Proceedings of the 58th International Convention of Society of Wood Science and Technology
June 7-12, 2015 Jackson Lake Lodge, Grand Teton National Park, Wyoming, USA

Life-cycle GHG emissions of electricity from syngas produced by pyrolyzing woody biomass

Hongmei Gu, Ph.D[1]*
Richard Bergman, Ph.D[1]

[1]U.S. Forest Service Forest Products Laboratory
Madison, Wisconsin, USA
**Corresponding author*
hongmeigu@fs.fed.us

Abstract

Low-value residues from forest restoration activities in the western United States intended to mitigate effects from wildfire, climate change, and pests and disease need a sustainable market to improve the economic viability of treatment. Converting biomass into bioenergy is a potential solution. Life-cycle assessment (LCA) as a sustainable metric tool can assess the impact of new bioenergy systems. Using the internationally accepted LCA method, this study evaluated the syngas electricity produced via a distributed-scale biomass pyrolysis system called the Tucker Renewable Natural Gas (RNG) system (pyrolysis system developed by Tucker Engineering Associates, Locust, NC). This system converts woody biomass in a high temperature and extremely low oxygen environment to a medium-energy synthesis gas (syngas) that is burned to generate electricity. The pyrolysis process also produces biochar as a byproduct and low-energy (unused) syngas as a waste. Results from the life-cycle impact assessment include an estimate of the global warming (GW) impact from the cradle-to-grave production of syngas for electricity. It showed a notably lower GW impact value (0.142 kg CO_2-eq /kWh) compared to electricity generated from bituminous coal (1.08 kg CO_2-eq /kWh) and conventional natural gas (0.72 kg CO_2-eq /kWh), when the carbon sequestration benefit from the biochar byproduct is included. In addition, the evaluation of the GW impact for Tucker syngas electricity showed the highest GHG emissions came from burning propane to maintain the endothermic reaction in the Tucker RNG unit. Using the previously unused low-energy (waste) syngas to supplement propane use would further reduce GHG emissions (ie fossil CO_2) associated with syngas electricity by 20%.

Keywords: Bioenergy, life-cycle assessment, GHG emission, syngas electricity, woody biomass.

Introduction

Restoration treatments on western U.S. forests produced large quantities of woody biomass that can be used as feedstock for production of biofuels and other bioproducts. Producing bioenergy and bioproducts from such forest thinning or timber harvest byproducts would contribute to achieving broad national energy objectives, including the nation's energy security and reduction of greenhouse gas emissions from fossil fuels.

The U.S. Department of Energy and the U.S. Department of Agriculture are both strongly committed to expanding the role of biomass as an energy source and envision a 30% replacement of the current U.S. petroleum consumption with biofuels by 2030 (Perlack et al 2005). Biomass fuels and products are one way to reduce the need for oil and gasoline imports while supporting the growth of agriculture, forestry, and rural economies. Also, expanding biofuels and bioproducts production from biomass has the potential to reduce net greenhouse gas (GHG) emissions and improve local economies and energy security. The 2007 Energy Independence and Security Act (EISA) sets aggressive goals for moving biofuels into the marketplace to reduce the nation's dependence on foreign sources of energy and reduce GHG emissions by increasing the supply of renewable fuels from 4 billion gallons in 2006 to 36 billion by 2022 with 16 billion gallons cellulosic biofuel (EISA 2007). Schnepf and Yacobucci (2013) define cellulosic biofuel as renewable fuel derived from any cellulose, hemicellulose, or lignin sources that has life-cycle GHGs at least 60% less than the baseline life-cycle GHGs from gasoline or diesel as transportation fuel. Life-cycle assessment (LCA) is the pre-eminent and internationally accepted method for categorizing life-cycle GHGs.

LCA as a science-based tool is useful in assessing the claim that expanding bioenergy production from woody biomass has the potential to reduce net GHG emissions. Information provided by this analytical tool is essential for policy makers to make evidence-based judgments on expanding renewable energy production. LCA considers direct and related processes, flows of raw materials and intermediate inputs, waste, and other material and energy outputs associated with the entire product chain or system. Broadly, LCA can assess new products, new processes, or new technologies in an analytically thorough and environmentally holistic manner to guide more robust deployment decisions. LCA can calculate GHG and other emissions over a part or all of the whole life cycle of a product. One huge benefit is that LCA provides sustainability metrics for comparing competing products.

