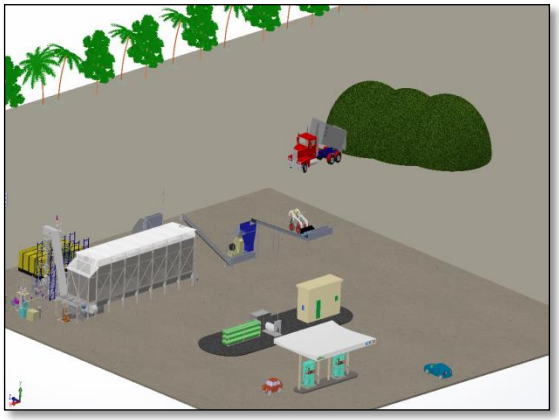
Proposed Low Carbon Fuel Standard (LCFS) Pathway for the Production of Biomethane from the Clean Thermal Biomass Conversion (CTBC) of Organic Green Wastes



New Pathway Proposal

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Interra Energy, Inc.

Pathway Proposal

Proposed Low Carbon Fuel Standard (LCFS) Pathway for the Production of Biomethane from the Clean Thermal Biomass Conversion (CTBC) of Organic Green Wastes

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Executive Summary

I. Overview

Interra is proposing a Low Carbon Fuel Standard (LCFS) Clean Thermal Biomass Conversion Pathway (CTBC Pathway) for the production of biomethane from organic green wastes. By definition, a clean thermal biomass conversion process is one in which the biomass is converted in a continuous feed pressurized reactor. The pressurized reactor is heated to 750º F to 1,150º F and the biomass stays in the system for approximately 25 minutes. The process change of the organic material results in a biomethane gas, biochar, and water. To establish the carbon intensity (CI) of the fuel for the proposed pathway, Interra has modeled an initial composition of 100 percent green wastes (comprised of equal proportions of leaves, grass clippings, weeds, yard trimmings, wood waste, branches and stumps, home garden residues, and other miscellaneous organic materials). Staff assumes for the purposes of this analysis that the CTBC facility would be sited adjacent to a landfill, or local transfer station, minimizing any transportation distance differentials between feedstock delivered to the CTBC facility and wastes delivered to disposal or recovery facilities (landfill or composting).

Interra modeled a majority of the proposed pathway after an internal ARB pathway titled - Production of Biomethane from High Solids Anaerobic Digestion (HSAD) of Organic (Food and Green) Wastes (HSAD Pathway). The front-end processes and diversion is the same as the HSAD pathway, except this pathway focuses solely on diverting organic green waste and not food waste. The back-end processes are similar, in that the HSAD Pathway produces a compost based soil amendment and this pathway produces a biochar based soil amendment. Most of the calculations, tables, and figures used in the HSAD Pathway documentation are included in this pathway documentation, with slight changes based on differences in the pathway processes and technologies. A comparison of the scope of the pathways is included in the following figures and table.

The main difference between the pathways comes from the technology that will process the green waste feedstock. In the HSAD Pathway, an anaerobic digester is used to process the feedstock, resulting in a biomethane gas and digestate. The biomethane is used as a fuel and the digestate remnants are composted. In this proposed pathway, the feedstock is processed through a clean thermal biomass conversion technology. This technology produces a biomethane gas and a biochar co-product. A portion of the biomethane gas can be converted to electricity to power on-site energy needs.

The biogas produced from the CTBC of the organic matter (mostly methane (CH_4) and carbon dioxide (CO_2) in equimolar proportions) would be purified to pipeline quality biomethane, or be made available on-site at the facility to fuel transit buses and other compressed natural gas (CNG) fueled-vehicles. Interra estimates that for pipeline quality fuel, the purified biomethane (product gas) would be compressed and injected into the utility company's natural gas transmission grid at a connector located approximately five miles from the CTBC facility. Additionally, the process co-product (Biochar) would be integrated with fill material. The result would be a high-quality biochar co-product that could be marketed as a soil amendment.

Figure 1: Schematic of High Solids Anaerobic Digestion (HSAD) Pathway - Proposed by ARB Staff June 28, 2012

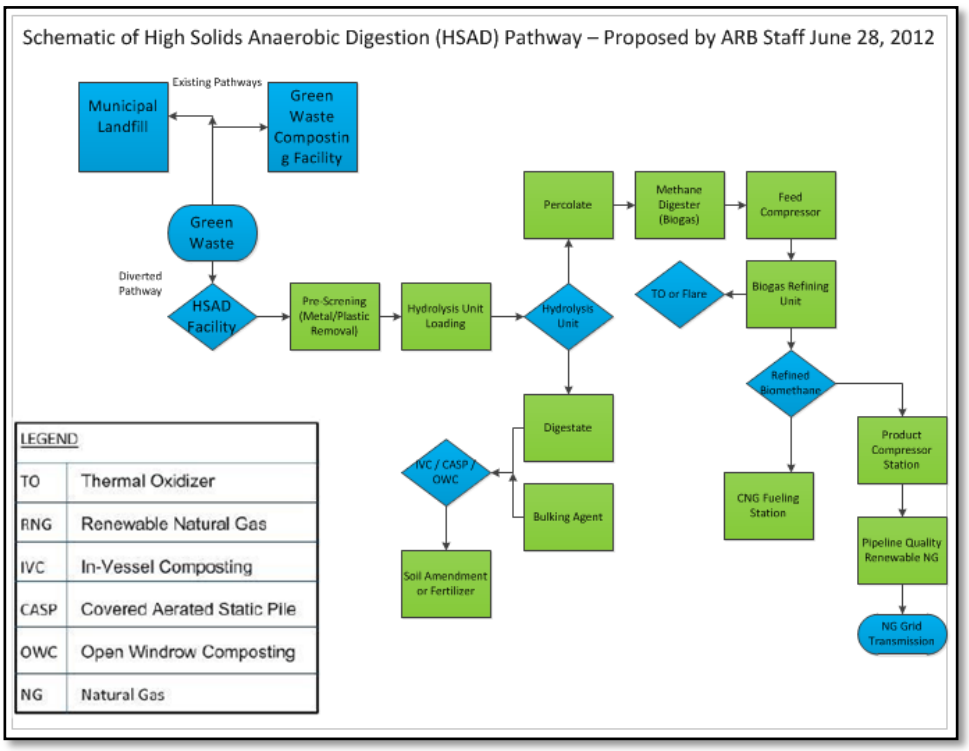


Figure 2: Schematic of Clean Thermal Biomass Conversion Pathway with Changes from HSAD Pathway Highlighted

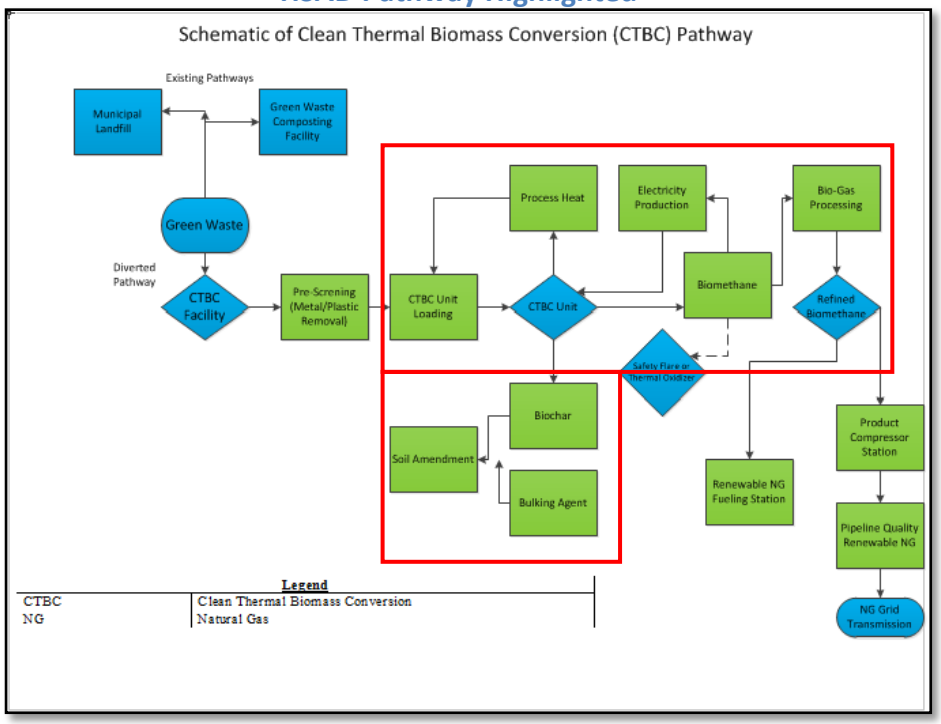


Table 1: Comparison of HSAD and CTBC Pathways

	HSAD Pathway	CTBC Pathway	Units
Feedstock Throughput	100,000	42,188	Tons / year
Fuel Energy Value	238,199,913	105,478,530	MJ / year
Carbon Intensity Value	-15.29	-24.09	g CO_2e / MJ
MJ Per Ton	2382.00	2500.20	MJ/ton
Emission Reduction Per Ton	-36,426.44	-60,242.33	g CO_2e / ton

As can be seen in Table 1, the CTBC process is favorable to the lowest CI pathway in ARB's portfolio in terms of efficiency and environmental attributes. The proposed CTBC Pathway produces 5% more MJ per ton of feedstock processed and has 65% more emission reductions per ton of feedstock than the existing HSAD Pathway. So, while each unit, or project, under the CTBC Pathway does not process as much feedstock as the HSAD Pathway, the CTBC Pathway technology is far more efficient and results in more emission reductions per ton processed. If throughput is a concern, multiple CTBC units can be sited at a single project site, which would result in greater emission reductions per ton because the loading, unloading, and processing equipment emissions can be shared across multiple units. Thus, the proposed pathway offers the lowest CI pathway in ARB's portfolio along with one of the most efficient technology for generating renewable biofuels.

This document presents the results of a life cycle analysis (LCA) performed on the CTBC Pathway described above. Interra collected the process-related information used to perform this LCA from industry, consultants, and academics. Specifically, Interra used the existing ARB Pathway – Production of Biomethane from High Solids Anaerobic Digestion of Organic (Food and Green) Waste (HSAD Pathway).[1] Interra combined process energy consumption (petroleum diesel, electricity, and natural gas) with published empirical biogas yield factors for various organic substances to develop a greenhouse gas (GHG) emissions profile for the proposed CTBC Pathway, and to estimate the CI value of the transportation fuel produced.

Interra used the staff estimates from the HSAD pathway to estimate the upstream energy use for the production of petroleum diesel and electrical energy (fuel cycle emissions) by using the California-Modified Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation model (CA-GREET) (Argonne National Laboratory; and Life Cycle Associates LLC, 2009). However, not all greenhouse gases (GHG) emissions from this pathway could be estimated using CA-GREET. Interra therefore relied upon published research, process efficiencies and yields, and scientific principles to estimate the pathway CI.

A model was developed that considered the totality of all emissions occurring within the system boundaries: process and fugitive emissions (including biogenic emissions), credits for avoided landfilling and composting emissions from the disposal of green wastes, emission credits for the carbon sequestration in biochar, and a co-product credit for the displacement of synthetic fertilizers by the biochar produced.

