Supply Chains using Modular Biomass Gasification and Carbon Activation" was funded to develop an advanced modular commercially viable thermochemical conversion technology (Miller and others 2014, 2015; RMRS 2016). The technology was designed to process forest biomass and convert it to biofuels and bioproducts in ways that meet objectives for environmental sustainability and economic efficiency. The Tucker RNG unit was modified to meet specifications for deployment by small- and medium-scale sawmills (i.e., 20 to 50 million board feet (47,195 to 117,987 m^3) in annual production capacity) to convert forest treatment residues and mill byproducts into value-added biofuel and bioproducts. The product systems investigated in this project provide scientifically sound and independently reviewed (third party) results on the practice of bioenergy and bioproducts production from forest biomass. The advantages demonstrated from a comparative analysis practice can be used to justify further research and commercialization of the studied technology.

Motivation

Given the threats from catastrophic wild forest fires and insect or disease outbreaks to the U.S. forest reserves, managing lands and forests for a healthy and sustained environment has become an imperative and eminent issue (Trumbore and others 2015). Management of these threats requires restoration treatments such as forest health thinning and regeneration harvests. Forest thinning and regeneration harvests produce large quantities of woody biomass that can be used as feedstock for production of biofuels and other bioproducts (Stokes and others 2016). Additionally, the decline of pulp and paper industries in the United States, particularly in the inland west, has created a need for alternative outlets for the excessive woody biomass generated from forest thinning and regeneration harvests. Converting such underutilized woody biomass to biofuel and bioproducts is not only the solution for these problems but also a good practice for clean energy efforts. This study focused on utilizing woody biomass from small-diameter

trees as a feedstock. Thus, this endeavor was important for forest management, U.S. pulp and paper industries, and world biomass sustainability. Using renewable energy sources such as biofuels to replace fossil fuel energy could decrease GHG emissions while increasing national energy security by decreasing dependence on foreign fuels (CBO 2012).

The motivation for undertaking this assessment was to provide a better understanding from a life-cycle perspective of the energy balance and the environmental impacts of the practice of thermally converting forest and mill residuals into biobased energy and biobased products using the Tucker RNG unit as the core process. The LCA approach assesses and compares new technologies in a scientifically sound and environmentally holistic way for more robust deployment decisions.

Intended Audience

This project disseminated new information, knowledge, and applications developed from a wide range of studies to many different stakeholders. Science-based assessments of forest biomass feedstock production and new bioenergy technologies and associated co-products are essential tools for all stakeholders who are working to expand biobased renewable energy production, including production of biofuels from biomass. With the development of a woody biomass carbonization system co-located at sawmills, the integration of advanced technologies into the existing forest industry operations can be examined for its environmental impacts by the LCA method. This could help revitalize the declining primary lumber mills and logging industries, providing new opportunities for product outlets and rural jobs. In addition, expanding biobased energy and biobased products production using forest biomass as feedstock can contribute to achieving broad national energy objectives, including decreasing net GHG emissions by displacing fossil fuel consumption and improving energy security (EISA 2007).

With LCA, the environmental aspects and potential impacts associated with a product, process, or service can be assessed by compiling an inventory of relevant energy and material inputs and environmental releases, evaluating the potential impacts associated with identified inputs and releases, and interpreting the results to help make a more informed decision. The environmental impact results from this LCA on converting forest and manufacturing residues to syngas electricity and biochar AC provided scientific-based information for policy makers to make better choices in forest management, bioenergy development, and woody biomass utilizations. Also, the LCA results could help biochar agricultural researchers in elaborating the environmental benefit for biochar application and processing (Anderson and others 2016, Bergman and others 2016a, Groot and others 2018, RMRS 2016). Entrepreneurs who work in the pyrolysis/gasification technology development field can also find industrial and governmental support with this study. The LCA analysis on environmental impacts for this novel technology can provide stakeholders a sound basis to make informed decisions on process and technology improvements. It can also raise awareness for using woody biomass to address climate change concerns.

Results from this LCA are intended to be used in a comparative assertion for future disclosure to the public. Therefore, this LCA was third-party verified. This extra level of effort was aimed at performing a comparative assertion between the new biobased products and commercially available products.

Methods

Study Scope

The scope of the study was to cover the life-cycle environmental impacts from resource extraction to final disposition of syngas electricity and to production of biochar (biobased) AC and compare these bioproducts with their alternatives made from natural gas and coal. Material and energy balances were used to quantify the emissions, resource consumption, and cumulative energy use (i.e., environmental stressors) of all processes during transformation of forest residues into electricity and AC. The results were then used to evaluate the environmental impacts of the process so that efforts could focus on mitigating possible effects. The project constructed a cradle-to-grave LCA for electricity and cradle-to-gate LCA for AC according to ISO 14040 and 14044 (ISO 2006a, 2006b) to evaluate the environmental impacts compared with fossil-fuel-based products on a functionally equivalent basis. LCAs for coal AC and natural gas electricity were constructed from peer-reviewed literature and other secondary and tertiary sources. The study analyses determined the biobased product's contribution to cumulative energy consumption, air pollution, water pollution, solid waste production, and climate change relative to its commercially available alternative products.

Functional Unit

Performance Characteristics of the Two Primary Products

Two primary products from the whole process chain were electricity generated from syngas produced by the Tucker RNG unit and AC converted from biochar produced by steam activation through rotary calciners. The Tucker RNG unit is an advanced thermochemical conversion system. Electricity was generated with a commercial generator (Caterpillar Inc., Peoria, Illinois, USA) burning syngas produced from the Tucker RNG unit. The new improvement on the Tucker RNG (carbonization) unit will allow the system to deliver more than 1.0 MW of electricity and

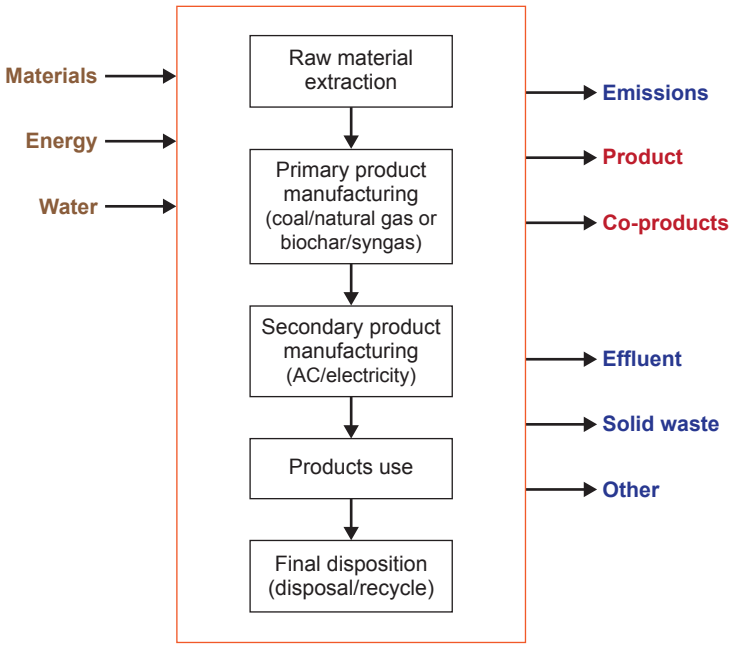

Figure 1. Full life cycle for activated carbon (AC) and synthesis gas electricity.

produce 10% to 15% (by dry weight) biochar in a low-dust environment (Gu and Bergman 2016, Bergman and others 2016a). The upgraded Tucker RNG unit needs to produce about twice the amount of syngas to generate the same electricity as natural gas does, because the higher heating value (HHV) of the produced syngas was measured at 19.7 MJ/m^3, which is about 50% of the natural gas HHV at 38.3 MJ/m^3 (Gu and Bergman 2017).

Biochar from the carbonization unit possessed the physical and chemical properties that can improve nutrients and water holding capacity in some soils. After steam activation, these properties were significantly improved with high surface area and high porosity, which were then ideal for adsorbing contaminants from liquid and gases, potentially adding value by meeting commercial specifications for AC used in filtering applications. Most commercial AC is made from bituminous coal or sub-bituminous coal with a surface area between 400 and 1,600 m^2 g^{-1}. AC from our biomass feedstock forest residues and mill residues has a surface area of 575 m^2 g^{-1} and 1,283 m^2 g^{-1}, respectively, as cited from a previous study (Anderson and others 2013). This made this project's biochar a desirable precursor for the production of AC. Although the economic efficiency and AC consistency make biochar to AC less competitive than fossil coal, the environmental impact determined from LCA results and the renewable benefit and distributed production of AC from biomass can provide advantages in some markets and to some individual users. AC consistency was improved after the upgrades.

Two Functional Units Defined

Functional unit is a reference unit which can be used to quantify the performance of a product system. It is also a reference related to the inputs and outputs. The FU for the cradle-to-gate biochar AC LCA was 1 kg of AC produced, whereas 1 kWh of electricity generated was selected as the FU for the cradle-to-grave syngas electricity supply chain. Material flows, energy use, and emission data will be standardized within the system boundaries based on each of the FU.

System Boundary

This project evaluated the life-cycle environmental impacts of electricity and biochar AC produced from biomass feedstock and fossil fuels. The project evaluated electricity and AC from raw material extraction to final disposition if required. Disposition refers to the final state of the product, whether it is landfilled, combusted, mulched, reused, or recycled. Figure 1 shows a general LCA boundary for electricity and AC from cradle to grave.

Biobased Products System

In this project, electricity and AC derived from the primary products syngas and biochar produced from the Tucker RNG unit were defined as biobased products and were compared with commercially available products from coal and natural gas. The entire product system for biobased products includes: feedstock extraction from the forests, chipping and screening at the mill, drying of the chips as feedstock, thermochemical reaction (woody biomass carbonization) in the Tucker RNG unit, separating gas and

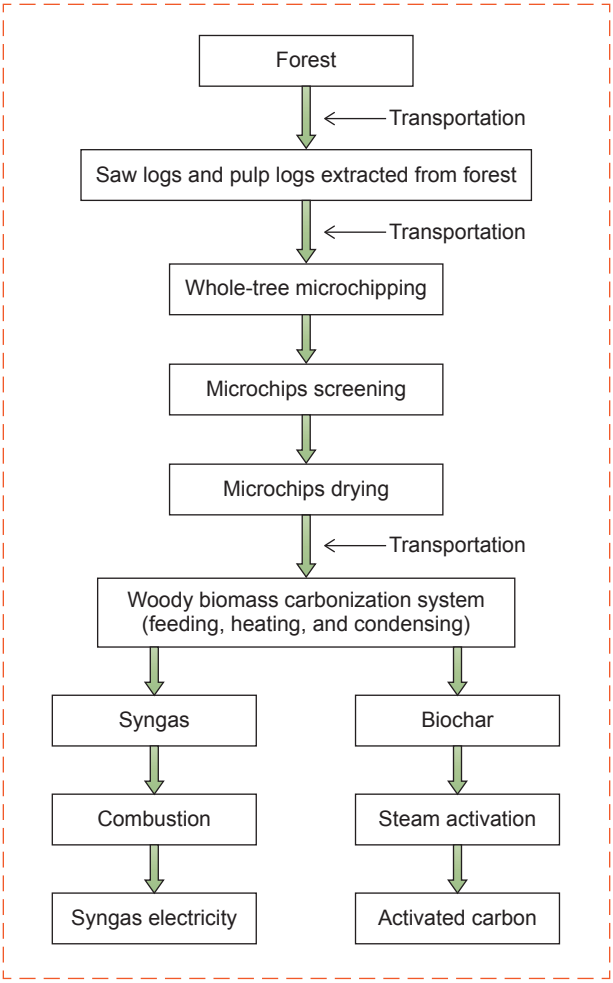

Figure 2. Process flow for new biobased products using Tucker renewable natural gas unit woody biomass carbonization technology.

solid products, cooling, and collecting and storing the two primary products (syngas and biochar). Secondary products were produced from the application; therefore, the processes of converting syngas to electricity and activating biochar to AC were included (Fig. 2).