For our study, we applied LCA to the electricity generated from the synthesis gas (syngas) produced by a distributed-scale advanced biomass pyrolysis system, which will be referred to in this paper as the Tucker (developed by Tucker Engineer Associate, Locust, NC) renewable natural gas (RNG) unit. This study is part of a larger USDA project developing and evaluating the Tucker RNG unit that could generate bioenergy and bioproducts for higher value markets. The Tucker RNG unit uses high temperature conversion (>750 °C) in an extremely low oxygen environment to convert the feedstock from forest thinning and mill residues into the syngas that can be used for heat and electricity and into biochar for soil amendment or as a precursor in the manufacturing of activated carbon and other industrial carbon products. Syngas-generated electricity is intended to substitute a portion (marginal part) of grid electricity generated from fossil fuels, most commonly natural gas and coal. The system was specifically designed to generate a high-quality biochar to become activated carbon and not as a soil amendment which sells at a lower price. However, LCA can focus on life-cycle stages that may not be considered once a process becomes commercialized but still in the development phase to evaluate what-if scenarios. In the present study, the what-if scenario was burning syngas to generate electricity with the biochar as a byproduct.

In this paper, LCA will estimate the GHG emission performance from the Tucker RNG technology in reference to established electricity technologies including fossil fuels. Coal and natural gas provide the primary energy sources for the US electrical grid (EIA 2015). This is the first study to evaluate the production of syngas electricity from a distributed-scale thermochemical conversion system in the United States. We will answer the question of how much GHG emissions in kg CO_2-eq can be reduced by substituting fossil fuel electricity with forest residue-derived syngas electricity. Applying LCA can help to compare the processes or technologies for energy and environmental benefits and identify the hotspots (highest points) for energy consumption and GHG emissions.

Methods

The goal of this study was to estimate the GW impact of the electricity generated from the syngas produced by Tucker RNG unit with biomass residue as the feedstock and compare the results to a fossil fuel reference. To achieve this goal, the life-cycle inventory (LCI) for syngas electricity from cradle-to-grave including processes of raw material extraction, transportation, feedstock processing, pyrolysis conversion, and syngas electricity generation was modeled and conformed to the ISO 14040 and 14044 standards (ISO 2006a,b). LCI needs to be built before the impact analysis can be done. LCI is the data collection portion of a LCA. It tracks and quantifies inputs and outputs of a system including detailed resources, raw material, and energy flows.

Primary data were collected from a one-hour continuous run of the Tucker RNG unit for the pyrolysis converting process. The feedstock was wood chips processed from under-utilized small-diameter logs extracted from National Forests with a mix of conifer species dominated by lodgepole pine (*Pinus contorta*), Douglas fir (*Pseudotsuga menziesii*), and ponderosa pine (*P. ponderosa*). Before feeding into the Tucker RNG unit, the chips were dried to less than 10% moisture content (MC) to improve the performance in Tucker RNG unit. The LCI model was constructed in three parts 1) upstream model, including forest management, thinning material extraction, transportation, and feedstock processing; 2) pyrolysis thermal conversion model; 3) downstream model, including the generation of electricity from the primary product syngas and application of biochar as byproduct.

The focus of this study and the conversion technology is on syngas generation and burning to generate electricity. Therefore, the primary product from the Tucker RNG unit is considered to be syngas, while biochar from the system is considered a byproduct. The environmental burdens were assigned 100% to the syngas as the product of interest. Since biochar is considered as byproduct in this study, it will not take any environmental burden from the LCA output, but its role for long-term carbon storage in the soil will be analyzed for carbon sequestration benefits. Secondary data were drawn from peer-reviewed literature according to CORRIM guidelines (CORRIM 2010). 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 outputs and cumulated energy consumption (PRé Consultants 2015). Within the SimaPro software, the inventory data were compiled into the impact category indicator of interest, global warming (GW).

Scope

This study covers the partial cradle-to-grave LCA of electricity generated from syngas produced by pyrolyzing woody biomass. LCI data for producing syngas from the Tucker RNG pyrolysis unit was already constructed by Bergman and Gu (2014) and was incorporated into the model. The present LCA was classified as a partial LCA because the study only covered global warming and no other impact categories that are included in a full LCA. In addition to the LCA on syngas electricity from this study, data from LCI databases for electricity generated from other sources, such as coal, natural gas, and biomass were drawn and analyzed for a comparative partial LCA to examine the marginal effects on electricity grid. The electricity grid is comprised of many regions comprised of various energy sources (USEPA 2014a). The USEPA has broken the U.S. electricity grid into “eGrids” (USEPA 2014a).The eGrid system from the Northwest (NWPP) region included in the comparison to syngas electricity is referred to as NWPP. The eGrid NWPP is representative of year 2008 mix of fuels used for utility electricity generation in the northwestern United States. Fuels include coal, biomass, petroleum, geothermal, natural gas, nuclear, hydroelectric, wind, and other energy sources. NWPP electricity grid covers area including Washington, Oregon, Idaho, Utah, most of Montana, Wyoming, Nevada, and northern parts of California, Arizona, and New Mexico. It is intended that the Tucker RNG syngas provide marginal electricity for the grid because of its distributed-scale size.

Functional unit

Functional unit is the reference unit used to quantify the environmental performance of a product system. It is also a reference related to the inputs and outputs. Because the goal of this research is to compare the GHG performance of electricity generated from Tucker RNG syngas to that of electricity generated from other source, the functional unit is defined as production of 1 kWh of electricity. Material flows, energy use, and emission data are standardized based on this functional unit within the system boundaries described in the following section. The present study does not include grid losses.

