California Environmental Protection Agency

Air Resources Board

Proposed Low Carbon Fuel Standard (LCFS) Pathway for the Production of Biomethane from High Solids Anaerobic Digestion (HSAD) of Organic (Food and Green) Wastes

Staff Report

Stationary Source Division
Fuels Evaluation Section

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State of California
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STAFF REPORT

Proposed Low Carbon Fuel Standard (LCFS) Pathway for the Production of Biomethane from High Solids Anaerobic Digestion (HSAD) of Organic (Food and Green) Wastes

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STATE OF CALIFORNIA
AIR RESOURCES BOARD

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Comments on this document may be submitted directly to the attention of Kamal Ahuja (Air Resources Engineer) by email to kahuja@arb.ca.gov.

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Executive Summary

Staff is proposing a Low Carbon Fuel Standard (LCFS) high solids anaerobic digestion pathway (HSAD Pathway) for the production of biomethane from organic food and green wastes. By definition, a high solids anaerobic digestion process is one in which the percentage total solids of the feedstock is greater than 15 percent, and little or no water is added to the fermentation vessels. Staff expects the feedstocks to be comprised of 25-35 percent total solids. The HSAD process would be based on a multi-stage, mesophilic destruction of the organic food and green wastes, with accommodations for small proportions of food-contaminated non-recyclable (soiled) paper, and fats, oils, and greases (FOG) in the feedstock. To establish the carbon intensity (CI) of the fuel for the proposed pathway, staff has modeled an initial composition of 40 percent food wastes and 60 percent green wastes (comprised of equal proportions of leaves, grass, and brush). Staff assumes for the purposes of this analysis that the HSAD facility would be sited adjacent to a landfill, or local transfer station, minimizing any transportation distance differentials between feedstocks delivered to the HSAD facility and wastes delivered for disposal or recovery.

Biogas produced from the anaerobic digestion 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. Staff 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 HSAD facility. Additionally, the process solid residue (digestate) would be composted using either the in-vessel composting (IVC) or the covered aerated static pile (CASP) mechanisms. Open windrow composting would also be an acceptable composting method albeit with higher estimated fossil fuel usage than either CASP or IVC. The result would be a high-quality compost co-product that could be marketed as either a fertilizer or soil amendment.

This document presents the results of a life cycle analysis (LCA) performed on the HSAD Pathway described above. Staff collected the process-related information used to perform this LCA from industry, consultants, and academics. Staff 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 HSAD Pathway, and to estimate the CI value of the transportation fuel produced. Staff assumed that grid-based marginal electricity would power the anaerobic digestion and biogas purification processes. Additionally, some of the refined biogas is assumed to be consumed in a boiler to provide process steam for digester heating purposes. Staff estimated 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. Staff 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 food and green wastes, and a co-product credit for the displacement of synthetic fertilizers by the compost produced from process residue. Staff's model and supporting calculation methodology will be posted to the LCFS public web site for review, along with this pathway document.

CARBON CREDIT FOR AVOIDED EMISSIONS

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. An anaerobic digester can also accomplish the decomposition of organic matter to produce CH_4 and CO_2 by simulating the conditions in a landfill, 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 anaerobic digestion of organic matter in an artificial reactor warrants a credit that exceeds the flaring credit included in the LFG pathway. Therefore, staff has developed 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 an anaerobic digestion facility for biogas production. The value and derivation of this credit is discussed in Section VIII of this report.

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 HSAD 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 HSAD 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, staff has used that value in this analysis. 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.[1]

MODELED RESULTS

The CI for the HSAD 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 aerobic and anaerobic biochemical processes. Staff's estimate of the well-to-wheel (WTW) CI for the HSAD Pathway is -15.29 g CO_2e / MJ of energy. A summary of the process parameters for the HSAD 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 HSAD Pathway Characteristics

Parameter	Value	Units
Feedstock 1 Organic Food Wastes	40,000 (40 %)	short tons per year (tons / year)
Feedstock 2 Organic Green Wastes	60,000 (60 %)	short tons per year (tons / year)
Net Annual Biomethane Production Rate	242,776,246	standard cubic feet per year (scf / year)
Fuel Energy Value	238,199,913	mega-joules per year (MJ / year)
Net Annual GHG Emissions	-3,642,643,637	grams CO_2 equivalent / year (g CO_2e / year)
Process	High Solids (Dry) Anaerobic Digestion	25-35 percent Total Solids
Primary Product Fuel	Biomethane	-
Co-Product	Fertilizer / Soil Amendment (Compost)	-
Total Fossil Fuel Energy Use		-
- No. 2 Diesel Fuel	71,916	gallons per year (gal / year)
- Grid Electricity Use	6,491,985	kilo-watt hours per year (kWh / year)
- Natural Gas	4,927,429	standard cubic feet per year (scf / year)

[1] 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 HSAD Pathway is presented in Table ES-2 below. The material and energy balances, GHG emissions, and proposed CI for the HSAD Pathway are based on one full year of operation.

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

Parameter	Value	Units	Reference
HSAD Process GHG Emissions	24,220,062,198	g CO_2e / year	Table VI-5
HSAD Process Net Heat Loading Requirements	267,388,043	g CO_2e / year	Table IV-1
Compost Operations GHG Emissions	14,706,483,260	g CO_2e / year	Table VII-3
HSAD Wastes Loading GHG Emissions	174,566,466	g CO_2e / year	Based on Tables II-2 and II-6
Compost Operations Fossil Fuel Use GHG Emissions	546,746,602	g CO_2e / year	Based on Tables II-4 and II-6
Total HSAD Wastes Loading & Composting Fuel Use GHG Emissions	721,313,068	g CO_2e / year	Based on Table II-6
Total Fuel Cycle Electric Use GHG Emissions	2,458,505,316	g CO_2e / year	Based on Table V-2
Total Low Sulfur Diesel Well-to-Tank GHG Emissions	197,919,954	g CO_2e / year	Based on Table II-7
Total HSAD Process and Compost Operations GHG Emissions (A)	42,571,671,837	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-2
Less Carbon Credit for Avoided Landfilling & Composting Emissions (C)	55,398,857,358	g CO_2e / year	Section VIII (a), Table VIII-1
Less Compost Emissions Reduction Factor (CERF) (D)	4,711,783,026	g CO_2e / year	Section VIII (b)
Net GHG Emissions (1) (Sum A-D Above)	-3,642,643,637	g CO_2e / year	-
Biomethane Fuel Energy Value (2)	238,199,913	MJ / year	Table III-3[a]
Proposed HSAD Pathway Carbon Intensity Value (1 ÷ 2)	**-15.29**	**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).

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 HSAD 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 feedstocks 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. Staff has conducted a WTW analysis for biogas produced from the anaerobic digestion of organic food and green wastes in a high solids (dry fermentation) anaerobic digester. 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.

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 HSAD 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. Staff used this California-modified GREET model to calculate GHG emissions from the HSAD Pathway whenever the necessary emissions factors were present in the model. Staff 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

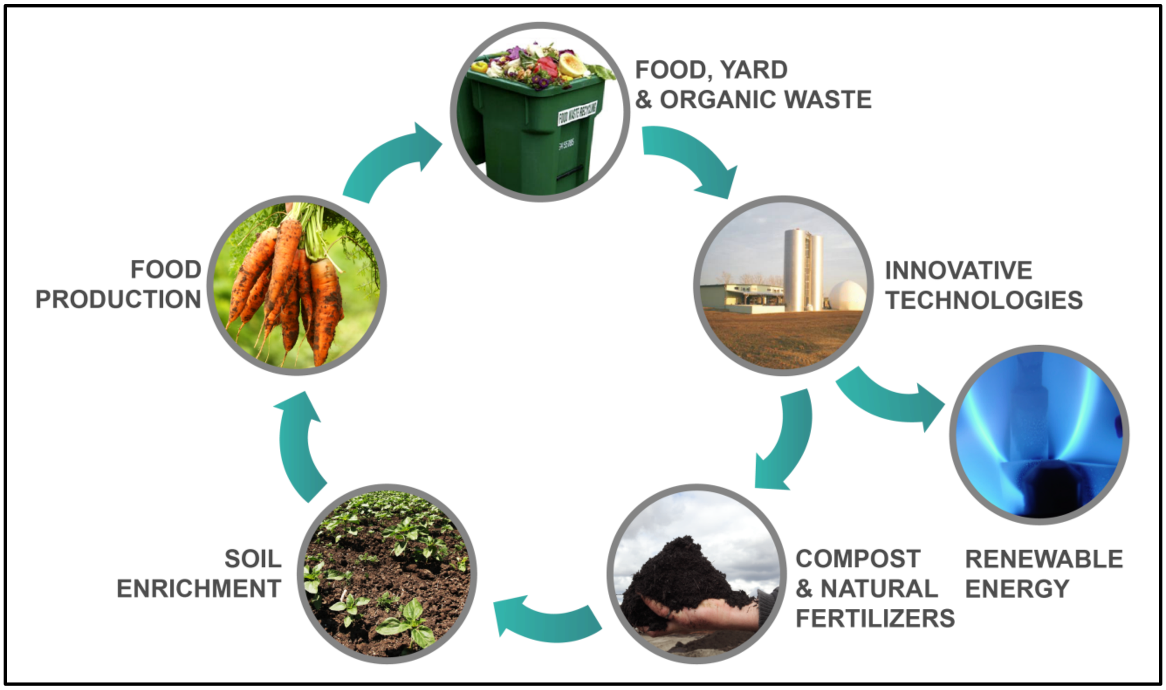
The WTT and TTW emissions estimates presented in the following sections include analyses of the process conditions, and the applicability of credits for avoided landfilling and composting emissions, and for co-products produced.

HIGH SOLIDS ANEROBIC DIGESTION PATHWAY

The HSAD pathway developed in this document primarily converts two categories of organic wastes into biogas, and eventually, biomethane. The first, food wastes, consists of pre-consumer food wastes from food-processing companies, and commercial food waste from delis and bakeries, restaurants, hotels, hospitals, and cafeterias. These wastes typically find their way to a landfill. The second, green wastes, consists of yard clippings, grass, leaves, and brush from curbside pickup programs that typically find their way to composting facilities, as well as to landfills. By diverting organic food and green wastes destined for a landfill or a composting facility to an anaerobic digester, a useful transportation fuel can be produced, a valuable co-product (fertilizer) can be derived, and GHG emissions can be avoided. Figure I-1 below illustrates how these waste streams are transformed into useful energy and soil enrichment 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 anaerobic digestion. The feedstocks for the HSAD Pathway developed herein are characterized in Section II.

Figure I-1
Proactive Utilization of Waste Streams to Derive Useful Products[a]



a. Illustration Courtesy of Harvest Power, Inc.

Diverted organic food and green wastes enter the HSAD Pathway system boundary when they are trucked to the HSAD facility. Staff based its pathway analysis on a modeled throughput of 100,000 short tons per year of wastes consisting of approximately 40 percent food and 60 percent green wastes.

The high solids, or dry fermentation process, differs from wet fermentation in the amount of total solids contained in the organic wastes. The HSAD process, by definition, accepts organic wastes with 25-35 percent total solids content. Despite this high solids content, very little energy is expended to pre-process and screen the wastes for metal and large objects in a HSAD operation. Nor is extensive screening, grinding, or slurrying required for HSAD. The organic wastes are first percolated in tunnels under mesophilic conditions (35°C, or 95°F). The percolate liquid (sometimes called hydrolysate) is then pumped to methane digesters, which are a series of reactor-like vessels. During its residence in the digesters, the liquid hydrolysate decomposes to produce methane (CH_4) and carbon dioxide (CO_2). As these gases collect in the digester header space, they are drawn off, compressed, and routed to a biogas purification unit. The biogas collected has a composition of approximately 65 percent CH_4 and 35 percent CO_2 and is refined to nearly pure biomethane. Biogas yield estimates are discussed in Section III.