Biobased Product System Description

The system boundary started with forest management operations in natural forests, from where the raw material, logs, were extracted and then transported by logging trucks to a nearby primary lumber mill and processed into microchips to the desired size and moisture content required by the Tucker RNG unit. The feedstock was then continuously fed into the Tucker RNG unit and heated at an elevated temperature (870 °C (1,600 °F)) under an oxygen-starved environment to produce two primary (core) products—syngas and biochar. The two primary products were then converted into the higher-value products of electricity and AC (Fig. 2).

Log (Forest Residue) Extraction from the Forest

Detailed data on forest harvesting activities to generate the raw material were collected using a survey (Appendix A). During harvesting, saw logs were removed to be processed into structural elements such as framing lumber. However, not all trees are created equal in terms of quality or size. The lower quality logs extracted from national forests (under-utilized, small-diameter) were a mix of conifer species dominated by lodgepole pine (*Pinus contorta*), Douglas-fir (*Pseudotsuga menziesii*), and ponderosa pine (*Pinus ponderosa*). Harvest included felling, skidding, processing, and loading for both commercial thinning and final harvest operations. The activities associated with harvesting were captured by an inland west forest resource project completed by Oneil and others (2010), and the impacts associated were reported as such. Saw logs and the other logs (referred to as pulp logs) were trucked for 120 km and then shipped by rail for 395 km to a sawmill for further processing. Pulp logs for this case were processed into whole-tree microchips.

Whole-Tree Microchipping Process

Detailed information for the microchips on energy values and physical and chemical properties was provided by gas chromatograph analysis. The feedstock for the Tucker RNG unit was produced at Tricon Timber in St. Regis, Montana, USA, a processer of small-diameter logs. The sawmill produces chips from both its primary lumber production activity and whole trees if these trees are not of high enough quality to be processed into lumber. These whole-tree chips provide an additional source of revenue for the facility. 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% moisture content (MC) as required for carbonization. To quantify physical properties, energy values, and chemical compositions of the whole-tree chips, proximate and ultimate material analyses were conducted, and results are shown in Table 1.

Primary Product Production—Biochar and Synthesis Gas

The RNG unit is a distributed-scale thermochemical conversion system comprised of active and passive sections (i.e., chambers). It is engineered to maximize syngas output in a virtually oxygen-free environment. The whole-tree microchips are fed into the reaction chamber, which operates at a temperature between 760 °C (1,400 °F) and 870 °C (1,600 °F) and is fired by three propane burners. The residence time for woody biomass feedstock for the carbonization unit is estimated at 3 min for the complete reaction (1.5 min per section). In a previous study (Anderson and others 2013) on the system before the upgrade, it was estimated that 19% and 14% by weight of input biomass (logging and mill residues, respectively) remained in solid form as biochar and approximately 73% of biomass carbon was converted to gas form as syngas during the conversion process (Gu and Bergman 2016).

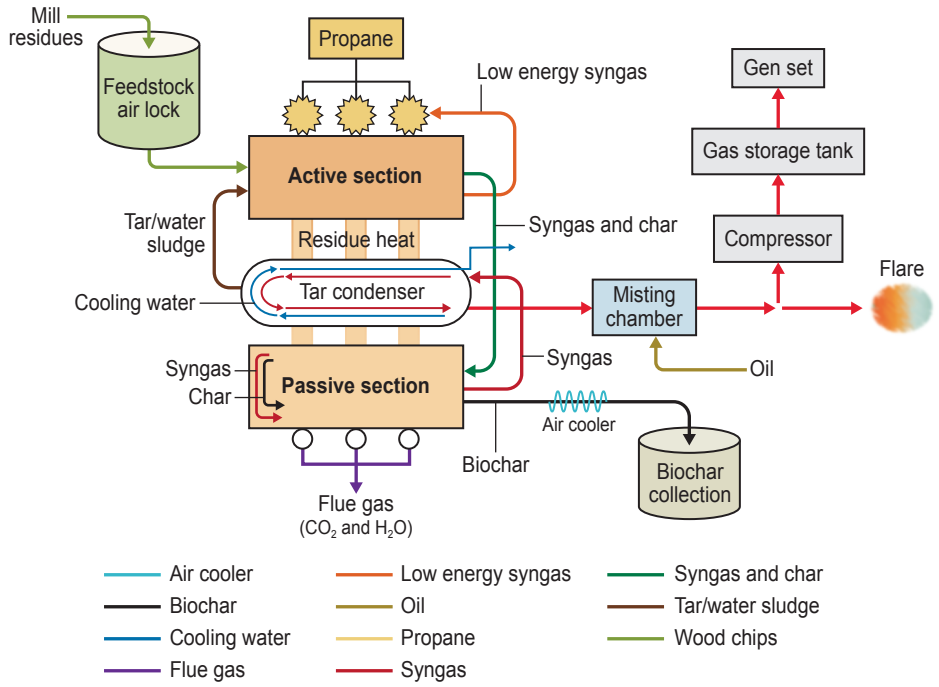

Figure 3. Woody biomass carbonization unit process diagram (source: Bergman and others 2016a).

Table 1—Properties of whole-tree microchip feedstock and associated biochar product (Gu and Bergman 2016)

	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	100.00	100.00
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	100.00	100.00

As previously mentioned, the carbonization unit has two thermal reaction chambers (see Fig. 3). The first chamber is called the Mable (active) section with three propane burners providing continuous active heating. Feedstock (i.e., microchips) is sent in by an air-locked auger system into the active chamber for high-temperature heating. Temperature in the active section reaches 870 °C (1,600 °F). Then the generated biochar, syngas, and residual heat are transferred to the Ethyl (passive) section (Fig. 3), which does not use an active heat source but only the residual heat from the active chamber passed through three pipes connected between the two sections. The biochar entering the passive chamber moves through two 3-m-long retorts for a total of 6 m. In the passive chamber, further conversion of higher molecular chain gases to methane occurs from using nickel embedded in the retort as a catalyst. The temperature measured at the entry of the passive section is about 760 °C (1,400 °F), and at the exit, it is about 510 °C (950 °F) (Gu and Bergman 2016).

To enable proper utilization of the syngas leaving the passive section, it was cooled in a tar condenser. The tar condenser used twin screws to remove tar buildup from the condensing of tars caused by the cooling of the syngas. The tar condenser used potable water for indirect cooling. Water temperature and flow rates were measured online during operations. To generate a low-energy syngas, the residual tars from the condenser were then augured back into a smaller retort inside the active section. This occurred in conjunction with production of the product gas, a medium-energy syngas. The medium-energy syngas went through

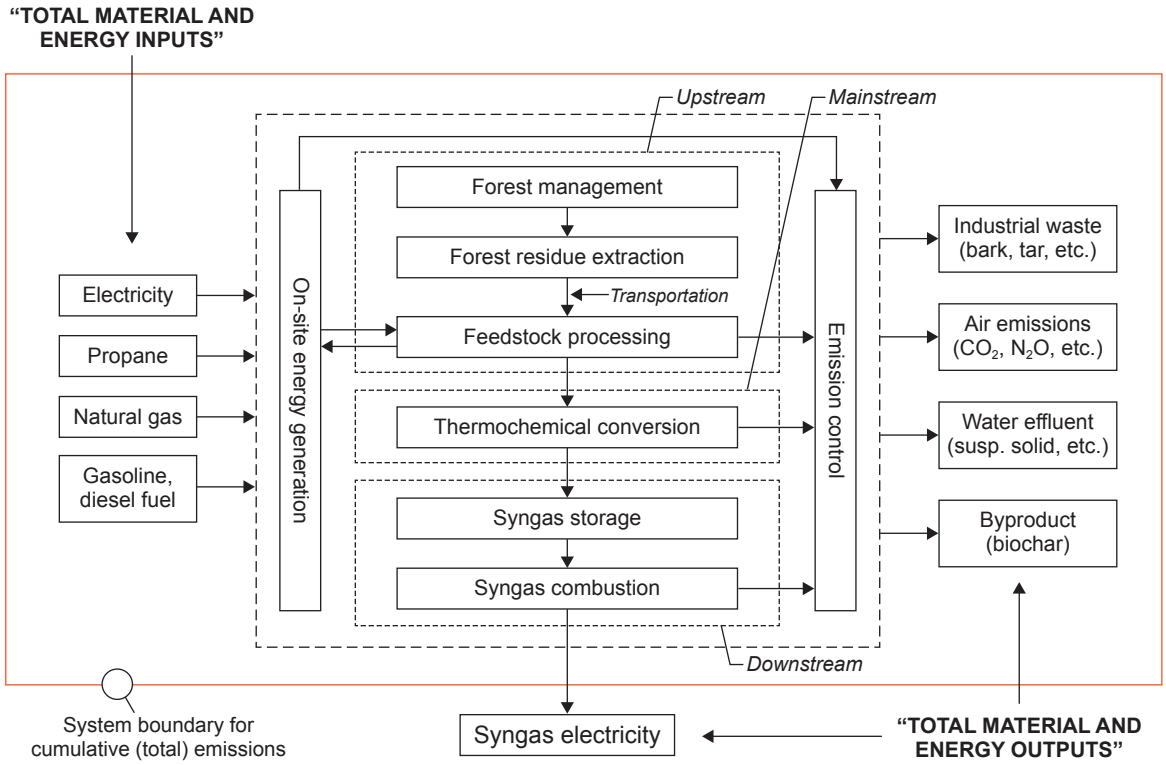

Figure 4. System boundary for the life cycle of generating synthesis gas electricity (source: Gu and Bergman 2017).

a misting chamber for additional cooling (Fig. 3), which removed oil and tars, before leaving the carbonization unit for outside gas storage. The two primary products from the carbonization system, biochar and medium-energy syngas, were collected at separated outlets. The exhaust gas from propane combustion 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 have been compressed to higher pressures as needed for combustion into electricity. The properties for the gases were measured at standard temperature and pressure.

The two primary products from the carbonization unit were analyzed for their properties. The unit was designed to produce more syngas but less biochar on a mass basis. Therefore, the output percentages on a mass basis for syngas, biochar, and wastewater tar were 65%, 14%, and 21%, respectively. The gas chromatography test shown in Table 2 provides the gas composition, gross heat, and net heat value of combustion for the medium-energy syngas for use in electricity generation. The coproduct biochar was intended to be used as a precursor for AC with results from proximate and ultimate material analyses shown in Table 1 (Gu and Bergman 2016).