Unit processes

To do the life cycle impact assessment (LCIA), the syngas electricity system was built from unit processes. LCI databases contain large lists of unit processes. In the product system, starting from the functional unit, related processes are called on and built into the process tree with inputs and outputs matched to the delivery of the functional unit. For the reference fossil fuel chains, the GHG performance was calculated using data from the USLCI Database (NREL 2012).

Processes for the upstream model of forest management and log extraction in the USLCI Database were used (NREL 2012). Chip processing was modeled with the specific operational data collected as part of this study. Then the pyrolysis conversion process was modeled using Tucker RNG unit specific operation data collected on the system for a 1-hour continuous run. The downstream electricity generation process was modified for Tucker syngas from the USLCI natural gas electricity generation process.

The mainstream model of this study was thermochemical conversion with the Tucker RNG unit. As mentioned previously, Bergman and Gu (2014) provided a detailed analysis of the Tucker RNG unit itself.

The process for electricity generation from the Tucker RNG syngas is similar to the process for natural gas electricity. Electricity is produced from burning the Tucker RNG syngas in a commercial 1.6 MWe Caterpillar generator derated to 1.2 MWe because the syngas has relatively low energy density compared to natural gas. Using wood, the Tucker RNG unit must produce about two times the volume of syngas to generate the same electricity as natural gas. The higher heating value (HHV) of the produced syngas is 19.5 MJ/m^3, one half of the natural gas HHV at 38.3 MJ/m^3. The main components by mass of the syngas are carbon monoxide (55.5%), carbon dioxide (20.1%), and methane (9.2%).

Compiling process data

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 to the environment. The model then relates them to the 100-y GW impact according to the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) method (IPCC 2007; Bare 2011). TRACI 2.1 method is now incorporated in the SimaPro software, version 8 used in the present study.

System boundary

Defining the system boundary selects the unit processes to be included in the system. Based on our goal to determine the environmental impacts of syngas electricity, we drew our system boundary to include the upstream of material handling, main conversion process with the Tucker RNG unit, and the downstream electricity product production. Figure 1 shows the system boundary defined for this partial cradle-to-grave LCA study. The Tucker thermochemical process includes feedstock conveyance, active reacting, passive reacting, condensing, tar cracking, cooling, collecting, and storing. The cumulative system boundary includes both on- and off-site emissions for all material and energy consumed. Fuel and electricity use for the upstream feedstock processing and Tucker pyrolysis converting process were included in the cumulative boundary (solid line) to calculate the total emissions. The on-site emissions include the processes within the dotted line (Fig 1). The off-site emissions include the grid electricity production, transportation, and fuels produced off-site but consumed onsite.

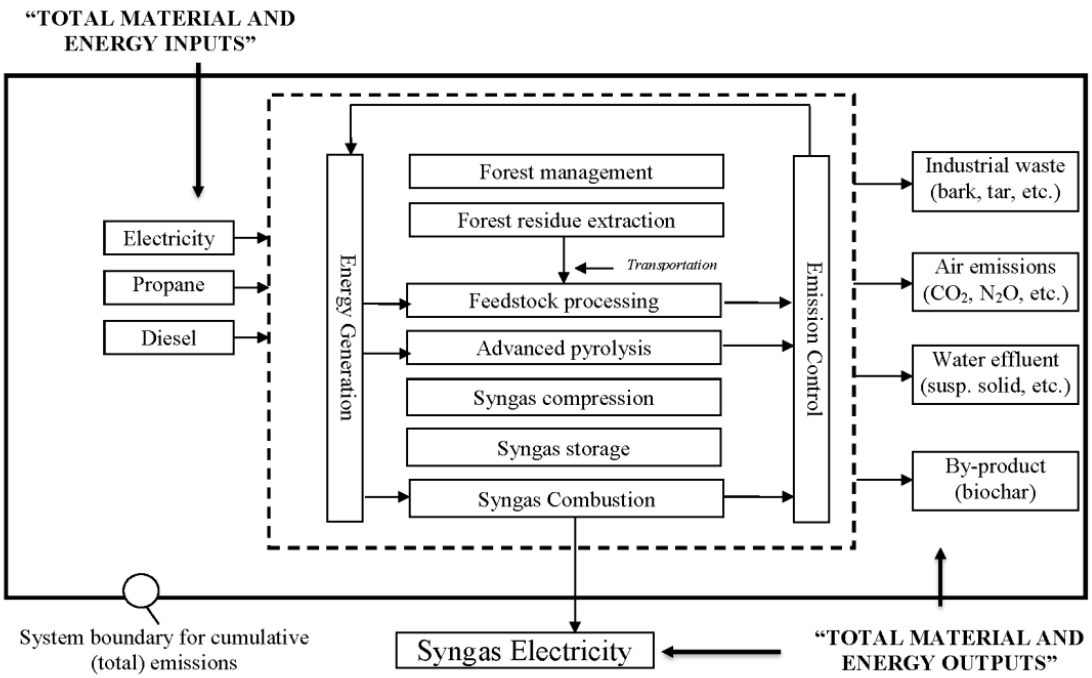

Figure 1. System boundary for the life cycle of generating synthesis gas electricity.

