CRADLE-TO-GRAVE LIFE CYCLE ASSESSMENT OF SYNGAS ELECTRICITY FROM WOODY BIOMASS RESIDUES[1]

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Abstract. Forest restoration and fire suppression activities in the western United States have resulted in large volumes of low-to-no-value residues. An environmental assessment would enable greater use while maintaining environmental sustainability of these residues for energy products. One internationally accepted sustainable metric tool that can assess environmental impacts of new bioenergy conversion systems is the life cycle assessment (LCA). Using the LCA method, this study evaluated the synthesis gas (syngas) electricity produced via a distributed-scale biomass thermochemical conversion system called the Tucker renewable natural gas (RNG) system. This system converts woody biomass in a high-temperature and extremely low-oxygen environment to a medium-energy syngas that is burned to generate electricity. The system also produced biochar as a by-product and tar as a waste. Results from the life cycle impact assessment included an estimate of the global warming (GW) impact from the cradle-to-grave production of syngas for electricity. When the carbon sequestration effect from the biochar by-product was included, GW impact value (0.330 kg CO_2-eq/kWh) was notably lower compared with electricity generated from bituminous coal (1.079 kg CO_2-eq/kWh) and conventional natural gas (0.720 kg CO_2-eq/kWh). Other environmental impacts showed that syngas electricity ranged between the direct-biomass-burned electricity and fossil-fuel-combusted electricity for different impact categories. This occurred because, although the woody biomass feedstock was from a renewable resource with less environmental impact, propane was consumed during the thermochemical conversion. Specifically, the evaluation showed that the highest greenhouse gas (GHG) emissions contribution came from burning propane that was used to maintain the endothermic reaction in the Tucker RNG unit. If the tar waste from the system were converted into a low-energy syngas and used to supplement propane consumption, a further decrease of 41% in GHG emissions (ie fossil CO_2) could be achieved in this cradle-to-grave assessment.

Keywords: Bioenergy, woody biomass, syngas electricity, life cycle analysis, environmental assessment.

INTRODUCTION

There has been a great demand on management of US western forests to decrease threats from insect and disease outbreak, invasive species, and in particular, forest fires. Restoration treatments on western US forests produce large quantities of woody biomass that can be used as feedstock for production of biofuels and other bioproducts (Tilman et al 2009). Producing bioenergy and bioproducts from such forest thinning or timber harvest by-products could contribute to reaching broad national energy objectives, including the nation's energy security and lowering greenhouse gas (GHG) emissions from fossil fuels, a major cause of climate change, according to the International Panel on Climate Change (IPCC 2014).

The US Department of Energy (DOE) and the US Department of Agriculture (USDA) are both strongly committed to increasing the role of

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biomass as an energy source. Both agencies hope to replace 30% of the current US petroleum consumption with biofuels by 2030 (Perlack et al 2005). Biomass fuels and products are one way to lower the requirement for oil and gasoline imports while supporting the growth of agriculture, forestry, and rural economies (Naik et al 2010; USDOE 2016). Also, increasing biofuel and bioproduct production from biomass has the potential to decrease net GHG emissions and improve local economies and energy security. The Biomass Research and Development Initiative (BRDI) was formed by USDA and DOE as an interagency program to support the creation of a biomass-based industry in the United States for energy production and environmental safety. This study was part of one of these BRDI projects in which the team conducted an integrated evaluation of biomass feedstock production, logistics, conversion, distribution, and end use focused on an innovative thermochemical conversion system for existing forest industry operations (Miller et al 2014, 2015) which life cycle assessment (LCA) research was part of.

LCA research was conducted to evaluate the net life cycle GHG emissions and energy balance for woody biomass residue to bioenergy and bioproduct conversion and then compare the life cycle impact assessment (LCIA) outcomes to fossil-based alternatives. LCA is a well-established and internationally accepted method for categorizing life cycle GHG and environmental performance metrics (ISO 2006a, 2006b). Thus, it is often used as a science-based tool to evaluate assertions that increasing bioenergy production from woody biomass can lower net GHG emissions. Within the LCA framework, to quantify the various impacts from air and water emissions released to the atmosphere during product production, the categorized life cycle inventory (LCI) flows are characterized into common equivalence units that are then summed to provide an overall impact category total. Different LCIA impact categories cover different emissions (ie LCI flows).

The use of LCA to evaluate the environmental impacts from converting biomass to bioenergy, including electricity, has been studied intensively in recent years (Cherubini and Stromman 2011; Sebastian et al 2011; Steubing et al 2011; Field et al 2013; Hertwich et al 2013; Pierobon et al 2014; Stephenson and MacKay 2014). In particular, Stephenson and MacKay (2014) from the UK Department of Energy and Climate Change performed a scenario analysis using North American woody biomass for the United Kingdom's electricity in 2020. They found that the lowest GHG impact can be achieved by using forest or mill residues or trees killed from natural disturbance, which is the feedstock that would otherwise be burned as waste (<100 kg CO_2-eq/MWh). Pierobon et al (2014) used radiative forcing analysis to evaluate the environmental impact of woody-biomass-based bioenergy conversion. Pierobon et al (2014) incorporated the dynamics of carbon sequestration, decomposition of residues, and biomass processing in the life cycle analysis framework of bioenergy and concluded that the adverse global warming (GW) impact associated with biomass collection and burning from industrial forests can be fully offset by the carbon sequestration during forest growth within about 18 yr. To put biomass (wood) electricity production into context, according to the US Energy Information Administration (USEIA), wood-powered electricity is estimated to be 43.4 million MWh for the year 2016 which is a considerable value for many countries but it is only about 1% of the US electrical grid (USEIA 2016). Regardless of the current value for the United States, there is huge potential in increasing wood-powered electricity (USDOE 2016). Thus, as it is in this case, it is critical that LCAs continue to evaluate new technologies as they are developed. LCA can focus on parts of the life cycle of the technology that may not be considered once a process becomes commercialized. It can do this while the process is still in the development phase to evaluate what-if scenarios.