Secondary Products Production—Syngas Electricity

Syngas was comprised of low- and medium-energy constituents. The low-energy syngas was intended as a propane substitute to maintain the endothermic reaction,

Table 2—Gas composition and heating value for Tucker renewable natural gas (RNG) medium-energy syngas from gas chromatography (Gu and Bergman 2016)

Tucker RNG syngas	Chemical formula	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

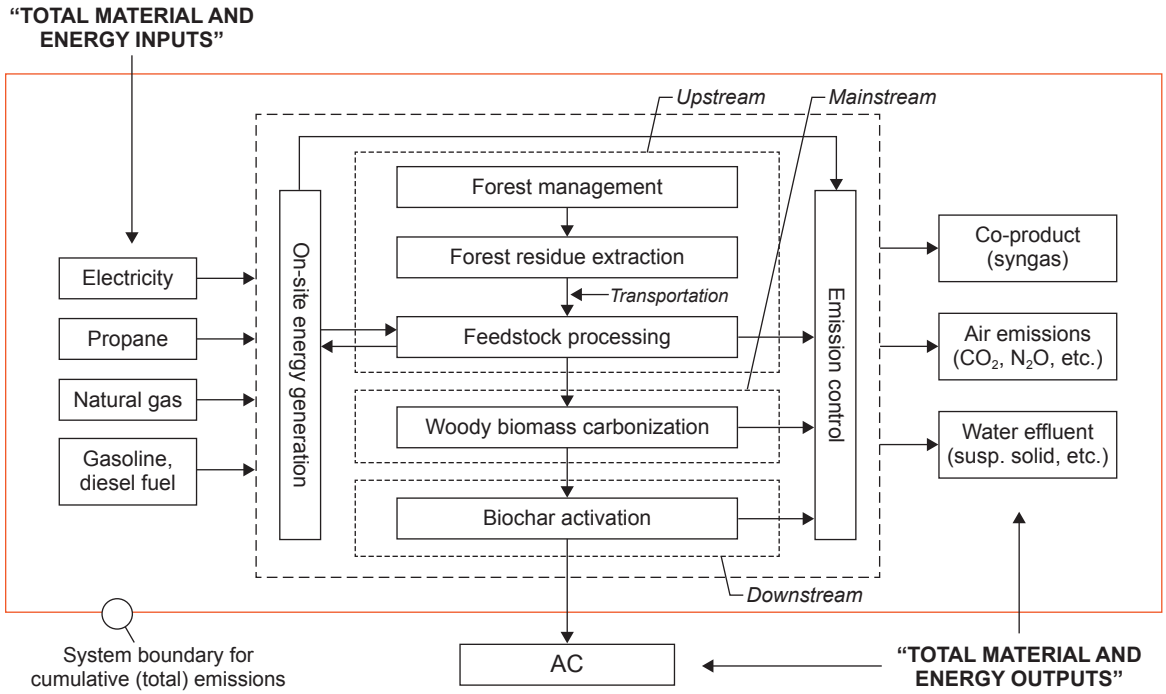

Figure 5. System boundary of activated carbon (AC) produced from forest residues (Gu and others 2018).

whereas the medium-energy supplied a generator to produce electricity for the power grid. The solid product biochar has three applications: (1) biochar for soil amendment; (2) substitute for coal to burn for heat and electricity; (3) higher-value products such as AC from biochar activated through high-temperature steam or chemicals such as potassium hydroxide.

Syngas can be used as fuel to create electricity, either through burning in a gas turbine or generator. In this project, electricity was produced from the gas-fired generator using medium-energy syngas. Figure 4 shows the system boundary for the cradle-to-grave LCA of generating syngas electricity.

Secondary Products Production—Biochar Activated Carbon

To produce biochar AC, the carbonization process is followed by steam activation, where a rotary calciner can be attached to the outlet of the woody biomass carbonization unit. Appendix B provides the engineering estimates to match biochar output to a rotary calciner developed from working with RBS-ARVOS Group's engineering team (ARVOS Inc., Naperville, Illinois, USA). Because the rotary calciner required heating, attaching it directly to the carbonization unit saves energy because the biochar does not need to be cooled down from 550 °C (1,000 °F) to prevent self-ignition upon exposure to air. Figure 5 shows the system boundary for the cradle-to-gate LCA of biochar AC production.

There are several ways to activate biochar including steam and chemical activation as subsequently detailed. For this project, biochar was activated using steam in a rotary calciner. Steam for the activation process was produced by water indirectly heated from burning natural gas. Figure 6 shows a schematic for the steam activation production of AC from biochar.

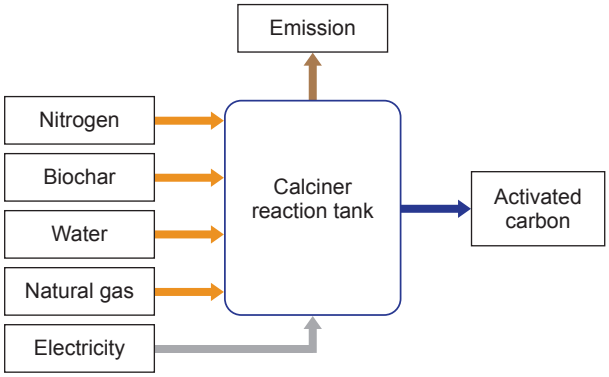

Figure 6. Steam activation of biochar.

Physical and chemical procedures are commonly used for producing AC. Physical activation involves a two-step process, i.e., carbonization followed by activation using steam, oxygen, or carbon dioxide as an activating agent. Carbonization and activation processes occur in a single stage for the chemical activation process, which uses chemicals as the activating agent such as zinc chloride, phosphoric acid, and potassium hydroxide. There is a newer activation procedure using microwave-induced potassium hydroxide to produce coconut-shell-based AC (Iqbaldin and others 2013, Yagmur and others 2008). As might be

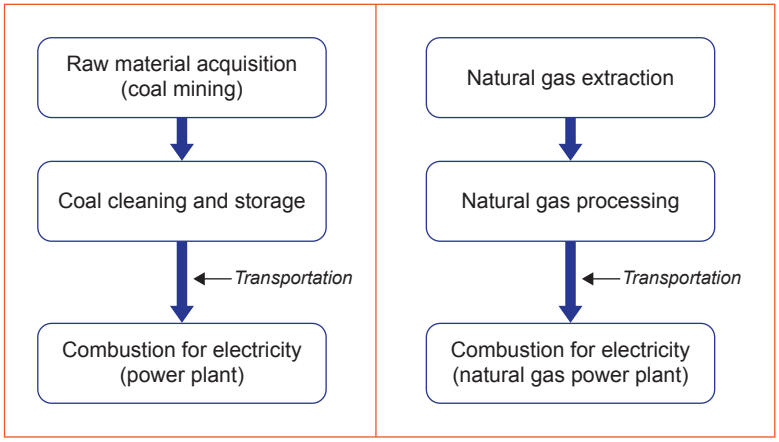

Figure 7. System flows for coal and natural gas power plants.

expected, AC can be produced from various carbonaceous materials, such as coconut shells (Laine and Yunes 1992), bagasse and rice husk (Kalderis and others 2008), macadamia nutshell (Ahmadpour and Do 1997), waste tea (Yagmur and others 2008), paper mill sludge (Khalili and others 2000), and olive waste cake (Hjaila and others 2013). Several LCA analysis studies were performed for the environmental impacts associated with AC preparations from these different raw materials. Saffarian (2009) defined the boundary system for granular activated carbon (GAC) from coal extraction to GAC production. Saffarian (2009) assumed that the spent GAC could be reactivated after one year of use. In addition, Saffarian (2009) included the natural gas extraction and transportation to the GAC manufacturing plant. Hjaila and others (2013) applied LCA analysis on producing 1 kg of AC from the byproduct of olive waste cake and found the GW impact at 11.1 kg CO_2-eq/kg AC. Bayer and others (2005) also reported a similar result with a GW impact of 11 kg CO_2-eq/kg AC for virgin GAC made from hard coal. This analysis did not include any downstream impacts after the production of AC from steam activation.

Fossil-Fuel-Based Product Systems

Coal and Natural Gas Electricity

For comparative assertion, fossil-fuel-derived commercial products of electricity and AC were assessed for environmental impact using available data in the U.S. Life-Cycle Inventory (LCI) Database and other secondary data sources. System boundaries for the electricity from coal and natural gas were designed based on the National Renewable Energy Laboratory (NREL) U.S. LCI Database (NREL 2012) and literature (NETL 2010, Dones and others 2007, Spath and others 1999).

In this study, the U.S. LCI Database dataset for electricity environmental impact from coal and natural gas was used for our comparative analysis (NREL 2012). Figure 7 shows the system flow for coal and natural gas power. The LCA for electricity from coal includes three steps—raw material extraction (coal mining), coal cleaning and storage, and transportation of coal to power plants for power production. The solid waste generated is primarily coal ash and flue gas. Transportation use of barge, diesel truck, and train is included in the dataset (NREL 2013). Natural gas power production also starts with material extraction. Then the raw gas is refined and piped to the power plant and combusted to produce electricity (Dones and others 2007). Transportation with pipeline, diesel truck, and train is included in the dataset (NREL 2013). No waste is specified in the dataset.

In the core module, to be consistent, the infrastructural impacts from system or plant building, foundations, roads, and respective construction processes for both fossil-fuel- and biomass-based systems were omitted in this study.

Coal Activated Carbon

Activated carbon made from coal starts with raw material extraction or coal mining from nature, and then the coal is processed into commercial products. In the system to produce AC from coal, coal processing is referred to as primary production (Fig. 8). The coal first goes through the carbonization process with a temperature of about 800 °C (1,472 °F). During the carbonization process, most of the noncarbon elements such as oxygen, hydrogen, and nitrogen are eliminated as volatiles. The fundamental carbon groups remain as cross-linked aromatic sheets stacked together to form pores. These pores are further enhanced to generate high surface area and absorption during the activation process. In addition to GAC, there is also another common type of AC made from coal, referred to as powdered activated carbon (PAC), which means it is in powdered state. Other AC products are extruded activated carbon (EAC) and bead activated carbon (BAC). After the use stage of GAC, it can be reactivated for reuse until it becomes inert, and then it is landfilled where the carbon stored remains in its present form for millennia. The reactivation process is assumed to have the same environmental impact

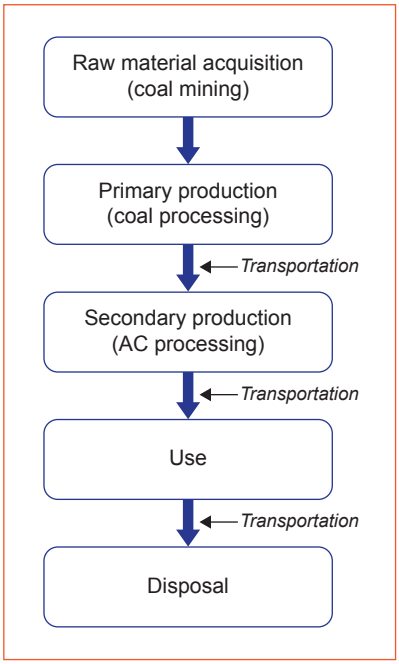

Figure 8. System flow for activated carbon (AC) from coal.

as the original activation process. In this project, to compare coal AC with AC from woody biomass carbonization, the reactivation process was not included. For comparison with alternative commercial AC products on the market, the coal AC model available in the Agri-footprint Database was used (PRé Consultants 2017). The coal AC model was based on Bayer and others (2005). It was modified by adding the coal combustion emission profile to the activation process.

Allocation Procedure

Allocation is required to partition the inputs, emissions, and wastes when multiple products result from a single process as in this study. There were two primary biobased products, biochar and syngas. The fossil-fuel-derived alternatives do not require any allocation because no co-products or byproducts were generated during their production. However, allocation may have been included to generate the LCI databases used in the study. Allocations of the environmental impacts from the LCA results were examined with mass allocation being the primary allocation approach. Alternative allocation approaches such as economic (revenue) and energy were considered but not chosen. Mass allocation was selected because mass data were readily available from the analyses to consider only biochar and syngas as products, not the wastewater tar produced from the novel thermochemical conversion system. In addition, the economic allocation approach had too much uncertainty regarding the price for high-grade biochar along with the potential revenue for syngas from generating electricity and renewable energy credits. Furthermore, the energy allocation approach could have been an option if we were going to use the biochar as an energy product but that idea ran counter to the goal of the whole project. Regardless, the authors conducted mass and energy balances to show the differences as detailed later in the report. No environmental burdens were assigned to the waste products.

Life-Cycle Impact Assessment Method and Types of Impacts

TRACI Impact Category Method is Primary

After the LCIs were constructed for products of biochar AC and syngas electricity, the environmental midpoint impact categories were estimated. TRACI determines the characterization of ten environmental stressors that have potential effects, including ozone depletion (kg CFC-11 eq), GW (kg CO_2 eq), tropospheric ozone (smog) formation (kg O_3 eq), acidification (kg SO_2 eq), eutrophication (kg N eq), human health cancer effects (CTUh), and human health noncancer effects (CTUh), human health respiratory effects (kg $PM_{2.5}$ eq), ecotoxicity (CTUe), and fossil fuel depletion (MJ surplus). TRACI 2.1 is embedded in SimaPro 8 LCA modeling software (Bare 2011, IPCC 2007, PRé Consultants 2017). As an alternative, cumulative energy (primary energy) (MJ-eq) from biomass and fossil fuel contribution can be calculated directly from LCI flows and reported. Solid waste as well as water impacts were also reported.