[1] http://www.arb.ca.gov/fuels/lcfs/2a2b/internal/hsad-rng-062812.pdf

It should be noted that a portion of the biomethane produced could be used to produce electricity to power CTBC process and ancillary equipment. For the purposes of this document, Interra assumes that the electricity required is procured from the grid. This is the most conservative estimate as emissions from electricity from the grid are higher than emission from power produced on-site.

II. Carbon Credit for Avoided Emissions

The carbon credit for avoided emission was introduced by ARB staff in the HSAD Pathway. Previous ARB LCFS pathways such as the landfill gas (LFG) to liquefied natural gas (LNG) pathway (ARB, 2009a) have included a process credit for avoiding the flaring of landfill gas collected by landfill collection and control systems required at the landfills. The collection systems, however, do not collect all of the landfill gas generated by the anaerobically decomposing organic matter in the landfill. Uncollected LFG fugitive emissions that contain methane contribute to atmospheric warming. A CTBC system can also accomplish the decomposition of organic matter to produce CH_4 and CO_2, albeit with greater accountability for materials and energy transfers within the system boundaries. By avoiding most of the fugitive LFG emissions that naturally occur in a landfill, the biogas production pathway based on the CTBC of organic matter in an artificial reactor warrants a credit that exceeds the flaring credit included in the LFG pathway. Therefore, following the staff recommendations in the HSAD pathway, Interra will include a carbon credit model that results in a higher carbon credit for avoided fugitive GHG emissions when organic wastes destined for a landfill or composting facility are diverted to a CTBC facility for biogas production. The value and derivation of this credit is discussed in Section VIII of this report.

III. Landfill Gas Collection Efficiency

An important variable that influences the CI for the proposed HSAD Pathway is the efficiency of landfill gas collection systems. The size of the CTBC Pathway carbon credit is largely determined by the assumed efficiency of such systems. Lower LFG collection efficiencies in landfills mean that a higher percentage of fugitive GHGs are released to the atmosphere, and that more fugitive GHGs are prevented by the diversion of wastes from landfills to CTBC facilities. Although the available collection efficiency estimates are highly variable, the point estimates have tended to range between 75-85 percent (U.S. EPA, 1998; ARB, 2009d; ARCADIS U.S., 2012). Because 75 percent is a commonly used value in studies focusing on landfill gas generation and collection, ARB staff has used that value in previous analysis, and Interra uses that figure here. As additional data on LFG collection efficiencies in place at compliant landfills becomes available, staff will consider amending the value of the carbon credit for avoided emissions used in this analysis.[2]

[2] As pathway CIs are revised, however, previously earned credits are not retroactively adjusted to reflect the revised values. Only credits earned subsequent to CI revisions are affected. A detailed WTW analysis of the GHG emissions from the proposed CTBC Pathway is presented in Table ES-2 below. The material and energy balances, GHG emissions, and proposed CI for the CTBC Pathway are based on one full year of operation.

IV. Modeled Results

The CI for the CTBC Pathway estimated herein is based on energy inputs from CA-GREET, as well as several factors obtained from other sources, such as CalRecycle, ARB, and published research on biomass conversion processes.

Interra's estimate of the well-to-wheel (WTW) CI for the HSAD Pathway is -24.09 g CO_2e / MJ of energy. A summary of the process parameters for the CTBC Pathway that contribute to the carbon intensity value of the fuel are presented in Table ES-1 below for all components of the pathway.

Table ES-1
Summary of the CTBC Pathway Characteristics

Parameter	**Value**	**Units**
Feedstock: Organic Green Wastes	42,188 (100 %)	short tons per year (tons / year)
Net Annual Biomethane Production Rate	111,150,000	standard cubic feet per year (scf / year)
Fuel Energy Value	105,478,530	mega-joules per year (MJ / year)
Net Annual GHG Emissions	-2,541,503,457	grams CO_2 equivalent / year (g CO_2e / year)
Process	Clean Thermal Biomass Conversion	
Primary Product Fuel	Biomethane	-
Co-Product	Biochar	-
Total Fossil Fuel Energy Use		-
- No. 2 Diesel Fuel	17,405	gallons per year (gal / year)
- Grid Electricity Use	3,750,000	kilo-watt hours per year (kWh / year)

Table ES-2
Summary of GHG Emissions and Proposed CI Value

Parameter	Value	Units	Reference
CTBC Process GHG Emissions	23,325,185,245	g CO_2e / year	Table VI-5
CTBC Wastes Loading GHG Emissions	174,562,143	g CO_2e / year	Based on Tables II-2 and II-4
Total Fuel Cycle Electric Use GHG Emissions	1,420,119,549	g CO_2e / year	Based on Table V-2
Total Low Sulfur Diesel Well-to-Tank GHG Emissions	47,897,831	g CO_2e / year	Based on Table II-5
Total CTBC Process and Operations GHG Emissions (A)	24,967,764,768	g CO_2e / year	Sum Above
Tank-to-Wheel (TTW) GHG Emissions from RNG Combustion (B)	13,896,324,909	g CO_2e / year	Table VIII-3
Less Carbon Credit for Avoided Landfilling & Composting Emissions (C)	21,213,362,726.79	g CO_2e / year	Section VIII (A), Table VIII-2
Less Compost Emissions Reduction Factor (CERF) (D)	5,740,777,500	g CO_2e / year	Section VIII (B)
Less Biochar Emission Reduction Factor (E)	14,451,452,908		Table VII-1
Net GHG Emissions (1) (Sum A-E Above)	-2,541,503,457	g CO_2e / year	-
Biomethane Fuel Energy Value (2)	105,478,530	MJ / year	Table III-2[a]
Proposed CTBC Pathway Carbon Intensity Value (1 ÷ 2)	**-24.09**	**g CO_2e / MJ**	

[a] Based on Lower Heat Value (LHV) of 930 Btu / scf for Natural Gas, as found in the Fuel Specs tab of CA-GREET, version 1.80b, December 2009 (Life Cycle Associates LLC. And Systems Assessment Section, 2009).

Narrative

I. Introduction

The use of life cycle analysis (LCA) to estimate the CI of a transportation fuel requires a full well-to-wheels (WTW) accounting of the GHG emissions from the production, processing, distribution, and combustion of that fuel. The system boundary within which this accounting takes place includes the upstream (fuel cycle) emissions from the energy consumed to produce and distribute the process fuels such as petroleum based diesel, and electricity used to power the CTBC Pathway process. A WTW analysis is comprised of two components:

- A Well-to-Tank (WTT) component, which accounts for the energy use and emissions from the delivery of the feedstock to the facility; processing, production, and refining of the fuel, and the distribution of the final product; and
- A Tank-to-Wheels (TTW) analysis, which accounts for the emissions from the actual combustion of the fuel in a motor vehicle used for motive power. For this pathway, combustion of the fuel is assumed to occur in a heavy-duty, natural-gas-fired vehicle.

WTT emissions are sometimes referred to as well-to-pump emissions, while TTW emissions are sometimes referred to as pump-to-wheels emissions. Interra has conducted a WTW analysis for biogas produced from the processing of organic green wastes in a CTBC system. Under this pathway, the biogas produced is purified to biomethane, which could then be compressed and sold onsite or transmitted in the natural gas pipeline.

A. Use of the CA-GREET Model for LCA Analysis

A California-specific version of an LCA model called the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model, originally developed by Argonne National Laboratory and Life Cycle Associates (Argonne National Laboratory and Life Cycle Associates LLC, 2009), was the source of some of the energy use and greenhouse gas (GHG) emissions data used to develop the CI for the CTBC Pathway. The California-specific version of the model, known as CA-GREET contains California-specific emission factors, electrical generation energy mixes, and transportation distances. The analytical methodology inherent in the original GREET model was not changed. Interra used this California-modified GREET model to calculate GHG emissions from the CTBC Pathway whenever the necessary emissions factors were present in the model. Interra relied on published factors, and actual process efficiencies and yields when required factors were not available in the CA-GREET model.

The analysis that follows uses conventions and technical terms with specific meanings that are defined here:

- CA-GREET employs a recursive methodology to calculate energy consumption and emissions. To calculate WTT energy and emissions, the values being calculated are often utilized in the calculation. For example, crude oil is used as a process fuel to recover crude oil. The total crude oil recovery energy consumption includes the direct

crude oil consumption and the energy associated with crude recovery (which is the value being calculated).

- Btu/MMBtu is the energy input necessary in BTU, or Btu to produce one million BTU of a finished (or intermediate) product. This description is used consistently in GREET for all energy calculations.
- gCO_2e/MJ provides the total greenhouse gas emissions on a CO_2 equivalent basis per unit of energy (MJ) in a given fuel. Methane (CH_4) and nitrous oxide (N_2O) are converted to a CO_2 equivalent basis using IPCC global warming potential (GWP) values and included in the total. CA-GREET assumes that VOC and CO are converted to CO_2 in the atmosphere and includes these pollutants in the total CO_2 value using ratios of the appropriate molecular weights.
- Process Efficiency for any step in GREET is defined as the ratio of energy output to the sum of the energy output and energy consumed.
- Note that rounding of values has not been performed in several tables in this document. This is to allow stakeholders executing runs with the GREET model to compare actual output values from the CA-modified model with values in this document.
- As used in this document, the term – upstream refers to the energy use and emissions associated with the inputs supplied to the fuel production process. In the case of most fuels, the two upstream processes considered in the WTT analysis are the production of diesel fuel, and the generation of electricity. In the case of diesel fuel, the energy used to extract, process, and transport the fuel are quantified. In the case of electrical generation, the energy needed to produce and transport the fuels used to generate the electrical energy are considered. In both cases, the expenditure of this energy results in GHG emissions.
- The fuel production process can yield what are known as co- products. The biodiesel production process, for example, yields glycerin as a co-product. If that glycerin is sold, it displaces glycerin from other sources. The GHGs associated with the production of glycerin from those other sources could be greater than the GHGs associated with the biodiesel co-product. As an example, glycerin from the production of biodiesel sometimes displaces glycerin produced from petrochemicals. This indicates that biodiesel should be credited for the GHG reduction associated with this displacement.
- Production and feedstock production emissions are also adjusted to reflect material losses incurred during the production process. These are accounted for through the use of a capture efficiency

The WTT and TTW emissions estimates presented in the following sections include analyses of the process conditions, and the applicability of credits for avoided landfilling and composting emissions, and for co- products produced.

