GASIFICATION BIOENERGY PROJECTS: IMPACTS AND BENEFITS TO AIR QUALITY

White Paper Addressing Air Quality Concerns with Community-Scale Biomass Gasification Projects

Introduction

This white paper addresses the sources of air emissions benefits and impacts from community-scale bioenergy[1] development utilizing sustainably harvested forest-sourced biomass. Community-scale distributed generation is an important component of the overall energy portfolio throughout the Sierras. The utilization of forest-sourced biomass will support responsible forest management projects that will protect communities in the Sierras by decreasing the risk of severe wildfires[2,3] and improving air quality,[4] supporting and expanding employment local opportunities,[5] and providing a sustainable source of renewable energy with locally available feedstock.

Gasification technology was reviewed in this white paper as an emerging California market for community-scale biomass power. Gasification technology has been shown to be cost effective at the community-scale level and to reduce air emissions when compared to traditional direct combustion.

This paper does not identify all of the potential air benefits and impacts associated with a specific bioenergy project. The paper reviews criteria pollutants including nitrous oxides (NO_x), particulate matter (PM), carbon monoxide (CO), and volatile organic compounds (VOC) along with greenhouse gas emissions including methane (CH_4) and carbon dioxide (CO_2) that are prevalent throughout most community-scale projects sited in the Sierra Nevada Mountain region.

Process and Material Flow

The white paper utilizes a holistic approach to review air quality contributions of biomass gasification projects. The analysis relies on several important assumptions applicable to bioenergy development across forested landscapes. These assumptions include:

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[1] Community-scale bioenergy is defined as less than 3 MW per California Senate Bill 1122 (Rubio 2012).

[2] Stephens, Scott L., et al. "Fire treatment effects on vegetation structure, fuels, and potential fire severity in western US forests." *Ecological Applications* 19.2 (2009): 305-320.

[3] Saah, David, et al. "Developing an Analytical Framework for Quantifying Greenhouse Gas Emission Reductions from Forest Fuel Treatment Projects in Placer County, California." *Spatial Informatics Group* 2012.

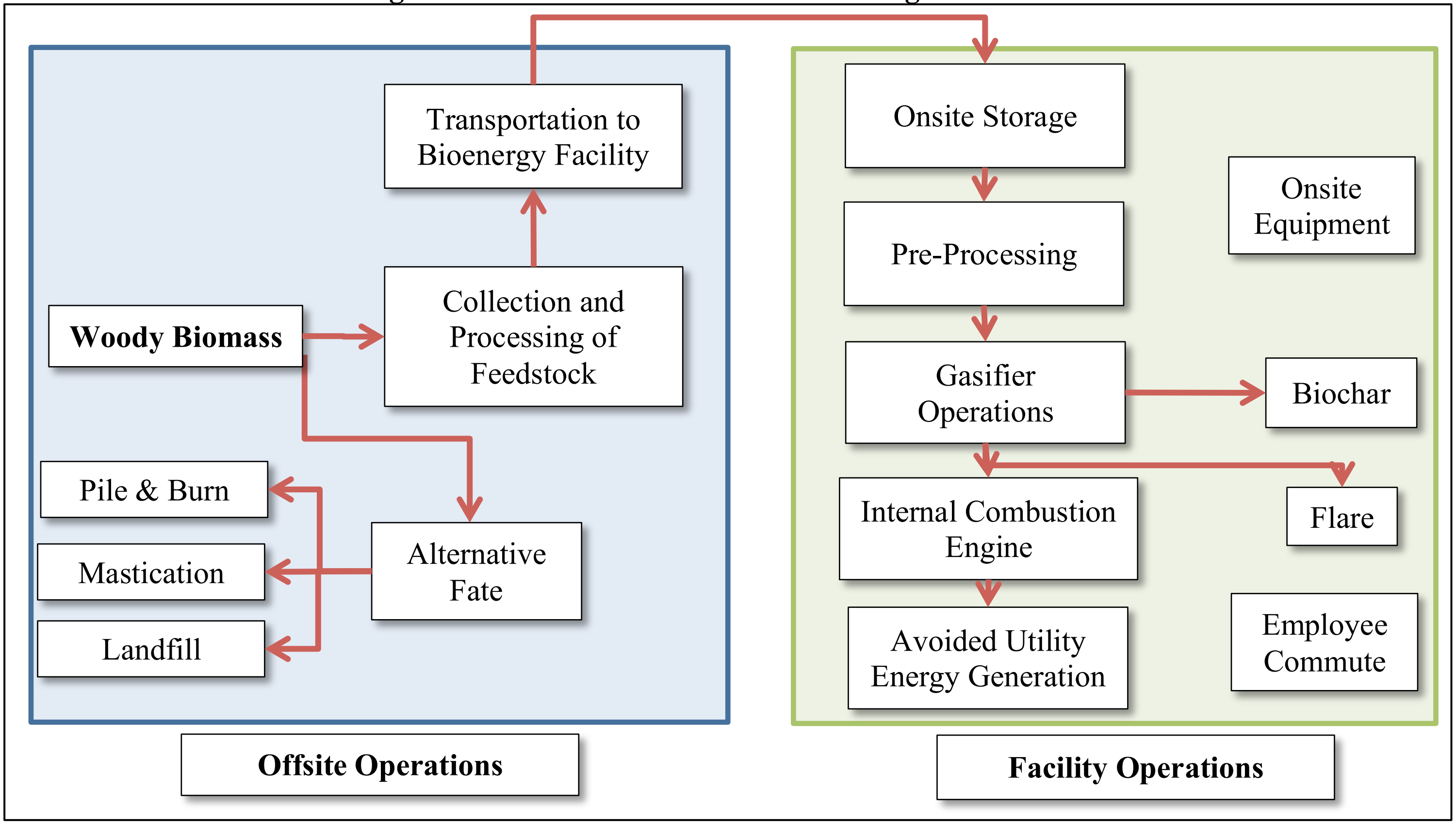
[4] Primarily through the utilization of forest-sourced materials with pile and burn alternative fates.