LCI and LCIA Indicators

The life-cycle impact assessment (LCIA) phase establishes links between the life-cycle inventory results and potential environmental impacts. Environmental impacts are determined using the TRACI impact category method (Bare 2011). The LCIA calculates impact indicators, such as GW and smog. These impact indicators provide general, but quantifiable, indications of potential environmental impacts. Table 3 summarizes the target impact indicator, the impact category, and means of characterizing the impacts for five of the ten impact categories previously listed that are consistent with the requirements of the wood products product category rule (FPInnovations 2015).

Each impact indicator is a measure of an aspect of a potential impact. LCIA does not make value judgments about the impact indicators, meaning that no single indicator is given more or less value than any of the others. All are presented as equals. Additionally, each impact indicator value is stated in units that are not comparable with others. For the same reasons, indicators should not be combined or added.

Table 3—Selected impact indicators, characterization models, and impact categories

Impact indicator	Characterization model	Impact category
Greenhouse gas (GHG) emissions	Calculate total emissions in the reference unit of CO_2 equivalents for CO_2, methane, and nitrous oxide along with other GHGs.	Global warming
Releases to air decreasing or thinning of ozone layer	Calculate the total ozone forming chemicals in the stratosphere including CFCs, HCFCs, chlorine, and bromine. Ozone depletion values are measured in the reference units of CFC equivalents.	Ozone depletion
Releases to air potentially resulting in acid rain (acidification)	Calculate total hydrogen ion (SO_2) equivalent for released sulfur oxides, nitrogen oxides, hydrochloric acid, and ammonia. Acidification value of SO_2 mole-eq. is used as a reference unit.	Acidification
Releases to air potentially resulting in smog	Calculate total substances that can be photo-chemically oxidized. Smog forming potential of O_3 is used as a reference unit.	Photochemical smog
Releases to air potentially resulting in eutrophication of water bodies	Calculate total substances that contain available nitrogen or phosphorus. Eutrophication potential of N-eq. is used as a reference unit.	Eutrophication

Data Quality

For comparative LCAs intended for the public, ISO 14044 (ISO 2006b) lists ten data quality criteria that must be addressed, which are subsequently discussed.

Time-Related Coverage

Primary data were collected during the years 2013 and 2014 for the carbonization unit operation and rotary calciner and during 2012 for whole-tree microchip production. Secondary data for fossil fuel products came from literature in the last ten years and from LCI databases including the U.S. LCI Database (NREL 2012). Primary data on feedstock preparation and processing were collected by site visits and surveys from sawmills including forest management and harvesting operations as well as the thermochemical conversion unit and the rotary calciner that converted biochar into AC through a steam process. A range of data from sawmill production data were used in the LCA analysis for the generality presumption.

Geographical and Technological Coverage

Different processes occurred in different locations. In 2013, as part of the overall BRDI project, an upgrade was completed on the Tucker RNG unit in Locust, North Carolina, USA. Whereas the Tricon Timber sawmill built in 1989 is in St. Regis, Montana, USA. For the project analysis, all operations were assumed to occur in western Montana. Thus, the only transportation data included in the analysis were for the raw material brought to western Montana (i.e., St. Regis).

Representation

The Tucker RNG unit is a novel biomass thermochemical conversion technology. Thus, no direct comparisons are available for this technology.

Precision

No variances were provided because the present study evaluated a single system not on an industry level. However, the authors provided process-specific data wherever possible.

Completeness, Consistency, and Uncertainty

Measures of completeness and consistency were provided including a listing of limitations and assumptions. To deal with potential unknowns, sensitivity and scenario analyses were conducted to address these issues as necessary. A mass balance from material input to material output and energy balance of the woody carbonization unit and a sensitivity analysis will be conducted to address completeness, consistency, and uncertainty in data quality. Sensitivity analysis highlights the most important set of model parameters to determine if data quality needs to be improved and to enhance interpretation of results.

Reproducibility

To enable others to reproduce the results, the sawmill survey is provided in Appendix A as well as the inputs into the LCA modeling software, SimaPro, used to develop the LCI and LCIA.

Table 4—Higher heating values (HHV) used to calculate energy values from raw material resources

	HHV		
Fuel	Btu/lb	MJ/kg	MJ/L or MJ/m^3
Coal	11,260	26	
Distillate fuel oil	19,577	46	38.759
Liquid petroleum gas	23,236	54	26.628
Natural gas	23,409	54	38.335
Residual fuel oil	18,680	43	41.822
Wood	9,000	21	
Uranium	1.64E+08	3.84E+05	
Gasoline	20,808	48	34.871
Diesel	18,932	44	38.728

(Source: Franklin Database. http://www.fal.com/lifecycle-services.htm)

Data Sources

For the biobased products, primary data sources were collected directly from the sawmill, the carbonization unit, and the steam activation process. Secondary data on emissions by fuel type and electricity were obtained from the U.S. LCI Database (NREL 2012). Secondary data were also synthesized from published data sources, government and industry reports, and economic data.

Assumptions and Limitations

For the woody biomass carbonization unit, syngas produced from woody biomass held on average 19.7 MJ/m^3 for the gross heat of combustion and 18.3 MJ/m^3 for the net heat of combustion (Table 2). These energy values were based on the 1-hour run using whole-tree microchips from Tricon Timber.

Transportation of biochar, biochar spreading, soil management practices, and their associated environmental impacts were not included in this study.

Using HHV, this study converted fuel from its volume or mass basis to its energy value. HHV represents the (gross) energy content of a fuel with the combustion products at 25 °C (77 °F) with all water vapor brought to liquid form. Lower heating value (net energy) maintains the water in the combustion product in vapor form at 150 °C (302 °F). However, HHV is the preferred method in the United States to calculate energy values (EIA 2019). HHVs are listed in Table 4.

Cut-Off Criteria

Cut-off criteria specifies the quantities of material or energy flow or the level of environmental significance associated with the product system or unit processes to be excluded from a study. For this study, a 1% cut-off of mass and energy in and out of the system was applied in the model to minimize the effect. In addition, material and energy with less than 0.1% environmental significance in the model output were not included. All materials used that had a substantial environmental impact were tracked. For the present study, mass and energy that contributed less than 1% to the total output were not modeled in the SimaPro LCA software. Initially, all LCI flows were included in the impact categories. The final analysis included any mass or energy resource that resulted in a greater than 2% change to any impact category.

Type of Critical Review

Because of the comparative nature of this study and its intended release to the public, the ISO 14044 (2006b) requirement of a critical review was satisfied. The external review was conducted by James Salazar, M.S., Senior Research Associate at the Athena Sustainable Materials Institute (Ottawa, Ontario, Canada). In addition, three publications used to compile the LCA results went through a peer review process (Gu and Bergman 2016, 2017; Gu and others 2018).

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

Value Choices

Midpoint indicators from TRACI 2.1 (Bare 2011) were used for expressing results from the impact assessment to avoid value judgments from weighting. Ignoring potential increases in forest stocks for unharvested wood implies a value choice for continued reliance on managing the use of forest stocks for wood products rather than forest preservation.

Interpretation

The interpretation evaluates results for midpoint indicators in light of the assumptions and limitations previously outlined. Results from the sensitivity analysis were also addressed as part of the interpretation.

Biogenic Carbon Accounting

Accounting for the biogenic carbon emitted and stored in the biomass from bioenergy conversion processes is currently under debate (Sejio 2013). The differences in bioenergy (especially wood bioenergy) carbon counting were summarized by Nepal and Skog (2014). Three options discussed by U.S. EPA (EPA 2011) included (1) carbon neutral for bioenergy from wood—since biomass is inherently carbon neutral, carbon emissions from biomass removal and combustion for bioenergy will be offset (Bergman and others 2014); (2) net effect on GHG emissions occurs from initial combustion of woody biomass to bioenergy with a limited temporal scale and

Table 5—Process inputs and energy flows for the 1-h thermochemical conversion run with 263 kg/h (12% MC)[a] woody biomass (Gu and Bergman 2016)

Energy sources	Material flows		Energy flows (MJ)	Energy flows (%)
Flow into the system				
Chip processing at Tricon Timber				
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 wood fuel		3.77	0.2
Truck transportation to Tricon Timber	120 km		75.82	3.2
Railroad transportation to Tricon Timber	395 km		21.34	0.9
Thermochemical conversion				
Parasitic electricity[b]	2.87 kWh		31.31	1.3
Propane gas (thermal energy)[c]	18.06 m^3		1,707.55	72.8
Total			2,345.2	100
Flow out of the system				
Products	(kg/h)	(%)		
Syngas[d]	172	82.5	3,091	70.8
Biochar[e]	36	17.5	1,274	29.2
Total			4,365	100
Net energy gain				
Per hour			2,019.8 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 values (HHV) 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.
[e]For the whole-tree chips, HHV for biochar was obtained from the proximate test by Hazen Research, Inc. (Golden, CO), on May 16, 2013.

static forest stand consideration (i.e., forest regrowth is not considered). Specifically, the initial combustion of biomass to energy, which releases CO_2 emissions into the atmosphere, is considered the same as fossil fuel combustion because no CO_2 is pulled from the air into growing trees (Manomet Center for Conservation Sciences 2010); and (3) fraction of wood emissions that should be counted as equal to fossil fuel emissions. Nepal and Skog (2014) modeled mathematically based on this assumption and predicted that 78% to 80% of wood energy carbon emissions would be offset by 2060. This aligned with other research stating a substantial portion of biomass carbon emissions from increased wood energy use would be offset during the next 50 years (Bird and others 2011, Miner and others 2014, Pierobon and others 2014). In this LCA study, the authors adopted a 100-year time horizon for climate change impact estimation, which is consistent with the TRACI impact category method (Bare 2011). Therefore, this study considered a net-zero biogenic carbon flux (i.e., the carbon flux out equals the carbon flux in during a 100-yr time horizon) except for the biogenic carbon found in AC. However, the biogenic carbon sequestered in the biochar AC was not accounted for in the analysis because the analysis was only from cradle-to-gate although AC is expected to degrade little even after landfilling for a very long period (Bergman and others 2016b). Given sufficient time, complete forest regeneration occurs. Thereby, biogenic carbon emissions from using woody biomass for energy are balanced out with respect to the atmosphere. Therefore, consistent with Bare (2011), biogenic CO_2 was given a characterization factor of zero when calculating GW impact.

The International Panel on Climate Change (IPCC 2006, 2014) also supports the carbon neutral hypothesis, which considers the carbon dioxide emissions from biomass as part of the natural carbon cycle. Because no more carbon is released than was absorbed during the lifetime of the biomass, biofuels from biomass such as organic waste, wood residues, and agricultural fiber are considered carbon neutral and are not counted in the greenhouse gas emissions calculation.

Results and Discussion

This report compiles the results from previous work on the woody biomass carbonization unit, syngas electricity, and biochar AC. The following describes the flows and

Table 6—Cradle-to-gate cumulative energy demand for producing syngas and biochar from carbonizing 1 oven-dry (OD) kg whole-tree chips

			Higher heating values		Energy	
Substance	Unit	Value	(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		332,000	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

life-cycle impacts associated with these product systems. To comply with the ISO 14044 reporting requirements, the LCIA results are relative expressions and do not predict impacts on category endpoints, the exceeding of thresholds, safety margins, or risks.