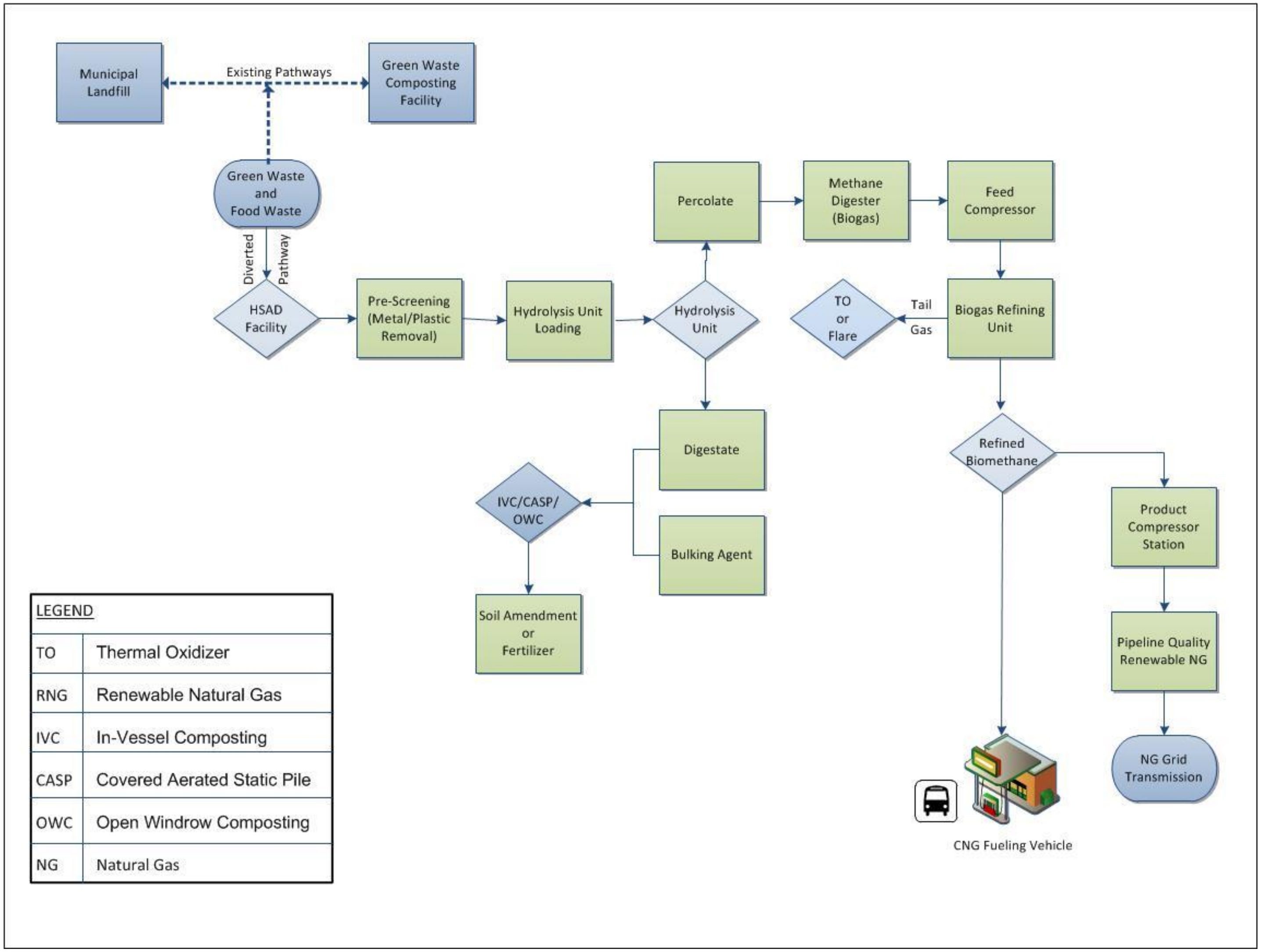
The solid residue (digestate) that is left behind in the hydrolyzing units after its most volatile carbon content has been stripped is subsequently transferred either to another vessel or outdoors for composting. Composting is an aerobic process under which microbes further act on the organic fraction of the residue. This analysis considered three methods for composting organic materials: open windrow composting, covered aerated static piles (CASP), and in-vessel composting (IVC). Staff assumes that since open windrow composting is more fossil fuel energy intensive than either of the other two composting methods, it is less likely to be encouraged as the dominant composting process. A bulking agent (typically fresh green waste) is added to the digestate to produce a stable compost mixture. The finished compost is sold as a high-quality fertilizer or soil amendment. Compost (co-product) operations are discussed in Section VII.

HSAD process emissions are discussed 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). The result is a high-purity biomethane stream (98-99 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, staff 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.

Staff has estimated a co-product credit for fertilizer produced either by the Open Windrow, IVC, or CASP composting methods. 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. Staff 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 compost produced from the digestate.

A schematic of the HSAD process is presented in Figure I-2 below.

Figure I-2
Schematic of the High Solids Anaerobic Digestion (HSAD) Pathway



LEGEND

TO	Thermal Oxidizer
RNG	Renewable Natural Gas
IVC	In-Vessel Composting
CASP	Covered Aerated Static Pile
OWC	Open Windrow Composting
NG	Natural Gas

II. Feedstock Characterization and Energy Use

a. Feedstock Characterization

Staff developed the life cycle CI for the HSAD Pathway by estimating the energy consumption and GHG emissions associated with the production of biomethane from an organic waste mixture comprised of approximately 40 percent food wastes and 60 percent green wastes.

Staff expects the food waste feedstock for the process to be composed mostly of pre-consumer organic food wastes procured from industrial food-processing companies, and commercial food waste from grocery stores, cafeterias, hospitals, soup kitchens and shelters, restaurants, bakeries, and delis as well as other sources. Staff has not included residential food wastes in the HSAD Pathway model. As food waste collection and diversion programs develop in counties and localities across the State, residential food wastes could potentially become a valuable resource that augments the production of biogas in an anaerobic digester.

As of the end of 2011, there were 53 food wastes collection programs in California. San Francisco has established an ambitious program that encompasses about 90 percent of its 350,000 households. Alameda County's food waste collection program began in 2002 and has over 365,000 single family homes participating (Yepsen, 2012). California has seen an increase in the number of food-waste collection programs, but even with this increase, it is estimated that only 10 percent of the six million tons of food waste disposed in the State is collected (Yepsen, 2012). The majority of the food wastes is still destined for the landfill (Climate Action Reserve, 2010; Arcadis US, 2012) and is an important determinant in the carbon credit model for avoided landfilling emissions.

The green wastes could be procured from curbside yard waste collection programs also implemented in local communities across the State. Additionally, green wastes from landscaping services could contribute to this resource. Staff assumes that the composition of the green wastes would be approximately equal proportions of grass, leaves, and brush. Staff 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 HSAD process would be augmented with wastes that have equivalent or greater yields of biogas. Such wastes may include the following: mixed paper wastes, and fats, oils, and greases (FOG). 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. The availability of fats, oils, and greases will be dependent upon local jurisdictions and collection systems; in 2009, twenty FOG collection programs were in place.[2]

Staff has determined that the majority of the green-waste are destined for a green-waste composting facility. Statistics suggests that this amount 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)

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**

Staff has also assumed that, for the purposes of this pathway, the biogas yields from the feedstocks might average on an annual basis to approximately represent the yield from a waste stream consisting of

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

40 percent food wastes and 60 percent green wastes. The biogas yields from the food-green wastes could be successfully augmented by the addition of 5-10 percent of food-contaminated (soiled) non-recyclable paper, or even FOG as a substitute.

b. Feedstock Energy Use

Staff will next present the fossil fuel energy consumption for loading the organic wastes into the HSAD process. Staff has assumed that the HSAD facility would be sited at a location adjacent to the local landfill, or a local transfer station, so that transportation distance differences between delivery of wastes destined for disposal or recovery, and the proposed HSAD facility would be minimized.

In a typical HSAD facility, organic wastes are dumped into an open receiving hall. After the wastes are pre-screened[3], the wastes piles are worked and transferred to the hydrolysis percolation units where the hydrolysis and acidogenesis phases of the four phase anaerobic digestion process commences. 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 30,000 tons per year of food and green wastes, in a 40:60 proportion, 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 total fossil fuel based energy (low-sulfur diesel) requirement for the HSAD Pathway is based on a scale-up ratio of projected fuel use for 100,000 tons less 5,000 tons per year (pre-screened inert materials). The total fossil fuel-based energy use for hydrolysis unit loading is presented in Table II-2 below.

[3] Staff expects that a minimal amount of wastes pre-screening will occur in a HSAD operation. For this pathway, staff 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.).

Table II-2
Estimate of Fossil Energy Use for Hydrolysis 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%	
Fossil Energy Type:	Low-Sulfur Diesel	
Fuel LHV: (No. 2 Diesel)	127,464	Btu per gallon
Fossil Energy Use (30,000 tons/year)	5,221	gallons / year
Projected HSAD Pathway Throughput:	95,000[a]	short tons / year
Total Fuel Use for Hydrolysis Loading:	**17,404**	**gallons / year**

a. Annual Throughput = 100,000 tons less 5,000 tons (Inerts).

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 digestate or residue from the hydrolysis unit of the HSAD process is the primary feedstock for the production of compost, the HSAD Pathway co-product. The digestate is moved to outdoor piles and is blended with a bulking agent to begin the composting process. Earth-moving equipment such as front-end loaders and windrow turners are also used to work the compost piles. Composting operations, including associated emissions are discussed in Section VII. In this section, however, staff will present an estimate of the amount of fossil fuel energy consumed during compost production.

Based on an annual throughput of 30,000 tons per year, over 80 percent of which emerges as digestate, staff anticipates the need for approximately 5,500 gallons per year of low-sulfur diesel. This quantity has been based on empirical measurements for composting using CASP. The total fossil fuel energy requirement for the composting operations is based on a scale-up ratio of projected fuel use for 100,000 tons less 5,000 tons per year (pre-screened inert materials) of wastes feedstock, and a digestate yield of approximately 80 percent. The total fossil fuel-based energy use for composting operations is presented in Table II-3 below.

Table II-3
Estimate of Fossil Energy Use
Covered Aerated Static Pile (CASP) Composting

Parameter	Type / Value	Unit
Equipment:	Front End Loader	195 kW (3)
Annual Feedstock Throughput	30,000	tons per year
Projected Digestate Yield	24,255	tons per year
Fossil Energy Type:	Low Sulfur Diesel	
Fuel LHV:	127,464	Btu / gallon (LHV)
Estimated Fossil Energy Use	5,547	gallons / year
Modeled Pathway Throughput	100,000	short tons / year
Projected Digestate Yield	79,738	short tons / year
Total Fuel Use for CASP Composting:	**18,237**	**gallons / year**

The proposed HSAD Pathway permits the flexibility to choose either composting method. For open windrow composting, the amount of fossil fuel use is expected to be higher since fossil fuel energy intensive equipment such as windrow turners are employed to aerate the compost media and turn over the soil. An estimate of total petroleum based fossil fuel use during open windrow composting is presented in Table II-4 below:

Table II-4
Estimate of Fossil Energy Use for Open Windrow Composting

Parameter	Type / Value	Unit
Annual Raw Food and Green Wastes Throughput	86,167.80	metric tons
Digestate Yield	0.84	
Digestate Throughput	72,324.60	metric tons
Bulking Agent Addition Ratio	0.41	
Bulking Agent Throughput	29,587.33	metric tons
Initial Total Compost Material Throughput	101,911.93	metric tons
Open Windrow Estimated Diesel Use Factor	0.34	gallon per metric ton
Estimated Diesel Fuel Use for Open Windrow Composting	34,594.78	gallons / year
Finished Compost Yield	0.45	
Throughput of Finished Compost	46,024.74	metric tons
Finished Compost Capping Diesel Fuel Use Factor 1	0.17	gallon per metric ton (4 Cap)
Finished Compost Capping Diesel Fuel Use 1	7,724.42	gallons / year
Estimate 1 for Open Windrow Composting Fuel Use (Low)	**42,319**	**gallons / year**
Finished Compost Capping Diesel Fuel Use Factor 2	0.43	gallon per metric ton (6 Pass)
Finished Compost Capping Diesel Fuel Use 2	19,916.34	gallons / year
Estimate 2 for Open Windrow Composting Fuel Use (High)	**54,511**	**gallons / year**

The total fossil fuel use for the HSAD Pathway consists of the sum of the fuel used to load the hydrolysis unit and to compost the digestate. This total is the total fuel usage identified in Tables II-2 and the higher of the fuel usages identified in Tables II-3 and II-4 above. This total is presented in Table II-5.