[5] Morris, Gregory Paul. "The value of the benefits of US biomass power." *National Renewable Energy Laboratory*, 1999.

- Biomass feedstock is a waste stream, as the feedstock is not grown or harvested for the primary or explicit use in a bioenergy facility;
- The air quality benefits, including most notably greenhouse gas benefits, of the regrowth of biomass over time is not applicable to bioenergy projects as the harvest and growth of this material was not for bioenergy; and
- Bioenergy production and development is not inherently carbon neutral.

Figure 1 shows the extent of the processes and materials directly attributed to bioenergy production.

Figure 1. Process and Material Flow Diagram



Air Quality Impacts

Potential emissions points through the process include but are not limited to:

- Collection and processing of feedstock;
- Transportation to a bioenergy facility;
- Onsite storage of feedstock;
- Pre-Processing (e.g. drying);
- Internal combustion engine emissions;
- Flare emissions;
- Employee commute; and
- Onsite equipment use.

Alternative Disposal Methods

Utilizing biomass energy for energy production diverts woody biomass from alternative fates including pile and burn, mastication/spreading, and landfill disposal. Pile and burn and mastication/spreading are the primary disposal alternatives in the Sierras, although some woody biomass waste material is occasionally hauled to a landfill for disposal. Table 1 shows air pollutant emission factors for biomass processing for energy

Table 1. Emission Factors for Biomass Disposal Activities

	NO_x [lb/BDT]	PM [lb/BDT]	CO [lb/BDT]	CH_4 [lb/BDT]	VOC [lb/BDT]	CO_2 [lb/BDT]
Pile & Burn[6,7,8,9, 10]	6.0-9.2	8.0-19.1	74-150	0.2-12.2	10-15	2,920-3,674
Mastication/ Spreading[11,12]				0-130		3,160-3,200
Landfill[13,14]				0-430		64.5-2,400

Collection and Processing of Feedstock

The collection and processing of feedstock encompasses the work performed in the forest beyond the primary harvesting plan (e.g., timber sales, fuels management). Table 2 shows air pollutant emission factors for biomass processing for energy. Note that processing for bioenergy feedstock is primarily biomass collection and chipping or grinding.

Table 2. Emission Factors for Processing of Feedstock

	NO_x [lb/BDT]	PM [lb/BDT]	CO [lb/BDT]	CH_4 [lb/BDT]	VOC [lb/BDT]	CO_2 [lb/BDT]
Processing for bioenergy feedstock[15,16,17]	0.2-0.9	0.03-0.16	0.29-0.30	0-0.015	0.01-0.09	27.4-60.0

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[6] Morris, Gregory Paul. "The value of the benefits of US biomass power." *National Renewable Energy Laboratory*, 1999.