Project limitations

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

Cut-off rules

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

Results and Discussion

The environmental impact assessment for producing 1 kWh of bioelectricity from an advanced pyrolysis converting technology using wood residues was carried out using LCA and the results were described below.

LCIA of syngas electricity

The GW impact from the partial cradle-to-gate LCA for syngas electricity was 0.525 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, with syngas production releasing 72% (0.378/0.525) of the total. Feedstock processing is the second highest emission and includes extraction of forest thinning materials, transportation, and size reduction and pretreatment of the feedstock. About 27% of the total GHG emission was from this feedstock processing upstream stage, which leaves only 1% of GHG emission associated with the syngas electricity generation process. The GW impacts were summarized from fossil CO_2, CH_4 (mainly fossil), and N_2O emissions. The fossil CO_2 emissions for the three stages calculated by SimaPro were 0.002, 0.334, and 0.095 kg/kWh, for syngas electricity generation, Tucker RNG gas, and feedstock processing, respectively. The fossil CH_4 emissions for the three stages were 1.23E-5, 0.0002, and 9.4E-5 kg/kWh, with N_2O emissions broken into 1.07E-5, 1.23E-7, and 3.55E-7 kg/kWh. N_2O emissions were much smaller in quantity but have a much larger GW impact by mass than fossil CO_2 (IPCC 2007).

In terms of the type of energy consumed in each of the three stages, more renewable biomass energy is consumed in the feedstock processing stage than both the syngas producing and electricity generation stage because it uses biomass heating for feedstock drying and some processing. CO_2 emissions from burning woody biomass are not considered in estimating the GW impact because the 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 endothermic reaction of the Tucker RNG unit was sustained by propane combustion; therefore, pyrolysis conversion was identified as the major fossil fuel energy consumption (ie environmental hot spot) for the whole system. For a comparison, Steubing (2011) reports a GW impact of 0.103 kg CO_2-eq/kWh for a Swiss case where the syngas is primarily composed of CH_4 and very little fossil fuel (ie gas) is consumed in the production of syngas unlike the Tucker RNG unit (Steubing et al 2011).

Carbon sequestration effect from biochar

In this analysis, biochar was produced from Tucker RNG unit as a byproduct, thus taking no environmental burden from the process. However, in the case of biochar, the resultant product is highly stable and recalcitrant, with high carbon content, so that decomposition is delayed for hundreds to thousands of years, beyond current GHG accounting time frames (Cowie et al 2013). Thus, it is important to model this delay in emissions to demonstrate the direct climate change impacts from biochar in the system. As mentioned previously, all environmental burdens were assigned to syngas electricity because biochar was designated as a byproduct.

Biochar is characterized by stable aromatic C structures, low bulk density, and 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. The movement of C from one reservoir in the ecosystem to another is called *carbon accumulation*. The movement of C from 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 C 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 et al (2014), we calculated a

Carbon Stable Factor for the biochar generated from the Tucker RNG unit of 85%. With this, the total C 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 the total GHG emission accounting for the entire process. The sequestration of the biochar C directly reduces the GW impact as shown in Fig 1. However, transportation of biochar, biochar spreading, and soil management practices and their associated environmental impacts were not included in this study. The GHG emissions from burning fossil fuels from these activities would likely reduce the benefits of applying biochar as a soil amendment (Gaunt and Lehmann 2008).

Comparing GHG Emissions of Syngas Electricity to Other Electricity Technologies

LCA for coal electricity, natural gas electricity, direct biomass combustion electricity, and the Northwest eGrid profile electricity were performed in the SimaPro software with the data from the built-in USLCI Database. Figure 2 shows the results of GHG emission data summarized from LCA. For 1 kWh electricity generated from the Tucker syngas converted from forest residue chips the GHG emissions were estimated to be 0.525 kg CO_2-eq/kWh without taking biochar carbon sequestration into consideration. This is close to the total GHG emission from the eGrid for Northwest region (0.499 kg CO_2-eq/kWh). However, coal and natural gas electricity has a substantially higher value than our studied syngas electricity (1.079 kg CO_2-eq/kWh and 0.72 kg CO_2-eq/kWh, respectively). Electricity generated from biomass direct combustion has a lower GW impact (0.087 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 biochar carbon sequestration effect, the GHG emission value for our studied syngas electricity was reduced by more than 70% to 0.142 kg CO_2-eq. Thus, a notable influence was discovered from carbon sequestration by the byproduct biochar when included and should be emphasized in future analysis for biobased renewable electricity-generating technologies.