Table II-5
Estimate of Total Fossil Fuel Based Energy Use

Earth Moving Equipment Usage	Annual Quantity (gallons per year)
Total Fuel Use for Hydrolysis Loading:	17,404
Total Fuel Use for Composting Operations:	54,511
Total Fossil Fuel Use	**71,915**

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 digestate composting operations. Staff assumes that both hydrolysis unit loading as well as composting operations would utilize Front-End Loaders. Open windrow composting is additionally expected to employ windrow turners, water trucks, and dump trucks. To assess process emissions from fossil energy use, staff approximated the emissions from the earth-moving equipment by using the diesel farm tractor emissions factor from CA-GREET (version 1.80b, December 2009).

$$Total\ Fuel\ Consumption\text{: } 71{,}915\ gallons\ per\ year \qquad (a)$$

$$Fuel\ Lower\ Heat\ Value\text{: } \frac{127{,}464\ Btu}{gallon\ (low\ sulfur\ diesel)} \qquad (b)$$

$and,$

$$\boldsymbol{Total\ Annual\ Fossil\ Fuel\ Energy\ Consumption}$$
$$=\ (a\ x\ b)$$
$$= \mathbf{9,166.64}\ \frac{\boldsymbol{MMBtu}}{\boldsymbol{year}}$$

The total GHG emissions estimate from combustion of fossil fuels during materials handling (waste loading and compost operations) is shown in Table II-6 below.

Table II-6
Material Handling GHG Emissions

Pollutant	Emissions Factor[a] (g / MMBtu)	Annual Emissions (g / year)	Annual GHG Emissions (g CO_2e / year)
VOC	107.69	987,145	3,079,893
CO	402.58	3,690,271	5,793,726
CH_4	9.72	89,069	2,226,714
N_2O	0.92	8,433	2,513,118
CO_2	77,204.08	707,699,618	707,699,618
		Total Annual Emissions (g CO_2e / year)	**721,313,068**

[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-6. The total emissions are calculated from emissions factors obtained from CA-GREET
(version 1.80b, December 2009).

Table II-7
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	89,809	280,205
CO	26.88	246,389	386,831
CH_4	101.29	928,447	23,211,184
N_2O	0.23	2,079	619,555
CO_2	18,918.90	173,422,179	173,422,179
		Total Annual Emissions	**197,919,954**

[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.

In addition to fossil fuel use, CASP composting operations consume electrical energy for material aeration, filtration, and conveyance. Staff anticipates the amount of electrical energy use to be approximately 52,000 kWh per year (based on 30,000 tons of annual waste throughput). When scaled to represent the HSAD Pathway process load of 100,000 tons per year, the estimated annual electrical energy demand for CASP composting operations is estimated to be 173,000 kWh per year.

$$\boldsymbol{Estimated\ Electrical\ Energy\ Demand\ (CASP\ Composting\ )}$$

$$= \ 51{,}794\ kWh\ per\ year\ for\ (30{,}000\ tons\ per\ year\ throughput)$$

$$= \ 51{,}794\ x\ \left(\frac{100{,}000\ tons}{30{,}000\ tons}\ Scale - up\ ratio\right)\ kWh\ per\ year$$

$$= \ \mathbf{172{,}647\ kWh\ per\ year}$$

The GHG emissions from electrical generation (fuel cycle emissions) are discussed in Section V. Since open windrow composting has a net higher fossil energy consumption that either CASP or IVC composting, the CI for the HSAD Pathway is conservatively based on open windrow composting as the default method. Correspondingly, the estimated electrical energy demand for CASP or IVC composting is for informational purposes only.

III. Biogas Yield Estimates

Staff estimated the biomethane yield for the food and green wastes from biogas yield factors (m^3 / dry metric ton) developed for the respective wastes. Staff then converted the biogas yield estimates to biomethane yield by assuming the quality of the biogas to be 65 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:

- food wastes (70 percent);
- leaves and brush (30 percent);
- grass (60 percent); and
- mixed paper, which represents office, coated, newspaper, and corrugated containers (5-6 percent).

The food wastes factors were found to yield biogas ranging from 139 to 225 cubic meters per metric ton, wet basis. Staff assumes that, in the future, residential waste collection programs implemented in communities across California would contribute to landfill waste diversion and waste-to-fuel programs. Therefore, in addition to the food waste factors, staff obtained biogas yield estimates for the organic fraction of household wastes. These secondary factors were found to range from 135 to 361 cubic meters per metric ton, wet basis.

The biogas yield factor for food wastes delivered to the HSAD facility is assumed to be a simple average of the factors for food wastes and the organic fraction of household wastes. This yield factor was found to be 215 cubic meters per metric ton, wet basis. Food waste is expected to comprise approximately 40 percent of the wastes feedstock stream.

Similarly, green waste is expected to comprise approximately 60 percent of the waste feedstock stream. Staff assumes that the green waste would be sourced from residential and commercial yard waste with equal proportions of leaves, grass, and brush in the mix. The biogas yield estimate for green wastes is expected to be 90 cubic meters per metric ton, wet basis.

Biogas Yield estimates for various organic wastes which could potentially comprise the feed stream for the HSAD process are presented in Table III-1 below.

Table III-1
Biogas Yield Estimates from Organic Wastes

Type of Waste	Estimate 1 (a) (Nm^3/metric ton, wet)	Estimate 2 (b) (Nm^3/metric ton, wet)	Estimate 3 (c) (Nm^3/metric ton, wet)	Estimate 4 (d) (Nm^3/metric ton, wet)	Average Yield for HSAD Pathway
Food	139	185	225	-	
Household Wastes			361	135	
Average Food Wastes					**215**
Leaves	89	108	-		
Grass	67	140			
Brush	33	104			
Average Green Wastes	**63**	**118**			**90**
FOG		**1,658**	**790**		**612 (e)**
Office Paper	314		522		
Newspaper	107		144		
Coated Paper	122				
Corrugated Containers	223		409		
Mixed Paper (Average)	**189**		**390**	**360**	**289**

[a] De la Cruz / Barlaz, 2010.
[b] Chynoweth / Turick / Owens / Jerger / Peck, 1993.
[c] Schievano / Scaglia / D'Imporzano / Malagutti / Gozzi / Adani, 2009.
[d] Davidsson, Gruvberger, Christensen, Hansen, & Jansen, 2007.
[e] Staff assumes that biogas yield is based on dewatered FOG (50 percent strength).

Based on an annual throughput of 100,000 tons per year less 5,000 tons of estimated / pre-screened inerts, the average daily biogas yield is expected to be 1.2 million standard cubic feet (mm scf) of biogas per day, or an average yield of over 800 standard cubic feet per minute (scfm). This represents a biomethane potential of approximately 530 scfm. Biogas and biomethane production levels from HSAD of the feedstock are presented in Table III-2 below.

Table III-2
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)
FOGs	612	21,613	0%	-	-
Food/Household Wastes	215	7,602	40%	95	717,873
Green & Yard Wastes	90	3,192	60%	142	452,147
Mixed Paper	289	10,217	0%	-	-
				Biogas Potential	1,170,020 (scf / day)
				Average Daily Throughput	236.08 (tons / day)
				Annual Throughput	95,000 (tons / year)
				Annual Throughput	86,168 (m.t. / year)
				Biogas Potential	813 (scf /min)
				Annual Biogas Potential	427,057,379 (scf / year)
				Biomethane Potential	528 (scf /min)
				Ann. Biomethane Potential	**277,587,296 (scf / year)**

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

Staff notes that biogas yield does not represent the final energy of the product gas. Fugitive biogas losses from the feed compressor (to the biogas refining plant), adsorber capture losses, and product compressor losses additionally reduce the biomethane potential to 470 scfm (see discussion in Section VI). After the biogas has been stripped of its carbon dioxide, staff assumes that part of the remaining biomethane will support the heat requirements of the digesters. This parasitic heat load is discussed in Section IV. The net annual yield of biomethane (production potential) is expected to be over 240 million standard cubic feet of biomethane, and is derived as follows.

Table III-3
Net Annual Biomethane Potential

Source	Biomethane Potential	Unit
Biogas Potential	813	(scf / min)
Biomethane Potential	528	(scf / min)
Feed Compressor Losses	(8.70)	(scf / min)
Adsorber Capture Losses	(41.70)	(scf / min)
Product Compressor Losses	(9.40)	(scf / min)
Annual Biomethane Potential with Losses	471	(scf / min)
Annual Biomethane Potential with Losses	247,703,674	(scf / year)
Digester Heating Requirements	(4,927,429)	(scf / year)
Net Annual Biomethane Production Potential	**242,776,246**	**(scf / year)**
Net Annual Biomethane Energy Potential	**238,199,913**	**(MJ / year)**

IV. HSAD Process

For the purposes of establishing the CI for the HSAD Pathway, staff has simulated biogas production in a high-solids, mesophilic, multi-staged, dry fermentation operation. 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.

The high solids anaerobic digestion (HSAD) process is characterized as an efficient and economical process that requires little pre-processing of wastes (no grinding, slurrying, extensive screening, or filtering is typically required), and relative to low-solids anaerobic digestion systems, has lower water use and shorter reactor residence times to achieve destruction of organic wastes for the production of biogas. The organic matter is biochemically degraded into organic acids (often called "hydrolysate") by a percolation process (Harvest Power, n.d.). After a residence of 14 days in the hydrolyzing units, the digestate is removed and transferred to covered aerated static piles (CASP), where their aerobic conversion to finished compost product begins. The finished compost is then screened, cured, aged, and sold as a soil amendment or fertilizer.

The liquid hydrolysate in the hydrolyzers is drained to buffer tanks and then pumped to methane digesters. The methane digesters contain methanogenic bacteria that consume part of the organic fraction to produce biogas of higher methane content than that produced from comparable wastes in a landfill. It is estimated that the hydrolysate establishes a residence period of an additional 14 days in the methane digesters for a total residence time of approximately 28 days. The biogas collects in the digester header space and is routed to the biogas purification system, where the separation of the methane and carbon dioxide primarily occurs, along with removal of some other trace impurities, such as hydrogen sulfide, to produce pipeline quality biomethane fuel.

Several technologies can be utilized to refine the biogas: pressure-swing adsorption (PSA), water scrubbing, scrubbing with amine solution (MEA), and membrane separation. Although each technology has its own advantages and disadvantages, staff has based its assessment on the use of the PSA system. The technologies suggested are comparable, however, and achieve the same endpoint. While PSA may have a slightly lower methane recovery potential than the other proposed biogas purification technologies, the advantages of PSA make it a viable and sustainable technology for the HSAD Pathway. It is a chemical-free technology, and the presence of methane in the tail gas flare reduces the need to augment the flare gas with additional fuel. Staff also envisions a HSAD Pathway based on conservative assumptions that would qualify a larger number of facilities under the umbrella of the fuel's carbon intensity.

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 HSAD 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, hydrolysis unit loading, bioreactor (methane digester) operation, gas pre-treatment, exhaust fan and blower, instrument air, and power, plant, and lighting (PPL) is estimated to be approximately 1.8 million kilowatt hours per year (kWh / year). Staff assumes that the electricity for the HSAD process will be provided from the public grid, although the entire plant load could be supplied by power derived from the biogas generated by the organic wastes. For this assessment, staff has further assumed that the electricity consumed at the plant is generated using the California Marginal[4] portfolio of electric generating assets specified in CA-GREET.

While staff has modeled an organic waste composition of approximately 40 percent food waste and 60 percent green waste, the HSAD process can accept small quantities of fats, oils, and greases (FOG), as well as mixed paper, especially if the paper is soiled with food wastes. A FOG pre-conditioning and metering system in which the FOG stream is blended with the hydrolysate or directly introduced into the methane digesters[5] would consume marginal amounts of power compared to the total HSAD process load. The electrical energy use for a FOG delivery system is estimated to be approximately 71,260 kWh per year.

The HSAD process is expected to operate in batch mode under mesophilic conditions (i.e., temperatures of 86°F – 100°F) which are optimal for the presence of mesophilic organisms to achieve methanogenic conversion of the waste acids to methane and carbon dioxide. Total heat load, including methane digester heating requirements are estimated to be as follows:

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[4] See the "Regional LT" worksheet in Argonne National Laboratory, and Life Cycle Associates LLC (2009).