Woody Biomass Carbonization Unit

Material and Energy Flows

Primary data of feedstock processing, transportation, and the pyrolysis process were collected from a whole-tree chipping operation and 1-hour continuous run of the Tucker RNG unit with consumption of 263 kg coniferous microchips at 12% MC feedstock (Table 5). Without considering the waste tar sludge in the output, the two primary products from the unit, syngas and biochar, have a mass ratio of 4.8:1 and energy content ratio of 2.4:1. Net energy gain is one way to calculate the energy efficiency of a new technology, and the energy efficiency is an important parameter to investigate, which can be done using LCI flows. Fossil energy replacement ratio (FERR) is defined as the ratio of bioenergy output from the system to fossil energy put into the system (Geottemoeller and Geottemoeller 2007). In the carbonization unit, a net energy gain of 8.7 MJ/OD kg chips was obtained (OD, oven-dried). In addition, the system also had a positive FERR of 1.88, which means 1.88 MJ of renewable bioenergy products (syngas and biochar) were produced for every 1 MJ of nonrenewable fossil energy consumed in the process within the defined boundary. When only considering the carbonization process, a FERR of 2.54 was calculated previously in the study (Gu and Bergman 2016). The FERR decreased to 1.88 because this analysis considered more stages of the carbonization process. However, this result was consistent with other published results. For example, Patzek and Pimentel (2005) and Metzger (2006) found energy yields between 0.7 and 2.2 MJ/MJ for the corn ethanol production process, whereas Steele and others (2012) approximated 2 MJ/MJ for the Southern-Pine-derived bio-oil production process.

Cumulative Energy Demand

Table 6 shows a total cumulative energy demand (CED) of 13.9 MJ/OD kg of feedstock found within the defined boundary. Propane use for heating conversion was the highest energy component (52%), followed by drying with wood fuel (27%). Renewable biomass energy and nonrenewable fossil fuel contributed 27% and 72% of total CED, respectively.

Table 7 summarizes the emissions to air, water, and soil, in which the total fossil CO_2 emissions were about 0.534 kg for every 1 OD kg of woody biomass carbonized, and the total biogenic CO_2 emission was 0.159 kg/OD kg of woody biomass. Other emissions came from transportation, whole-tree chipping, and off-site electricity generation.

Syngas Electricity

The environmental impact assessment for generating 1 kWh of electricity from syngas derived from carbonizing woody biomass was carried out using LCA and the results are subsequently described.

Life-Cycle Impact Assessment of Syngas Electricity

Table 8 lists the cradle-to-grave life-cycle environmental impacts of syngas electricity. The GW impact from the cradle-to-grave LCA for syngas electricity was 0.748 kg CO_2-eq/kWh without considering biochar's potential for carbon sequestration. The GW impact results were divided into three stages: feedstock processing, syngas production, and syngas electricity generation, with syngas production releasing 60.8% of the total GHG emissions. Feedstock processing was the second highest emission because it includes the harvesting of whole-tree logs,

Table 7—Cradle-to-gate life-cycle inventory flows for carbonizing 1 oven-dry kg of whole-tree chips (Gu and Bergman 2016)

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

Table 8—Life-cycle impact assessment results for cradle-to-grave syngas electricity generation (Gu and Bergman 2017)

			Feedstock processing		Syngas production		Syngas electricity generation	
Impact category	Unit	Total	Value	(%)	Value	(%)	Value	(%)
Ozone depletion	kg CFC–11 eq	8.39E–09	9.25E–12	0.1	8.38E–09	99.9	0	0.00
Global warming	kg CO_2 eq	0.748	0.287	38.3	0.454	60.8	0.0069	0.93
Smog	kg O_3 eq	0.143	0.095	66.5	0.024	16.8	0.0239	16.7
Acidification	kg SO_2 eq	0.0053	0.004	69.3	0.001	17.8	0.0007	12.8
Eutrophication	kg N eq	0.0003	1.80E–04	56.7	9.51E–05	30.0	4.23E–05	13.3
Carcinogenics	CTUh	9.25E–09	2.71E–09	29.3	6.48E–09	70.1	6.11E–11	0.66
Noncarcinogenics	CTUh	9.45E–08	3.02E–08	32.0	6.16E–08	65.2	2.64E–09	2.79
Respiratory effects	kg $PM_{2.5}$ eq	1.74E–04	1.21E–04	69.5	0.00003	16.9	2.36E–05	13.6
Ecotoxicity	CTUe	1.73	0.55	31.8	1.177	68.2	0.00053	0.03
Fossil fuel depletion	MJ surplus	1.26	0.42	33.2	0.841	66.8	0	0.00

log transportation, and size reduction and pretreatment (screening and drying) of the feedstock. About 38.3% of the total GHG emission was from this feedstock processing upstream stage, which leaves about 0.93% of GHG emissions associated with the syngas electricity generation process (Table 8).

In terms of the type of energy consumed in each of the three stages, more renewable biomass energy was consumed in the feedstock processing stage than either the syngas producing or the electricity generation stages because the feedstock processing stage uses wood heating for drying and some processing. Biogenic CO_2 emissions from burning woody biomass were not considered in estimating the GW impact because woody biomass consumption is equal to tree regrowth for a given period. Feedstock drying and processing took place at a sawmill with a wood boiler producing process heat for drying the chips. Because the endothermic reaction of the carbonization unit was sustained by propane combustion, the thermochemical conversion was identified as the major fossil fuel energy consumption stage (i.e., environmental hot spot) for the whole system. For a comparison, Steubing and others (2011) reported a GW impact of 0.103 kg CO_2-eq/kWh for a Swiss case in which the syngas was primarily composed of CH_4 and very little fossil fuel (i.e., gas) was consumed in the production of syngas, unlike the case of the Tucker RNG unit.

Carbon Sequestration Effect from Biochar

Gu and Bergman (2017) conducted a scenario analysis considering syngas electricity as a single product system. Biochar, which was considered a co-product previously, was now a byproduct and thus had no environmental impacts associated with it. In the case of this particular biochar, the resultant product was highly stable and recalcitrant, with high carbon content. Therefore, decomposition would be delayed for hundreds to thousands of years, beyond current GHG accounting time periods (Cowie and Cowie 2014, Bergman and others 2016b, Gu and others 2018). Thus, it is important to model this delay in emissions to demonstrate the direct climate change impacts from biochar in the syngas electricity production system. As mentioned previously, all environmental burdens were assigned to syngas electricity because biochar was designated as a byproduct.

Biochar is characterized by specific properties such as low bulk density, high ash content, and stable aromatic carbon structures. Because of its recalcitrant properties, the storage of biochar in soils represents a long-term removal of atmospheric carbon, i.e., carbon sequestration (Sohi and others 2010). There are two types of carbon transfers. The transfer of carbon from one reservoir in the ecosystem to another is called carbon accumulation. The transfer of carbon from the atmosphere into a reservoir is called carbon sequestration. According to IPCC (2007), carbon sequestration can be defined as "the uptake of C-containing substances, and in particular CO_2, into another reservoir with a longer residence time".

If the biochar produced from the Tucker RNG unit as a byproduct is intended to be applied as a soil amendment, the benefit of carbon sequestration to slow or even reverse the increase in atmospheric concentration of CO_2 may apply to the GHG emission accounting. From the material ultimate chemical analysis, biochar from forest thinning residue has a fixed carbon content as high as 90% on a dry weight basis. Based on Wang and others (2014), we calculated a carbon stable factor of 85% for the biochar generated from the carbonization unit. With this, the total carbon in the biochar produced as a byproduct for generating 1 kWh syngas electricity can be calculated and converted to CO_2-equivalent weight, as a reduction in total GHG emission accounting for the entire process. The sequestration of the biochar carbon directly reduced the GW impact (Fig. 9). However, transportation of biochar, biochar spreading, soil management practices, and their associated environmental impacts were not included in this study. The GHG emissions from burning fossil fuels for these activities would probably decrease the benefits of applying biochar as a soil amendment (Gaunt and Lehmann 2008).

Comparing Syngas Electricity to Electricity from Other Sources

Figure 9 summarizes the GHG emission of the LCA results for coal electricity, natural gas electricity, direct biomass combustion electricity, and the Northwest eGrid profile electricity using SimaPro software and the built-in U.S. LCI Database. For 1 kWh of electricity generated from the syngas produced from carbonizing forest residue chips, the GHG emissions were estimated to be 0.748 kg CO_2-eq/kWh without taking biochar carbon sequestration into consideration. This is close to the total GHG emission from natural gas electricity (0.720 kg CO_2-eq/kWh). However, eGrid for the Northwest region and coal electricity have substantially different values from our studied syngas electricity (0.499 and 1.079 kg CO_2-eq/kWh, respectively). Electricity generated from direct combustion of biomass has a lower GW impact (0.046 kg CO_2-eq/kWh) because of less fossil fuel consumption and neutral impact to the environment from biogenic CO_2 emission, which is the major emission from the Tucker RNG unit technology. When including the biochar carbon sequestration effect, the GHG emission value for our studied syngas electricity was reduced by more than 50% to 0.365 kg CO_2-eq. (This number supercedes the value of 0.330 stated in the prior publication (Gu and Bergman 2017)). Thus, a notable influence was discovered from carbon sequestration by the byproduct biochar when it was included, and this should be emphasized in future analysis of biobased renewable electricity-generating technologies.

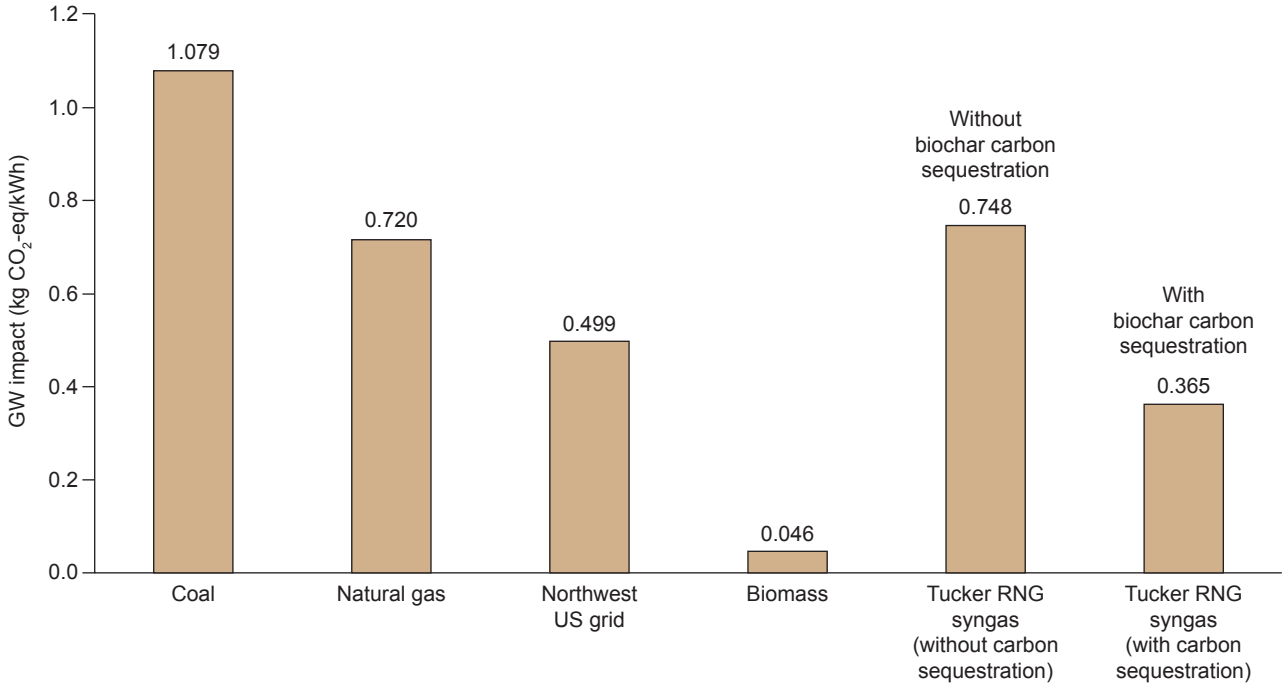

Figure 9. Global warming (GW) impacts for various electricity sources and technologies with and without carbon sequestration accounting (Gu and Bergman 2017) (RNG, renewable natural gas).