B. Clean Thermal Biomass Conversion Pathway

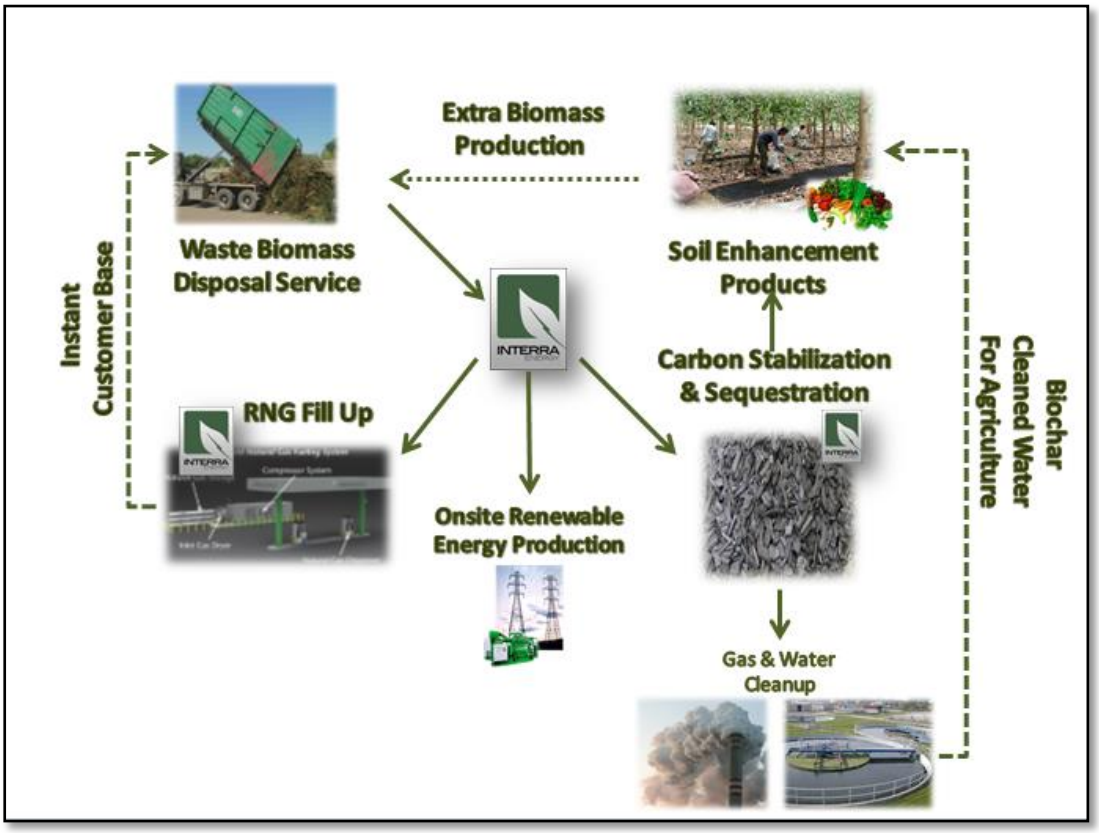
Interra modeled a majority of the proposed pathway after an internal ARB pathway titled - Production of Biomethane from High Solids Anaerobic Digestion (HSAD) of Organic (Food and Green) Wastes.[3] This pathway borrows calculations from the up-stream and down-stream

[3] Please see Executive Summary Section I and Figures 1 &2 to see the differences in the pathway processes.

emission calculations, as those portions of the process are similar. The main difference from the HSAD Pathway to this CTBC Pathway is the technology used to process the feedstock to generate biomethane gas.

The CTBC pathway developed in this document converts organic green wastes into biomethane. Green waste consists of leaves, grass clippings, weeds, yard trimmings, wood waste, branches and stumps, home garden residues, and other miscellaneous organic materials from curbside pickup programs that typically find their way to composting facilities, as well as to landfills. By diverting organic green wastes destined for a landfill or a composting facility to a CTBC facility, a useful transportation fuel can be produced, a valuable co-product (biochar) can be derived, and GHG emissions can be avoided. Figure 3 illustrates how these waste streams are transformed into useful energy and soil enrichment products.

Figure 3: Proactive Utilization of Waste Streams to Derive Useful Products



Organic waste diversion programs implemented by State agencies and local communities could ensure a steady supply of organic waste to biogas producers. Community-based residential waste collection and diversion programs can further ensure a steady supply of feedstock for CTBC. The feedstock for the CTBC Pathway developed herein are characterized in Section II.

Diverted organic green wastes enter the CTBC Pathway system boundary when they are trucked to the CTBC facility. Interra based its pathway analysis on a modeled throughput of 42,187.50 short tons per year of wastes consisting of 100 percent green wastes.

Very little energy is expended to pre-process and screen the wastes for metal and large objects in a CTBC operation. Nor is extensive screening, grinding, or slurrying required for CTBC.

The biogas collected after the green waste has been processed by the CTBC reactor has a composition of approximately 35 percent CH_4 and 65 percent CO_2 and is refined to nearly pure biomethane via an integrate water scrubbing system and additional catalysts. Biogas yield estimates are discussed in Section III.

The CTBC process is discussed in more detail in Section IV. Several processes can be employed to strip the biogas of its CO_2 and other impurities (among them, hydrogen sulfide or H_2S), including using the biochar co-product as an activated carbon filter. The result is a high-purity biomethane stream (90-99 percent CH_4). Biogas purification technology process emissions are discussed in Section VI. The refined biomethane can be sold as compressed natural gas (CNG) or further pressurized in a product compressor for pipeline transmission. For this analysis, Interra has assumed a biomethane discharge pressure of no greater than 800 psig, and a tie-in to the utility company's natural gas transmission system at a distance of approximately 5 miles from the production facility. Biomethane compression and transmission emissions are also discussed in Section VI.

A solid residue (biochar) is also produced by the reactor. A bulking agent (typically fresh soil or composted green waste) is added to the biochar to produce a stable soil amendment mixture. The finished product is sold as a high-quality soil amendment. Biochar (co-product) operations are discussed in Section VII.

Interra has used previous staff estimated regarding the co-product credit for soil amendment produced from the biochar co-product. This co-product credit is further discussed in Section VIII. Lastly, a summary of all emissions, including the overall pathway WTW CI is presented in Section VIII. Interra has also broken the WTW estimate into WTT and TTW components. TTW emissions are calculated assuming that the fuel produced is used to power heavy-duty natural-gas-fueled vehicles. The CI value is reported in units of grams of CO_2-equivalent per megajoule (MJ) of fuel energy, which expresses the total greenhouse gas emissions on a CO_2 equivalent basis. The pathway CI value also includes all applicable carbon credits from avoided landfilling and composting emissions, and a credit for the displacement of commercially manufactured fertilizer by the biochar soil amendment produced from the process.

A schematic of the CTBC process is presented in Figure 4 below.

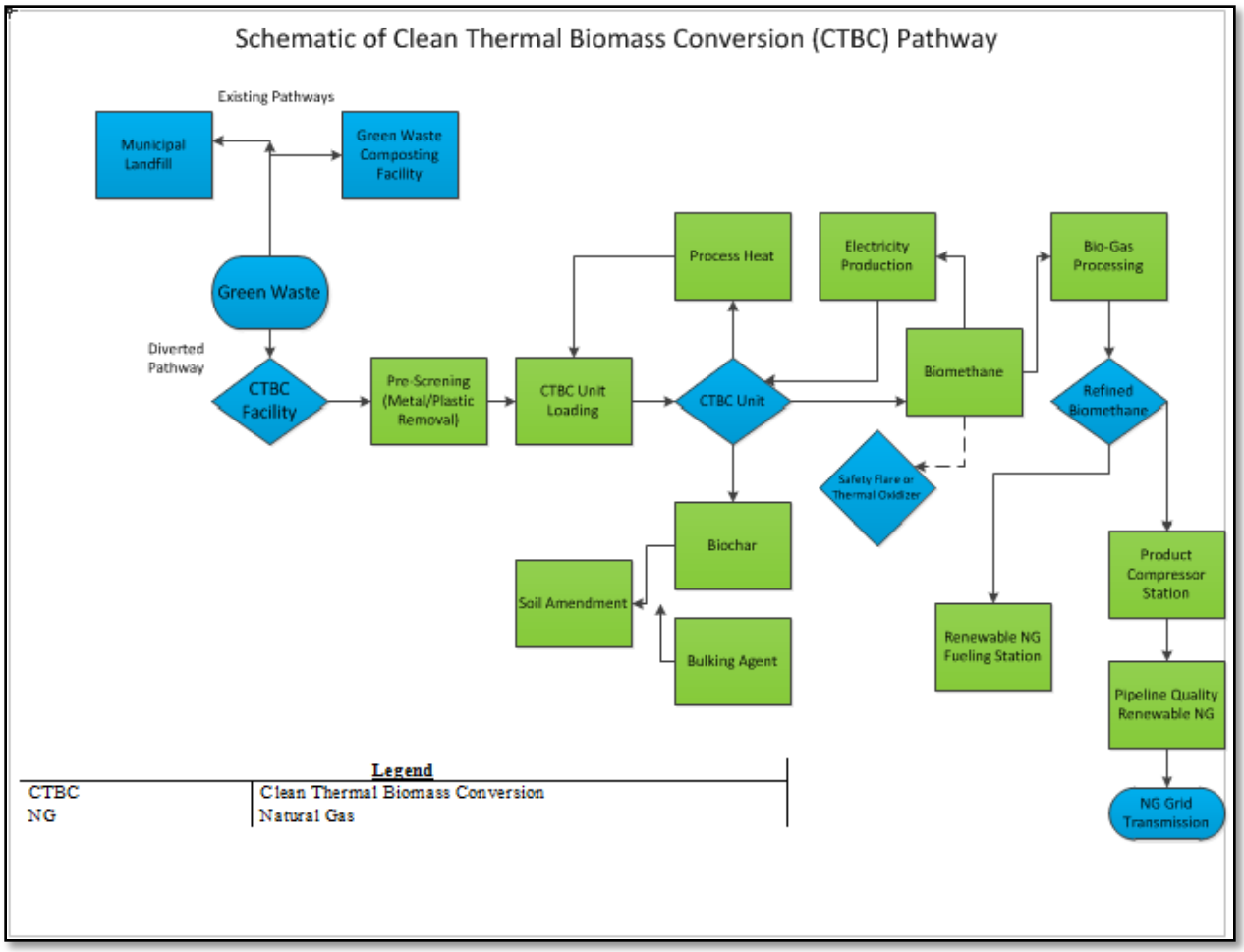


Figure 4: Schematic of Clean Thermal Biomass Conversion Pathway

II. Feedstock Characterization and Energy Use

A. Feedstock Characterization

Interra developed the life cycle CI for the CTBC Pathway by estimating the energy consumption and GHG emissions associated with the production of biomethane from an organic waste mixture comprised of 100 percent organic green waste.

The green wastes could be procured from curbside yard waste collection programs implemented in local communities across the State. Additionally, green wastes from landscaping services could contribute to this resource. Interra assumes that the composition of the green wastes would be approximately equal proportions of leaves, grass clippings, weeds, yard trimmings, wood waste, branches and stumps, home garden residues, and other miscellaneous organic materials. Interra recognizes that seasonality might be an important factor influencing the availability of green-waste resources. While the feedstock characterization model makes no adjustment for seasonal variation, staff assumes that during periods of low green wastes availability, the feedstock for the CTBC process would be augmented with wastes that have equivalent or greater yields of biogas, primarily other forms of wood waste including the following: mixed paper

wastes, non-treated construction wood waste, and agricultural residues. In 2008, disposed paper material amounted to an estimated four million tons in the State, or 17 percent of the overall waste-stream and could be sourced if green-waste feedstock levels fall short.