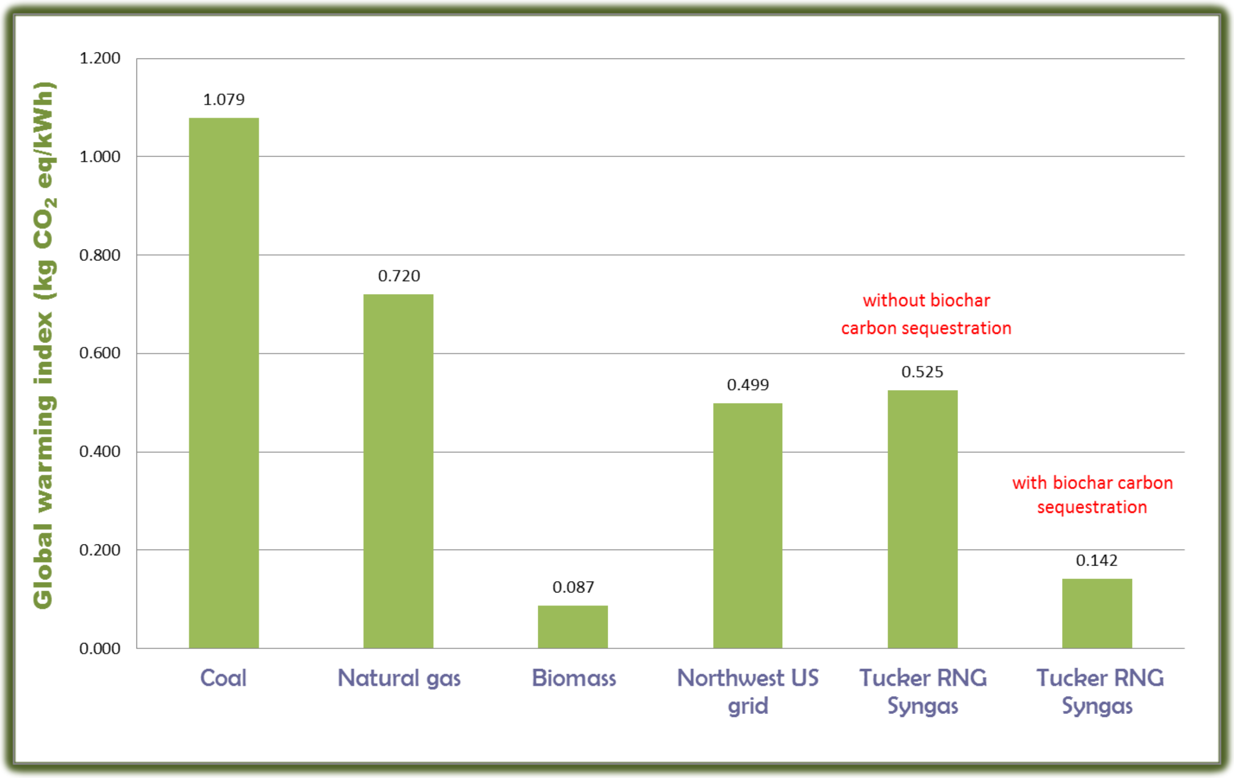

Figure 2. Global warming impacts for various electricity sources and technologies, and for Tucker syngas electricity with and without carbon sequestration accounting.

GHG Performance Indicator

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

$(GHG_{fossil\ or\ other} - GHG_{syngas})/GHG_{fossil\ or\ other}$ = GHG performance (in percentage)

This GHG performance indicator represents the GHG improvement of the syngas electricity over fossil or other source equivalent. The GHG emission for syngas electricity with biochar carbon sequestration is used in the calculations. The indicators are shown in Fig 3. The GHG performance of the studied syngas electricity demonstrated a greater than 80% improvement over the fossil fuel electricity (coal and natural gas), and about 71% improvement over the commercial NWPP eGrid electricity GHG performance. However, there is a negative improvement (–63%) for the syngas electricity over the biomass electricity because of less fossil fuel consumption in the direct biomass combustion to electricity system. Biomass-direct combustion process for electricity is simple and more straightforward than the biomass derived syngas electricity technology. In addition, no additional fossil fuel use is required to keep the reaction going during direct combustion, unlike the Tucker RNG unit. Therefore, it performs better in GHG emission than the studied syngas electricity system.