Greenhouse Gas Performance Indicator

The GHG performance indicator from Sebastian and others (2011) can be used to compare GHG performance between syngas electricity and fossil or other based electricity, which was described as follows: GHG performance (in percentage) = (GHG fossil or other – GHG syngas)/GHG fossil or other. Figure 10 provides a comparison of results for different electricity sources. The GHG performance of the studied syngas electricity when accounting for biochar sequestration demonstrated a greater than 66% improvement compared with coal electricity, about 44% improvement compared with natural gas electricity, and 27% improvement compared with commercial eGrid electricity for western Montana where the woody carbonization unit would be installed for operation. The biomass direct combustion process for electricity is simple and more straightforward than the syngas electricity technology. In addition, no additional fossil fuel use was required to keep the reaction going during direct combustion, unlike the carbonization unit. Therefore, it performs better in GHG emissions than does the studied syngas electricity system.

In some cases, the process of producing electricity from biomass feedstock is energy intensive and therefore can show higher GHG emissions than fossil fuel electricity (Sebastian and others 2011). Turconi and others (2013) did a thorough review on LCA research for various electricity generation technologies and compared environmental impacts for these technologies. Figure 10 shows the range of data collected by Turconi and others (2013) and this study's syngas electricity GW impact value. The Tucker syngas electricity GW impact is close to or within the range of renewable-energy-generated electricity including biomass, hydropower, solar energy, and wind electricity. These all have significantly less GW impact than the nonrenewable fossil-fuel-generated electricity, including hard coal, lignite, natural gas, and oil.

Scenario Analysis

Quantifying the GW impact showed both the carbon benefits (e.g., low GHG emissions) and the carbon "hotspots" such as burning propane to maintain the endothermic reaction in the Tucker RNG unit. If reducing or substituting propane usage in the Tucker RNG unit is possible, the GW impact could be further reduced. During the pyrolysis conversion in the Tucker RNG system, low-energy (waste) syngas was produced without being collected for use. We anticipate collecting and using this low-energy syngas to supplement propane usage would further reduce GHG emissions (i.e., fossil-fuel-based CO_2) associated with syngas electricity. Therefore, we conducted a scenario analysis with 30% propane reduction with the substitute of now-unused low-energy syngas produced from the Tucker RNG unit. The GW impact decreased by 41% in total for the cradle-to-grave syngas electricity.

Biochar Activated Carbon

The cradle-to-gate LCIA results for producing 1 kg of biochar AC are presented in this section. In addition, the environmental impacts associated with biochar AC

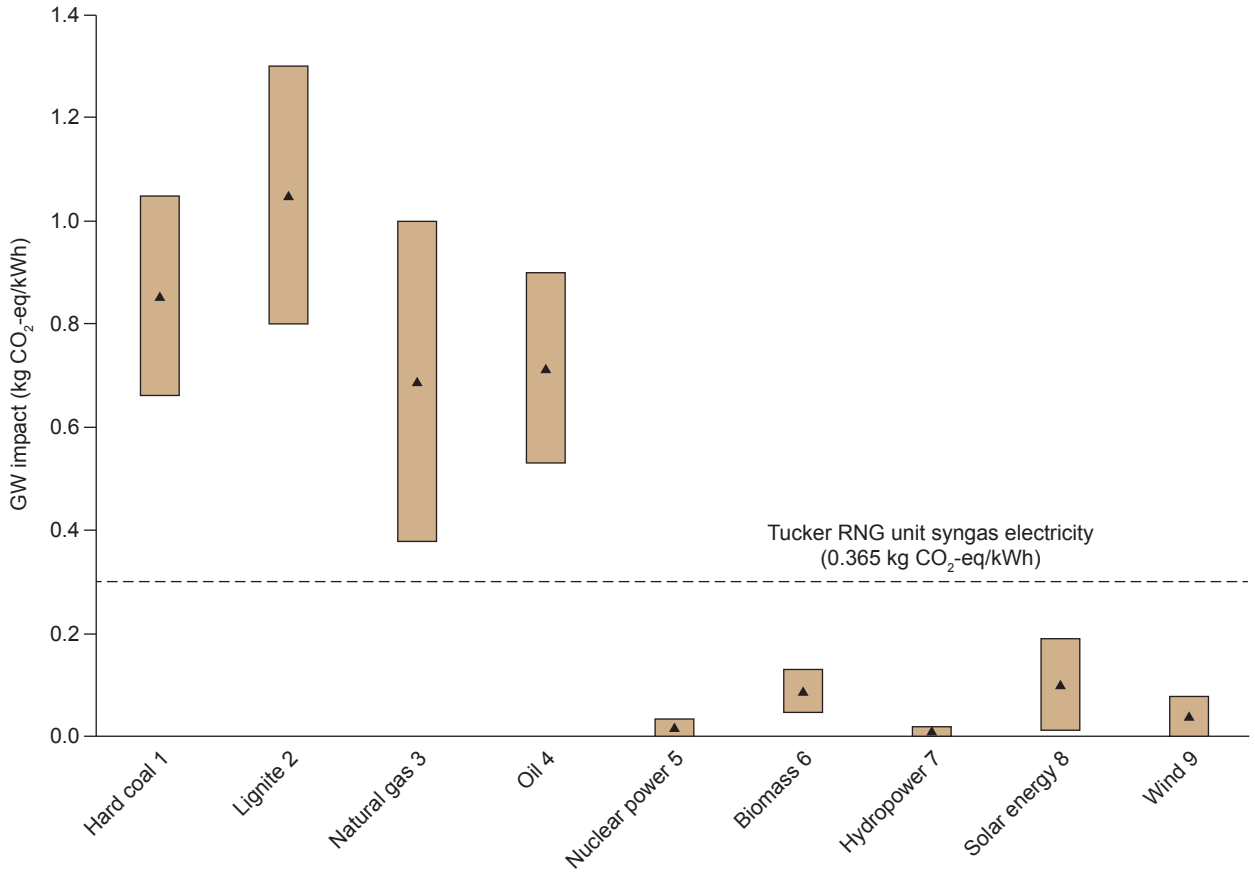

Figure 10. Global warming (GW) impacts for various electricity generating technologies and the syngas electricity estimated (Gu and Bergman 2017) (RNG, renewable natural gas).

production system are compared with the coal AC product. During the carbon activation life-cycle stage, no allocation approach was required when producing AC from either feedstock (biochar or coal). All environmental impacts were assigned to these two incoming feedstocks.

Life-Cycle Inventory

The cradle-to-gate model inputs and outputs including all the materials, energy, and cumulated emissions for producing 1 kg of AC from woody biomass residues and coal are presented in Table 9. For biochar AC, the fossil CO_2 emissions were captured in the inputs and their background processes. Only direct emissions from converting biochar into AC from steam activation in the rotary calciner are listed.

Table 10 presents the emission profile of biochar activation. The CO_2 emissions dominated the cradle-to-gate air emissions. The fossil CO_2 emissions resulted from the combustion of liquefied petroleum gas (LPG) and natural gas used in the system. LPG was used during the carbonization process. Natural gas was used in the activation process to provide heat to the system and generate superheated steam. The biogenic CO_2 was mainly caused by the upstream drying process. Biogenic CO_2 was assumed to be carbon neutral and did not contribute to the GW impact. Fossil fuel extraction and production processes were responsible for the water emissions, whereas no specific water emissions were detected in biomass carbonization and activation processes.

Cumulative Energy Demand

The cumulative energy demand data for biochar and coal AC are presented in Tables 11 and 12, respectively. For biochar AC, cumulative primary energy demand (CPED) required to produce 1 kg of biochar AC was 158 MJ and most CPED was derived from natural gas (64.5%) followed by crude oil. Natural gas was consumed primarily for thermal energy for the activation process and super-heated steam generation. Renewable energy use accounted for 11.2% of the total CPED, mostly resulting from use of wood and wood waste as fuel (Gu and others 2018). The total CPED for coal AC was 241.6 MJ (Table 12). Most energy came from natural gas (56.8%) followed by coal (33.9%). The contribution of renewable energy to total CPED was minor (below 1%).

Life-Cycle Impact Assessment

The LCIA results for cradle-to-gate biochar AC compared with cradle-to-gate coal AC are provided in Table 13. The

Table 9—Process inputs and outputs for biochar and coal activated carbon (AC) from cradle-to-gate, on a per kilogram AC basis (Gu and others 2018)

Biochar AC	Amount	Unit
Output		
Product		
AC, biochar	1	kg
Emissions to air		
Carbon dioxide, biogenic	1.81	kg
Water H_2O	0.09	kg
Nitrogen (N_2)	1.83	kg
O_2/oxygen	1.59	kg
H_2/hydrogen	0.005	kg
CO/carbon monoxide	0.009	kg
CH_4/methane	0.001	kg
SO_2/sulfur dioxide	0.001	kg
HCl/hydrogen chloride	1.25E–06	kg
NOx/nitrogen oxide	9.06E–05	kg
Particulates	0.046	kg
C_2H_4O/acetaldehyde	1.14E–05	kg
C_6H_6/benzene	8.56E–05	kg
CH_2O/formaldehyde	2.73E–08	kg
CH_4O/methanol	4.10E–06	kg
$C_{10}H_8$/naphthalene	7.23E–06	kg
C_6H_6O/phenol	2.04E–06	kg
C_3H_6O/propanal	7.14E–08	kg
Emissions to water		
Waste steam	2.11	kg
Input		
Tucker RNG biochar	2.11	kg
Natural gas	2.33	m^3
Nitrogen, liquid	0.15	kg
Drinking water	2.11	kg
Electricity, at eGrid, NWPP	1.7	kWh

Coal AC (Bayer's model with coal combusted emission)	Amount	Unit
Output		
Product		
AC, coal	1	kg
Emissions to air		
Water	12	kg
Acetaldehyde	1.10E–06	kg
Acrolein	1.32E–08	kg
Arsenic	3.08E–07	kg
Benzene	0.000284	kg
Beryllium	2.40E–07	kg
Cadmium	1.48E–07	kg
Carbon dioxide, fossil	8.52	kg
Carbon monoxide, fossil	0.002041	kg
Chromium	2.11E–05	kg
Formaldehyde	1.99E–05	kg
Hydrogen fluoride	0.001489	kg
Lead	8.60E–06	kg
Manganese	2.87E–06	kg
Mercury	2.00E–06	kg
Methane, fossil	0.00006	kg
Nickel	1.98E–05	kg
Nitrogen oxides	0.021362	kg
Particulates, > 2.5 μm < 10 μm	0.001362	kg
Particulates, unspecified	0.009672	kg
Biphenyl	3.75E–05	kg
Naphthalene	0.000195	kg
Phenanthrene	1.02E–05	kg
Selenium	1.95E–06	kg
Sulfur dioxide	0.136347	kg
Volatile organic compounds	0.000205	kg
Emissions to water		
Oils, unspecified	3.27E–06	kg
Suspended solids, unspecified	6.55E–06	kg
Waste to treatment		
Solid waste, unspecified	0.031947	kg
Combustion byproducts	0.0408	kg
Input		
Materials/fuels		
Hard coal	3	kg
Drinking water	12	kg
Transport	0.4	tkm
Electricity/heat		
Natural gas	3.3	m^3
Electricity mix	1.6	kWh

Table 10—Life-cycle inventory flows for biochar activation, cradle-to-gate

Substance	kg/kg activated carbon
Air emission	
Carbon dioxide, fossil	7.769
Carbon dioxide, biogenic	2.569
Water	2.207
Nitrogen	1.834
Oxygen	1.590
Sulfur dioxide	0.055
Particulates	0.046
Methane	0.032
Nitrogen oxides	0.020
Carbon monoxide, fossil	0.020
Hydrogen	0.005
Volatile organic compounds (VOC)	0.002
Carbon monoxide, biogenic	0.0014
Nonmethane VOC	0.0011
Sulfur oxides	0.0010
Water emission	
Suspended solids, unspecified	0.411
Chloride	0.373
Sodium	0.105
Solved solids	0.059
Calcium	0.033
Lithium	0.009
Magnesium	0.006
Barium	0.005
COD, chemical oxygen demand	0.003
Bromide	0.002
BOD5, biological oxygen demand	0.002
Sulfate	0.0009
Iron	0.0008
Strontium	0.0006
Aluminum	0.0003
Oils, unspecified	0.0002