Previously, ARB staff determined that the majority of the green-waste are destined for a green-waste composting facility. The following figures come from the analysis conducted by staff for the HSAD Pathway. Statistics suggests that the amount of green waste going to composting operations could be as high as two-thirds of the total amount of green waste generated (Climate Action Reserve, 2010). The other one-third of the green wastes is believed to be destined for the landfill. The fate of the green wastes is also an important determinant of the carbon credit model for avoided composting emissions.

California's geography and climate limit the development of a statewide seasonal green waste feedstock assessment. Operators generally do not separate collected green waste by specific material type. Sacramento, as an example, has the following seasonal variability for green waste material collected (CalRecycle, 2010):

Table II-1
Seasonality of Collected Green Material (City of Sacramento)[4]

Monthly Green Wastes Collected (tons)			
Month / Year	**2006**	**2007**	**2008**
January	7,836	4,785	9,976
February	4,452	4,205	4,583
March	4,547	6,233	6,444
April	6,225	6,803	6,495
May	7,528	6,602	6,658
June	6,501	5,224	6,340
July	4,686	4,858	5,504
August	5,071	5,236	3,979
September	5,986	4,517	4,652
October	7,304	6,438	5,741
November	10,175	8,693	7,317
December	9,942	7,598	10,570
Average Monthly	**6,688**	**5,933**	**6,522**

B. Feedstock Energy Use

Interra will next present the fossil fuel energy consumption for loading the organic wastes into the CTBC process. Interra has assumed that the CTBC facility would be sited at a location adjacent to the local landfill, or a local transfer station, so that transportation distance differences

[4] http://www.calfog.org/GreaseFacilities.html

between delivery of wastes destined for disposal or recovery, and the proposed CTBC facility would be minimized.

In a typical CTBC facility, organic wastes are dumped into an open receiving hall. After the wastes are pre-screened[5], the wastes piles are worked and transferred to a day bin for drying. Recycled heat from the CTBC reaction is used to heat the incoming waste feedstock.

Waste loading is achieved by working payloads of organic wastes feedstock dumped to the receiving hall with a front-end loader. Based on a throughput of 42,000 tons per year of green wastes staff anticipates the need for one 195 kW (260 hp) rated Front- End Loader to be operated for approximately 6 hours a day, 1,200 total hours a year.

The calculations below are conservative estimates. The CTBC process can be set up such that feedstock loading can be fueled/powered by the biomethane produced by the process. In that case, no fossil energy emissions would be associated with this part of the pathway.

The total fossil fuel based energy (low-sulfur diesel) requirement for the CTBC Pathway is based on a projected fuel use for 42,000 tons of feedstock. The total fossil fuel-based energy use for CTBC unit loading is presented in Table II-2 below.

Table II-2
Estimate of Fossil Energy Use for Unit Loading

Parameter	Type / Value	Unit
Equipment:	Front End Loader	
Rated Output:	195 (261)	kW (hp)
Hours of Operation:	1,200	hours per year
Annual Loads:	208	loads per year
Average Daily Operation:	6	hours per day
Average Hourly Output:	35%	
ICE Engine Efficiency:	42%	
Energy Type:	No. 2 Diesel, CNG from CTBC Process	
Fuel LHV: (No. 2 Diesel)	127,464	Btu per gallon

[5] Interra expects that a minimal amount of wastes pre-screening will occur in a CTBC operation. For this pathway, Interra has based their analysis on 5 percent of the wastes delivered being removed due to pre-screening of metal objects (for examples, forks and knives, etc.).

Energy Use (30,000 tons/year)	5,221	gallons / year
Projected CTBC Pathway Throughput:	42,000	short tons / year
Total Fuel Use for Unit Loading and Biochar Moving:	**17,404**	**gallons / year**

The annual energy consumption for the Front End Loader is based on the following analysis:

$$\boldsymbol{Wastes\ Loading\ Energy\ Consumption}$$

$$= 195\ kW\ x\ 35\ percent\ (Average\ Hourly\ Output)\ x\ 1{,}200 \frac{hours}{year}$$

$$= 81{,}900\ \frac{kWh}{year}$$

Assuming an internal combustion engine (ICE) efficiency of 42 percent, and a throughput of 95 percent of the design load, the total fossil fuel energy consumed is estimated to be as follows:

$$\boldsymbol{Wastes\ Loading\ Fossil\ Fuel\ Consumption}$$

$$= 81{,}900\ \frac{kWh}{year}\ x\ 3{,}412.96\ \frac{Btu}{kWh}\ x\ \frac{1\ gal\ diesel}{127{,}464\ Btu}\ x\ \frac{1}{0.42\ (ICE\ eff.)}$$

$$= \frac{5{,}221\ gal}{year}\ for\ \left(30{,}000\ \frac{ton}{year} payload\ \ x\ 95\%\right)$$

$$= 5{,}221\ gal\ \ x\ \ \frac{100{,}000\ tons}{30{,}000\ tons}\ x\ 95\%\ (scale - up\ ratio)$$

$$= \mathbf{17{,}404}\ \frac{\boldsymbol{gallons\ low - sulfur\ diesel}}{\boldsymbol{year}}$$

The biochar co-product is moved to outdoor piles and is blended with a bulking agent to form a soil amendment end-product. Earth-moving equipment such as front-end loaders are used to work the piles. These emissions are included in the 17,404 gallon requirement.

The total fossil fuel use for the CTBC Pathway consists of the sum of the fuel used to load the CTBC unit. This total is the total fuel usage identified in Table II-2 above. This total is presented in Table II-3.

Table II-3
Estimate of Total Fossil Fuel Based Energy Use

Earth Moving Equipment Usage	Annual Quantity (gallons per year)
Total Fuel Use for CTBC Loading:	17,404
Total Fossil Fuel Use	**17,404**

Process emissions from the combustion of fossil fuel occur when low-sulfur diesel fuel is consumed by the earth-moving equipment used in waste loading and biochar operations. Interra assumes that both CTBC unit loading as well as biochar operations would utilize Front-End Loaders, water trucks, and dump trucks. To assess process emissions from fossil energy use, Interra approximated the emissions from the earth-moving equipment by using the diesel farm tractor emissions factor from CA-GREET (version1.80b, December 2009).

The total GHG emissions estimate from combustion of fossil fuels during materials handling (waste loading) is shown in Table II-4 below.

Table II-4
Material Handling GHG Emissions

Pollutant	Emissions Factor[a] (g / MMBtu)	Annual Emissions (g / year)	Annual GHG Emissions (g CO_2e / year)
VOC	107.69	238,895	745,353
CO	402.58	893,068	1,402,117
CH_4	9.72	21,555	538,878
N_2O	0.92	2,041	608,190
CO_2	77,204.08	171,267,605	171,267,605
		Total Annual Emissions (g CO_2e / year)	**174,562,143**

[a] CA-GREET Version 1.80b, December 2009. See Worksheet -EF,‖ Emission Factors of Fuel Combustion for Stationary Applications (grams per MMBtu of fuel burned) (Farming Tractor).

Fuel cycle or upstream emissions are emissions associated with the production of the net quantity of low-sulfur diesel fuel consumed during feedstock loading and to work the compost piles using earth-moving and turning equipment. A complete lifecycle analysis requires that the emissions associated with fuel production be accounted for. These emissions are known as upstream or fuel cycle emissions. The fuel cycle emissions associated with the fuel use described in this section are shown in Table II-5. The total emissions are calculated from emissions factors obtained from CA-GREET (version 1.80b, December 2009)

Table II-5
Fuel Cycle (Well-to-Tank) GHG Emissions for Diesel Production

Pollutant	Fuel Cycle Emissions Factor (g / MMBtu)[a]	Total Annual Emissions Based on Energy Use (g / year)	Annual Emissions (g CO_2e / year)
VOC	9.80	21,734	67,811
CO	26.88	59,628	93,616
CH_4	101.29	224,690	5,617,247
N_2O	0.23	503	149,936
CO_2	18,918.90	41,969,220	41,969,220
		Total Annual Emissions	**47,897,831**

[a] CA-GREET Version 1.80b, December 2009. See Worksheet -Petroleum, Summary of Energy Consumption and Emissions: Btu or Grams per mmBtu of Fuel Throughput at Each Stage, and Energy Use and Total Emissions.

The GHG emissions from electrical generation (fuel cycle emissions) are discussed in Section V.

III. Biogas Yield Estimates

Interra estimated the biomethane yield for the green wastes from biogas yield factors (m^3 / dry metric ton) developed for the respective wastes and from internal modeling done on Aspen+. Interra then converted the biogas yield estimates to biomethane yield by assuming the quality of the biogas to be 35 percent methane. Another factor critical to the conversion is the organic fraction moisture content. This factor is used to convert the yield estimates from a dry basis to a wet basis. The following moisture contents were assumed to be applicable to the specific wastes types:

- wood waste (30 percent)
- leaves and brush (30 percent);
- grass (60 percent); and
- mixed paper, which represents office, coated, newspaper, and corrugated containers (5-6 percent).

Green waste is expected to comprise 100 percent of the waste feedstock stream. Interra assumes that the green waste would be sourced from residential and commercial yard waste with equal proportions of leaves, grass clippings, weeds, yard trimmings, wood waste, branches and stumps, home garden residues, and other miscellaneous organic materials. The biogas yield estimate for green wastes is expected to be 221.05 cubic meters per metric ton, wet basis.

Based on an annual throughput of 42,187.50 tons per year, the average daily biogas yield is expected to be 1,097,746 million standard cubic feet (mm scf) of biogas per day, or an average yield of 772 standard cubic feet per minute (scfm). This represents a biomethane potential of approximately 247 scfm. Biogas and biomethane production levels from CTBC of the feedstock are presented in Table III-1 below.

Table III-1
Biogas and Biomethane Production Estimates

Organic Component	Biogas Yield (Nm^3 / metric ton)	Biogas Yield (scf / metric ton)	Staff Modeled Organic Fraction	Average Daily Component Throughput (short tons / day)	Biogas Generation Potential (scf / day)
Wood Waste	232.68	8,213.59	80%	108	887,067.81
Green & Yard Wastes	221.05	7,802.91	20%	27	210,678.61
Mixed Paper	289	10,217	0%	-	-
				Biogas Potential	1,097,746 (scf / day)
				Average Daily Throughput	135 (tons / day)
				Annual Throughput	42,187.50 (tons / year)
				Annual Throughput	38,271.86 (m.t. / year)
				Biogas Potential	772 (scf /min)
				Annual Biogas Potential	346,510,864 (scf / year)
				Biomethane Potential	247 (scf /min)
				Ann. Biomethane Potential	**111,150,000 (scf / year)**

m.t. = metric tons; scf = standard cubic feet; min = minute; N = Normal

Table III-2
Net Annual Biomethane Potential

Source	Biomethane Potential	Unit
Biogas Potential	772	(scf / min)
Biomethane Potential	247	(scf / min)
Feed Compressor Losses	N/A	*Unit operates at pressure

Adsorber Capture Losses	N/A	*3% loss included in potential number
Product Compressor Losses	(9.40)	(scf / min)
Annual Biomethane Potential with Losses	238.60	(scf / min)
Annual Biomethane Potential with Losses	107,505,000	(scf / year)
Net Annual Biomethane Production Potential	**107,505,000**	**(scf / year)**
Net Annual Biomethane Energy Potential	**105,478,530**	**(MJ / year)**

IV. Clean Thermal Biomass Conversion (CTBC) Process

For the purposes of establishing the CI for the CTBC Pathway, Interra has simulated biogas production in a clean thermal biomass conversion process. The biogas produced by the process is then refined, compressed, and could be either dispensed at the facility natural gas vehicle fueling station, or could exit the process and enter the natural gas transmission system as pipeline quality biomethane.