[7] Springsteen, Bruce, et al. "Emission reductions from woody biomass waste for energy as an alternative to open burning." *Journal of the Air & Waste Management Association* 61.1 (2011): 63-68.

[8] Lee, Carrie, et al. "Greenhouse gas and air pollutant emissions of alternatives for woody biomass residues." *Stockholm Environmental Institute*, 2010.

[9] Jones, Greg, et al. "Forest treatment residues for thermal energy compared with disposal by onsite burning: Emissions and energy return." *Biomass and Bioenergy* 34.5 (2010): 737-746.

[10] Cabin Creek Biomass Facility Project DEIR, July 2012, State Clearinghouse #2011122032, Placer County Community Development Resources Agency

[11] Morris, Gregory Paul. "The value of the benefits of US biomass power." *National Renewable Energy Laboratory*, 1999.

[12] Lee, Carrie, et al. "Greenhouse gas and air pollutant emissions of alternatives for woody biomass residues." *Stockholm Environmental Institute*, 2010.

[13] Morris, Gregory Paul. "The value of the benefits of US biomass power." *National Renewable Energy Laboratory*, 1999.

[14] Micales, Jessie A., and Kenneth E. Skog. "The decomposition of forest products in landfills." *International Biodeterioration & Biodegradation* 39.2 (1997): 145-158.

[15] Springsteen, Bruce, et al. "Emission reductions from woody biomass waste for energy as an alternative to open burning." *Journal of the Air & Waste Management Association* 61.1 (2011): 63-68.

Transportation to a Bioenergy Facility

Woody biomass feedstock is transported to a bioenergy facility in chip vans.[18] Table 3 shows the resulting emissions factors.

Table 3. Biomass Feedstock Transportation Emission Factors[19]

	NO_x [lb/mi]	PM [lb/mi]	CO [lb/mi]	CH_4 [lb/mi]	VOC [lb/mi]	CO_2 [lb/mi]
Chip Van Transportation[20,21,22]	0.016-0.034	0.0006-0.0020	0.0013-0.075	0.002	0.0004-0.0055	2.57-4.43

Onsite Storage

Wood chips, when stored onsite, produce emission through the aerobic and anaerobic decomposition of the woodchip material with time. Emissions from onsite storage are primarily a function of time and degree of compaction within the piled material. Increased compaction yields increased anaerobic activity and with concomitant increased methane emissions. The focus for emissions from onsite storage is methane emissions due to the relatively long decomposition time compared to storage time.[23,24,25] With significant greenhouse gas potential,[26] methane emission contributions to the overall air quality impacts should be addressed. Table 4 indicates a range of published emission factors in pounds per cubic foot of wood storage per day.

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[16] Lee, Carrie, et al. “Greenhouse gas and air pollutant emissions of alternatives for woody biomass residues.” *Stockholm Environmental Institute*, 2010.

[17] Cabin Creek Biomass Facility Project DEIR, July 2012, State Clearinghouse #2011122032, Placer County Community Development Resources Agency

[18] The Cabin Creek EIR identifies these chip vans as T6 Medium-Heavy Duty Diesel instate construction trucks with a gross vehicle weight rating greater than 26,000 lbs.

[19] TSS notes that the sited studies do not directly address wood chip pile emissions for bioenergy storage, but represent the best available information at this time.

[20] EMFAC Emissions Database, 2011. http://www.arb.ca.gov/emfac/

[21] Springsteen, Bruce, et al. “Emission reductions from woody biomass waste for energy as an alternative to open burning.” *Journal of the Air & Waste Management Association* 61.1 (2011): 63-68.

[22] Cabin Creek Biomass Facility Project DEIR, July 2012, State Clearinghouse #2011122032, Placer County Community Development Resources Agency

[23] Busse, Matt D. "Downed bole-wood decomposition in lodgepole pine forests of central Oregon." *Soil Science Society of America Journal* 58.1 (1994): 221-227.

[24] Chambers, Jeffrey Q., et al. “Decomposition and carbon cycling of dead trees in tropical forests of the central Amazon.” *Oecologia* 122.3 (2000): 380-388.

[25] Boddy, Lynne, and Sarah C. Watkinson. “Wood decomposition, higher fungi, and their role in nutrient redistribution.” *Canadian Journal of Botany* 73.S1 (1995): 1377-1383.