[5] Pursuant to Staff conversation with Richard York, Chairman & Co-Founder, FOG Energy Group, on August 14 -15, 2011.

$$
\begin{array}{lr}
\textit{Wastes Loading} & 452{,}265\ kWh \\
\textit{Skin Losses} & 272{,}386\ kWh \\
\textit{Heat Losses in Biogas} & 90{,}578\ kWh \\
\underline{\textit{Less Metabolic Enthalpy}} & \underline{(589{,}660)\ kWh} \\
\boldsymbol{Annual\ Process\ Heat\ Demand}: & \boldsymbol{225{,}569\ \ kWh}
\end{array}
$$

Heat losses from sources such as tunnel openings are estimated to be 30 percent. Therefore, the net annual heat demand is estimated to be

$\boldsymbol{Net\ Heat\ Demand}$

$$
= \frac{225{,}569\ kWh\ per\ year}{(1-0.30)}
$$
$$
= \boldsymbol{322{,}242\ kWh\ per\ year}
$$

The net annual heat demand for the HSAD Pathway is therefore estimated to be as follows:

$\boldsymbol{HSAD\ Pathway\ Net\ Annual\ Heat\ Demand}$

$$
= 322{,}242 \text{ kWh per year } \text{x} \left(\frac{100{,}000 \text{ tons}}{30{,}000 \text{ tons}} \text{ Scale} - \text{up Ratio}\right)
$$
$$
= 751{,}897 \text{ kWh per year}
$$
$$
= 751{,}897 \text{ kWh per year } \text{x} \left(\frac{1 \text{ Btu}}{3{,}412.96 \text{ kWh}}\right)
$$
$$
= \boldsymbol{3{,}666{,}007\ Btu\ per\ year}
$$

For most anaerobic digestion processes, digester heat is typically supplied by systems that recover heat from internal combustion engines (ICE) exhaust gases. Some facilities may also have a combined heat and power (CHP) operation that makes the facility self-sufficient for low heat demand applications. Staff assumes that the heat demand for the HSAD Pathway described above will be provided in the form of steam that is generated using process biogas. A small amount of biomethane is assumed to be diverted from the output stream to a small industrial natural gas boiler.

Assuming the natural gas steam boiler to have an efficiency of 80 percent,[6] the net annual energy and fuel requirements are estimated to be:

[6] CA-GREET v.1.80b (Dec-09), "Inputs" Worksheet (Cell B436). Energy Efficiency of Steam Boilers for Steam Generation (for steam co-generation in many Well-to-Pump Facilities.

$$HSAD\ Process\ Heat\ Loading\ Energy\ Requirements$$

$$= \left(3{,}666{,}007\ \frac{Btu}{year}\right)\ x\ \frac{1}{0.80\ Eff}$$

$$= \left(4{,}582{,}508{,}532\ \frac{Btu}{year}\right)\ x\ \frac{1\ year}{8{,}760\ hours}$$

$$= \mathbf{523{,}117.41\ Btu\ per\ hour}$$

$$HSAD\ Process\ Heat\ Loading\ Fuel\ Requirements$$

$$= \left(523{,}117.41\ \frac{Btu}{hour}\right)\ x\ \frac{1\ scf\ Methane}{930\ Btu\ (LHV)}$$

$$HSAD\ Process\ Net\ Annual\ RNG\ Requirements$$

$$= \mathbf{4{,}927{,}429\ scf\ RNG\ per\ year}$$

The GHG emissions associated with the combustion of approximately 5 million cubic feet of biomethane were estimated using CA-GREET factors and are shown in Table IV-1 below:

Table IV-1
Digester Heat Loading GHG Emissions

Pollutant	Emissions Factor[A] (g / MMBtu)	Annual Emissions (g / year)	Annual GHG Emissions (g CO_2e / year)
VOC	2.417	11,076	34,557
CO	28.822	132,077	207,361
CH_4	1.100	5,041	126,019
N_2O	0.315	1,443	430,160
CO_2	58,176	266,589,946	266,589,946
		Total Annual Emissions	**267,388,043**

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) (Small Industrial Boiler (10-100 mmBtu/hr input)).

Additional grid electric use is anticipated during wastes screening and processing, FOG preconditioning and blending, biogas purification, and biomethane compression and transmission, and during the composting of the digestate process which involves aeration, bio-filtration, and material conveying. This analysis is provided in the next section.

V. Facility Electrical Energy Load

For a HSAD operation that processes 100,000 tons per year of food and green wastes, staff anticipates a process electrical energy load of approximately 1.8 million kilowatt hours per year for waste pre-screening and processing. An additional 71,000 kilowatt hours per year is requested to accommodate FOG pre-conditioning and blending with digester feed.

$$\boldsymbol{Electrical\ Demand\ for\ Anaerobic\ Digestion}$$
$$= \mathbf{1,810,200}\ \boldsymbol{kWh\ per\ year}$$

$$\boldsymbol{Electrical\ Demand\ for\ FOGs\ Pre-Conditioning\ and\ Blending}$$
$$= \mathbf{71,259}\ \boldsymbol{kWh\ per\ year}$$

The total electrical energy requirements for biogas purification is based on the use of an electrical feed compressor, 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 500 kW, or 4.6 million kilowatt hours per year.

$$\boldsymbol{Electrical\ Demand\ for\ Biogas\ Refining}$$
$$= 500\ kW\ \ x\ \ 8{,}760\ hours\ year\ x\ \frac{1}{0.95\ compressor - pump\ efficiency}$$
$$= \mathbf{4,610,526}\ \boldsymbol{kWh\ per\ year}$$

The estimated electrical demand identified above is based on proprietary equipment counts for the respective process units.

Staff notes that in addition to the load demand from the HSAD process units, electrical energy is also used to power equipment in use during composting operations. The aeration equipment, biofilter exhausts, and screening, conveying, and transmission equipment all require electrical energy. It is estimated that composting operations will draw a total of 173,000 kilowatt hours per year of electrical energy. However, fossil fuel based energy use during open windrow composting (which has minimal electrical energy demand) is estimated to be higher than total fossil fuel and electrical energy use during CASP or IVC composting. Therefore, total electrical energy demand for the HSAD facility will be approximately 6.5 million kilowatt hours per year. A summary of the total electrical energy demand for the facility is presented in Table V-1 below.

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

Purpose	Operation	Demand (kWh / year)
Wastes Screening and Processing	HSAD Process	1,810,200
FOGs Preconditioning & Blending	HSAD Process	71,259
Biogas Purification, Compression, & Transmission	Biogas Refining	4,610,526
	Total Annual Demand (kWh)	**6,491,985**

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)

Pollutant	Feedstock (g / mmBtu)	Fuel (g / mmBtu)	Total[a] (g / mmBtu)	Emissions (g / year)	GHG Emissions (g CO_2e / year)
VOC	16.70	5.67	22.37	495,733.88	1,546,690
CO	15.55	39.68	55.23	1,223,668.59	1,921,160
CH4	270.51	7.04	277.55	6,149,730	153,743,250
N2O	0.14	2.48	2.62	58,037	17,295,044
CO2	6,833.08	96,249.68	103,082.76	2,283,999,172	2,283,999,172
				Total Annual Emissions	**2,458,505,316**

[a] 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.

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 (98-99 percent). The biomethane exits the adsorbers 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 HSAD facility. However, staff assumes that since the biomethane meets or exceeds the standards for pipeline quality natural gas,[7] a compressor will be required to further compress the biomethane to utility company pipeline pressure specifications.

Feed and product compressors, as well as compressors used in transmission and distribution, are a significant source of fugitive as well as point-source GHG emissions. Staff 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] Staff 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-2 below. Staff has determined the impact of feed and product compressor methane losses to be an equivalent loss of 5.7 scfm and 9.4 scfm, respectively. These losses represent a charge on the net biomethane fuel generation potential of approximately 8 million standard cubic feet per year, or a decrease in the energy input value of the transportation fuel by approximately 7.8 million MJ / year for the HSAD process.

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[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 Staff conversation with Jack Dunlap, PG&E, on December 29, 2011.

Table VI-1
Feed and Product Gas Compressor Operating Specifications

Parameter	Feed Gas Compressor	Product Gas Compressor	Unit
Type	Reciprocating	Reciprocating	
Fuel Type	Electric	Electric	
Number of Compressor Seals/Cylinders	4	4	
Number of Pressurized Operating Hours	7,000	7,000	per year
Number of Pressurized Idle Hours	1,000	1,000	per year
Number of De-pressurized Idle Hours	760	760	per year
Gas Quality 1	0.65	0.99	Methane (CH_4)
Gas Quality 2	0.35	0.01	Carbon Dioxide (CO_2)

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

Emissions Source	Emissions (metric tons CO_2e/year)
Feed Compressor to Biogas Purification Unit	
- Compressor Seals	665.08
- Compressor Blow Down	717.17
- Pressure Relief Valves	141.66
- Miscellaneous Emissions	68.53
TOTAL EMISSIONS FROM FEED COMPRESSOR	*1,592.44*
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	**4,092.51**

In addition to the sources of point and fugitive GHG emissions identified above, staff has estimated the GHG emissions potential from biomethane compression and transmission in the pipeline. Staff estimated transmission GHG emissions using the CA-GREET model.[9] Furthermore, staff assumed a tie-into the utility company's natural gas transmission system at a distance of five miles. 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).

Staff estimated the total process GHG emissions for the HSAD Pathway by using 100,000 tons per year of food and green wastes as a basis. Staff adjusted the biogas yield from the anaerobic digestion of the wastes to account for the biogas refining efficiency, and feed gas and product gas compressor losses discussed above in this Section. A step-by-step walk through of the GHG emissions from the HSAD process is presented in Table VI-4 below:

[9] CA-GREET Version 1.80b, December 2009. See worksheet modules "T&D" and "T&D FlowChart"

Table VI-4
HSAD Process GHG Emissions

Parameter	Value	Units
Estimated Food and Green Wastes Annual Throughput Less Contaminants	95,000	short tons/year
Estimate of Biogas Yield from Digesters Less Feed Compressor Fugitive Losses	(812.5-8.7) = 803.8	scfm
Estimate of Biomethane Yield (65 percent) in Feed Gas to Biogas Purification Unit	522.5	scfm
Therefore, CO_2 Yield (35 percent):	281.3	scfm
Biogas Refining Adsorber Capture Efficiency (PSA)	92	percent
Tail Gas Methane to Flare or Thermal Oxidizer	41.8	scfm
Biomethane Yield and Flow rate to Compression / Liquefaction Plant:	480.7	scfm
Net Product Gas Less Methane Emissions from Product Compressor	471.3	scfm
Fugitive Biomethane Emissions Not Going to Flare (Volumetric Flow Rate)	9.4	scfm
Fugitive Biomethane Emissions Not Going to Flare (Mass Flow Rate)	11,392.23	g CH_4 / hour
Flare Destruction Efficiency:	99.77	percent
Equivalent CO_2e Emissions (GWP CH_4 = 25)	284,806	g CO_2e / hour
Annualized Equivalent CO_2e Emissions from Uncombusted Flare Methane	2,494,898,372	g CO_2e / year (A)
Total Biomethane and CO_2 to Flare	323.1	scfm
"Pass Through" CO_2 Emissions from Flare (Volume Basis):	276.6	scfm
Uncombusted Flare Methane Emissions (Volume Basis):	0.11	scfm
Uncombusted Flare Methane Emissions (Mass Basis):	131.5	g CH_4 / hour
Equivalent CO_2e Emissions (GWP CH4 = 25)	3,286	g CO_2e / hour
Annualized Equivalent CO_2e Emissions from Uncombusted Flare Methane:	28,786,739	g CO_2e / year (B)
Combusted CO_2 Emissions from Flare ($CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$)	4,863,345,978	g CO_2 / year (C)
"Pass Through" CO_2 Emissions from Flare (Mass Basis):	8,073,100,223	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)
HSAD Process GHG (CO_2e) Emissions (A + B + C + D + E)	**19,591,167,935**	**g CO_2e / year**

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

- Feed and 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 HSAD plant to the utility company's natural gas distribution system estimated in Table VI-3 above; and
- The HSAD 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)
HSAD Process CO_2e Emissions	19,591,167,935
Total Feed and Product Gas Compressor Emissions	4,092,507,254
Transmission to Pipeline Emissions	536,387,008
Total Annual HSAD Process GHG Emissions (g CO_2e)	**24,220,062,198**

VII. Co-Product Composting Operations

The solid residue that is left behind in the hydrolyzing (percolating) units after the hydrolysate is removed is high in organic nutrients and could be further composted into a soil amendment or fertilizer. Additional composting stabilizes the material and generally improves its usability. HSAD digestate is typically blended with a bulking agent that may comprise of "overs,"[10] or fresh green wastes, and the combined material is then composted. As shown below, the addition of the bulking agent has no significant impact on the GHG emissions from the digestate composting process. Once the compost is cured, the finished compost is screened and the larger bulking agent particles are removed and recycled back into the process.