A. Brief Explanation of CTBC Reactor Process

The CTBC Pathway results in feedstock being processed through a pressurized reactor developed by Interra Energy. The reactor is approximately 65 feet long but only 16 inches in diameter (not including the support structure). Modeling predicts that an 8-inch diameter inner-reactor tube, acting as the heat-exchange surface that recycles waste heat, has sufficient surface area to recycle enough heat to continuously process approximately 7,200 lbs. (dry basis) of biomass per hour without additional heat input. The biochar and gas products exiting the heat-exchange reactor zone give up enough heat to drop from a peak temperature in the range of 750º F to 1,150º F down to roughly 360º to 750ºF before exiting the system. It takes roughly 3.5 minutes for the feedstock to travel through the inner-reactor tube, then an additional 20 minutes to traverse the outer reactor zone.

The innovative design of Interra's technology addresses two fundamental technical problems faced by existing biofuel projects. First, the reactor aims to address the current inefficient management of heat within existing technologies by maximizing the amount of heat recycled within the biofuel system. The second technical problem relates to difficulties in adapting current reactor geometries and configurations to be able to cost effectively take advantage of the several benefits pressurization provides, including additional thermal efficiency and the beneficial shifting of product yield ratios. These technical problems harm the efficiencies and economics of currently commercial biofuel generation technologies.

Part of the innovative design of the technology includes an integrated gas upgrading system. The reactors water scrubbing system is more closely related to a chemical process than a thermal process. First, the gas to be cleaned is pressurized up to 1 MPa and pumped to the bottom of a pressurized column. Once in the column, the gas encounters a shower of water raining down from above and pooling up on the bottom of the column covering up the drain. Because the

drain on the bottom is covered with water, the only direction the gas can go is up against the direction of the water shower. The water must be slowly drained out of the bottom of the column and out of the pressurized zone of the system without allowing the drain opening to uncover. The gas reaching the top of the column has been stripped of nearly all of its CO_2, yet nearly all of the methane remains, exiting the system.

The biogas exits the reactor and is routed to an additional biogas purification system (if necessary), where the separation of the methane and any remaining carbon dioxide occurs, along with removal of some other trace impurities, such as hydrogen sulfide, to produce pipeline quality biomethane fuel.

The biomethane can exit the biogas purification system at a pressure of approximately 100 psig, which is suitable for a small natural gas fuel dispensing station sited at the CTBC facility. For the purposes of this pathway, staff assumes that the biomethane would be compressed to 600-800 psig, and then tie into the natural gas transmission system at a distance of approximately 5 miles.

The total annual electrical power requirements for feedstock pre-treatment, unit loading, gas pre-treatment, exhaust fan and blower, instrument air, and power, plant, and lighting (PPL) is estimated to be approximately 1.5 million kilowatt hours per year (kWh / year). This will be discussed in Section V. Interra assumes that the electricity for the CTBC process will be provided by power derived from the biogas generated by the organic wastes.

V. Facility Electrical Energy Load

For a CTBC operation that processes 42,187.50 tons per year of green wastes, Interra anticipates a process electrical energy load of approximately 200 kW, or 1.5 million kilowatt hours per year for waste pre-screening and processing.

The total electrical energy requirements for biogas purification is based on the use of a vacuum pump, a product gas compressor, and miscellaneous instrumentation and controls. The load demand from biogas purification, compression, and transmission is estimated to be approximately 300 kW, or 2,250,000 million kilowatt hours per year. The estimated electrical demand identified above is based on proprietary equipment counts for the respective process units.

These numbers are used here as conservative estimates. The CTBC process can generate electricity on-site to power all of these needs, and still produce biomethane gas for transportation fuel. If that were the actual operational conditions, then there would be far less emissions from the on-site power generation than from the California Marginal Energy Mix.

Table V-1
Total Electrical Energy Demand for the CTBC Pathway

Purpose	Operation	Demand (kWh / year)
Wastes Screening and Processing	CTBC Process	1,500,000

Biogas Purification, Compression, & Transmission	Biogas Refining	2,250,000
	Total Annual Demand (kWh)	**3,750,000**

Staff used the CA-GREET model to estimate the fuel-cycle energy use and emissions from electrical generation. These estimates are based on the California Marginal electrical mix. The results are summarized in Table V-2 below.

Table V-2
Fuel Cycle Emissions from Electrical Generation
(California Marginal Energy Mix)[6]

Pollutant	Feedstock (g / mmBtu)	Fuel (g / mmBtu)	Total (g / mmBtu)	Emissions (g / year)	GHG Emissions (g CO_2e / year)
VOC	16.70	5.67	22.37	286,353	893,423
CO	15.55	39.68	55.23	706,834	1,109,739
CH4	270.51	7.04	277.55	3,552,301	88,807,534
N2O	0.14	2.48	2.62	33,524	9,990,228
CO2	6,833.08	96,249.68	103,082.76	1,319,318,633	1,319,318,633
				Total Annual Emissions	**1,420,119,549**

VI. Biogas Purification, Compression and Transmission

The specific GHG emissions that are estimated in this Section are related to compression and transmission of the feed biogas and the refined biomethane. Once the biogas has been purified by stripping its carbon dioxide and trace impurities, such as hydrogen, the near-pure biomethane product gas is primarily high-quality methane in composition (90-99 percent). The biomethane exits the system at a pressure of approximately 100 psig, which is suitable for storage and low-volume dispensing from an on-site natural gas vehicle fueling station at the CTBC facility. However, Interra assumes that since the biomethane meets or exceeds the standards for pipeline

[6] CA-GREET Version 1.80b, December 2009. *See* Worksheet -Electric,‖ Fuel-Cycle Energy Use and Emissions of Electric Generation: Btu or Grams per mmBtu of Electricity Available at User Sites (wall outlets) (Based on California Marginal Use). The Feedstock factor represents the emissions from the energy expended to procure the fuel for electrical generation, and the Fuel factor represents the emissions from the fuel expended to produce the electrical energy.

quality natural gas,[7] a compressor will be required to further compress the biomethane to utility company pipeline pressure specifications.

Product compressors, as well as compressors used in transmission and distribution, are a significant source of fugitive as well as point-source GHG emissions. Interra has estimated that high efficiency electric compressors could serve the purpose of achieving feed gas (to biogas purification unit) pressures of 100 psig, as well as product gas pipeline pressures of 600-800 psig required to tie into the natural gas transmissions system.[8] Interra has further assumed that a connector of approximately five linear miles will be required to tie into the transmission system.

Compressor specifications for estimating GHG emissions are presented below in Table VI-1. GHG emissions sources during compression and transmission include compressor seals, fugitive emissions from compressor blow down of open ended line valves, emissions from pressure relief valves, and other miscellaneous emissions sources. An estimate (ARB, 2009b) of these emissions is presented in Table VI-1 below. Interra uses previously published ARB staff determinations of the impact of product compressor methane losses to be an equivalent loss of 9.4 scfm.

Table VI-1
Feed and Product Gas Compressor Operating Specifications

Parameter	**Product Gas Compressor**	**Unit**
Type	Reciprocating	
Fuel Type	Electric	
Number of Compressor Seals/Cylinders	4	
Number of Pressurized Operating Hours	7,000	per year
Number of Pressurized Idle Hours	1,000	per year
Number of De-pressurized Idle Hours	760	per year
Gas Quality 1	0.99	Methane (CH_4)
Gas Quality 2	0.01	Carbon Dioxide (CO_2)

[7] In summary, as required by the San Diego Air Pollution Control District (SDAPCD) Rule 30 (Biomethane Gas Delivery Specifications Limits and Action Levels), specifications for pipeline quality bio-methane include a fuel higher heat value (HHV) of 990-1,150 Btu/cubic foot, a Wobbe Number (WN) of 1,279-1,385, be commercially free of Siloxanes, and have a Hydrogen Sulfide concentration of no greater than 0.25 grain / 100 scf (~ 8 ppm).
[8] Pursuant to ARB Staff conversation with Jack Dunlap, PG&E, on December 29, 2011 (as cited in the HSAD Pathway).

Table VI-2
Estimate of Feed and Product Compressor GHG Emissions

Emissions Source	Emissions (metric tons CO_2e/year)
Product Compressor to Natural Gas Pipeline	
- Compressor Seals	1,023.54
- Compressor Blow Down	1,153.07
- Pressure Relief Valves	218.01
- Miscellaneous Emissions	105.46
TOTAL EMISSIONS FROM PRODUCT COMPRESSOR	2,500.07
Total Compressor Emissions	**2,500.07**

In addition to the sources of point and fugitive GHG emissions identified above, Interra used ARB staff estimates of the GHG emissions potential from biomethane compression and transmission in the pipeline. ARB staff estimated transmission GHG emissions using the CA-GREET model.[9] Furthermore, ARB staff assumed a tie-into the utility company's natural gas transmission system at a distance of five miles. ARB staff assumed the use of electric compressors. These emissions are presented in Table VI-3 below

Table VI-3
Estimate of GHG Emissions from Transmission of RNG

Pollutant	Emissions Factor[a] (g / mmBtu RNG Transported)	Total Emissions (g/ year)	Total GHG Emissions (g CO_2e/ year)
VOC	0.21	46,463	144,966
CO	2.02	46,463	72,948
CH_4	2.86	643,584	16,089,591
N_2O	0.02	4,731	1,409,945
CO_2	2,299.85	518,029,048	518,029,048
		Total Emissions	**536,387,008**

[a] CA-GREET Version 1.80b, December 2009. See Worksheets "T&D" and "T&D Flow Chart" Modules, Calculations of Energy Use and Emissions: Transportation and Distribution of Energy Feedstocks and Fuels (Energy Consumption and Emissions of Feedstock and Fuel Transportation).

Interra estimated the total process GHG emissions for the CTBC Pathway by using 42,187.50 tons per year of green wastes as a basis. Interra adjusted the biogas yield from the processing of the wastes to account for the biogas refining efficiency, and product gas compressor losses discussed above in this Section. A step-by-step walk through of the GHG emissions from the CTBC process is presented in Table VI-4 below:

[9] CA-GREET Version 1.80b, December 2009.