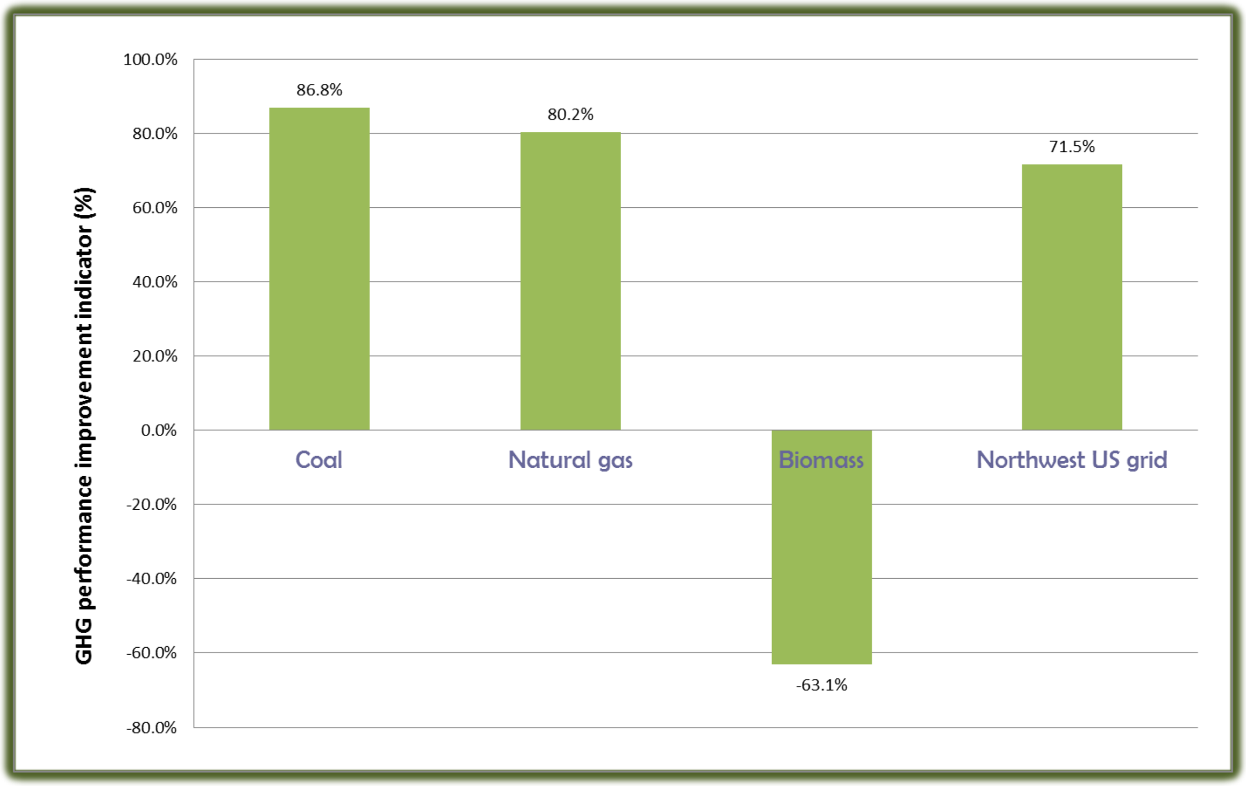

Figure 3. GHG performance indicator for the electricity generated from the Tucker RNG syngas compared to other electricity generation technologies.

In some cases, the process of producing bioelectricity from biomass feedstock is energy-intensive and therefore performs even worse for GHG emissions than fossil fuel electricity (Sebastian et al 2011). Turconi et al (2013) did a thorough review on LCA research for various electricity generation technologies and compare environmental impacts for these technologies. Figure 4 shows the range of data collected by Turconi et al's (2013) paper and our studied syngas electricity GW impact value. The Tucker syngas electricity GW is close or within the range of renewable energy generated electricity including biomass, hydropower, solar energy, and wind electricity. These are all significantly lower than the nonrenewable fossil fuel generated electricity, including hard coal, lignite, natural gas, and oil.

Scenario Analysis

Quantifying GW showed both the carbon benefits (eg low GHG emissions) and the carbon "hotspots" such as from 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 (waste) syngas to supplement propane usage would further reduce GHG emissions (ie fossil 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 GWP improved by 20% in total for the cradle-to-grave syngas electricity.