[26] 1 lb CH_4 = 21 lb CO_2e

Table 4. Wood Chip Storage Emission Factors

	NO_x [lb/ft^2-day]	PM [lb/ft^2-day]	CO [lb/ft^2-day]	CH_4 [lb/ft^2-day]	VOC [lb/ft^2-day]	CO_2 [lb/ft^2-day]
Wood Chip Storage[27,28]	-	-	-	0.0008-0.0123	-	-

Pre-Processing

Pre-processing for forest biomass gasification projects is typically limited to feedstock drying when necessary. Forest-sourced feedstock may range from 20% to 60% moisture content.[29,30,31,32] Gasification technologies vary by manufacturer; however typically require feedstock to be dried to 5% to 20% moisture content.[33,34] Table 5 shows emission factors for feedstock drying based on comparable wood product manufacturing.

Table 5. Dryer Emission Factors

	NO_x [lb/BDT]	PM [lb/BDT]	CO [lb/BDT]	CH_4 [lb/BDT]	VOC [lb/BDT]	CO_2 [lb/BDT]
Wood Drying[35,36]	0.024-0.31	0.42-2.2	0.12-1.2	0-0.25	0.21-1.0	38.2-311

Internal Combustion Engine Operations

In gasification technology, the gasifier itself is not an air emissions source. Gasification units typically convey feedstock into the vessel via an air locked chamber and the output is biochar and synthesis gas (syngas). The syngas is subsequently conditioned to remove water and tars. The tars are reintroduced into the gasifier, and the water is stored to buffer against dry feedstock and ambient conditions. Excess water is traditionally pre-treated prior to disposal offsite at any appropriate water treatment facility. The two sources of air pollutant emissions in the system are the internal combustion engine and a flare. These devices are not utilized simultaneously. The primary recipient of syngas is the internal combustion engine and the flare is installed for

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[27] Wihersaari, Margareta. "Evaluation of greenhouse gas emission risks from storage of wood residue." *Biomass and Bioenergy* 28.5 (2005): 444-453.

[28] PCF*plus*, "Methane and nitrous oxide emissions from biomass waste stockpiles." Report 12. World Bank Project No. 1050. August 2002.

[29] Stevens, Christian. *Thermochemical processing of biomass: conversion into fuels, chemicals and power*. Ed. Robert C. Brown. Vol. 12. John Wiley & Sons, 2011.

[30] Lee, Carrie, et al. "Greenhouse gas and air pollutant emissions of alternatives for woody biomass residues." *Stockholm Environmental Institute*, 2010.

[31] Wihersaari, Margareta. "Evaluation of greenhouse gas emission risks from storage of wood residue." *Biomass and Bioenergy* 28.5 (2005): 444-453.

[32] PCF*plus*, "Methane and nitrous oxide emissions from biomass waste stockpiles." Report 12. World Bank Project No. 1050. August 2002.

[33] "Renewable Energy Technologies: Cost Analysis Series – Biomass for Power Generation" *International Renewable Energy Agency*. Volume 1. Issue 5. June 2102.

[34] Ciferno, Jared P., and John J. Marano. "Benchmarking biomass gasification technologies for fuels, chemicals and hydrogen production." *US Department of Energy. National Energy Technology Laboratory* (2002).

[35] Milota, Michael R. "Emissions from wood drying." *Forest Prod. J* 50 (2000): 10-20.

[36] Environmental Protection Agency: AP-42 Chapter 10 Section 6.2

instances when the engine must be turned off. The flare is not used during typical operations but may be required for startup, shutdown, and unscheduled maintenance.

Emission factors shown in Table 6 are representative of permitted biomass gasification projects in California. The San Joaquin Valley Air Pollution Control District (SJVAPCD) has evaluated and issued permits for two gasification projects (0.5 MW and 1.0 MW, rich-burn engines). Note that SJVAPCD did not calculate CH_4 or CO_2 emissions for these permits.

Table 6. Internal Combustion Engine and Flare Emission Factors

	NO_x	PM	CO	CH_4	VOC	CO_2
Internal Combustion Engine [lb/bhp-hr] [37,38,39]	0.00024	0.00011	0.0013	0.070-1.45 lb/MMBtu	0.00024	110-206 lb/MMBtu
Flare [lb/MMBtu] [40]	0.068	0.008	0.37	0.077	0.063	12.9

Avoided Utility Electricity Generation

The avoided emissions from displacing fossil fuel generated electric power by biomass generated electric power depend on the electricity profile of the utility from which electricity would otherwise be sourced. Electricity profiles for the California electric utilities servicing the Sierras are shown in Table 7.