Commercial-scale composting operations in California employ three main composting methods: open windrows composting (OWC), covered aerated static piles (CASP), and in-vessel composting (IVC). Staff will present an overview of each method, and estimate the contribution of composting emissions to the CI of the HSAD Pathway.

a. Composting Methods

<u>Open Windrow Composting:</u>

In this method, by far the dominant one in California, organic materials are formed into elongated piles up to 1000' long, 20' wide, and 8' tall. Operators may use any combination of hand sorting, mechanical trammeling, grinding, and mixing to remove contaminants and prepare the material for the windrow compost process. A typical summer green waste mix may be fairly close to the optimal carbon-to-nitrogen ratio (estimated to be 30:1) for aerobic windrow composting. If the composter has accepted other ingredients, such as wet grass, food wastes, cannery wastes, winery wastes, or manure, it will need to be mixed with a bulking agent such as leaves or woody wastes. The optimal mix for digestate is not yet known, but it is likely to need dry, carbon-rich materials.

At a typical operation, windrows are mechanically churned with a diesel-powered windrow turner at least 10 times over a period of 60-90 days. Windrow composting is an aerobic process; turning ensures that all materials are fully composted, and that air can

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[10] A "bulking agent" is typically high-carbon materials such as woody waste, sawdust, etc. "Overs", implies the oversized and uncomposted woody fraction left over when finished compost is screened. Once the C:N ratio and moisture content of the digestate is known, the optimal bulking agent can be determined.

penetrate deep into the pile. Turning occurs frequently in the beginning, and much less regularly later during the "curing" process. Before it is sold, windrow compost is required to undergo the "Process for Further Reduction of Pathogens," (PFRP) in which pile temperatures are maintained above 131°F (55°C) for a minimum of 15 days while the operators turn it a minimum of five times (CCR, 2012). Piles must be watered regularly throughout the "active" composting process to maintain optimum moisture, particularly during California's hot, dry summers.

Windrow composting has been the preferred method in California because of the large volumes of feedstock generated by the hundreds of municipal green waste collection programs begun in response to the passage of the Integrated Waste Management Act in 1989.[11]

Although the volatile organic compound emissions from the windrow composting of green wastes have been the focus of many studies, the results have been highly variable. These studies suggest that an emission factor of five pounds of VOC per ton of green waste feedstock is reasonable. Emissions could be higher, however, depending on feedstock composition, climatic conditions, and management practices. The VOCs emitted, primarily small chain alcohols are fairly ubiquitous and stable, and should not be considered potent precursors of ozone or secondary aerosols. The use of digestate as a composting feedstock may lower windrow VOC emissions because many of the most volatile compounds in the original organic wastes are removed during digestion.

A layer of fully cured finished compost, known as a pseudo-biofilter compost cap, is now required in two California air quality management districts in order to reduce windrow emissions (SJVUAPCD, 2011 and SCAQMD, 2003). Studies performed by CalRecycle show the technique can reduce emissions by up to 75 percent over the first two weeks (CalRecycle, 2007). According to San Joaquin Valley Unified Air Pollution Control District (SJVUAPCD) rules, recapping the windrow after each turn for the first 22 days reduces emissions by more than half. SJVUAPCD requires a windrow watering regime for small and mid-sized facilities, and credits this practice with a VOC reduction of about 25 percent.

Emissions of GHGs from this method of composting are less well known. Existing literature on this subject has focused on feedstocks and conditions that are not representative of California. CalRecycle has contracted with the University of California at Davis for a multi-year

[11] Pub. Resources Code, section 40050-40063.

evaluation of the GHG emissions directly related to compost production in windrows and covered aerated static piles, as well as from the use of the finished product on agricultural land. Data from this study should be available in 2014.

Covered Aerated Static Piles (CASP):

The covered aerated system constitutes a lower-cost bridge between open windrows and fully enclosed composting systems. These systems accomplish aeration through the use of blowers, but capture emissions and retain moisture by using a waterproof, breathable fabric covering. The cover itself functions as a capture device to reduce emissions, due in part to a moisture layer that develops on the inside of the cover. Emissions condense within this layer, drain back into the pile, and are consumed by the ongoing microbial activity. The gases could also be directed through an exhaust system to a biofilter. CASP operations are desirable where large volumes of highly putrescible materials such as post-consumer food waste must be processed in close proximity to odor-sensitive neighbors.

Prior to being placed into covered piles, arriving compostable materials must be sorted, ground, and blended in order to achieve the optimal carbon-to-nitrogen ratio, moisture content, and density. Once covered, a pile will typically remain in place for several weeks. Many operators will then move and re-cover the pile for another few weeks, before curing the compost in an open windrow. As long as the pile is capped with, an insulating layer of pathogen-reduced materials at least 12 inches thick, PFRP can be attained within three days of temperatures above 131°F (55°C).

Covered ASPs can provide emissions reduction of more than 95 percent reduction compared to an open windrow baseline. Costs and operational complexities have slowed implementation; however, air district policies are making such systems more common in California's local air basins that are non-attainment for ambient air quality standards for ozone. One major air district now requires an 80 percent reduction in emissions for new or expanded composting operations and offsets for the remaining emissions over 10 tons per year. Other districts will allow an increase in throughput without offsets as long as overall facility emissions do not increase. In both cases, covered ASP may be the most cost-effective solution.

Aerated static piles may also be operated without fabric covers, as is done at one large biosolids co-compost operation in Kern County. This facility achieves the 80 percent emissions reduction standard by use of powerful fans that vacuum air down through the pile and route it to a biofilter. Although static piles by their nature reduce the amount of diesel fuel energy needed to work the piles and produce compost, the larger fan configurations may consume significant amounts of electrical energy.

<u>In-Vessel or Enclosed Composting:</u>

Although it is the most expensive composting method, and in limited use, In-Vessel Composting (IVC) is more effective than the other two methods at reducing emissions. Emissions reductions of 95 percent or greater are possible with IVC. In California, three types of IVC facilities have been constructed:

- large, pressurized buildings in which all indoor air—including emissions from compost windrows, is continually routed through a biofilter;
- tunnel composting structures which are similar in structure and function to high-solids anaerobic digesters; and
- relatively tiny tubs and cylinders.

The last configuration may be favored at institutions such as college campuses that generate relatively small amounts of highly putrescible materials that can be composted and used on-site. Fully enclosed facilities may be necessary in highly populated areas where no composting odors are acceptable, or when an operator is handling sensitive feedstocks such as municipal solid waste, food wastes, or biosolids. In the largest fully enclosed facilities, all material handling, sorting, and blending is accomplished indoors.

Regardless of how the composting is done, once the compost is finished curing it must be screened to remove large, un-composted pieces, which are typically routed back into the beginning of the composting process. Many operators use a piece of equipment called an air-lift separator, or “Hurricane,” to remove bits of plastic and light contaminants. Once the product is cured, cleaned, and ready for sale, the operators must test it for two pathogens and nine heavy metals. Once the product has passed these tests, operators may blend in amendments such as gypsum, topsoil, or other minerals, as requested by the customers.

b. Composting GHG Emissions

In order to estimate the pathway GHG emissions and the offsetting carbon credit associated with the HSAD Pathway, staff has accounted for all emissions—including biogenic composting emissions occurring within the pathway system boundaries. In the resulting model, biogenic composting emissions are fully offset by the credit from avoided landfilling and composting emissions. This credit is discussed in Section VIII of this report.

Staff based carbon emission estimates from compost operations on estimates of digestate yield for the HSAD process. Furthermore, staff based carbon dioxide emissions factors on the dry weight reduction of the organic fraction of municipal solid wastes during open windrow composting (Komilis and Ham, 2004). Additionally, compost operation CH_4 and N_2O emissions, due to the high global warming potentials (GWP)[12], are significant. Staff used fugitive emissions factors for emissions from composting operations (ARB, 2011) to estimate both CH_4 and N_2O emissions. Based on a review of existing green waste composting operations, staff concluded that compost facility operators will employ biofilters to reduce volatile organic compound (VOC) and ammonia (NH_3) emissions. Biofilters have been shown to be effective at reducing nitrous oxide emissions (ECS, 2007) as well. Staff has therefore based its compost operations emissions estimates on the level of control typically achieved by biofilter use. The use of this pathway carbon intensity value is therefore contingent upon the deployment of biofilters to control VOC emissions.

Compost operations produce GHG emissions from two sources: the equipment used to transfer materials and work the piles, and the fans used to force air through the aerated static piles. The emissions from these sources are estimated in Section II, above. Electrical and diesel GHG emissions from the compost operations are also discussed in Section II.

Staff estimated GHG emissions based on an annual throughput of 30,000 tons per year of mixed food and green wastes. Staff then applied a scale-up ratio to estimate the emissions for an annual throughput of 100,000 tons per year of organic feedstock. Factors for estimating GHG emissions are presented in Table VII-1 and Table VII-2 below:

[12] The GWPs for methane (CH_4) and nitrous oxide (N_2O) used in this pathway analysis were 25 and 298, respectively (CA-GREET version 1.80b, December 2009).

Compost CO_2 Emissions

The derivation of the estimated CO_2 emissions from the composting of HSAD digestate is summarized in Table VII-1. The basis for these estimates is as follows:

$$CO2\ Yield = DR\ x\ (490\ \pm 18) \frac{g\ C}{dry\ kg\ of\ organic\ fraction\ of\ MSW}$$

$where,$

$$DR\ = dry\ weight\ reduction\ of\ the\ organic\ fraction\ of\ the\ MSW$$

Table VII-1
Estimated CO_2 Emissions from Composting Operations

Parameter	Parameter Identifier	Value	Unit
Dry weight		0.4186[a]	-
CO_2 Yield		205.12	g C / dry kg of the organic fraction of wastes
CO_2 Yield	A	752,093	g CO_2 / metric ton total solids (TS) digestate
Digestate Yield	B	0.8413	Wet Basis
Digestate total solids Yield / Metric Ton of Digestate Yield	C	0.1955	-
Annual Throughput of Raw Organic Wastes (Less Inerts)	D	86,168	Metric tons organic food and green wastes
Composting CO_2 Emissions (1)	**(A x B x C x D)**	**10,631,715,546**	**g CO_2 / year**

[a] DR fraction is based on empirical measurements of digestate and finished compost yields (Staff Correspondence dated September 29, 2011).

Compost CH_4 and N_2O Emissions

Staff estimated uncontrolled methane and nitrous oxide emissions from the compost operations using fugitive emissions factors for composting (ARB, 2011). To reflect reductions from the biofilters that some local air districts require, VOC emissions were reduced by 80 percent. Emissions of CH_4 and N_2O, as adjusted for the atmospheric warming potential, are summarized in Table VII-2 below.

Table VII-2
Estimate of CH_4 and N_2O Emissions from Composting Operations

Parameter	Equation Identifier	Value	Unit
Uncontrolled CH_4 Emissions Factor		4.10	g / kg wastes (wet basis)
N_2O Emissions Factor		0.09	g / kg wastes (wet basis)
VOC Control Efficiency (a)		80 percent	
CH_4 Emissions GWP		25	
N_2O Emissions GWP		298	
Controlled GHG Emissions Factor (CH_4 + N_2O)	A	56,340	g CO_2e / metric ton (wet basis)
Digestate Yield	B	0.84	wet basis
Annual Throughput of Raw Organic Wastes	C	86,168	metric tons
Composting CO_2e Emissions (2)	**(A x B x C)**	**4,074,767,713**	**g CO_2e / year**

[a] Based on SCAQMD Rule 1133.3 "Technology Assessment for Proposed Rule 1133" (Appendix C). Also see SJVAPCD Rule 4565, Sec 5.3.3 for Biofilter performance on Compost Piles.