Table VI-4
CTBC Process GHG Emissions

Parameter	Value	Units
Estimated Green Wastes Annual Throughput Less Contaminants	42,187.50	short tons/year
Estimate of Biogas Yield from Process	772	scfm
Estimate of Biomethane Yield (35 percent) in Feed Gas to Biogas Purification Unit	270.20	scfm
Therefore, CO_2 Yield (65 percent):	501.80	scfm
Biogas Refining Adsorber Capture Efficiency (PSA)	92	percent
Tail Gas Methane to Flare	0.00	scfm
Biomethane Yield and Flow rate to Compression / Liquefaction Plant:	262.09	scfm
Net Product Gas Less Methane Emissions from Product Compressor	252.69	scfm
Fugitive Biomethane Emissions Not Going to Flare (Volumetric Flow Rate)	8.1	scfm
Fugitive Biomethane Emissions Not Going to Flare (Mass Flow Rate)	8,796.46	g CH_4 / hour
Flare Destruction Efficiency:	99.77	percent
Equivalent CO_2e Emissions (GWP CH_4 = 25)	219,911.61	g CO_2e / hour
Annualized Equivalent CO_2e Emissions from Uncombusted Flare Methane	1,649,337,056	g CO_2e / year (A)
Total Biomethane and CO_2 to Flare or water wash	501.80	scfm
"Pass Through" CO_2 Emissions from Flare (Volume Basis):	497.04	scfm
Uncombusted Flare Methane Emissions (Volume Basis):	0.00	scfm
Uncombusted Flare Methane Emissions (Mass Basis):	0.00	g CH_4 / hour
Equivalent CO_2e Emissions (GWP CH4 = 25)	0.00	g CO_2e / hour
Annualized Equivalent CO_2e Emissions from Uncombusted Flare Methane:	0.00	g CO_2e / year (B)
Combusted CO_2 Emissions from Flare (CH_4 + $2O_2$ ---> CO_2 + $2H_2O$)	0.00	g CO_2 / year (C)
"Pass Through" CO_2 Emissions from Flare (Mass Basis):	14,508,417,557.48	g CO_2 / year (D)
Secondary N_2O Emissions from Flare	13,862,539	g N_2O / year
Equivalent CO_2e Emissions of N_2O Emissions Above	4,131,036,624	g CO_2e / year (E)
CTBC Process GHG (CO_2e) Emissions (A + B + C + D + E)	**20,288,791,327**	**g CO_2e / year**

The total GHG emissions from the CTBC production and transport process consist of the following:

- Product gas compressor emissions estimated in Table VI-2 above;
- GHG emissions from transmission of biomethane in the natural gas pipeline system that conveys the biomethane from the CTBC plant to the utility company's natural gas distribution system estimated in Table VI-3 above; and
- The CTBC process GHG emissions estimated in Table VI-4 above.

These emissions are summarized in Table VI-5 below.

Table VI-5
Total Process, Compression, and Transmission GHG Emissions

Process Segment	**GHG Emissions (g CO_2e / year)**
CTBC Process CO_2e Emissions	20,288,791,327
Total Product Gas Compressor Emissions	2,500,007,000
Transmission to Pipeline Emissions	536,387,008
Total Annual CTBC Process GHG Emissions (g CO_2e)	**23,325,185,245.48**

VII. Co-Product Biochar Operations

The solid residue that is left behind in the CTBC units after the gas is removed is called biochar. Biochar is a solid material obtained from the *carbonization* of biomass. Carbonization is the process of converting feedstock into biochar through reductive thermal processing. The process involves a combination of time, heat, and pressure exposure factors that can vary between processors, equipment, and feedstock.

Biochar may be added to soils with the intention to improve soil functions and to reduce emissions from biomass that would otherwise naturally degrade to greenhouse gases. Biochar also has appreciable carbon sequestration value. These properties are measurable and verifiable in a characterization scheme, or in a carbon emission offset protocol.

Biochar is the carbon (C) rich product when green waste biomass, such as wood, or leaves, is heated with little or no available oxygen. In more technical terms, biochar is produced by thermal decomposition of organic material under limited supply of oxygen (O_2), and at relatively low temperatures (<700°C). This process often mirrors the production of charcoal, which is perhaps the most ancient industrial technology developed by humankind. However, it distinguishes itself from charcoal and similar materials by the fact that biochar is produced with the intent to be applied to soil as a means to improve soil health, to filter and retain nutrients from percolating soil water, and to provide carbon storage.

Biochar is typically blended with a bulking agent that may comprise of compost or fresh soil, and the combined material is then bagged and sold as a soil amendment.

The carbon sequestration potential of biochar is explained below.

A. Biochar Carbon Sequestration

Biochar production represents a strategy to impact the release of CO_2 from the breakdown of organic matter in soil by converting organic matter into biochar using a process of thermal stabilisation. Biochar decomposes and releases CO_2 very slowly with long mean residence times in soil, ranging from 1,000 to 10,000 years, with 5,000 years being a common estimate.[10,11] Without thermal stabilization, the same biomass will release all the carbon it contains to the atmosphere in a short period of time, with much of the carbon being lost within a few months and with the majority of the carbon being lost within 10 years due to incorporation into soil, agricultural burning, composting, or even use for biofuels.

Stabilisation of carbon in biochar represents an opportunity to remove CO_2 from the atmosphere by converting biomass into a stable form of carbon and preventing the release of this carbon back to the atmosphere. Where prior management for biomass includes incorporation in soil, production of biochar from this biomass represents an opportunity to lock in and stabilize the carbon that decomposing biomass would otherwise release into the atmosphere.[12]

When added to soil, biochar continues to store carbon and enhance soil quality. Using biochar can increase agricultural production without increasing cropped area, all the while reducing fertilizer and water inputs.

Typically 80-90% of C added to soil as plant biomass will be lost as CO_2 after 10 years. The amount remaining after 10 years is influenced mainly by soil type and environmental factors. Although the decomposition of plant material in soil is a complex process, simple models have successfully described the long-term dynamics of soil C and are widely used to predict the carbon that will remain from the organic matter applied to soil. Such models have informed both national greenhouse inventory assessments and proposed carbon offset methodologies.

Biochar is formed when organic matter is heated in the absence of oxygen (or partially combusted in the presence of a limited oxygen supply). The release of C when organic matter is transformed into biochar differs markedly from non-transformed organic matter. Carbon is released in three distinct phases, as biochar is produced and applied to soil: A) rapid release of approximately 50% of the C in the feedstock during thermal transformation (i.e. during the CTBC reaction); B) release of labile mainly volatile C through rapid biotic decomposition; and

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[10] Cheng, C., Lehmann, J., Thies, J., and Burton, S. (2008) Stability of black carbon in soils across a climatic gradient *J. Geophysical Res.* Vol 113. G02027, 10 pp

[11] Warnock, D. D. and Lehmann, J. (2007) 'Mycorrhizal responses to biochar in soil – concepts and mechanisms' *Plant & Soil.* vol 300. pp 9-20

[12] Lehmann, J., Gaunt, J., Rondon, M. (2006) Biochar sequestration in terrestrial ecosystems – a review. Mit. Adapt. Strat. Global Change, 11, pp 403-427.

C) long-term slow release of C due biotic and abiotic breakdown of resistant C forms.

Table VII-1 gives the GHG Emission Reductions from the stable carbon contained in biochar. A discussion of the methodology used to calculate the figures follows.

Table VII - 1

	GHG Emission Reductions	Units
Biochar – Stable Carbon	.59	Mg CO_2e / Mg-1 DM
Throughput (Dry Basis)	27,000	Tons / year
Annual Emission Reduction	14,451.45	Mg CO_2e / year
Total Annual GHG Emission Reductions from Biochar Sequestration	**14,451,452,908**	**g CO_2e**

The following analysis stems from a report on biochar carbon sequestration used by consultants to calculate the biochar sequestration of Interra's CTBC process. The criteria is currently being vetted by the American Carbon Registry to establish a methodology for carbon credits for biochar projects, due to be released in the Fall of 2014.[13]

1. Measurement of Long term Stable Carbon contained in Biochar

During the thermal transformation of biomass to produce biochar the structure of the organic matter that was used as a feedstock is fundamentally transformed. The proportion of aromatic structures increases and as temperatures increase these become increasingly ordered until graphite like structures are formed (Downie et al. 2009). This transformation releases a portion of C contained in the feedstock and the C remaining is rendered more stable than in the original feedstock.

Longitudinal decomposition studies utilizing biochar to establish the long-term stable C component are lacking. In the absence of such date there are a number of evidence sources that can be used to inform our understanding of the longevity of biochar when added to soil. These were reviewed by Lehmann et al. (2009) and the evidence was summarized by DeGryze et al. (2010). Three general approaches have been adopted in the literature:

- **Rates calculated from incubation studies using "aged charcoal"**. Soils containing old charcoal (such as Amazonia Dark Earths) or samples of old / aged biochar are studied to assess turnover.
- **Radiocarbon dating**. Uses radiocarbon techniques to assess the age of biochar samples or soils containing biochar.
- **Large scale C budgeting / balances** . This approach has been applied at various scales. With assumptions as to the rate of biochar formation the age and mean residence time of biochar required to explain current levels of biochar in soil.

[13] http://americancarbonregistry.org/carbon-accounting/methodology-for-biochar-projects

Taken in isolation each of the approaches described above can be criticized and has flaws. However, they represent reinforcing and independent sources of evidence that all point to a mean residence time for biochar in soil of 100s to 1000's of years. Recall that where the alternative management is incorporation in soil under aerobic conditions residence time in soil is a 'few' years (Baldock and Smernik, 2002).

Despite the evidence that biochars are inherently stable, they contain a labile C component that is accessible to biotic and abiotic oxidation processes in soil.

Thus, there are two requirements:

- To establish that feedstock has been transformed from its original form into a more stable biochar
- To estimate the long term stable C contained in biochar.

2. Indicator of transformation of organic matter

During the heating associated with the reaction and associated transformation of organic structures the molar ratio of H:C and O:C decrease as connections to protons and OH groups are shed.

Data summarized from a number of sources by Krull et al. (2009) showed that H:C and O:C ratios tended to be highest in feedstock materials and low-temperature biochars, partially charred plant materials and biochars produced during very short heating intervals. Lower ratios were observed in naturally produced wood char, vegetation fire residues, biochar produced in the laboratory under high temperatures, and/or prolonged heating

The H:C and O:C ratios decreases with increasing production temperature or prolonged heating. The H:C ratio of unburned fuel materials, such as cellulose or lignin, is approximately 1.5. Kuhlbusch and Crutzen (1996) used molar H:C ratios of ≤ 0.2 to define 'black carbon'. Graetz and Skjemstad (2003) concluded that temperatures during biomass burning are predominantly greater than 400°C (smouldering combustion) and that chars formed during these temperatures are likely to have H:C ratios of <0.5. Spokas http://www.ars.usda.gov/SP2UserFiles/person/41695/Presentations/ISTC2010.pd summarized the relationship between molar O:C and thermo-chemical conversion products as shown in the schematic below.

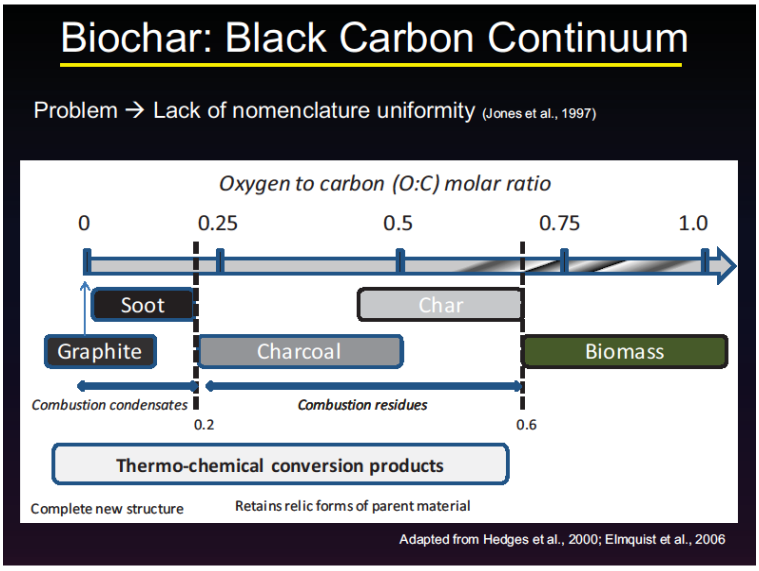

Figure 5: Biochar - Black Carbon Continuum

The H:C and O:C ratios can be measured using a procedure called Ultimate analysis, this is a quantitative analysis in which percentages of all elements in the substance are determined. International standards under ASTMS (www.astm.org) exist for ultimate analysis, the relevant method is (ASTM D3176).