From the review on LCA work for bioenergy systems by Cherubini and Stromman (2011), it was found that the net GHG emissions from biomass-generated electricity are usually 5-10% of those from fossil-fuel-based electricity, and

GHG emissions could be lower if the feedstock biomass is derived from residue streams such as logging slash and small-diameter trees. All the studies reviewed by Cherubini and Stromman (2011) assumed neutral climate impact from biomass combustion in terms of CO_2 emissions. Steubing et al (2011) conducted a cradle-to-grave LCA of a polygeneration unit that produced synthesis gas (syngas) for heat, electricity generation, and transportation fuel. They compared the results with a fossil-fuel-based system. Their study showed substantially less contribution to climate change when syngas was substituted for fossil fuel, but these benefits were partially offset by other environmental effects related to human health and eutrophication. They considered syngas from wood used for transportation fuel as a promising technology in light of growing demand for renewable transportation fuels. Field et al (2013) did a case study on a Colorado regional coproduction of biochar and bioenergy from biomass residue feedstock. Their financial analysis suggested that the returns were generally greater when biochar was used for energy (biocoal) than when used for soil amendment (biochar), whereas biochar application had greater GHG mitigation value than did biocoal.

The goal of this study focused on the downstream process of burning syngas produced from a distributed-scale advanced biomass pyrolysis system which will be referred to as the Tucker (developed by Tucker Engineering Associates, Inc., Locust, NC) renewable natural gas (RNG) unit to generate electricity. The authors will answer the question of how much environmental impact can be decreased if woody-biomass-derived syngas electricity is substituted for fossil-fuel-based electricity. Applying LCA can help to compare the processes or technologies for energy and environmental benefits and identify the environmental "hot-spots" (highest points) of the various impact categories.

METHODS

For this study, the LCA assessed electricity generated from the syngas produced from the Tucker RNG unit. The LCI model was constructed in three parts: 1) upstream model, including forest management, log extraction, transportation, and feedstock processing; 2) mainstream model, thermochemical conversion including Tucker RNG unit process; and (3) downstream model, including generation of electricity from the primary product syngas and the impacts from carbon sequestration by biochar, a by-product from the system (Fig 1). For further reference, Gu and Bergman (2016) detailed most of the first two parts of the LCI including feedstock processing and thermochemical conversion and their data were used in this analysis. For the Tucker RNG unit, the product produced by mass by far was syngas with some biochar generated. Because this study focused on the generation of electricity from syngas, all environmental burdens were assigned to the syngas as the product of interest. Thus, biochar took zero environmental burden from the LCA output as a by-product from the system, but its role for long-term carbon storage in the soil was analyzed for carbon sequestration benefits in the LCA in offsetting the syngas electricity environmental impacts.

Primary data were collected from the sawmill chip operation in St. Regis, MT, and a single 1-h continuous run of the Tucker RNG unit. The feedstock was wood chips processed from under-used small-diameter logs extracted from Rocky Mountain National Forest with a mix of conifer species dominated by lodgepole pine (*Pinus contorta*), Douglas fir (*Pseudotsuga menziesii*), and ponderosa pine (*Pinus ponderosa*). Before feeding into the Tucker RNG unit, the chips were force-dried to 12% MC by a sawdust drier to improve the chips' performance in the Tucker RNG unit. Secondary data were drawn from the US LCI Database (NREL 2012) and peer-reviewed literature. With the material and energy inputs and reported emissions, the cradle-to-grave LCI model for the Tucker RNG syngas electricity was built in SimaPro 8 to estimate the environmental impacts and cumulated energy consumption (PRé Consultants 2016). Within the SimaPro software, the inventory data

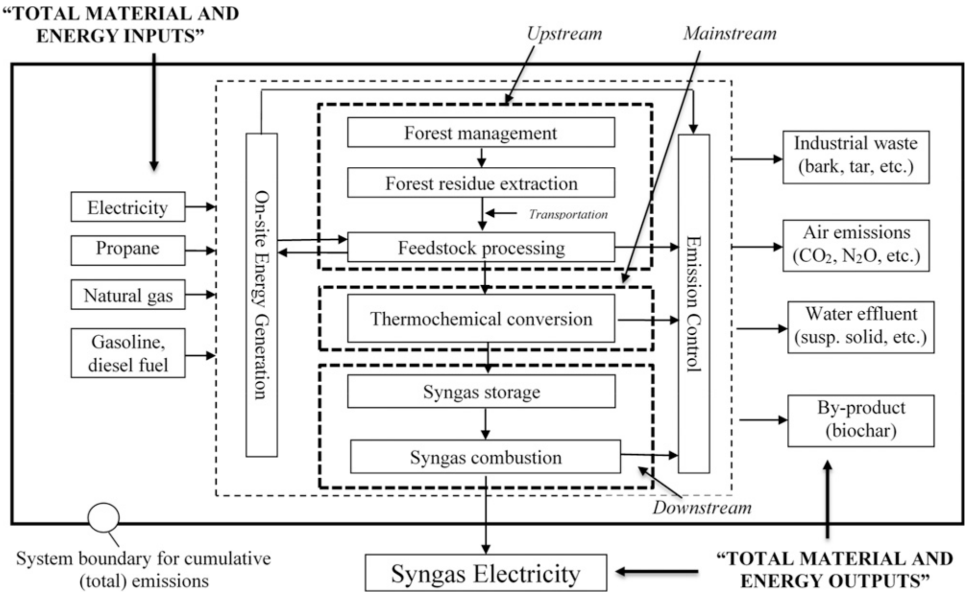

Figure 1. System boundary for the life cycle of generating synthesis gas electricity.

were compiled into the impact category indicators of interest, such as GW, acidification, eutrophication, etc.