Table 11—Cradle-to-gate cumulative energy consumption for biochar activation

Energy sources	Energy (MJ/kg activated carbon)	Percentage
Natural gas	102.10	64.5
Crude oil	22.63	14.3
Coal, 26.4 MJ per kg	14.49	9.2
Uranium oxide, 332 GJ per kg, in ore	1.37	0.9
Wood and wood waste	17.66	11.2
Storage hydro	0.05	0.0
Other biomass	0.017	0.0
Hydro	0.014	0.01
Wind	0.002	0.00
Total	158.33	100.0
Renewable	17.74	11.2
Nonrenewable	140.58	88.8

Table 12—Cradle-to-gate cumulative energy consumption for coal activation (Gu and others 2018)

Energy sources	Energy (MJ/kg activated carbon)	Percentage
Coal	85.81	35.5
Uranium	8.21	3.4
Natural gas	142.17	59.0
Crude oil	4.21	1.7
Peat	0.037	0.02
Hydro	0.99	0.4
Wind	0.16	0.1
Solar	0.039	0.02
Geothermal	0.00013	0.0001
Total	241.62	100.0
Renewable	1.37	0.6
Nonrenewable	240.25	99.4

Table 13—Comparison of cradle-to-gate life-cycle impact assessment results for biochar activated carbon (AC) and coal AC (Gu and others 2018)

Impact category	Unit[a]	Biochar AC	Coal AC
Ozone depletion	kg CFC-11 eq	2.73E–08	2.44E–07
Global warming	kg CO_2 eq	8.60	18.28
Smog	kg O_3 eq	0.51	0.78
Acidification	kg SO_2 eq	0.070	0.23
Eutrophication	kg N eq	0.277	0.002
Carcinogenics	CTUh	2.87E–08	9.74E–08
Noncarcinogenics	CTUh	5.75E–07	2.24E–06
Respiratory effects	kg $PM_{2.5}$ eq	0.004	0.01
Ecotoxicity	CTUe	12.30	11.32
Fossil fuel depletion	MJ surplus	17.09	22.65

[a]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.

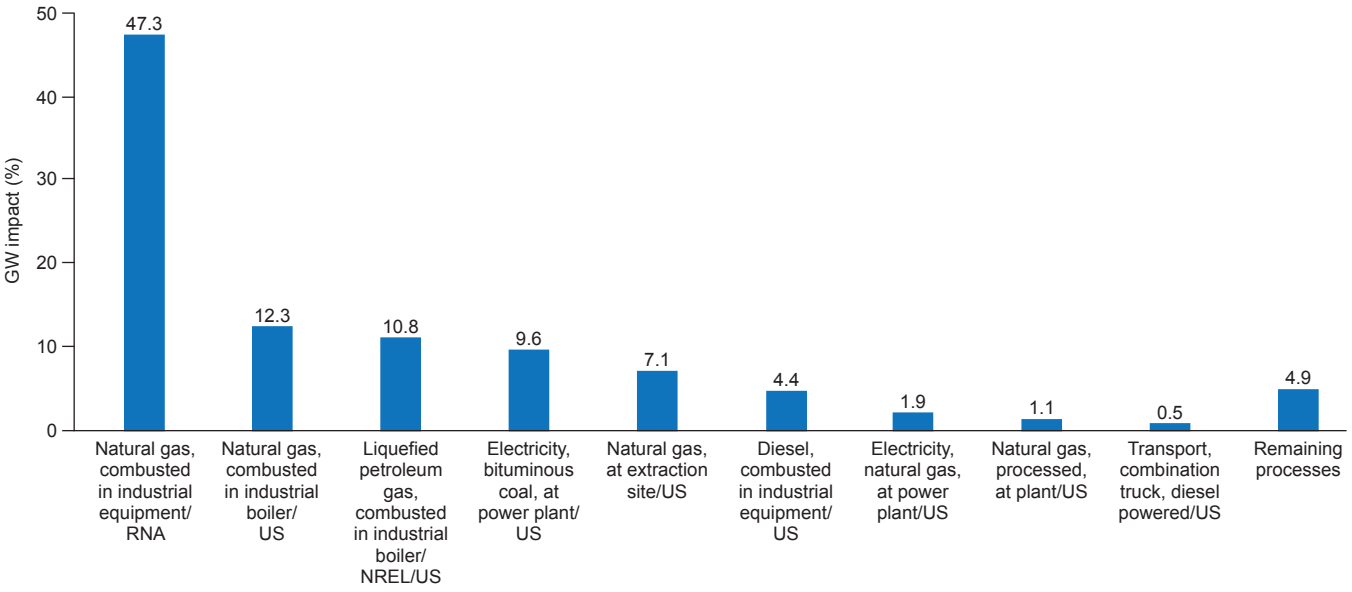

Figure 11. Contribution to global warming (GW) impact for cradle-to-gate biochar activated carbon production (RNA, North America; NREL, National Renewable Energy Laboratory).

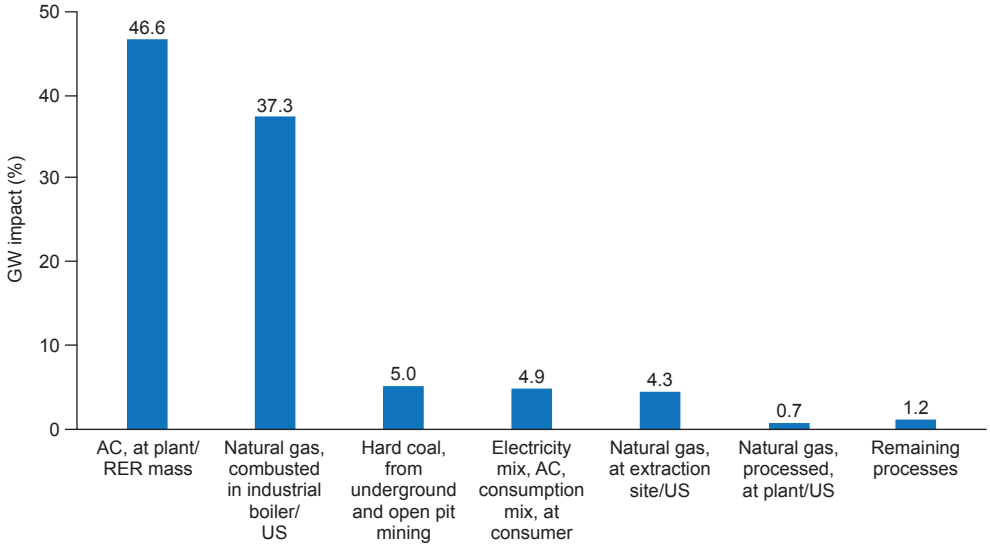

Figure 12. Contribution to global warming (GW) impact for cradle-to-gate coal activated carbon (AC) production (RER, Europe).

biochar AC supply chain had a lower environmental impact compared with coal AC for most impact categories. Only the eutrophication and ecotoxicity impacts were higher for the biochar AC supply chain compared with coal AC. The higher eutrophication impact was because of the nitrogen use in the biochar activation process. Nitrogen was used as the purge gas. The GW impact resulting from coal AC at 18.3 kg CO_2 eq/kg AC produced was two times higher than that for biochar AC, which was 8.6 kg CO_2 eq/kg AC produced. The biogenic carbon emissions resulting from the biochar AC were about 2.57 kg biogenic CO_2/kg AC. If biogenic emissions are accounted for, the GW impact is still 39% lower compared with coal AC production.

Contribution of system inputs to the GW impact are presented in Figure 11 for biochar AC and in Figure 12 for coal AC. Natural gas combustion was the main contributor to the overall GW impact for the biochar AC system. This was followed by other fossil-fuel-based energy consumption including LPG and electricity generated at a coal power plant. GW impact for transportation and natural gas processing were minor. For coal AC production, the coal

Table 14—Life-cycle impact assessment differences when substituting natural gas heating with syngas generated during woody biomass carbonization process, 1 kg activated carbon (AC) (Gu and others 2018)

Impact category	Unit[a]	Biochar AC with syngas heating	Biochar AC with natural gas heating	Reduction percentage
Ozone depletion	kg CFC-11 eq	7.98E–08	2.73E–07	–192
Global warming	kg CO_2 eq	7.63	8.6	11
Smog	kg O_3 eq	1.13	0.51	–122
Acidification	kg SO_2 eq	0.05	0.07	28
Eutrophication	kg N eq	0.28	0.28	0
Carcinogenics	CTUh	8.41E–08	2.87E–08	–193
Noncarcinogenics	CTUh	8.55E–07	5.75E–07	–49
Respiratory effects	kg $PM_{2.5}$ eq	0.0018	0.0037	50
Ecotoxicity	CTUe	15.82	12.30	–29
Fossil fuel depletion	MJ surplus	11.78	17.09	31

[a]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.

activation process had the highest contribution followed by natural gas combustion.

Alternative Scenario Analysis

This scenario considered the thermochemical conversion system was a two-product system and used mass allocation. The heat supplied to the carbon activation process can be provided by natural gas combustion or electricity. Syngas produced at the carbonization stage was used in a generator to produce electricity. The effect on the environmental impacts of substituting natural gas as the heat source with the syngas from the Tucker RNG system was investigated (Table 14). The amount of natural gas that was substituted with syngas was calculated using the heat content of syngas (19.7 MJ/m^3) and natural gas (37.7 MJ/m^3). The environmental benefits achieved were notable in the impact categories of ozone depletion, smog, respiratory effects, and carcinogenics. Substitution of natural gas with syngas resulted in an 11% decrease in GW impact.

Life-Cycle Interpretation

Interpreting life-cycle impacts provides stakeholders and policy decision makers with more insight on the LCIA results. For this study, the authors focused on GHG emissions although all life-cycle impacts were evaluated.

Conclusions and Recommendations

Syngas Electricity

Generating electricity from woody biomass product systems such as the Tucker RNG unit can result in notable GHG reduction compared with fossil fuel product systems. In addition, syngas electricity generated from Tucker RNG syngas is a renewable energy source because it consumes forest thinnings and mill residues. Furthermore, systems such as the Tucker RNG unit reduce energy dependency on fossil fuel or other nonrenewable sources. Energy from biomass or its pyrolysis products used to substitute fossil-fuel-based energy leads to avoidance of CO_2 emissions associated with fossil fuel use.

Sequestering the biochar produced as a byproduct from thermochemical conversion processes such as the Tucker RNG unit can lower the GHG emissions associated with generating electricity. This occurs because the carbon stored in the biochar equates to CO_2 removed from the atmosphere.

The sum of these two effects associated with syngas electricity of using sustainably sourced woody biomass as a feedstock and sequestering biochar lowers the GW impact (i.e., GHG emissions) substantially. It is known that electricity from burning fossil fuels is the main contributor to the GW impact (Hertwich and others 2013); thus, the consumption of biomass (directly combusted or indirectly derived) for bioelectricity is assumed to be carbon neutral. Carbon neutrality for the biomass burned to generate electricity continues to be questioned, although the EPA has issued a statement establishing the carbon neutrality of woody biomass used for energy production at stationary sources. This statement will be used as EPAs framework for any future regulatory action (EPA 2018). Regardless, GHG emissions are generated that effect GW because the whole life cycle of the biomass is assessed, which means there are fossil CO_2 emissions from the cultivation, harvesting, processing, and transportation processes for woody biomass utilization. This study tracked these GHG emissions including fossil CO_2, and they were included in the analysis. Overall, woody biomass systems using sustainably sourced feedstock resulted in low-carbon products.