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[37] San Joaquin Valley Air Pollution Control District Authority to Construction No. N-8071-1-0 and N-8071-2-0

[38] Environmental Protection Agency: AP-42 Chapter 3 Section 2

[39] Code of Federal Regulations. Part 98-Mandatory Greenhouse Gas Reporting. Subpart C. Table C-1.

[40] Environmental Protection Agency: AP-42 Chapter 13 Section 5

Table 7. Pacific Gas & Electric Power Content Labels, 2011[41]

	Natural Gas	Coal	Nuclear	Renewables	Large Hydroelectric	Other	Unspecified Power
Pacific Gas & Electric	25%	0%	22%	19%	18%	1%	15%
Southern California Edison	27%	8%	24%	19%	7%	0%	15%
San Diego Gas & Electric	42.8%	2.7%	20.4%	15.7%	0%	0%	18.4%
Liberty Power	37%	8%	16%	15%	13%	0%	12%
Los Angeles Department of Water & Power	17%	41%	11%	19%	3%	0%	9%
Truckee-Donner Public Utilities District	8%	47%	0%	39%	0%	0%	6%
Plumas Sierra Co-Op	19%	0%	0%	5%	45%	0%	31%
California State Combined Power Mix	**37%**	**8%**	**16%**	**14%**	**13%**	**0%**	**12%**

Avoided emissions will be calculated strictly from the generation of electricity from specific fuel sources. While the procurement and processing of feedstock can yield significant additional air emissions,[42,43,44,45] these life cycle emissions are not reviewed based on the conservative assumption that the marginal decrease in alternative fuel demand does not proportionately decrease the emissions associated with procurement of the alternative fuels. Thereby emissions from nuclear, renewables, large hydroelectric, and other will be considered zero. Unspecified power is predominantly power purchased from out-of-state and where the power mix is unknown. Unspecified power will not be assigned air emissions for the purposes of this white paper. Emissions from natural gas and coal powered sources are thereby the primary avoided emissions sources.

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[41] California Energy Commission: http://www.energy.ca.gov/sb1305/labels/

[42] Jaramillo, Paulina, W. Michael Griffin, and H. Scott Matthews. "Comparative life-cycle air emissions of coal, domestic natural gas, LNG, and SNG for electricity generation." *Environmental Science & Technology* 41.17 (2007): 6290-6296.

[43] Meier, P. J., and G.L. Kulcinski. "Life-Cycle Energy Costs and Greenhouse Gas Emissions for Gas Turbine Power." *Energy Center of Wisconsin* (2000).

[44] Fthenakis, Vasilis M., and Hyung Chul Kim. "Greenhouse-gas emissions from solar electric-and nuclear power: A life-cycle study." *Energy Policy* 35.4 (2007): 2549-2557.

[45] Spath, Pamela L., Margaret K. Mann, and Dawn R. Kerr. "Life cycle assessment of coal-fired power production." No. NREL/TP-570-25119. *National Renewable Energy Lab.*, Golden, CO (US), 1999.

Table 8. Avoided Power Generation Emission Factors

	NO_x	PM	CO	CH_4	VOC	CO_2
Natural Gas Fired Power [lb/MMscf][46]	190	7.6	84	2.3	5.5	120,000
Coal Fired Power [lb/ton$_{coal}$][47]	5-33	0.8A-10A	0.5-18	0.01-0.06	0.04-0.11	4,810-6,250

Note: S is the weight percent sulfur in the fuel and A is the ash content by weight.

The amount of electricity from natural gas and coal sources is proportional to the utility's power content label. The quantity of fossil fuels displaced should utilize the conversion factors shown below:

- Natural Gas: 8,152 Btu/kWh[48]
- Natural Gas: 1,022 Btu/scf[49]
- Coal: 10,444 Btu/kWh[50]
- Coal: 19,341 MMBtu/ton[51]

Biochar

The primary byproduct of gasification technology is biochar. Biochar is the fixed carbon structure of the feedstock that is not broken down during the gasification process. Biochar has a half-life of 1,000 years, making it a carbon sink when utilized for agricultural applications.[52,53,54] Typically, 5% to 15% of the original woody biomass feedstock input is removed as biochar.[55,56] Biochar is used for the enhancement of soil quality, water quality, and agricultural productivity.[57,58,59,60]