For assessing the environmental impacts of electricity production, the Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI) method was used. TRACI is a midpoint-oriented LCIA method developed by the US Environmental Protection Agency (EPA) specifically for the United States using input parameters consistent with US locations (Bare 2011). TRACI is available through LCA software modeling such as SimaPro used in this analysis (PRé Consultants 2016). This study included the LCIA impact categories of fossil fuel depletion (MJ), GW (kg CO_2-eq), acidification (kg SO_2-eq), eutrophication (kg N-eq), ozone depletion (kg CFC-11-eq), smog (kg O_3-eq), carcinogens (CTUh), noncarcinogens (CTUh), respiratory effects (kg PM2.5-eq), and ecotoxicity (CTUe). Other impact measures as cumulative (total) energy demand (primary energy) (MJ-eq), including the contributions from both nonrenewable sources such as fossil fuel and renewable sources such as biomass, hydropower, and wind power, were summarized from the LCI flows.

Scope

This study covered the cradle-to-grave LCA of electricity generated from syngas derived from pyrolyzing woody biomass. LCI and LCIA data for producing syngas from the Tucker RNG pyrolysis unit were already constructed by Gu and Bergman (2016) and were incorporated into the model. In addition to the LCA on syngas electricity, data from LCI databases for electricity generated from other sources including biomass, bituminous coal, lignite coal, anthracite coal, natural gas (NG), and a regional eGrid, were drawn and analyzed for a comparative LCA to examine the marginal GHG effects on the electricity grid (NREL 2012). The electricity grid is comprised of many regions with various energy sources (USEPA 2015). The EPA has broken the US electricity grid into "eGrids". The eGrid system from the northwest (NWPP) region was included in the analysis. The eGrid NWPP is representative of the mix of fuels used for electric utility in the northwestern

United States in 2008. Fuels include coal, biomass, petroleum, geothermal, NG, nuclear, hydroelectric, wind, and other energy sources. The NWPP electricity grid covers an area including Washington, Oregon, Idaho, Utah, most of Montana, Wyoming, Nevada, northern parts of California, Arizona, and New Mexico.

Functional Unit

Functional unit is the reference unit used to quantify the environmental performance of a product or a system. It is also a reference related to the inputs and outputs. Because the goal of this research was to compare the environmental performances of electricity generated from Tucker RNG syngas to those of electricity generated from other sources, the functional unit was defined as production of 1 kWh of electricity. Material flows, energy use, and emission data were standardized based on this functional unit and then compiled within the system boundaries described subsequently in the SimaPro model to quantify the GHG emissions and other environmental outputs. The input and output data for the SimaPro model are shown in Table 1.

System Boundary

Defining the system boundary selects the unit processes to be included in the system. Based on the goal to determine the environmental impacts of syngas electricity, the system boundary included the upstream feedstock processing, mainstream thermochemical conversion process with the Tucker RNG unit, and the downstream syngas electricity production (Fig 1). The Tucker thermochemical process included feedstock conveyance, active reacting, passive reacting, condensing, tar cracking, cooling, collecting, and storing. The cumulative system boundary included both on- and off-site emissions for all material and energy consumed. Fuel and electricity consumed for the upstream and mainstream processes were included in the cumulative boundary (solid line) to calculate the total emissions. The on-site emissions included the processes within the dotted line. The off-site emissions included the grid electricity production, transportation, and fuels produced off-site but consumed on-site.

Table 1. Gas composition and heating value for Tucker RNG syngas from gas chromatography (Source: Gu and Bergman 2016).

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

RNG, renewable natural gas.

Syngas Combustion Unit Processes

To conduct the LCI, the syngas electricity system was built from several unit processes within the upstream, mainstream, and downstream models. For the upstream model, the unit processes of Inland West forest management and forest residue (log) extraction in the US LCI Database were used (NREL 2012), whereas the feedstock (chipping and screening) process was modeled using the specific operational (primary) data collected from an operating sawmill in western Montana. The mainstream model of this study was thermochemical conversion (ie Tucker RNG unit). The downstream electricity generation process was modified from the US LCI NG electricity generation process for our specific syngas electricity. The input and output data for the downstream model are shown in Table 2. Using wood chips as the feedstock, the Tucker RNG unit must produce about two times the volume of syngas to generate the same electricity as NG, because the higher heating value (HHV) of the produced Tucker RNG syngas is 19.70 MJ/m^3, about half of the NG HHV at 38.3 MJ/m^3. The main components by volume of the syngas are carbon monoxide (48%), hydrogen (17%), and methane (15%), as shown in Table 1.

Starting with the functional unit of 1-kWh electricity generated, fuels and equipment use, and transportation requirements were compiled in the SimaPro model to quantify the GHG emissions and other environmental outputs. After running the model in SimaPro, the LCI flows were used to find the 100-y GW impact and LCIA outcomes from other impact categories according to the TRACI method (Bare 2011; IPCC 2014). TRACI 2.1 method incorporated in SimaPro 8.1 was used.

Table 2. Input and outputs for combusting syngas to generate 1-kWh electricity.

Output	Amount	Unit
Electricity, Tucker RNG[a] syngas	1	kWh
Input		
Tucker RNG[a] syngas	0.537	m^3
Direct emissions to air	Amount	Unit
Arsenic	1.91E-09	kg
Beryllium	1.15E-10	kg
Benzene	2.01E-08	kg
Cadmium	1.05E-08	kg
Carbon dioxide, fossil	0	kg
Carbon dioxide, biogenic	1.061	kg
Carbon monoxide, fossil	0	kg
Carbon monoxide, biogenic	0.0008	kg
Chromium	1.34E-08	kg
Cobalt	8.03E-10	kg
Formaldehyde	7.17E-07	kg
Lead	4.78E-09	kg
Manganese	3.63E-09	kg
Mercury	2.48E-09	kg
Methane, fossil	2.15E-05	kg
Dinitrogen monoxide	2.15E-05	kg
Naphthalene	5.83E-09	kg
Nickel	2.01E-08	kg
Nitrogen oxides	9.55E-04	kg
Particulates, >2.5 and <10 μm	7.23E-05	kg
Radioactive species, unspecified	2.04E-03	kBq
Selenium	2.29E-10	kg
Sulfur monoxide	6.04E-06	kg
VOC[b]	5.27E-05	kg

[a] RNG, renewable natural gas.
[b] VOC, volatile organic compounds.