The broader project details using the biochar as a co-product instead of a byproduct and then evaluating the additional life

cycle of producing AC. The reason is that biochar as AC has a higher market value than as a soil amendment. However, it takes processing in tightly controlled environments such as the Tucker RNG unit to generate the physical properties required, which means additional energy and materials are needed.

Biochar Activated Carbon

This study investigated the environmental and technical feasibility of converting forest and mill residues into AC using carbonization and steam activation processes. To ensure that the quality of the biochar AC was equivalent to coal AC, two indicators were investigated: Brunauer–Emmett–Teller (BET) surface area and iodine number. Analysis showed that both properties of the AC generated from biochar were compatible with commercial coal-based AC (Gu and others 2018).

The environmental impact analysis revealed that the biochar AC has a notable advantage over coal AC in the CED and GW impact categories. In this study, almost 35% less energy was required for cradle-to-gate biochar AC production compared with coal AC production. The GHG emissions for biochar AC production were less than half those of coal AC production (8.60 kg CO_2 eq compared with 18.28 kg CO_2 eq per kg of AC produced). This was because of both lower energy consumption and the biogenic carbon benefit from using woody biomass for both feedstock and processing. A 39% decrease in GW impact was achieved through substitution of coal AC with biochar AC. For the AC product system, carbonization and activation stages dominated the fossil energy use and GW impact. This was because of the natural gas and LPG used to supply heat to these processes. Contrarily, the majority of the upstream processes primarily consumed renewable woody biomass energy and woody biomass materials. A scenario analysis revealed that if the syngas produced at the carbonization process was used as a fuel substitute for natural gas in the activation process, GW impact could be reduced further by 11%.

The results of this study showed that forest biochar AC has potential for replacing coal AC as a renewable, sustainable alternative with better environmental performance. In addition, forest residues are low in value and use of them as biomass feedstock facilitates forest restoration by generating markets for this low-value product (Sahoo and others 2018, 2019). Another environmental benefit of valorizing wood harvested from sustainably managed forests includes improved air quality (Sifford and others 2017). This is because of avoided CO_2 and particulate matter emissions that would have resulted from burning the forest-thinning residues and from forest fires (Alanya-Rosenbaum and others 2018).

Completeness, Sensitivity, and Limitations

As with any study, data quality is critical to ensuring accurate results. To aid in this endeavor, the authors provided information on uncertainty and study limitations.

As mentioned previously, for bioproducts evaluated, the source data from the woody biomass carbonization came from a single run using a novel technology, which is a major limitation. Obviously, more runs would have provided us with an opportunity for more statistical analysis. However, the run selected to conduct the analysis on was the most consistent run on the material to be evaluated. In addition, transportation of biochar, biochar spreading, soil management practices, and their associated environmental impacts were not accounted for in the analysis.

Syngas Electricity

Table 8 shows that, for GHG emissions, the syngas production stage had the greatest effect on the whole cycle of generating syngas electricity. For the syngas production life-cycle stage, propane consumption primarily drove GHG emissions (i.e., global warming). Decreasing propane consumption by 20% resulted in decreasing GHG emissions for the whole life-cycle stage by 27%. As one could expect, minimizing the uncertainty of propane combustion would give the most accurate assessment of syngas electricity compared with all other inputs. For the comparative product of natural gas electricity, missing life-cycle stages in the LCI data, such as precombustion activities and transportation of natural gas from the natural gas plant, provided lower values for all the impact categories. To investigate its impact, the authors conducted an analysis that showed precombustion activities had a small effect, about 4% compared with the whole life cycle. As previously mentioned, more complete LCI datasets provide more accurate LCIA results, although for natural gas electricity, the effect of missing data was minor. Alternative scenario analysis showed that substitution of propane that is used for heating with low-energy syngas produced from the Tucker RNG unit decreased the GW impacts about 41%.

Biochar Activated Carbon

Table 13 shows all the life-cycle impact categories for producing AC. There were several limitations and assumptions in the analysis that could potentially affect the sensitivity of these results. The following three items should be considered a source of uncertainty for environmental impacts in addition to the ones already discussed.

(1) Coal AC process data in the publicly available databases and literature were incomplete and limited. Therefore, assumptions were made in this study to build a moderately complete coal AC LCA model. The main assumption

was required because of the lack of emission data for the only coal AC model available, which was found in the Agri-footprint database (based on Bayer and others (2005) in SimaPro). To develop a full coal AC model, coal combustion emission data were added from the U.S. LCI Database (NREL 2012). Until more coal AC LCA data become available, the authors are taking a conservative approach.

(2) The emission data for biochar AC were carefully measured at the RBS-Arvos laboratory and then scaled up approximately to the size of the Tucker RNG biochar output based on the RBS-Arvos engineering team's design.

(3) Downstream use and disposal phases (i.e., gate-to-grave stages) for both AC products were considered the same and thus were not included in the analysis.

Alternative scenario analysis was performed to investigate the effect of substituting natural gas as the heat source with the syngas from the Tucker RNG system. Substituting syngas for natural gas resulted in notable environmental benefits in the impact categories of ozone depletion, smog, respiratory effects, and carcinogenics.

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Appendix A—Forest Resource and Sawmill Survey

As part of the Biomass Research and Development Initiative project (joint venture agreement with Tricon # 11-JV-159), the US Forest Service Forest Product Laboratory is conducting a life-cycle assessment (LCA) of the Tucker Renewable Natural Gas (RNG) unit used to produce heat, electricity and biochar. The LCA requires detailed annual production information about many aspects of the feedstock supply chain.

We used Tricon Timber as the model for deployment in the Northern Rockies. The following information was needed for the LCA. We were particularly interested in the whole-tree chipping operation that is supplying the Tucker System. Our assumption is that only the whole-tree chipping operation supplied the Tucker RNG unit. Please identify (Y or N in the last column) any sensitive information that you would like to remain confidential.

Should we have a follow-up question about the data, please provide the name and the following information for the contact in your company.

Name: _____ Title: _____

Telephone: _____ Email: _____

Please send the completed survey to the following email or address. In addition, if you have questions about the survey, contact Rick Bergman or Nate Anderson at the listed phone/email.

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Annual supply chain information for whole tree chipping	Value	Units	Confidential? Circle Y or N
2012 RAW MATERIAL PROCUREMENT			
1. Logs procured for whole tree chipping are measured by (check): ☐ Weight ☐ Scale (specify): _____	_____	/ _____	Y or N
2. Total amount of whole tree chips produced in 2012		tons	Y or N
3. Specifications for these chips:	_____		

Maximum size		inches	Percent allowed over max		%
Minimum size		inches	Percent allowed over min		%
			Maximum dry weight		%
			Minimum dry weight		%

4. Average moisture content of Tricon whole tree chips _____ % Y or N

This percent is (check one):

☐ % of dry weight basis [(green wt-dry wt)/dry wt) x 100]

☐ % of green weight basis [(green wt-dry wt)/green wt) x 100]

5. Percent of 2012 chips produced that were made from:

Mill residues		%	Y or N
Whole-tree chipping on site in St. Regis		%	
Delivered as chips from in-woods chipping		%	

6. Source of logs for whole-tree chipping in 2012 (estimation is ok):

Federal land		%	Y or N
State land		%	
Private land		%	
Other		%	

7. What percent of your 2012 wood supply for whole-tree chipping was from (estimation is ok):

Natural forest		%	Y or N
Plantation or intensively managed with fertilizer, etc.		%	

How much fertilizer was added per acre? _____ pounds

8. What percent of your 2012 wood supply for whole-tree chipping was certified (estimation is ok):

Forest Stewardship Council (FSC)		%	Y or N
Sustainable Forestry Initiative (SFI)		%	
Other (describe): _____		%	
No certification		%	

9. What percent of your 2012 wood supply for whole-tree chipping was

Douglas fir		%	Y or N
True firs		%	
Larch		%	
Lodgepole pine		%	
Ponderosa pine		%	
Other species		%	

10. What is your average one-way trucking distance to the mill in St. Regis for logs used for whole-tree chipping? _____ miles Y or N

2012 RAW MATERIAL PROCESSING: CHIPPING

11. For the whole-tree chipping operation, what is the capacity of the equipment when the system is working at 100% capacity?		tons per hr	Y or N
12. When the whole-tree chipping operation is operating at 100% capacity, the estimated electricity consumed is:		kW	Y or N
13. What was the annual electricity consumed by the whole-tree chipping operation for 2012?		kWh	Y or N
14. Total annual use of on-site whole-tree chipper in 2012:		total hr per yr	Y or N

CHIPS PRODUCED FOR TUCKER RNG UNIT

Target feedstock specifications for the micro-chips were < 0.5 inch in the longest direction, <10% moisture content (wet basis), and clean, with minimal bark and needles. The species mix was 50% Lodgepole pine, 40% Douglas Fir/Larch, 10% Ponderosa Pine.

15. How much material was processed for the woody biomass carbonization system trials?		tons
16. For your operation, this is equivalent to how many thousand board feet (mbf) of logs using what scale? Scale: _____		mbf
17. Estimated moisture (wet basis) of the material when it shipped?		%

18. What percentage of this material was from:

Whole-tree chipping at the saw mill		%
Delivered as chips from in-woods chipping		%

19. Was the chipping process modified to produce a different size chip for the Tucker RNG unit material than you typically produce? Y or N

☐ change settings on the chipper

☐ double pass in the chipper

☐ Other

(describe):_____

21. What type of screening method was used?

☐ Trammel, Model:_____

☐ Rotary, Model:_____

☐ Other:_____ _____

22. How much power does the screening method use?		kW
23. What percent of time does the screening method operate compared to the chipping operation?		%

24. The Tucker RNG unit material required additional drying to less than 10% moisture content (wet basis). How was the material dried?

Description:

25. How many tons of whole-tree chips are dried at one time?		ton
26. How much time from wet to dry?		hr
27. How much energy is consumed during this time?		kWh or Btus

28. If drying chips to <10% moisture content (wet basis) was required for industrial scale operations at your facility, what would be your preferred drying setup in terms of the size and type of equipment and what type of fuel will be burned? For example, rotary (drum) dryers are often used to dry wood residues to produce pellets and can burn green/dry wood fuel, natural gas or propane.

Description:

Appendix B—Rotary Calciner Engineering Estimates

The feeding and reaction capacity of the pilot-scale calciner was very low compared with the upstream biochar output of approximately 33.3 kg/h from the woody biomass carbonization unit. Therefore, to model the production process from cradle to gate, we required an upscaled design of a calciner appropriately sized to the carbonization system from the RBS-ARVOS Group's engineering team. A 600-mm-diameter by 4.57-m-long heated, gas-fired rotary calciner was proposed by the RBS-ARVOS engineers, which was substantially larger than the pilot-scale unit (152 mm diameter by 0.9 m long). This design consisted primarily of an inclined rotating cylinder housed in a furnace along its active length. The cylinder, which was indirectly heated, was arranged in such a way that process off-gases and material passed continuously through the unit. For this process, the purge gas was preheated steam. The gross heat rate for the entire rotary calciner was estimated at 1,160 MJ/h fueled by natural gas with a higher heating value (HHV) of 52 MJ/kg. The steam used for the activation process was estimated at 1 kg of super-heated steam (at 900 °C) per kg of inputted biochar. Nitrogen was used as the cooler purge gas at the AC discharge. Nitrogen use for the upscaled calciner was estimated from the pilot-scale calciner (152 mm diameter) purge rate and was converted to the large commercial calciner (600 mm diameter). For upscaling, the report from the RBS-Arvos engineering group showed the required engineering estimation of energy consumption, including electricity and natural gas or propane, and material consumption, including nitrogen and steam. See Table 15 for the energy and mass inputs estimated for the upscaled calciner used for process-based LCA modeling.

Table 15—Mass and energy input estimated for upscale rotary calciner

Input	Unit	Amount
Feedstock – biochar	kg/h	33.60
Nitrogen	kg/h	2.41
Natural gas	m^3/h	36.96
Electricity	kWh	27