A summary of total direct CO_2 emissions from the compost operations identified in Table VII-1 (1) and other GHG emissions identified in Table VII-2 (2) is presented in Table VII-3 below:

Table VII-3
Summary of Total GHG Emissions from Compost Piles

Parameter	Identifier	Value	Unit
Composting CO_2 Emissions	(1) from Table VII-1	10,631,715,546	g CO_2 / year
Composting CO_2e Emissions	(2) from Table VII-2	4,074,767,713	g CO_2e / year
Total Composting GHG Emissions	**(1 + 2)**	**14,706,483,260**	**g CO_2e / year**

VIII. Credits and Proposed Carbon Intensity

a. Carbon Credit for Avoided Emissions

The breakdown of organic matter in an anaerobic digestion vessel 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 vessel, 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. Staff believes that the diversion of food and 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 anaerobic digestion facility has to the potential to impact the transportation component of the life cycle analysis,[13] emissions reductions from reduced waste processing at the landfill will be accounted for in this HSAD Pathway when and if the magnitude of the effect becomes clear in landfill emissions inventory data.

By diverting organic wastes such as food and 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 anaerobic digestion process, not only is a valuable transportation fuel and fertilizer produced, but the impact of decomposing organic matter on the environment is reduced. This greater accountability of material and energy flows makes it possible to estimate an HSAD carbon credit that exceeds the flaring credit associated with the simple capture and use of landfill gas (LFG). Hence, staff has created a carbon credit model for avoided landfilling and composting emissions from food and green wastes by accounting

[13] This 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.

for the GHG emissions from the carbon contained in the HSAD Pathway feedstock waste streams. A schematic of the carbon credit model for food wastes diverted from the landfill and composting waste streams appears in Figure VIII-1 below.

The carbon credit model developed from the schematic shown in Figure VIII-1 begins with the simplifying assumption that food wastes are comprised of a simple sugar ($C_6H_{12}O_6$). The moisture content of these wastes is assumed to be 70 percent. Given these assumptions, the carbon content of the feedstock waste stream comes to 12 percent. Of that 12 percent, 8 percent is assumed to be stable and not subject to rapid decomposition (Barlaz, 2008). This eight percent fraction is designated as "inactive," and is excluded from subsequent estimates of GHG emissions. All carbon except for this fraction is assumed to undergo either anaerobic digestion or aerobic conversion.

Staff assumes that the alternative destination of most of the food wastes that would be diverted to the HSAD Pathway would be the landfill. A small proportion would find its way to green waste composting facilities.

Of the methane that is generated by the decomposing food wastes in the landfill, staff estimates that approximately 75 percent would be captured by the landfill gas collection system and be directed to a flare, or a biogas fuel generator to produce power. The remainder of the methane is assumed to be fugitive, escaping to the atmosphere. Evidence suggests that a small fraction of the fugitive methane is oxidized to carbon dioxide in the soil cover as it makes its way from deep within the landfill to the surface. This rate has been found to be at least 10 percent (Chanton et al, 2009). The remaining 90 percent of the uncollected landfill gas makes up the fugitive LFG fraction. Of the LFG that is collected, staff assumes that, at a minimum, the gas could be combusted in a flare. The flare is assumed to have a 99.7 percent destruction efficiency. Approximately one percent of the collected LFG would not be destroyed by the flare.

A detailed overview of the food waste carbon credit model is shown in Figure VIII-2. The credit calculated is based on one metric ton of food wastes and then applied to the estimated annual throughput of wastes for the HSAD Pathway.

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

Basis: 1 Metric Ton Organic Wastes Feed (Wet Basis) (Diverted from Landfill)	Fraction Carbon 12.0%	Inactive Carbon 8.0%	Total Available Carbon 92.0%
(kg) 1000.0	(kg) 120.0	(kg) 9.6	(kg) 110.4

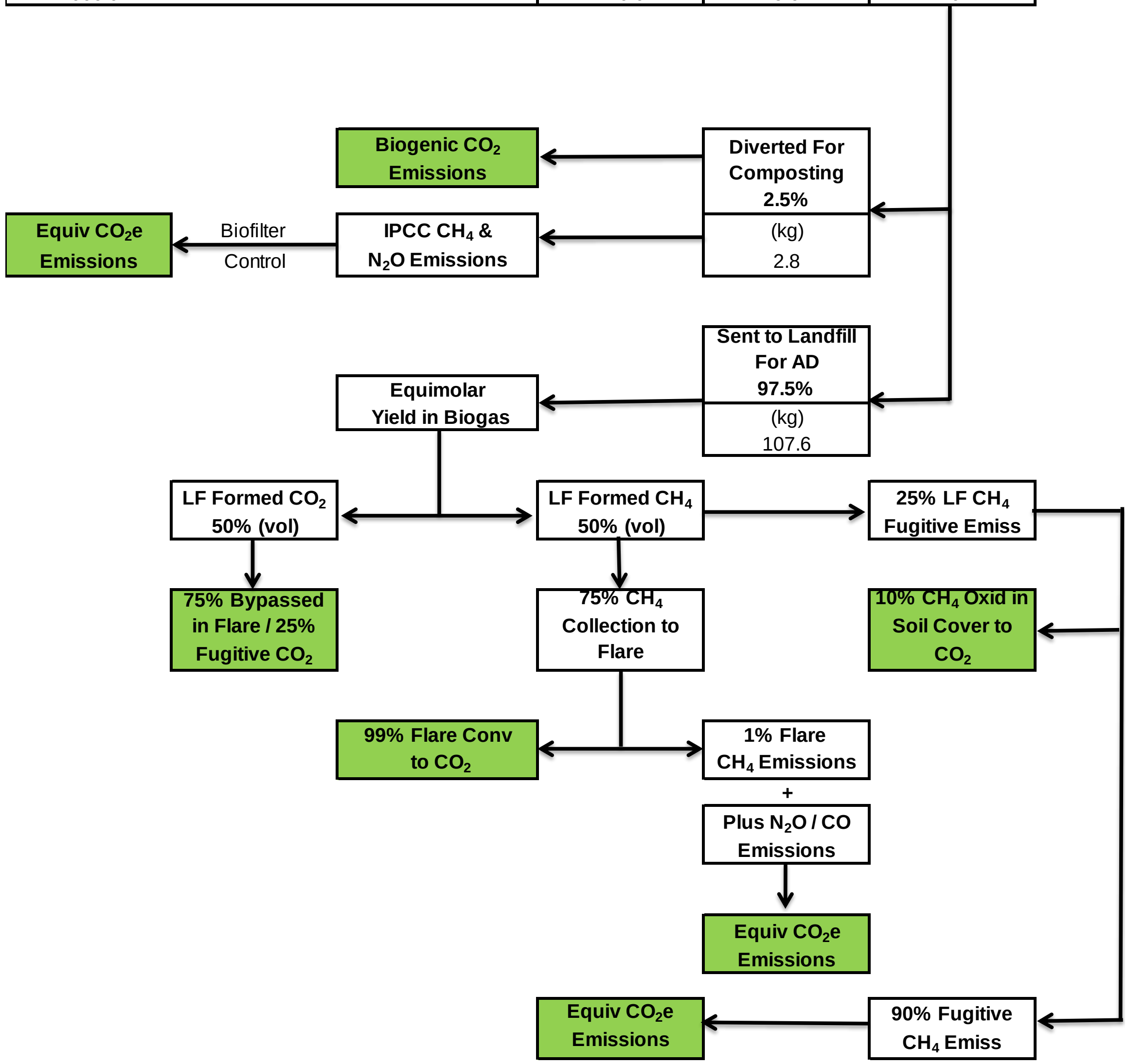

Figure VIII-2
Carbon Credit Model for Avoided Landfilling and Composting Emissions (Food Waste)

I. Basis: 1 Metric Ton of Food Wastes (Represented by Simple Sugar Molecule) Sent to Landfill or Compost Facility

Raw Organic Feed	Fraction Carbon	Total Carbon	INACTIVE C (Carbon Storage) (2)	AVAILABLE CARBON (kg) (3) TOTAL C (1)	C For COMPOSTING	C For AD in LF
(kg)		(kg)	**8.00%**	(kg)		(kg)
1000.00	0.12	120.00	9.60	110.40	2.79	107.61

II. Landfill Methane and CO_2e Emissions

For Equimolar Yields of CH4 and CO2 by AD; 1 kg-mol CH4 is produced for every 1 kg-mol of CO2 (C6 --> 3 CH4 + 3 CO2) (11)

Therefore, Amount of Carbon Used for Methane Production		53.81	kg C
Therefore, Amount of Carbon Used for Carbon Dioxide Production		53.81	kg C
Amount of Methane Produced		71.74	kg CH4 / metric ton
		4.48	kg-mol CH4 / metric ton
Amount of Carbon Dioxide Produced		197.29	kg CO_2 / metric ton
		4.48	kg-mol CO_2 / metric ton
1 kg-mol at STP ----> 22.4 x 1,000 liters, Therefore, Volume of Methane Produced		100,439.62	liters CH4 @ STP / metric ton
		100.44	**m3 CH4 @STP / metric ton**
1 kg-mol at STP ----> 22.4 x 1,000 liters, Therefore, Volume of Carbon Dioxide Produced		100,439.62	liters CO2 @ STP / metric ton
		100.44	m3 CO2 @STP / metric ton
Total Biogas Volume and Quality at Source	0.50	**200.88**	m3 Biogas @STP / metric ton
Staff Applied Landfill Gas Collection Efficiency		**75.00%**	
Therefore, Biogas Collected for Flaring:		150.66	m3 Biogas @STP / metric ton
Therefore, Fugitive Biogas Uncollected:		50.22	m3 Biogas @STP / metric ton
Fugitive Biomethane Emissions from Landfill (Volume Basis)		25,109.91	liters CH4 @STP / metric ton
- Percentage of Biomethane Assumed to be Oxidized to CO2 in Soil Cover (9)	CH4 Ox to CO2	**10.00%**	
- Net Fugitive Biomethane Emissions from Landfill (Volume Basis)	2,510.99	22,598.91	liters CH4 @STP / metric ton
Fugitive Biomethane Emissions from Landfill (Mass Basis):	1,793.56	16,142.08	grams CH4 / metric ton
Fugitive CO2 Emissions from Landfill (Volume Basis)		25,109.91	liters CO2 @STP / metric ton
Fugitive CO2 Emissions from Landfill (Mass Basis)	4,932.30	49,323.03	grams CO2 / metric ton
Given GWP of 25 for Methane, Equivalent CO2e Emissions from Landfill (Mass):		**457,807.38**	**g CO2e / metric ton**

III. Flare CO2e Emissions and Unflared Methane Emissions

Quantity of Biogas Collected and Sent to Flare:	150.66	m3 Biogas @STP / metric ton
Flare Destruction Efficiency (4):	**99.767%**	
Uncombusted Biomethane from Flare:	125.37	grams CH4 / metric ton
Given GWP of 25 for Methane, Equivalent CO2e Emissions from Flare (Mass):	3,134.25	g CO2e / metric ton
Uncombusted CO2 Emissions from Flare:	147,969.09	g CO2 / metric ton
CO2 Emissions from Biomethane Combustion:	147,624.32	g CO2 / metric ton
Secondary N2O Emissions from Flare (5):	47.53	g N2O / metric ton
Secondary CO Emissions from Flare (5):	55.52	g CO / metric ton
Total CO2e Emissions from Flare:	**312,979.67**	**g CO2e / metric ton**

IV. CO2e Emissions from Aerobic Composting of Organic Carbon

Organic Carbon Assumed to be Sent to Composting Facility:	2.79	kg C / metric ton
Organic Fraction that is Comprised of Food Wastes:	1.00	
Organic Fraction that is Comprised of Yard / Green Wastes:	-	
Yield of CO2 Based on Fractions of Food and Green / Yard Wastes (6):	1,030.86	g C / metric ton
Carbon Conversion to CO2:	3,779.84	g CO2 / metric ton
Add Transport Emissions Avoided for Transport to Compost Facility (If Any)		
Equivalent CH4 Emissions from Composting (7)	685.39	g CO2e / metric ton
Equivalent N2O Emissions from Composting (7)	622.70	g CO2e / metric ton
Total Avoided CO2 Emissions from NOT Composting:	**5,087.92**	**g CO2 / metric ton**

V. Calculated Theoretical Credit

Total Avoided Landfilling / Flaring / Composting Emissions (III + IV + V Above)			775,874.97	g CO2 / metric ton
Less Carbon Credit Offset for Long Term Land Application / Sequestration			-	g CO2 / metric ton
Net Carbon Credit for Avoided Landfilling or Composting Food & Green Wastes			**775,874.97**	**g CO2e / metric ton**
Estimated Food and Green Wastes Annual Throughput			100,000.00	short tons/year
Less Inert Media and Plastic / Metal Contaminants (5-10%) (8)	**INERT MEDIA:**	5%	5,000.00	short tons/year
Estimated Food and Green Wastes Pre-Screened Annual Throughput			95,000.00	short tons/year
Estimated Food and Green Wastes Pre-Screened Annual Throughput			86,167.80	metric tons/year
Estimated Fraction that is Green Wastes:			40.00%	
Potential Total Carbon Credit (Applied to OFMSW - Screened Throughput):			**26,742,175,836.69**	**g CO_2e/year**

Similarly, a schematic of the carbon credit model for diverting green wastes from landfill disposal or from green waste composting is shown in Figure VIII-3 below.