Project Limitations

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

Because the Tucker RNG syngas was similar to NG, the NG combustion emission profiles were assumed for Tucker RNG syngas electricity generation (Tucker 2016; Morris 2016).

For SimaPro modeling, liquid petroleum gas (LPG) was used as the proxy for propane. The US LCI Database indicates LPG is 100% propane. However, this is not the case because the emission profiles do not match when converting from mass to volume (Channiwala and Parikh 2002). Therefore, to convert the measured volume of propane gas consumed in the mainstream process to mass then to the volume of LPG (proxy for propane in the SimaPro model) based on the stoichiometry, a liquid density of 0.573 kg/L for LPG was calculated from the US LCI database and used in our model (Johnson 2016).

Cutoff Rules

If the mass or energy of a flow is less than 1% of the cumulative mass or energy of the entire model flow, it may be excluded, provided its environmental relevance is minor. This analysis included all the energy and mass flows for primary data.

RESULTS AND DISCUSSION

The environmental impact assessment for producing 1 kWh of syngas electricity from an advanced thermochemical converting technology using wood residues was carried out using LCA, and the results are described subsequently.

Life Cycle Inventory

Within the LCA method, the LCI phase measures all the raw materials and energy inputs for producing 1-kWh electricity from the syngas produced by the Tucker RNG unit within the defined system boundary (Fig 1). The emission profiles included activities associated with forest resource extraction and transportation of logs, chip production, and drying at the sawmill, thermochemical conversion with the Tucker RNG unit, and finally the syngas combustion for generating electricity. Major air and water emissions from the LCI flows are presented in Table 3. The GW impacts were derived primarily from fossil CO_2, CH_4 (mainly fossil), and N_2O emissions. The total fossil CO_2 emissions in the LCI flow (Table 3) calculated by SimaPro were 0.704 kg/kWh. The total fossil CH_4 emissions were 0.0012 kg/kWh and N_2O emissions were 0.0057 kg/kWh. CH_4 and N_2O emissions were much smaller in quantity but had a much greater GW impact by mass than did fossil CO_2 (IPCC 2014).

To ensure data quality, the material flow from the forest to syngas electricity generation was developed to produce 1 kWh of electricity. From the cradle-to-grave model built in this study, we summarized about 0.537 m^3 of syngas would be needed from pyrolyzing 0.888 kg of oven dry wood chips (mixture of several softwood species from West Inland National Forests) by the Tucker conversion unit. The wood chips are equated to about 0.0017 m^3 of whole tree logs extracted from the forest.

Life Cycle Impact Assessment

LCIA indicators from the three modeled processes along the whole life cycle are presented in Table 4 and Fig 2. The GW impact from cradle-to-grave LCA for syngas electricity was 0.748 kg CO_2-eq/kWh without considering biochar's potential for carbon sequestration (Table 4). After considering carbon sequestration from biochar, the value was decreased to 0.330 kg CO_2-eq/kWh for GW impact. Carbon sequestration by biochar is discussed subsequently. The GW impact results were divided into three stages: upstream feedstock processing, mainstream syngas production, and downstream syngas electricity. Syngas production released about 60.8% of the total GHG emissions (Fig 2 and Table 4). Feedstock processing contributed the second highest emission and included extraction of forest thinning materials, transportation, and size reduction and pretreatment of the feedstock. About 38.3% of the total GHG emission was from this upstream feedstock processing stage, which leaves only 0.93% of GHG emission associated with the downstream syngas electricity generation process. For comparison, Steubing (2011) reported a GW impact of 0.103 kg CO_2-eq/kWh for a case in which the syngas was primarily composed of CH_4 and very little fossil fuel (ie gas) was consumed in the production of syngas, unlike the Tucker RNG unit.

Table 3. Cradle-to-grave emissions for 1-kWh syngas electricity.

Substance	Emissions (kg)
Air emission	
Carbon dioxide, biogenic	1.333
Carbon dioxide, fossil	0.704
Nitrogen oxides	0.0057
Carbon monoxide, fossil	0.0035
Carbon monoxide, biogenic	0.0013
Sulfur dioxide	0.0010
Methane	0.0012
NMVOC	0.0004
Sulfur oxides	0.0003
VOC	0.0003
Particulates, >2.5 and <10 μm	0.0004
Sulfur monoxide	0.0002
Emission to water	
Chloride	0.026
Solved solids	0.021
Suspended solids, unspecified	0.013
Sodium, ion	0.0048
Calcium, ion	0.0015
Barium	0.0008
Calcium	0.00078
Magnesium	0.00045
COD	0.00062
DOC	0.00034
TOC	0.00034

NMVOC, nonmethane volatile organic compounds; VOC, volatile organic compounds; COD, chemical oxygen demand; DOC, dissolved organic carbon; TOC, total organic carbon.

Table 4. Life cycle impact assessment results for cradle-to-grave syngas electricity at various life cycle stages (without considering carbon sequestration by biochar).

Impact category	Unit	Total	Upstream feed stock processing value	Upstream feed stock processing (%)	Mainstream syngas production value	Mainstream syngas production (%)	Downstream syngas electricity generation value	Downstream syngas electricity generation (%)
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	2.71 E-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 PM2.5 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

Other impacts besides GW from each stage are shown in Table 4 and Fig 2. The syngas electricity stage generally had very little impacts in all the categories from the cradle-to-grave chain. Syngas production by the Tucker RNG unit imposed significant impacts in most of the categories, ie ozone depletion (99.9%), GW (60.8%), carcinogenics (70.1%), noncarcinogenics (65.2%), ecotoxicity (68.2%), and fossil fuel depletion (66.8%). This was because of the significant amount of propane consumption for thermochemical reaction heating. The feedstock process stage made significant impacts in smog (66.5%), acidification (69.3%), eutrophication (56.7%), and respiratory effects (69.5%). These were mainly from transportation fuel and electricity consumption.