Therefore it is proposed that an O:C ratio of <0.6 measured by ASTM D3176 or equivalent be used to indicate that the material has been transformed or stabilized through the CTBC process.

3. Estimation of stable C contained in biochar

Whilst the stabilization of C in biochar is obvious and molar O:C ratios provide an indicator thermal transformation, the C content measured by ultimate analysis is only a direct measure of the C that remains in a biochar sample after transformation, it does not reflect the long term C stable portion of biochar because it also includes the labile components.

As was discussed above the long term stable C is that portion that remains after the labile components that are subject to biotic and abiotic oxidation processes when added to soil is lost.

Currently this is an area of considerable research and debate and no established method exists. Incubation studies indicate that the amount released is typically small and it is released relatively rapidly when biochar is added to soil. However, as expected this is influenced by feedstock and process conditions.

A number of research groups are seeking to apply accelerated decomposition or oxidative procedures to measure this labile component, however at this time this remains an active field of study and no consensus exists.

Fixed C measured by proximate analysis has been proposed as a measure of stable C. Proximate analysis involves establishing the loss of material as samples are heated to predefined temperatures and typically reports volatile matter, fixed carbon, moisture content, and ash present in a fuel as a percentage of dry fuel weight. International standards under ASTMS exist

for this measure. ASTM D1672-84 measures volatile carbon by heating a sample to 950 Celsius in an inert atmosphere and any matter that leaves is considered volatile matter. The ash is generated by exposing the coal to air at 750 Celsius until all the available carbon is reacted to carbon dioxide and any metal salts are converted to the corresponding metal oxides.

McLaughlin et al. (2009) argues that incremental carbonization and calcination of the biochar sample, occurs whenever a char is heated above the highest treatment temperature (HTT) used in its production. As most biochars will be produced at temperatures between 450 – 650 celsius McLaughlin et al. (2009) proposed lowering the volatile matter – fixed carbon temperature to 450 Celsius, and the ashing temperature to 550 Celsius to minimize additional volatile generation.

Using this approach the proportion of volatile C was between 0.3 and 17% of total C (calculated as fixed + volatile C). Evidence of the relationship, if any, between Fixed C measured by proximate analysis and long term stable C does not exist.

Given research to establish biochar specific measures are underway we propose to adopt a conservative approach in the meantime. The fixed C measured by ultimate analysis is multiplied by a factor as a conservative estimate of the stable component.

Stable C is taken as the C content measured by ASTM D3176 or equivalent * 0.85.

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VIII. Credits and Proposed Carbon Intensity

This sections draws heavily on a similar section developed by ARB staff for the HSAD Pathway.

A. Carbon Credit for Avoided Emissions

The breakdown of organic matter in a CTBC reactor is similar to the decomposition of that material in a landfill. The difference between the two processes is that, in an artificially controlled and closed environment such as a reactor, there is greater accountability for materials and energy flows within system boundaries. The decomposition of organic matter primarily yields methane and carbon dioxide gases, which are known to contribute to atmospheric warming. The available research indicates that approximately 75 percent of the methane generated in a landfill can be captured and routed to a flare or be consumed as fuel to power vehicles and electrical generators (USEPA, 2008). The remaining 25 percent of the methane escapes to the atmosphere as fugitive emissions, contributing to the trapping of heat in the atmosphere.

The management of wastes at a landfill also produces emissions. Wastes are transported, emplaced, and covered using heavy-duty diesel-powered equipment. LFG capture and leachate management systems consume electrical energy. Over the longer term, landfills reach their full waste storage capacity and must be decommissioned, and new landfill sites must be developed. Research presented below (Barlaz and Levis, 2011) suggests that landfill and waste management emissions rates are a function of the amount of waste processed. These emissions are related to landfill construction, operations, gas and leachate management, long-term maintenance and monitoring, and final cover placement, and their corresponding emissions factors are presented in Table VIII-1 below:

Table VIII-1
Landfill Management Emissions Factors

Landfill Process	Emissions Factor	Units	Converted	Units
Construction	1.4	kg CO_2e / Mg	1,400	g CO_2 / metric ton
Operations	3.9	kg CO_2e / Mg	3,900	g CO_2 / metric ton
Final Cover Placement	1.2	kg CO_2e / Mg	1,200	g CO_2 / metric ton
Gas and Leachate Management	0.31	kg CO_2e / Mg	310	g CO_2 / metric ton
Maintenance and Monitoring	0.06	kg CO_2e / Mg	60	g CO_2 / metric ton
Total	**6.87**	**kg CO_2e / Mg**	**6,870**	**g CO_2 / metric ton**

This landfill management emission factor is reasonable for increases or decreases in waste volumes that are large enough to trigger corresponding increases or decreases in the amount of equipment in use, or in the intensity of equipment utilization. Landfill operations are unlikely to respond, however, to small changes in waste volumes. Interra believes that the diversion of

green wastes from a medium-to-large landfill will not be enough to trigger changes in equipment use, construction, and closure regimes. Although diversion of wastes to an CTBC facility has to the potential to impact the transportation component of the life cycle analysis,[14] emissions reductions from reduced waste processing at the landfill will be accounted for in this CTBC Pathway when and if the magnitude of the effect becomes clear in landfill emissions inventory data.

By diverting organic wastes such as green wastes from a landfill, however, fugitive GHG emissions from the landfill are avoided. By accounting for almost all of the material and energy within the system boundary of an CTBC process, not only is a valuable transportation fuel and soil amendment produced, but the impact of decomposing organic matter on the environment is reduced and the production of biochar sequesters a large portion of the carbon content. This greater accountability of material and energy flows makes it possible to estimate a CTBC carbon credit that exceeds the flaring credit associated with the simple capture and use of landfill gas (LFG). Hence, Interra will use the credit calculations that ARB staff has created in the HSAD Pathway. ARB staff created a carbon credit model for avoided landfilling and composting emissions from green wastes by accounting for the GHG emissions from the carbon contained in the HSAD Pathway feedstock waste streams.

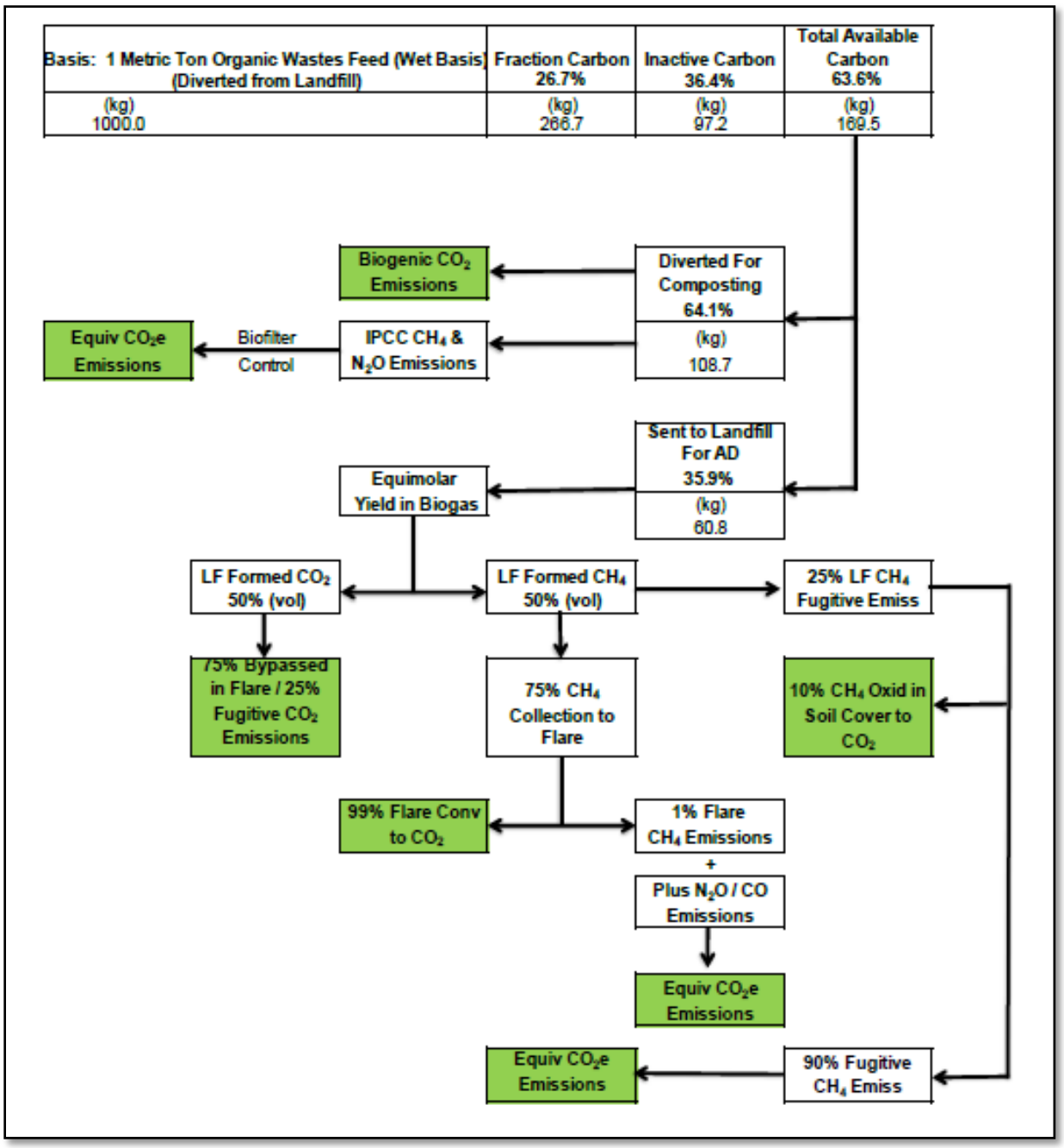
The carbon credit model developed from the schematic shown in Figure VIII-3 begins with the simplifying assumption that green wastes are comprised of the cellulose monomer $C_6H_{10}O_5$. Actual green wastes also contain significant amounts of hemicellulose and lignin. The green wastes making up the CTBC process feedstock stream are assumed to contain 40 percent moisture. Given these two assumptions, the overall carbon fraction of the feedstock comes to approximately 27 percent. Of that 27 percent, 36 percent is assumed to be stable and not subject to rapid decomposition (Barlaz, 2008). As such, this fraction is considered to be inactive and is excluded from subsequent GHG emissions estimates. All carbon except for this fraction is assumed to undergo either anaerobic digestion or aerobic decomposition.