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[46] Environmental Protection Agency: AP-42 Chapter 1 Section 4

[47] Environmental Protection Agency: AP-42 Chapter 1 Section 1 and Section 2

[48] U.S. Energy Information Administration: http://www.eia.gov/electricity/annual/html/epa_08_01.html

[49] U.S. Energy Information Administration: http://www.eia.gov/totalenergy/data/monthly/pdf/sec13.pdf

[50] U.S. Energy Information Administration: http://www.eia.gov/electricity/annual/html/epa_08_01.html

[51] U.S. Energy Information Administration: http://www.eia.gov/totalenergy/data/monthly/pdf/sec13.pdf

[52] Fowles, Malcolm. "Black carbon sequestration as an alternative to bioenergy." *Biomass and Bioenergy* 31.6 (2007): 426-432.

[53] Spokas, Kurt A. "Review of the stability of biochar in soils: predictability of O: C molar ratios"" *Carbon Management* 1.2 (2010): 289-303.

[54] Sohi, S. P., et al. "A review of biochar and its use and function in soil." *Advances in Agronomy* 105 (2010): 47-82.

[55] Ciferno, Jared P., and John J. Marano. "Benchmarking biomass gasification technologies for fuels, chemicals and hydrogen production." *US Department of Energy. National Energy Technology Laboratory* (2002).

[56] David A. Laird, Natalia P. Rogovska, Manuel Garcia-Perez, Harold P. Collins, Jason D. Streubel, Matthew Smith, R. 2011. Pyrolysis and Biochar – Opportunities for Distributed Production and Soil Quality Enhancement. In: Ross Braun, Douglas L. Karlen, and Dewayne Johnson (editors) Sustainable Alternative Fuel Feedstock Opportunities, Challenges and Roadmaps for Six U.S. Regions. Proceedings of the Sustainable Feedstocks for Advanced Biofuel Workshop. SWCS (publisher).

[57] Laird, David A. "The charcoal vision: a win–win–win scenario for simultaneously producing bioenergy, permanently sequestering carbon, while improving soil and water quality." *Agronomy Journal* 100.1 (2008): 178-181.

The concentration of carbon in biochar varies by feedstock. For woody biomass, residual carbon concentrations range from 70.8% to 82.7% of the biochar.[61,62] Based on these values, biochar carbon sequestration can range from 0.130 to 0.454 tons of carbon dioxide per BDT of feedstock consumed using .

Mobile Sources

Mobile sources include onsite equipment such as front loader, truck traffic for biochar transport to market (note that truck traffic for biomass feedstock delivery has already been addressed), and employee commute traffic.

Biochar is expected to be transported by a LHD2 truck (a light heavy duty diesel powered truck) under EMFAC2011 classifications.[63] Emission factors for this class of truck are shown in Table 9.

Table 9. Emission Factors for Biochar Pickup[64]

	SO_x [lb/mi]	NO_x [lb/mi]	PM [lb/mi]	CO [lb/mi]	CH_4 [lb/mi]	VOC [lb/mi]	CO_2 [lb/mi]
LHD2: Mountain Air Basin	0.000011	0.0097	0.00033	0.0026	-	0.000514	1.14

Employee traffic estimates should include one round trip commute to work and one roundtrip commute for lunch per employee per day. Table 10 has emission factors for personal vehicles for the Mountain Air Basin[65] fleet blend for 2014.

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[58] Lehmann, Johannes, John Gaunt, and Marco Rondon. "Bio-char sequestration in terrestrial ecosystems–a review." *Mitigation and adaptation strategies for global change* 11.2 (2006): 395-419.

[59] Chan, K. Y., et al. "Agronomic values of greenwaste biochar as a soil amendment." *Soil Research* 45.8 (2008): 629-634.

[60] Rondon, Marco A., et al. "Biological nitrogen fixation by common beans (Phaseolus vulgaris L.) increases with bio-char additions." *Biology and Fertility of Soils* 43.6 (2007): 699-708.

[61] Granatstein, D., C.E. Kruger, H. Collins, S. Galinato, M. Garcia-Perez, and J. Yoder. 2009. "Use of biochar from the pyrolysis of waste organic material as a soil amendment." Final project report. Center for Sustaining Agriculture and Natural Resources, Washington State University, Wenatchee, WA. 168 pp.