Cradle-to-grave cumulative energy consumption was calculated from the LCI output from the SimaPro model for 1-kWh syngas electricity and other fossil or biomass electricity. The

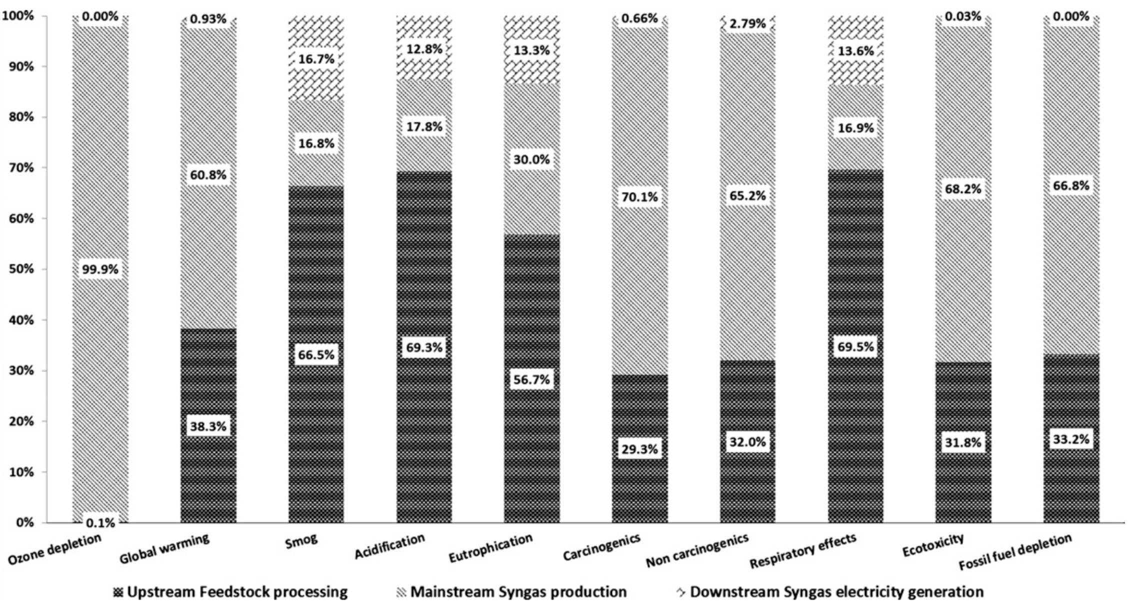

Figure 2. Contribution analysis for three stages within the cradle-to-grave system of the syngas electricity.

estimated cumulated energy demand values are shown in Table 5. An approximate 16.64 MJ of energy was needed to produce 1 kWh of electricity with the technology and material source studied in this project. This is at the high end of energy consumed to produce electricity with different technology and an alternative resource (Table 5). However, within the 16.64 MJ energy consumed, 38.7% was from a renewable energy source, such as biomass, wind, solar, or hydro and the rest (61.3%) was from nonrenewable fossil energy sources. 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 both the syngas producing and electricity generation stages because it used woody biomass heating for feedstock drying and some processing. Carbon dioxide (ie biogenic CO_2) emissions from burning woody biomass were tracked but not considered in estimating the GW impact. The neutrality assumption for biogenic carbon from wood is valid for the United States, because the national-level inventory reporting shows overall increasing and/or neutral forest carbon stocks in recent years (USFS 2011; Woodall et al 2015; USEPA 2016a). Feedstock drying and processing took place at the sawmill with a wood boiler producing process heat for drying. The endothermic reaction of the Tucker RNG unit was sustained by propane combustion; therefore, the thermochemical conversion was identified as the major fossil fuel energy consumption (ie environmental hot spot) for the whole system.

Carbon Sequestration Effect from Biochar

In this analysis, biochar was produced from the Tucker RNG unit as a by-product, thus taking no environmental burden from the process. The study allocated all environmental burdens to the syngas product. However, in the case of biochar, the resultant product is highly stable and recalcitrant, with high carbon content. Therefore, decomposition can be delayed for hundreds to thousands of years, beyond current GHG accounting time frames (Cowie and Cowie 2014). Thus, it is important to model this delay in the emissions to demonstrate direct climate change impacts from biochar in the studied system.

Biochar is characterized by stable aromatic C structures and low bulk density with high ash content. The stable storage of biochar in soils represents a long-term removal of atmospheric C, ie C sequestration (Sohi et al 2010). There are two types of carbon movements in the ecosystem. The movement of C from one reservoir to another is called carbon accumulation. The movement of C from the atmosphere into a reservoir is called carbon sequestration. According to Ciais et al (2013), carbon sequestration as a CO_2 removal method can be defined as the uptake of C-containing substances, and in particular CO_2, into another reservoir with a longer residence time. Biochar produced from this study will either be applied to the ground as soil amendment or used as a precursor for active carbon that can sequester carbon for hundreds of years with little degradation (ie C emissions).

Table 5. CED for 1-kWh electricity generated by different technologies.[a]

Type	Cumulated energy (MJ)
Electricity, biomass, at power plant/US	0.032
Electricity, Tucker RNG syngas, at eGrid, NWPP	16.64
Electricity, bituminous coal, at power plant/US	14.13
Electricity, lignite coal, at power plant/US	20.59
Electricity, anthracite coal, at power plant/RNA	17.12
Electricity, natural gas, at power plant/US	12.69
Electricity, at eGrid, NWPP, 2008/RNA U	7.28

CED, cumulated energy demand; NWPP, northwest power pool.
[a] RNG, renewable natural gas.