The assumptions about the alternative fate of green wastes will be summarized here:

- 75 percent of the methane generated in the landfill from green wasted would be collected and flared;
- The remainder escapes as fugitive emissions;
- About 10 percent of the fugitive methane is oxidized to CO_2 as it rises to the surface of the landfill (Chanton et al. 2009);
- The remaining 90 percent of the uncollected methane escapes to the atmosphere, exacerbating the trapping of atmospheric heat; and
- Of the green-waste-generated methane that is collected from
- the landfill, 99 percent is destroyed by the flare and one percent passes through the flare to the atmosphere intact.

[14] The HSAD Pathway assumes that the AD facility would be sited adjacent to a landfill, thereby minimizing any transportation distance differentials between the landfill and the AD facility. Interra assumes the same for the CTBC facility.

Figure VIII-1
Schematic of Natural Fate of Carbon in Green Waste



The total carbon credit for avoided landfilling and composting emissions when green wastes are diverted is the sum of the carbon credits from the green waste model.

Under the CTBC Pathway, an annual throughput of 38,271.85 metric tons per year of green wastes produces an estimated carbon credit of 21.2 billion g CO_2e per year. Table VIII-1 below presents a summary of the overall carbon credit for avoided emissions. The "Total Avoid

Landfilling / Flaring / Composting Emissions" figure comes directly from the ARB staff calculations in the HSAD Pathway.

Table VIII-2
Summary of Carbon Credits for Avoided Emissions

Parameter	Value	Unit
Estimated Green Wastes Pre-Screened Annual Throughput	38,271.85	metric tons / year
Total Avoided Landfilling / Flaring / Composting Emissions (Green Wastes)	554,281	g CO_2e / metric ton
Total Carbon Credit (Green Wastes)	21,213,362,736.79	g CO_2e / year
Applicable Carbon Credit for CTBC Pathway	**21,213,362,726.79**	**g CO_2e / year**

B. Co-Product Credit

The solid residue co-product (biochar) of the CTBC process contains organic nutrients that yield a high-quality material that is marketed as a soil amendment. The market impact of fully utilizing available resources by turning the feedstock into biochar is the displacement of synthetically produced fertilizer. The magnitude of this displacement effect can be estimated by assuming that the nutrients in the biochar product displace equal proportions of synthetically produced nitrogen, phosphorus, and potassium (NPK). The net GHG savings from the displacement of the synthetic fertilizer becomes the CTBC Pathway's co-product credit.

ARB Staff has estimated the GHG emissions reduction benefit from the displaced NPK fertilizer to be approximately 0.26 $MTCO_2e$ per ton of finished compost (ARB, 2011). Interra will conservatively use this number. This is conservative because biochar is a permanent soil enhancer, and will replace fertilizer for many years, while compost is a yearly replacement.

To calculate the emissions benefit, the basis must be changed from one ton of finished compost to one ton of feedstock. In making this change, the amount of bulking agent added to the biochar is subtracted. Interra estimates that the conversion factor to change the basis from one ton of finished product to one ton of biochar is approximately 0.64. To account for the yield of biochar, based on the mass of feedstock, staff estimate the conversion factor to be approximately 0.84. Therefore, the final compost emissions reduction factor (CERF) based on reduced fertilizer use is estimated to be:

$$\textbf{CERF} = 0.26 \frac{\text{MTCO2e}}{\text{ton compost}} \text{ x } \frac{0.64 \text{ ton compost}}{\text{ton digestate}} \text{ x } \frac{0.84 \text{ ton digestate}}{\text{ton feedstock (less inerts)}}$$

$$\text{CERF} = \frac{0.14 \text{ MTCO2e}}{\text{ton feedstock}} \text{ x } \frac{\text{short ton}}{2{,}000 \text{ lbs}} \text{ x } \frac{2{,}205 \text{ lbs}}{\text{metric ton}}$$

$$\text{CERF} = \frac{0.15 \text{ MTCO2e}}{\text{metric ton feedstock}}$$

CERF Annualized = 0.15 MTCO2e × 38,271.85 metric tons = 5,740.78 metric tons CO2e / year

Total Annualized Carbon Emission co-product credit:

= 5,740.78 metric tons CO2e × 1,000 kg × 1,000 g = **5,740,777,500 g CO2e / year**

C. Tank-to-Wheel Emissions

The Tank-to-Wheel Emissions for the CTBC Pathway will be the same as for the HSAD Pathway. As such, ARB staff estimates and figures from the HSAD Pathway are used. Staff assumed that the biogas produced in the HSAD process and eventually refined to pipeline quality biomethane would enter the transportation fuels market for natural-gas-fired heavy-duty vehicles, such as transit buses, and cargo delivery trucks. Staff has assessed tank-to-wheel GHG emissions based on the assumption that all carbon in the fuel would convert to carbon dioxide (ARB, 2009c). Staff has further assessed CH_4 and N_2O emissions from combustion of biomethane in the heavy-duty natural gas engine based on emissions factors of 0.0375 gram per mile. These CH_4 and N_2O emissions were further evaluated at their global warming potentials of 25 and 298, respectively, to determine total TTW GHG emissions.

The tank-to-wheels emissions for this pathway are summarized in Table VIII-3 below:

Table VIII-3
Estimate of Tank-to-Wheel GHG Emissions

Parameter	Parameter Identifier	Value	Unit
Product Gas Produced		242,776,246	scf / year
Product Gas Energy Density		20.4	g / scf
Product Gas Energy		4,952,635,407	g / year

Product Gas Carbon Content		0.724	g C / g Sales Gas
Product Gas Total Carbon Emissions		3,585,708,035	g C / year
CO_2 Emissions	A	13,147,596,127	g CO_2 / year
NGV Fuel Economy		4.8	MJ / mile
Annual Miles		50,343,529	miles / year
CH_4 Emissions		1,887,882	g CH_4 / year
CO_2e Emissions	B	47,197,059	g CO_2e / year
N_2O Emissions		1,887,882	g N_2O / year
CO_2e Emissions	C	562,588,940	g CO_2e / year
1% -Pass Through‖ CO_2 Emissions	D	138,942,783	g CO_2e / year
Total TTW GHG Emissions	**A + B + C + D**	**13,896,324,909**	**g CO_2e / year**

D. Proposed Biomethane Fuel Carbon Intensity

In this section, all the CTBC life cycle emissions and credits discussed in previous sections will be brought together so that the net pathway carbon intensity can be calculated. Those emissions and credits break down as follows:

- All well-to-tank process emissions, including upstream, fuel cycle emissions;
- Electrical energy, including upstream fuel cycle emissions;
- Carbon credits for avoided landfilling and composting emissions;
- Co-product credit for the synthetic fertilizer displaced by the biochar co-product; and
- Tank-to-wheels tailpipe GHG emissions.

A summary of all Well-to-Wheels emissions is presented in Figure VIII-4 below.

Table VIII-4
Proposed CI for CTBC Pathway

Estimated Net Annual Biomethane Production (scf / year)	Fuel Energy Value (MJ / year)	No. 2 Diesel Use (gal / year)	Grid Electricity Use (kWh / year)	Natural Gas Use (scf / year)
111,150,000	**105,478,530**			
GHG Emissions Source	**(g CO_2e / year)**			
CTBC Process GHG Emissions	23,325,185,245.48		3,750,000	
CTBC Wastes Loading Fossil Fuel Use & Emissions	174,562,143	17,405		
Total Fuel Cycle Electric Emissions	1,420,119,549			
Total Low Sulfur Diesel WTT Emissions	47,897,831			
Total CTBC Process Emissions	24,967,764,768			
GHG Emissions from CNG Combustion in HDV (TTW)	13,896,324,909			
Less Carbon Credit from Biochar Carbon Sequestration	-14,451,452,908			
Less Carbon Credit from "MODEL"	-21,213,362,726.79			
Less Compost Emissions Reduction Factor (CERF)	-5,740,777,500			
Net Annual GHG Emissions	-2,541,503,457			
Proposed CTBC Pathway CI (g CO_2e/MJ):	**-24.09**	**17,405**	**3,750,000**	

Based on the analysis in this report, staff estimates the CI of the biomethane fuel produced from the clean thermal biomass conversion of green wastes to be -24.09 g CO_2e / MJ of energy.

E. Conditions for Use of CI Value

Interra has stipulated some specific conditions that prospective users of this CTBC Pathway must meet. These conditions are not only based on model parameters, but also intended to offer the biofuel producer operating flexibility. These operating conditions are as follows:

- The organic waste feedstock stream must consist of green wastes.

- The pathway applies only to fuel produced by a clean thermal biomass conversion process operating at pressure. It does not apply to traditional thermal conversion processes such as incineration, combustion, or gasification.
- The annual organic waste throughput of the CTBC process must be equal to or greater than 30,000 tons.
- The process is based on the use of grid-based electricity generated from a marginal energy mix with a CI at or below the CI associated with 78.7 percent natural gas and 21.3 percent renewables (excluding large hydroelectric and biomass-based generation).
- If injected into a pipeline, the biomethane produced must conform to prevailing California[15] pipeline quality compositional and performance laws, regulations or standards, including any specifications imposed by the regulated utility and transmission companies on parameters such as the Wobbe Index, and trace impurity levels of compounds such as hydrogen sulfide (H_2S).
- The product gas discharge pressure must be no greater than 800 psig for tie-into the utility company's transmission system.
- The pathway co-product (Biochar) must not be used as a fuel source.

[15] As mandated by the California Public Utilities Commission (PUC), California Energy Commission (CEC), California Air Resources Board (ARB), or any other applicable State law.

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Appendix A

Additional Supporting Documentation

I. Appendix Figure A-1: Pathway Supplemental Questions

IX. PATHWAY SUPPLEMENTAL QUESTIONS

Annual volume of fuel produced using the proposed new pathway that would enter the California market (MGY):
.765

If the facility is not currently operating at full production capacity, when is full operational capacity expected?
06/15/2014

Does the applicant expect this volume to be achieved by a single or by multiple facilities?

☒ A Single Facility	☐ Multiple Facilities

If the applicant expects this volume to be achieved by multiple facilities, would all facilities be owned by a single firm?

☐ A Single Firm	☐ Multiple Firms

Lower Heating Value (LHV) of the fuel to be produced from the new pathway (MJ/gal):

The range of production volumes over which the proposed pathway carbon intensity value is valid. The values reported below must be supported in the documentation accompanying this application.

Production Volume Range	*Fuel Volume (MGY)*
Lower Bound	.130
Upper Bound	.765
Average Volume	.635

Please provide any information that may be helpful in determining the land use change impacts (if any) of the proposed pathway. Although it is ARB's responsibility to perform all land use change impact analyses, the applicant may provide any information that may be useful to the ARB in completing that analysis.

The proposed pathway willl not lead to land use changes. The feedstock will come from waste biomass sources that are currrently going to landfills or composting operations. No purpose grown feedstocks will be used.

II. Appendix Figure A-2: Facility Information

V. FACILITY INFORMATION

Facility No	Facility Name	Facility Address	City	Zip Code	State or Province	Country
1	Interra Pilot Facility	560 California 78	Brawley	92227	CA	Imperial
2						
3						