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 HSAD 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.

Because the assumptions about the alternative fate of green wastes are the same as the corresponding assumptions for food wastes, they will only 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.

Figure VIII-3
Schematic of Natural Fate of Carbon in Green Waste

Basis: 1 Metric Ton Organic Wastes Feed (Wet Basis) (Diverted from Landfill)	Fraction Carbon 26.7%	Inactive Carbon 36.4%	Total Available Carbon 63.6%
(kg) 1000.0	(kg) 266.7	(kg) 97.2	(kg) 169.5

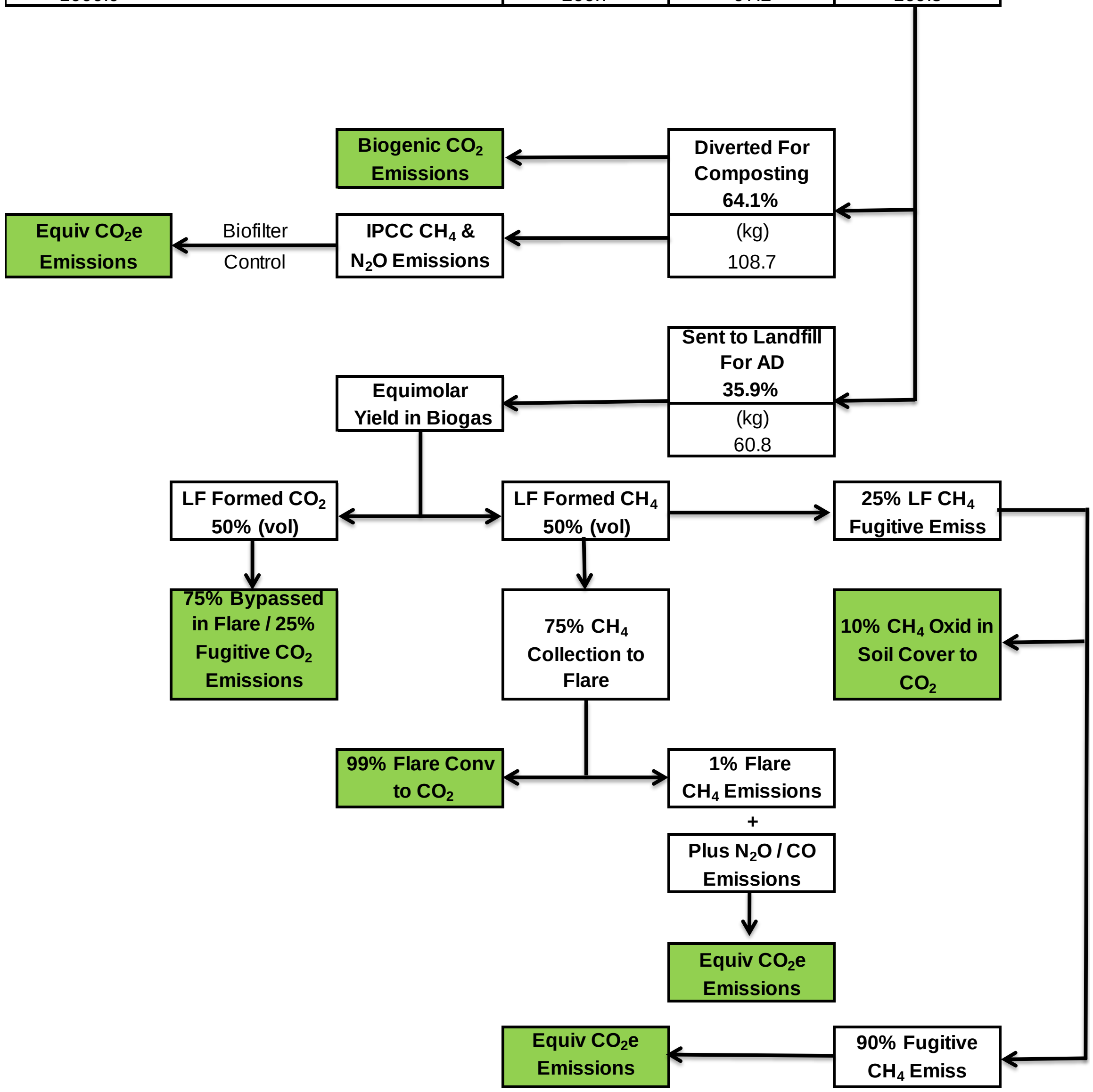

Figure VIII-4
Carbon Credit Model for Avoided Landfilling and Composting Emissions (Green Waste)

I. Basis: 1 Metric Ton of Cellulosic Biomass (Represented by Cellulose Molecule (Monomer)) Sent to Landfill or Compost Facility

Raw Organic Feed	Fraction Carbon	Total Carbon	INACTIVE C (Carbon Storage) (2)	AVAILABLE CARBON (kg) (3) TOTAL C (1)	C For COMPOSTING	C For AD in LF
(kg)		(kg)	**36.44%**			
1000.00	0.2667	266.67	97.17	169.49	108.66	60.83

II. Landfill Methane and CO_2e Emissions

For Equimolar Yields of CH4 and CO2 by AD; 1 kg-mol CH4 is produced for every 1 kg-mol of CO2 (C6 --> 3 CH4 + 3 CO2) (11)

Therefore, Amount of Carbon Used for Methane Production		30.42	kg C
Therefore, Amount of Carbon Used for Carbon Dioxide Production		30.42	kg C
Amount of Methane Produced		40.55	kg CH4 / metric ton
		2.53	kg-mol CH4 / metric ton
Amount of Carbon Dioxide Produced		111.52	kg CO_2 / metric ton
		2.53	kg-mol CO_2 / metric ton
1 kg-mol at STP ----> 22.4 x 1,000 liters, Therefore, Volume of Methane Produced		56,775.07	liters CH4 @ STP / metric ton
		56.78	**m3 CH4 @STP / metric ton**
1 kg-mol at STP ----> 22.4 x 1,000 liters, Therefore, Volume of Carbon Dioxide Produced		56,775.07	liters CO2 @ STP / metric ton
		56.78	m3 CO2 @STP / metric ton
Total Biogas Volume and Quality at Source	50.00%	**113.55**	m3 Biogas @STP / metric ton
Staff Applied Landfill Gas Collection Efficiency		**75.00%**	(Applies to Biogas Volume Only)
Therefore, Biogas Collected for Flaring:		85.16	m3 Biogas @STP / metric ton
Therefore, Fugitive Biogas Uncollected:		28.39	m3 Biogas @STP / metric ton
Fugitive Biomethane Emissions from Landfill (Volume Basis)		14,193.77	liters CH4 @STP / metric ton
- Percentage of Biomethane Assumed to be Oxidized to CO2 in Soil Cover (9)	CH4 Ox to CO2	**10.00%**	
- Net Fugitive Biomethane Emissions from Landfill (Volume Basis)	1,419.38	12,774.39	liters CH4 @STP / metric ton
Fugitive Biomethane Emissions from Landfill (Mass Basis):	1,013.84	9,124.56	grams CH4 / metric ton
Fugitive CO2 Emissions from Landfill (Volume Basis)		14,193.77	liters CO2 @STP / metric ton
Fugitive CO2 Emissions from Landfill (Mass Basis)	2,788.06	27,880.61	grams CO2 / metric ton
Given GWP of 25 for Methane, Equivalent CO2e Emissions from Landfill (Mass):		**258,782.79**	**g CO2e / metric ton**

III. Flare CO2e Emissions and Unflared Methane Emissions

Quantity of Biogas Collected and Sent to Flare:	85.16	m3 Biogas @STP / metric ton
Flare Destruction Efficiency (4):	**99.77%**	
Uncombusted Biomethane from Flare:	70.87	grams CH4 / metric ton
Given GWP of 25 for Methane, Equivalent CO2e Emissions from Flare (Mass):	1,771.69	g CO2e / metric ton
Uncombusted CO2 Emissions from Flare:	83,641.84	g CO2e / metric ton
CO2 Emissions from Biomethane Combustion:	83,446.96	g CO2e / metric ton
Secondary N2O Emissions from Flare (5):	26.87	g N2O / metric ton
Secondary CO Emissions from Flare (5):	31.38	g CO / metric ton
Total CO2e Emissions from Flare:	**176,917**	**g CO2e / metric ton**

IV. CO2e Emissions from Aerobic Composting of Organic Carbon

Organic Carbon Assumed to be Sent to Composting Facility:	108.66	kg C / metric ton
Organic Fraction that is Comprised of Food Wastes:	-	
Organic Fraction that is Comprised of Yard / Green Wastes:	1.00	
Yield of CO2 Based on Fractions of Food and Green / Yard Wastes (6):	26,079.10	g C / metric ton
Carbon Conversion to CO2:	95,623.36	g CO2 / metric ton
Add Transport Emissions Avoided for Transport to Compost Facility (If Any)		
Equivalent CH4 Emissions from Composting (7)	12,028.98	g CO2e / metric ton
Equivalent N2O Emissions from Composting (7)	10,928.77	g CO2e / metric ton
Total Avoided CO2 Emissions from NOT Composting:	**118,581**	**g CO2 / metric ton**

V. Calculated Theoretical Credit

Total Avoided Landfilling / Flaring / Composting Emissions (III + IV + V Above)			554,280.55	g CO2 / metric ton
Less Carbon Credit Offset for Long Term Land Application / Sequestration				g CO2 / metric ton
Net Carbon Credit for Avoided Landfilling or Composting Food & Green Wastes			**554,280.55**	**g CO2e / metric ton**
Estimated Food and Green Wastes Annual Throughput			100,000.00	short tons/year
Less Inert Media and Plastic / Metal Contaminants (5-10%) (8)	**INERT MEDIA:**	5.00%	5,000.00	short tons/year
Estimated Food and Green Wastes Pre-Screened Annual Throughput			95,000.00	short tons/year
Estimated Food and Green Wastes Pre-Screened Annual Throughput			86,167.80	metric tons/year
Estimated Fraction that is Green Wastes:			60.00%	
Potential Total Carbon Credit (Applied to OFMSW - Screened Throughput):			**28,656,681,521**	**g CO_2e/year**

The total carbon credit for avoided landfilling and composting emissions when food and green wastes are diverted is the sum of the carbon credits from the individual food and green waste models. The key difference between the two models is that a greater proportion of the carbon in the green waste remains inactive. More of the carbon in the food wastes is available to the anaerobic digestion process. In addition to that difference, green and food wastes do not make up equal proportions of the overall feedstock stream in this model. Green and food wastes enter the HSAD process in an approximate 60:40 ratio.

Under the HSAD Pathway, an annual throughput of 100,000 tons per year of food and green wastes produces an estimated carbon credit of 55.4 billion g CO_2e per year. Table VIII-1 below presents a summary of the overall carbon credit for avoided emissions.