If the biochar produced from the Tucker RNG unit as a by-product is intended to be applied as a soil amendment, the benefit of C sequestration to slow or even reverse the increase in atmospheric concentration of CO_2 should apply to the GHG emission accounting. From the material ultimate chemical analysis, biochar from forest thinning residue had a fixed carbon content as high as 90% on a dry weight basis (Gu and Bergman 2016). Based on Wang et al (2014), a carbon stable factor of 85% was calculated for the biochar generated from the Tucker RNG unit. With this, the total C in the biochar produced as a by-product for generating 1-kWh syngas electricity can be calculated and converted to CO_2-equivalent weight, as a decrease in the total GHG emission accounting for the entire process. The C sequestration by the biochar directly decreased the GW impact as shown in Fig 3. However, transportation of biochar, biochar spreading, and soil management practices and their associated environmental impacts were not included in this study because it is outside the boundary defined in this analysis. The GHG emissions from burning fossil fuels in these activities would probably decrease the benefits of biochar's carbon sequestration (Gaunt and Lehmann 2008; Bergman et al 2016).

Comparing GHG Emissions of Syngas Electricity with Other Electricity Technologies

LCA for coal electricity, NG electricity, biomass direct-combustion electricity, and the Northwest eGrid profile electricity were performed using SimaPro modeling software with the data in the US LCI Database. Figure 3 shows the cradle-to-grave results of GHG emission from the LCA output. For 1-kWh electricity generated by the Tucker syngas produced from forest residue chips, the cradle-to-grave GHG emissions were estimated to be 0.748 kg CO_2-eq/kWh without taking biochar carbon sequestration into consideration. When the carbon sequestration from the biochar by-product was applied, the GHG emissions were decreased by 56% to

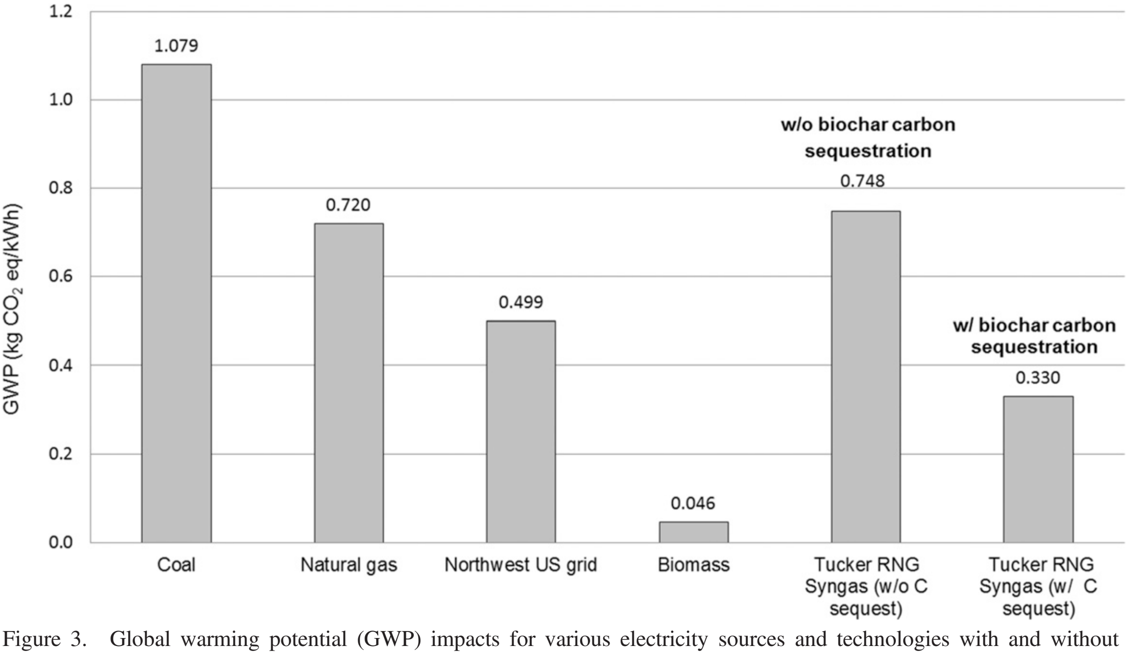

Figure 3. Global warming potential (GWP) impacts for various electricity sources and technologies with and without carbon sequestration accounting (RNG, renewable natural gas).

0.330 kg CO_2-eq/kWh. Thus, a notable influence was discovered from carbon sequestration by the by-product biochar when included and should be emphasized in future analysis of bio-based renewable electricity-generating technologies. Coal and NG electricity GW values of 1.079 and 0.72 kg CO_2-eq/kWh, respectively, were substantially higher than that of the syngas electricity studied here. Electricity generated from biomass direct combustion had a much lower GW impact (0.046 kg CO_2-eq/kWh) because of little fossil fuel consumption and neutral impact to the environment regarding biogenic CO_2 emission. To put these results in context, Schreiber et al (2012) did a meta-analysis of LCA for electricity generation from different regions (Europe, United States, Japan, and global) and different fuels (hard coal, lignite, and NG). They provided an absolute GW potential of the pulverized hard coal combustion technology without any carbon capture from 0.765 to 1.092 kg CO_2-eq/kWh. Then, in a systematic review (Whitaker et al 2012), an LCA of utility-scale coal-fired electricity generation systems reported 0.675 to 1.689 kg CO_2-eq/kWh.

GHG Performance Indicator

To compare GHG performance of the Tucker RNG syngas electricity to fossil or other based electricity, the GHG performance indicator from Sebastian et al (2011) is used here and defined as the following:

$$\left(\mathrm{GHG_{fossil\,or\,other}} - \mathrm{GHG_{syngas}}\right)/\mathrm{GHG_{fossil\,or\,other}} = \mathrm{GHG\,performance(in\,percent)}$$

This GHG performance indicator represents the GHG improvement of syngas electricity compared with fossil or other source equivalents. The GHG emission for syngas electricity with biochar carbon sequestration was used in the calculations. The performance indicators for electricity of various sources are shown in Table 6. The GHG performance of the studied syngas electricity demonstrated approximately 70% improvement compared with coal-based electricity, greater than 50% improvement compared with NG electricity, and even 34% improvement compared with commercial eGrid electricity for western Montana where a Tucker RNG unit was in the plans. However, this conversion-technology-produced syngas electricity cannot be compared with biomass direct-combustion electricity because the indicator was negative, as one would expect. This was because the biomass electricity consumed woody biomass, a carbon-neutral fuel as defined in the LCA, and consumed little fossil fuel in the process except for woody biomass processing and transportation. More significantly, no fossil fuel use was required to keep the reaction going for direct combustion unlike the thermochemical conversion mainstream process of the Tucker RNG unit. Thus, it performs much better for GHG emission reduction potential than the studied syngas electricity system. This particular result ought to be taken in context because the overall BRDI project is driven by exploring the opportunities and the economics of generating new bioenergy and bioproducts such as AC.