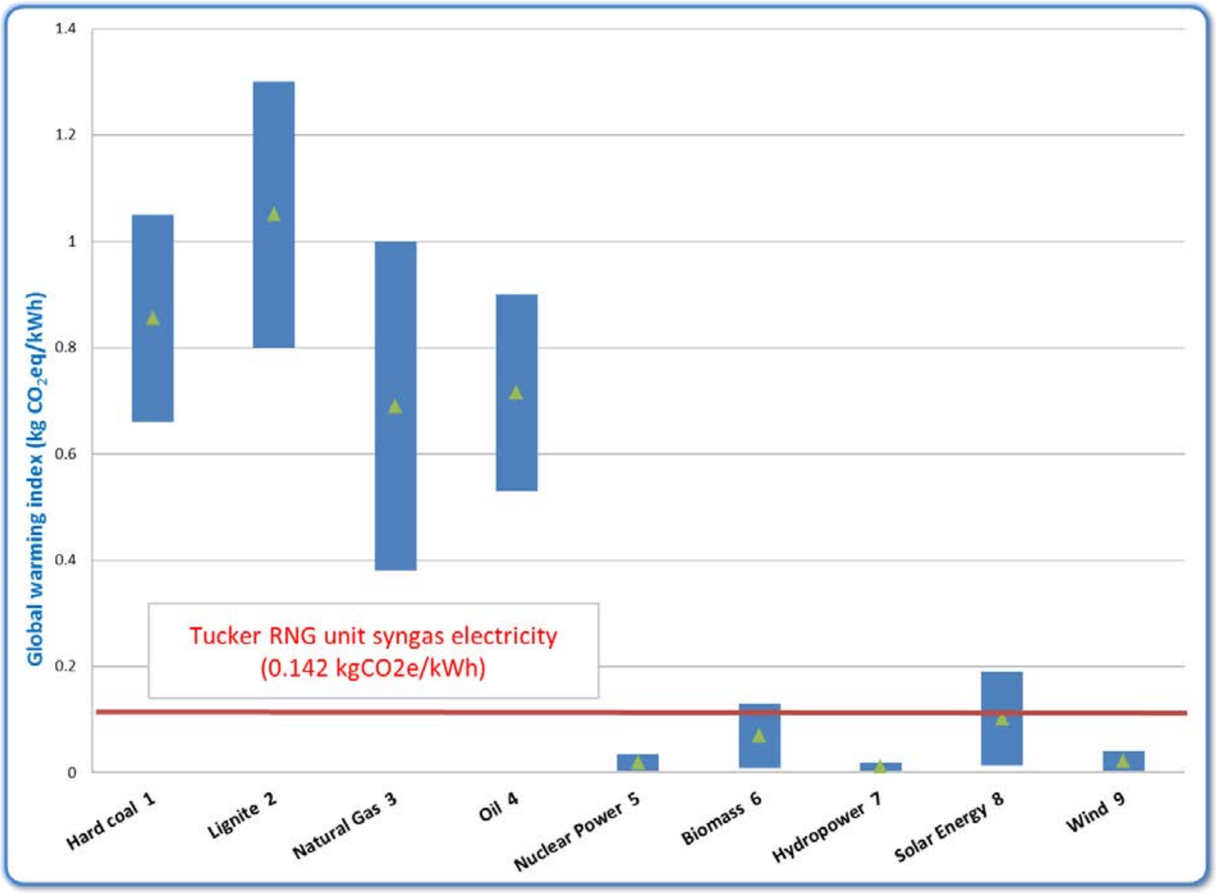

Figure 4. General range of global warming impact for various electricity generating technologies collected from literature and for syngas electricity estimated in this study.

Conclusion

Generating electricity from wood-biomass sources such as the Tucker RNG unit can result in notable GHG reduction in comparison to fossil fuels. In addition, syngas electricity generated from Tucker RNG syngas is from a renewable energy as it consumes forest thinning or mill residues. Furthermore, systems like the Tucker RNG unit reduce energy dependency on fossil fuel or other non-renewable 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 fuels use.

Sequestering biochar when 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 because of its long-term stability.

The sum of these two effects associated with syngas electricity of using woody biomass as a feedstock and sequestering biochar lowers the GW impact (ie GHG emissions) substantially. It is known that electricity from burning fossil fuels is the main contributor to the GW impact (Hertwich et al 2013); thus, the consumption of biomass (directly combusted or indirectly derived) for bioelectricity is assumed as carbon neutral. Carbon neutrality for the biomass burned to generate electricity continues to be questioned (USEPA 2014b). Regardless, GHG emissions are generated that impact GW because the entire life cycle of the biomass is assessed so there are fossil CO_2 emissions in the cultivation, harvesting, processing, and transportation processes. The present study tracked these GHG emissions including fossil CO_2 and thus was included in our analysis. One additional point was added for wood harvested from sustainably managed forests. By doing so, substantial C benefits are gained by avoiding CH_4 emissions related to burning or natural decomposition of forest thinning residues but instead converting them into biomass-based electricity.

Future works for the broader project details utilizing the biochar as a co-product instead of a byproduct and then evaluating the additional life cycle of producing activated C. The reason is that biochar as activated C 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 to make it so.

Acknowledgment

We thank Richard Tucker and David Barbee (Tucker Engineering Associates) for technical assistance. In addition, the authors especially thank Mark Knaebe (USDA Forest Service Forest Products Laboratory), Nathaniel Anderson (USDA Forest Service Rocky Mountain Research Station) and Prakash Nepal (U.S. Forest Service, Forestry Sciences Laboratory in Research Trainable Park, NC) for their peer review of this paper. We gratefully acknowledge financial assistance for this research project provided by the U.S. Department of Agriculture (USDA) National Institute of Food and Agriculture Biomass Research and Development Initiative (BRDI) award no. 2011-10006-30357. BRDI is a joint effort between the USDA and the U.S. Department of Energy.

References

Bare, J (2011) TRACI 2.0: the tool for the reduction and assessment of chemical and other environmental impacts 2.0. Clean Technologies and Environmental Policy, 13(5).