[62] Chan, K. Yin, and Zhihong Xu. "Biochar: nutrient properties and their enhancement." *Biochar for environmental management: science and technology. Earthscan, London* (2009): 67-84.

[63] Cabin Creek Biomass Facility Project DEIR, July 2012, State Clearinghouse #2011122032, Placer County Community Development Resources Agency

[64] EMFAC Emissions Database, 2011. http://www.arb.ca.gov/emfac/

[65] California Air Resources Board: Mountain Air Basin includes all of Plumas, Sierra, Nevada, Amador, Calaveras, Tuolumne, Mariposa, El Dorado, and Placer Counties expect that portion included in the Lake Tahoe Air Basin and Sacramento Valley Air Basin.

Table 10. Emission Factors for Personal Vehicles[66]

	SO_x [lb/mi]	NO_x [lb/mi]	PM [lb/mi]	CO [lb/mi]	CH_4 [lb/mi]	VOC [lb/mi]	CO_2 [lb/mi]
LDA, LDT1, LDT2: Mountain Air Basin Fleet Mix	0.0000089	0.00077	0.0000081	0.0077	-	0.00084	0.87

A front loader is expected to be used on any site with feedstock storage to move, pile, and compact feedstock. Emission factors for a rubber-tired front loader is shown in Table 11.

Table 11. Emission Factor for a Rubber-Tired Front Loader[67]

	SO_x [lb/hr]	NO_x [lb/hr]	PM [lb/hr]	CO [lb/hr]	CH_4 [lb/hr]	VOC [lb/hr]	CO_2 [lb/hr]
Rubber Tired Front Loader	-	1.10	0.04	0.35	0.01	0.12	148.84

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[66] EMFAC Emissions Database, 2011. http://www.arb.ca.gov/emfac/

[67] Cabin Creek Biomass Facility Project DEIR, July 2012, State Clearinghouse #2011122032, Placer County Community Development Resources Agency

Example Facility

The information for this section is based on a representative 1 MW gasification project using forest-sourced biomass. The assumptions in Table 12 are representative for any project utilizing the emission factors outlined in this white paper.

Table 12. Example 1 MW Biomass Gasification Facility Specifications

	Project Assumptions
Feedstock Consumption	8,000 BDT/yr
Feedstock Blend	80% Forest Source Material / 20% Other
Pile & Burn Fate	60% of Total Feedstock
Mastication Fate	20% of Total Feedstock
Landfill Fate	0% of Total Feedstock
Feedstock Delivery	30 mile one-way trip, 60 mile roundtrip
Delivery Size	12.5 BDT/trip
Feedstock Storage	3 months
Engine Size	Two 700 BHP Internal Combustion Engines
Engine Operations	7,446 hr/yr (85% capacity factor)
Flare Size	12 MMBtu/hr (assumes 28.4% engine efficiency)
Flare Operations	156 hr/yr (start up, shut down, unexpected maintenance)
Utility Location	PG&E
Biochar Production	8% of Incoming Feedstock
Biochar Haul Distance	500 miles, one-way: 15 tons/haul
Personal Vehicle Trips	24 one-way trips (6 employees per day)
Commute Trips	15 miles one-way, 30 miles per day
Lunch Trips	5 miles one-way, 10 miles per day
Front Loader Operations	8 hr/day

Based on the assumptions in Table 12, emissions potential is shown in Table 13 and Table 14. The emissions projections are shown using the average emission range based on the data displayed throughout the paper. The net projected emissions are shown in Table 15. Additionally, Figure 2 shows the variability between the high and low ranges of the data.

Table 13. Bioenergy Facility Potential Emissions

Emissions Source	NO_x [tons/yr]	PM [tons/yr]	CO [tons/yr]	CH_4 [tons/yr]	VOC [tons/yr]	CO_2 [tons/yr]
Processing for Biomass	2.254	0.291	1.177	0.042	0.190	168.5
Biomass Transportation	0.436	0.022	0.501	0.036	0.045	61.3
Wood Chip Storage	-	-	-	22.182	-	-
Feedstock Drying	0.668	5.240	2.640	-	2.187	698.4
Internal Combustion Engine	1.251	0.573	6.776	9.960	1.251	10,491.2
Flare	0.064	0.007	0.346	0.072	0.059	12.1
Biochar Production	-	-	-	-	-	-1,799.0
Biochar Pickup	0.207	0.007	0.055	-	0.011	24.3
Personal Vehicle Trips	0.006	0.00006	0.056	-	0.006	6.4
Front Loader Utilization	1.606	0.058	0.511	0.015	0.175	217.3
Total	**6.491**	**6.199**	**12.062**	**32.270**	**3.923**	**9,880.5**