Although not common, relatively high GHG emissions for biomass energy production do occur. In some cases, the process of producing bioelectricity from biomass feedstock is energy-intensive and therefore performs even worse for GHG emissions than does fossil fuel electricity (Sebastian et al 2011). Turconi et al (2013) thoroughly reviewed LCA research for various electricity generation technologies and compared environmental impacts for these technologies. Figure 4 shows the range of data collected

Table 6. GW reduction from Tucker RNG syngas electricity compared with the fossil fuel-based electricity.

	Coal	Natural gas	Northwest US eGrid	Tucker RNG syngas
GW	1.079	0.720	0.499	0.330
GW reduction (%)	69.4%	54.2%	33.9%	

GW, global warming; RNG, renewable natural gas.

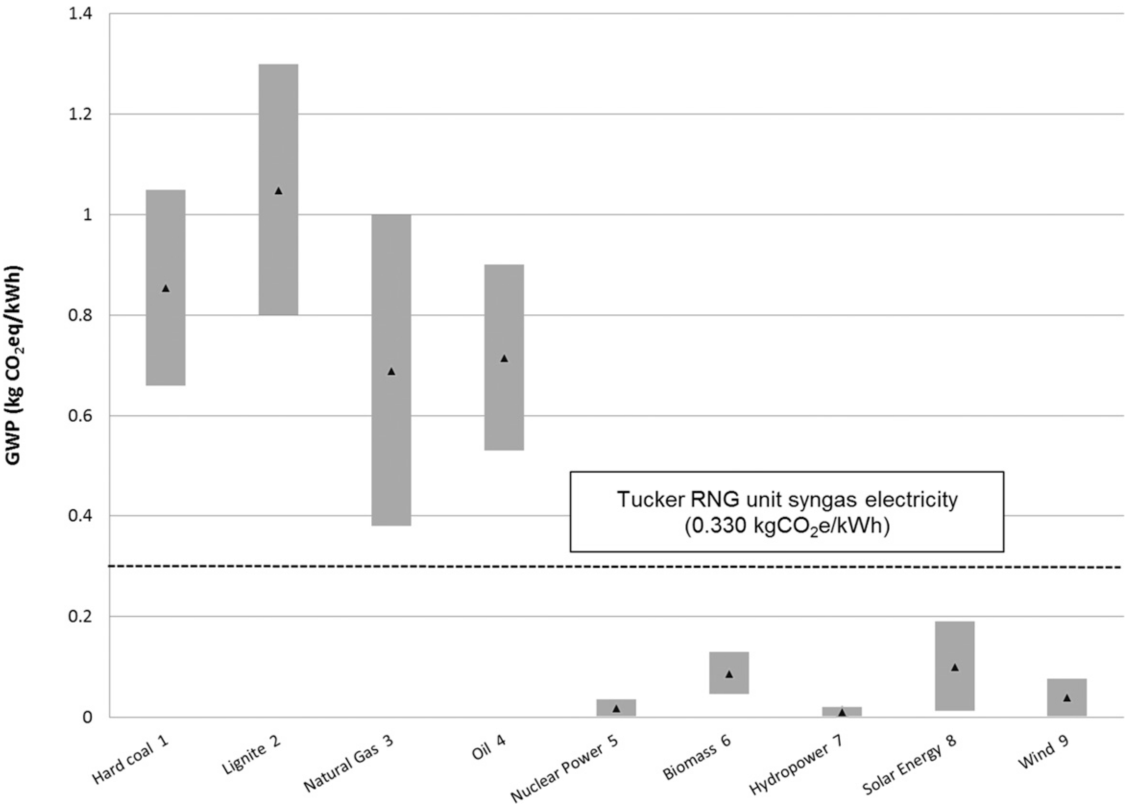

Figure 4. Global warming (GW) impact values for various electricity-generating technologies and the syngas electricity estimated in this study (RNG, renewable natural gas). Each bar represents the range of the GW values; midpoint on each bar represents the average represented GW.

by Turconi et al (2013) and the studied syngas electricity GW impact value. The ranges of the GW values discovered from the literature for each type of electricity technology were draw on the plot and with the midpoint on each bar showed as the averages. The Tucker syngas electricity GW was between that for renewable-energy-generated and fossil-fuel-based electricity technologies. Regardless of these outcomes, it is important to remember, one of the project's original goals was to produce a high-quality biochar (ie low variability in properties) as a precursor to activated carbon (AC), a high-value product, and not biochar as a soil amendment. This endeavor requires greater control of the thermochemical conversion process. Therefore, one could expect to have a GW impact higher than the one for biomass direct-combustion electricity seen in this study.

Table 7 reveals the cradle-to-grave LCA comparison of syngas electricity with other sources of electricity. The other environmental impacts of syngas electricity ranged between biomass-produced electricity and fossil-fuel-produced electricity in different impact categories because, although syngas electricity used woody biomass for its feedstock, propane gas was consumed during thermochemical conversion. Specifically, the LCA for syngas electricity showed the hotspot of the overall environmental impacts was from LPG (proxy for propane gas) combustion to maintain the thermochemical reaction in the mainstream process. Thus, a scenario with substituting the low-heat value waste tar

Table 7. Life cycle impact assessment result for cradle-to-grave syngas electricity and comparison with other electricity types.