Bergman RD, Gu H (2014) Life-cycle inventory analysis of bio-products from a modular advanced biomass pyrolysis system. In: Proceedings, Society of Wood Science and Technology 57th International Convention. June 23-27, 2014. Zvolen, Slovakia: 405–415.

Cowie AL, Cowie AJ (2013) Case Study - Rural Climate Solutions (University of New England/ NSW Department of Primary Industries) Life cycle assessment of greenhouse gas mitigation benefits of biochar. http://www.ieabioenergytask38.org/publications/T38_Biochar_case_study.pdf. (28 April 2015). CORRIM (2010) Research guidelines for life-cycle inventories. Consortium for Research on Renewable Industrial Materials. University of Washington, Seattle. 40 p.

EIA (2015) Annual Energy Outlook 2015. Figure 31. Electricity generation by fuel in the reference case, 2000-2040 (trillion kilowatthours). U.S. Energy Information Administration. http://www.eia.gov/forecasts/aeo/pdf/0383(2015).pdf (28 April 2015)

EISA (2007) Legal Reference—Energy Independence and Security Act of 2007. GPO (Government Printing Office). Gaunt J Lehmann J (2008) Energy balance and emissions associated with biochar sequestration and pyrolysis bioenergy production. College of Agriculture and Life Sciences, Cornell University. Environmental Science & Technology 42: 4152–4158.

Hertwich, E.G., Gibon, T., Bouman, E.A., Arvesen, A., Suh, S., Heath, G.A., Bergesen, J.D., Ramirez, A., Vega, M.I., and L. Shi. (2013) Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies. PNAS special feature. http://www.pnas.org/cgi/doi/10.1073/pnas.1312753111. 6 pp. (28 April 2015)

IPCC (2007) The physical scientific basis. Contribution of working group to the fourth assessment report of the intergovernmental panel on climate change, edited by S. Solomon et al, Cambridge Univ. Press, New York.

ISO (2006a) Environmental management—life-cycle assessment—principles and framework. ISO 14040. International Organization for Standardization, Geneva, Switzerland. 20 pp.

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

NREL (2012) Life-cycle inventory database project. National Renewable Energy Laboratory. https://www.lcacommons.gov/nrel/search. (accessed March 3, 2015).

Perlack PD, Wright LL, Turhollow AF, Graham RL, Stokes RJ, Erbach DC (2005) Biomass as feedstock for a bioenergy and bioproducts industry: The technical feasibility of a billion-ton: Annual supply. April 2005. A joint study sponsored by U.S. Department of Energy and the U.S. Department of Agriculture.
http://www1.eere.energy.gov/bioenergy/pdfs/final_billionton_vision_report2.pdf (28 April 2015)

PRé Consultants (2015) Life-Cycle assessment software package SimaPro 8 Update Instructions. Stationsplein 121, 3818 LE Amersfoort, The Netherlands. http://www.pre-sustainability.com/ (28 April 2015).

Schnepf R, Yacobucci BD (2013) Renewable fuel standard: overview and issues. Congressional Research Service Report for Congress no. 7-5700 https://www.fas.org/sgp/crs/misc/R40155.pdf (28 April 2015).

Sebastian F, Royo J Gomez, M (2011) Cofiring versus biomass-fired power plants: GHG (Greenhouse Gases) emissions savings comparison by means of LCA (Life Cycle Assessment) methodology. Energy 36: 2029-2037.

Sohi SP, Krull E, Lopez-Capel E, Bol R (2010) Chapter 2 – A review of biochar and its use and function in soil. Advances in Agronomy 105:47–82.

Steubing B (2011) Analysis of the availability of bioenergy and assessment of its optimal use from an environmental perspective. PhD dissertation, École polytechnique fédérale de Lausanne, Lausanne, Switzerland. 181 pp.

Steubing B, Zah R, Ludwig C (2011) Life cycle assessment of SNG from wood for heating, electricity, and transportation. Biomass Bioenerg 35(7):2950–2960.

Turconi R, Boldrin A, Astrup T (2013) Life cycle assessment of electricity generation technologies: Overview, comparability and limitations. Renewable and Sustainable Energy Reviews 28: 555–565. USEPA (2014a) eGRID 9th edition version 1.0: Year 2010 summary tables. United States Environmental Protection Agency. Washington, D.C. 13 p. http://www.epa.gov/cleanenergy/documents/egridzips/eGRID_9th_edition_V1-0_year_2010_Summary_Tables.pdf (27 March 2015).

USEPA (2014b) Carbon dioxide emissions associated with bioenergy and other biogenic sources. United States Environmental Protection Agency. Washington, D.C. http://www.epa.gov/climatechange/ghgemissions/biogenic-emissions.html (28 April 2015).

Wang Z, Dunn JB, Han J, Wang MQ (2014) Effects of co-produced biochar on life cycle greenhouse gas emissions of pyrolysis-derived renewable fuels. Biofuels and Bioprod Bioref. 8:189–204.