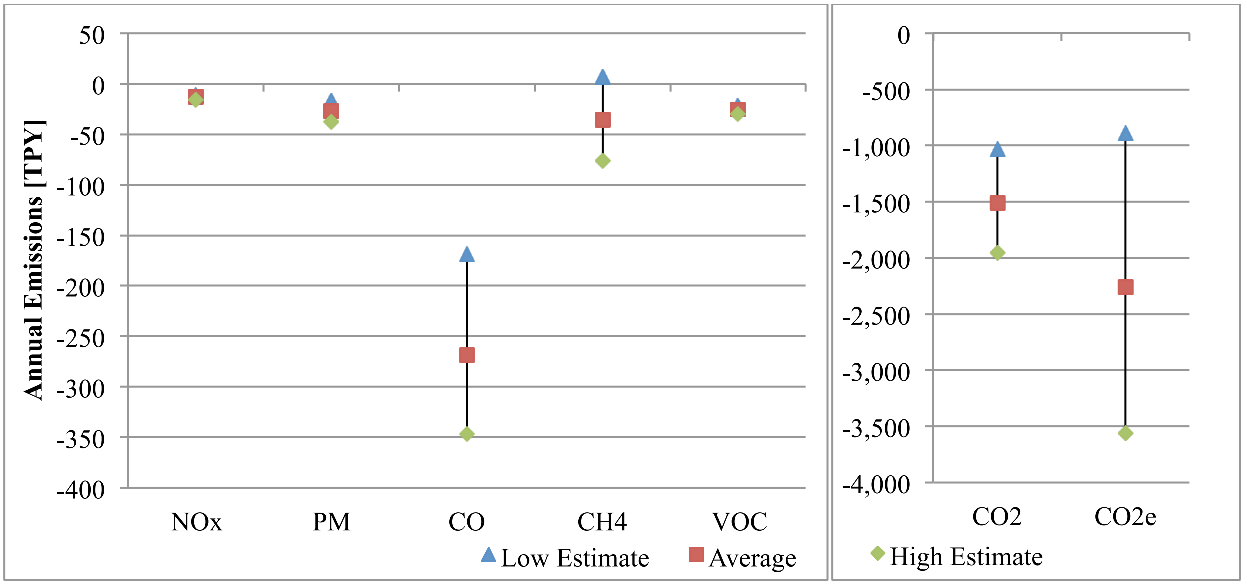
Table 14. Potential for Avoided Emissions

Emissions Source	NO_x [tons/yr]	PM [tons/yr]	CO [tons/yr]	CH_4 [tons/yr]	VOC [tons/yr]	CO_2 [tons/yr]
Alternative Fate						
Pile & Burn	17.765	33.444	280.330	15.840	29.593	7,958.4
Mastication	-	-	-	52.000	-	2,544.0
Utility Emissions	1.411	0.056	0.624	0.017	0.041	890.9
Total	**19.176**	**33.500**	**280.954**	**67.857**	**29.634**	**11,393.3**

Table 15. Net Projected Emissions

	NO_x [tons/yr]	PM [tons/yr]	CO [tons/yr]	CH_4 [tons/yr]	VOC [tons/yr]	CO_2 [tons/yr]	CO_2e [tons/yr]
Average Emission Factors Used	-12.685	-27.301	-268.89	-35.587	-25.710	-1,512.9	-2,260.2

Figure 2. Emission Projection Variability



The net emissions projections in Table 15 suggest that for the majority of criteria pollutants, community-scale forest bioenergy facilities can reduce overall emission rates primarily by avoiding pile and burn emissions and mastication/spreading practices.

For CO_2 emissions, results vary depending on the projected fuel blend and carbon dioxide assumptions for the internal combustion engine. Until more gasification projects are developed and operating, a challenge for predicting emissions will continue to be how to accurately portray the engine emission profile. The CO_2e reduction represents the combined projected emissions for CO_2 and CH_4 and demonstrates the importance of reducing methane emissions, a significant contribution to greenhouse gas emissions.