Impact category	Unit	Electricity, Tucker syngas	Electricity, biomass	Electricity, bituminous coal	Electricity, lignite coal	Electricity, anthracite coal	Electricity, natural gas	Electricity, at eGrid, NWPP
Ozone depletion	kg CFC-11 eq	8.393E-09	9.589E-14	1.942E-11	2.936E-11	8.593E-13	5.146E-13	7.590E-12
GW	kg CO_2-eq	0.330	0.046	1.079	1.189	1.262	0.720	0.499
Smog	kg O_3-eq	0.143	0.242	0.076	0.092	0.056	0.015	0.032
Acidification	kg SO_2-eq	0.005	0.001	0.009	0.013	0.017	0.006	0.004
Eutrophication	kg N-eq	3.17E-04	4.03E-05	1.37E-04	1.66E-04	1.01E-04	5.97E-05	5.96E-05
Carcinogenics	CTUh	9.25E-09	1.47E-09	7.57E-10	1.33E-09	1.34E-08	2.41 E-10	3.31 E-10
Noncarcinogenics	CTUh	9.45E-08	3.32E-10	2.30E-08	4.11E-08	8.52E-08	3.91 E-08	1.37E-08
Respiratory effects	kg PM2.5 eq	0.000174	0.000007	0.000453	0.000387	0.000978	0.000362	0.000217
Ecotoxicity	CTUe	1.727	0.006	0.082	0.145	0.203	0.933	0.153
Fossil fuel depletion	MJ surplus	1.258	0.005	0.057	0.104	0.183	1.691	0.239

NWPP, northwest power pool; GW, global warming.

from the process for LPG was analyzed and presented next.

Scenario Analysis

Quantifying GW showed both the C benefits of sequestering biochar and the C hot-spots such as from burning propane to maintain the endothermic reaction in the Tucker RNG unit. If decreasing or substituting propane usage in the Tucker RNG unit is possible, GW impact could be further decreased. During the thermochemical conversion process in the Tucker RNG system, low-energy (waste) syngas was produced without being collected for use. Collecting and using this low-energy (waste) syngas to supplement propane usage could further decrease the overall GHG emissions (ie fossil CO_2) associated with the cradle-to-grave LCA of syngas electricity. Therefore, a scenario analysis was conducted with a 30% propane use reduction by the substitution of now-unused low-energy syngas produced from the Tucker RNG unit. The GW impact was decreased by 41% in total from the cradle-to-grave LCA result for syngas electricity (from 0.330 to 0.195 kg CO_2-eq/kWh).

Another scenario analysis on the fuel source for the Tucker RNG unit was conducted. Propane was used for the thermochemical reaction heating in the system because of the limit of available fuel on-site. Therefore substituting propane with NG for reaction heating is assumed and modeled for the LCA analysis. To keep energy equivalence of 1708 MJ/hr, the required amount of NG for the same conversion was calculated based on the HHVs of propane and NG. Because NG (consisting primarily of methane) generates fewer CO_2 emissions per BTU than propane when burned, thus the LCA result demonstrated that the GW impacts for this scenario was reduced about 19% from the base case of propane heating.

Intention of this Tucker technology was to convert forest residues from restoration management to generate renewable energy to substitute for fossil fuel energy. Therefore, only when the renewable energy credit (REC) is gained for the bioelectricity generated from the Tucker RNG syngas, can profits be generated for investors who are interested in the Tucker technology. When no REC is applied for the Tucker syngas electricity studied here, the economy of such applications would hinder its push for the share on the electricity grid. Then the scenario of applying the bioenergy back to feed its own system to produce more valuable bioproducts would be a case for study. The LCA model was modified for this scenario and analysis was run for comparing the GW potential again. Results showed a 25% reduction in GW impact (in kg CO_2-eq) if recycling 50% of the output syngas back to the Tucker system for the thermochemical conversion process while simultaneously replacing propane with NG for the remainder.

CONCLUSIONS

Generating electricity from renewable sources such as woody biomass from sustainable forests can have relatively low GW impacts compared with electricity generated from coal and NG. In this study, generating electricity from the syngas through thermochemical conversion technology such as the Tucker RNG unit resulted in a notable GHG reduction compared with fossil-fuel-based electricity, especially considering the carbon sequestration effect of biochar by-product. Because of its long-term stability in the biochar, carbon stored in the biochar equates to CO_2 removed from the atmosphere. In particular, energy from woody biomass rather than fossil fuels leads to avoidance of fossil CO_2 emissions, which are a substantial contribution to climate change.

The sum of these two effects associated with syngas electricity, a renewable carbon-neutral resource and a C sequestration effect, notably lowers the GW impact (ie GHG emissions). It is known that burning fossil fuels for electricity generation is the main contributor to climate change (Hertwich et al 2013); thus, the consumption of biomass (directly combusted or indirectly derived) for bioelectricity is assumed to be carbon neutral. However, carbon neutrality for the biomass burned to generate electricity continues to be questioned (USEPA 2016). Regardless of biogenic C neutrality, GHG (ie fossil CO_2) emissions are generated from cultivation, harvesting, processing, and transportation processes that contribute to climate change. This study tracked these GHG emissions including fossil and biogenic CO_2 and were included in the analysis. In addition, consuming wood harvested from sustainably managed forests provides substantial air quality benefits by avoiding particulate matter and CO_2 emissions related to burning through forest fires or natural decomposition of forest thinning residues. As the most recent US Forest Carbon Accounting Framework (Woodall et al 2015) reported, the forest has numerous carbon pools that emit carbon through decay and combustion, but it serves an even more active role as a sink of carbon, in contrast to fossil fuels, which only serve as a carbon emission source.

Recommendations for future work for the broader project include using the biochar as a coproduct instead of a by-product in the LCA framework and then evaluating the additional life cycle stage of producing AC. The reason is that AC has a higher market value than biochar 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 required to make it, as this study has shown.

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