Table VIII-2
Summary of Carbon Credits for Avoided Emissions

Parameter	Identifier	Value	Unit
Estimated Food and Green Wastes Pre-Screened Annual Throughput		86,168	metric tons / year
Estimated Fraction that is Food Wastes		40 percent	
Estimated Fraction that is Green Wastes		60 percent	
Total Avoided Landfilling / Flaring / Composting Emissions (Food		775,875	g CO_2e / metric ton
Total Carbon Credit (Food Wastes)	A	26,742,175,837	g CO_2e / year
Total Avoided Landfilling / Flaring / Composting Emissions (Green		554,281	g CO_2e / metric ton
Total Carbon Credit (Green Wastes)	B	28,656,681,521	g CO_2e / year
Applicable Carbon Credit for HSAD Pathway	**A + B**	**55,398,857,358**	**g CO_2e / year**

[a] Even though green wastes generate fewer GHG emissions per metric ton and contain more inactive carbon than food wastes, they generate a larger carbon credit than green wastes. This is an artifact of the way the credits are calculated: green and food waste credits are weighted in a 60:40 proportion.

b. Co-Product Credit

The solid residue that remains in the HSAD hydrolyzing units (digestate) contains organic nutrients that, when further composted, yield a high-quality compost material that is marketed as a soil amendment or a fertilizer. However, composting of the remaining digestate is fossil-fuel-energy-intensive. In addition, the estimated emissions from green waste composting could have a big impact on the overall contribution to GHG emissions. A portion of these emissions could, however, be considered to be of biogenic origin. The market impact of fully utilizing available resources by composting the digestate is the displacement of synthetically produced fertilizer. The magnitude of this displacement effect can be estimated by assuming that the nutrients in the composted digestate displace equal proportions of synthetically produced nitrogen, phosphorus, and potassium (NPK). The net GHG savings from the displacement of the synthetic fertilizer becomes the HSAD Pathway's co-product credit.

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). 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 compost is subtracted. Staff estimates that the conversion factor to change the basis from one ton of finished compost to one ton of digestate is approximately 0.64. To account for the yield of digestate, 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:

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

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

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

$$\text{CERF (annualized)} = \frac{\text{0.15 MTCO2e}}{\text{metric ton feedstock}} \text{ x } \frac{\text{86,168 metric ton feedstock}}{\text{per year}}$$

$$\boldsymbol{CERF\ (annualized) = \frac{13,193\ metric\ ton\ CO2e}{year}}$$

Lastly, the credit is given for displacing commercially produced fertilizer in the open market. The finished compost is assumed to sell one-for-one with commercially produced fertilizer. The synthetic N displacement ratio is calculated based on the amount of final digestate in the finished compost material to the total amount of finished compost material. This ratio was found to be 0.36. In other words, the composting process achieves a reduction in mass of the original yield of digestate from the HSAD process. Staff assumes that all loss in mass ensues from the digestate and that the bulking agent is nothing but a tie-in component.

$$\boldsymbol{Total\ annual\ carbon\ emissions\ co-product\ credit}$$

$$= \frac{13{,}193\ metric\ ton\ CO2e}{year}\ x\ \frac{1{,}000\ kg}{metric\ ton}\ x\ \frac{1{,}000\ g}{kg}\ x\ \frac{0.36\ final\ digestate}{(finished\ compost)}$$

$$= \boldsymbol{\frac{4,711,783,026\ g\ CO2e}{year}}$$

c. Tank-to-Wheel Emissions

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-2 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 HSAD 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 compost co-product; and
- Tank-to-wheels tailpipe GHG emissions.

A summary of all Well-to-Wheels emissions is presented in Figure VIII-5 below.

Table VIII-4
Proposed CI for HSAD 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)
242,776,246	**238,199,913**			
GHG Emissions Source	**(g CO_2e / year)**			
HSAD Process GHG Emissions	24,220,062,198		6,491,985	
HSAD Process Heat Loading Requirements	267,388,043			4,927,429
HSAD Compost GHG Emissions	14,706,483,260			
HSAD Wastes Loading Fossil Fuel Use & Emissions	174,566,466	17,405		
HSAD Compost Operations Fossil Fuel Use & Emissions	546,746,602	54,511		
Total Fossil Fuel Use Emissions	721,313,068			
Total Fuel Cycle Electric Emissions	2,458,505,316			
Total Low Sulfur Diesel WTT Emissions	197,919,954			
Total HSAD Process Emissions	42,571,671,837			
GHG Emissions from CNG Combustion in HDV (TTW)	13,896,324,909			
Less Carbon Credit from "MODEL"	-55,398,857,358			
Less Compost Emissions Reduction Factor (CERF)	-4,711,783,026			
Net Annual GHG Emissions	-3,642,643,637			
Proposed HSAD Pathway CI (g CO_2e/MJ):	**-15.29**	**71,916**	**6,491,985**	**4,927,429**

Based on the analysis in this report, staff estimates the CI of the biomethane fuel produced from the high solids anaerobic digestion of food and green wastes to be -15.29 g CO_2e / MJ of energy.

e. Conditions for Use of CI Value

Staff has stipulated some specific conditions that prospective users of this HSAD 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 food and green wastes in an approximate 40:60 ratio. Small quantities of food-contaminated non-recyclable (soiled) paper, and fats, oils, and greases (FOG) may also be present.

- The pathway applies only to fuel produced by a multi-staged, mesophilic, dry fermentation (high solids anaerobic digestion or HSAD) process. It cannot be used by producers using a wet fermentation (wet AD) process.

- The annual organic waste throughput of the HSAD 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).

- The biomethane produced must conform to prevailing California[14] 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 facility may employ either one of three endorsed methods for composting of digestate media: open-windrow composting, covered aerated static piles (CASP) composting, or in-vessel composting (IVC).

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

- Composting facilities must employ biofilters during the active phase of the digestate composting process. In the case of IVC, the biofuel producer must ensure that exhaust gases are routed to a packed-bed biofilter.

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Appendix A
Additional Supporting Documentation

Table A-1
Estimation of Avoided CH_4 and N_2O Composting Emissions

CH_4 & N_2O EMISSIONS FROM COMPOSTING OF FOOD WASTES				
Basis:	1000	kg of Waste (1 metric ton)		
	2.79	kg C in Food Wastes Available Carbon for Composting		
	23	kg of Food Wastes Available for Composting per (1 metric ton)		
1	Methane (CH_4) Emissions Factor (a)		4.10	g CH_4 / kg of waste treated (wet)
2a	Uncontrolled Methane (CH_4) Emissions		95.19	g CH_4 / metric ton
2b	Controlled Methane Emissions (b)	80%	19.04	g CH_4 / metric ton
2c	Biofilter Methane Conversion		76.15	g CH_4 / metric ton is Oxidized in Biofilter
2d	Oxidation of CH_4 to CO_2 in Biofilter		209.42	g CO_2 / metric ton from Biofilter
3	CO_2e Emissions (GWP CH4 = 25)		**685.39**	**g CO_2e / metric ton**
4	N_2O Emissions Factor (a)		0.09	g N_2O / kg of waste treated (wet)
5a	Uncontrolled N_2O Emissions		2.09	g N_2O / metric ton
5b	Controlled N_2O Emiss Based on Biofilter Application	0%	2.09	g N_2O / metric ton
6	CO_2e Emissions (GWP N_2O = 298)		**622.70**	**g CO_2e / metric ton**
	Sum Compost CO_2e Emissions from (CH_4 + N_2O):		**1,308.08**	**g CO_2e / metric ton**
CH_4 & N_2O EMISSIONS FROM COMPOSTING OF GREEN WASTES				
Basis:	1,000.00	kg of Waste (1 dry metric ton)		
	108.66	kg C in Green Wastes Available Carbon for Composting		
	407.49	kg of Green Wastes Available for Composting per (1 metric ton)		
1	Methane (CH_4) Emissions Factor (a)		4.10	g CH_4 / kg of waste treated (wet)
2a	Uncontrolled Methane (CH_4) Emissions		1,670.69	g CH_4 / metric ton
2b	Controlled Methane Emissions (b)	80%	334.14	g CH_4 / metric ton
2c	Biofilter Methane Conversion		1,336.55	g CH_4 / metric ton is Oxidized in Biofilter
2d	Oxidation of CH_4 to CO_2 in Biofilter		3,675.52	g CO_2 / metric ton from Biofilter
3	CO_2e Emissions (GWP CH4 = 25)		**12,028.98**	**g CO_2e / metric ton**
4	N_2O Emissions Factor (a)		0.09	g N_2O / kg of waste treated (wet)
5a	Uncontrolled N_2O Emissions		36.67	g N_2O / metric ton
5b	Controlled N_2O Emiss Based on Biofilter Application	0%	36.67	g N_2O / metric ton
6	CO_2e Emissions (GWP N_2O = 298)		**10,928.77**	**g CO_2e / metric ton**
	Sum Compost CO_2e Emissions from (CH4 + N2O):		**22,957.76**	**g CO_2e / metric ton**

Footnotes:

(a) California Air Resources Board, "Method for Estimating Greenhouse Gas Emissions Reduction from Compost of Commercial Organic Wastes," (Table 3: Fugitive CH4 and N2O Emissions from Composting), Planning & Technical Support Division, November 2011.

(b) Staff assumes that SCAQMD Rule 1133.3 to control VOC Emissions from Compost piles by 80% will have Statewide Applicability (see SCAQMD Rule 1133.3 "Technology Assessment for Proposed Rule 1133" (Appendix C)).

Table A-2
Comparative Analysis of Composting Methods

	Open Windrow	CASP to Biofilter or Gore Cover System	Uncovered ASP to Biofilter	Positive ASP with Compost Cap	In Vessel Composting, Drum Style	In Vessel Composting, Tunnel Style	Indoor Windrow
Pile formation with loader (diesel, 250 hp)	Small, long piles. Longer distances	More compact piles	More compact piles	More compact piles	Possibly by hand or small loader	Loader or bulldozer, short distance, very compact pile	Yes
Turning with mechanical turner (diesel, 500 hp)	Yes, minimum 5 turns, 10-turn average, first 3 turns use maximum	Curing only, maximum 5 turns	Curing only, maximum 5 turns	Curing only, maximum 5 turns	If high enough volume, yes.	If not cured in tunnel, yes	Yes
Move piles to curing zone (diesel loader)	Probably	Yes	Yes	Yes	Yes	Unsure	Yes
Adding cap of finished compost	Yes, in some cases, loader or blower truck	No	Yes, loader or blower truck	Yes, loader or blower truck	No	No	No
High powered fans	No	Yes, electric	Yes, electric	No	No	Yes	Yes, up to 12 building changes per hour
Low powered fans	No	Possible, electric or generator	No	Yes, could be powered by generator or possibly solar	Possible, electric	No	No
Watering	Maximum water loss	Low water loss for Gore, medium for others	Medium water loss	Medium water loss	Low water loss	Medium water loss	Maximum water loss

Table A-3

Fuel Consumption Data for Off-Road Equipment[a]

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WHEEL LOADERS AND INTEGRATED TOOLCARRIERS

Model	Low		Medium		High	
	liter	U.S. gal	liter	U.S. gal	liter	U.S. gal
904H	4.4-6.3	**1.16-1.66**	6.3-8.2	**1.66-2.17**	8.2-10.1	**2.17-2.67**
906H	3.8	**1.01**	7.6	**2.01**	11.4	**3.02**
907H	3.8	**1.01**	7.6	**2.01**	11.4	**3.02**
908H	4.3	**1.14**	8.6	**2.28**	12.9	**3.42**
914G, IT14G	5.0-6.5	**1.0-2.0**	8.0-10.5	**2.0-2.5**	11.5-13.0	**3.0-3.5**
924H, 924Hz	3.5-5.8	**0.9-1.5**	5.8-8.1	**1.5-2.1**	8.1-15.0	**2.1-3.9**
928H, 928Hz	3.8-6.2	**1.0-1.6**	6.2-8.5	**1.6-2.2**	8.5-15.4	**2.2-4.0**
930H	3.8-6.2	**1.0-1.6**	6.2-8.5	**1.6-2.2**	8.5-15.4	**2.2-4.0**
938H, IT38H*	5.2-7.8	**1.4-2.0**	7.8-10.4	**2.0-2.7**	10.4-15.0	**2.7-4.0**
950H*	7.9-11.4	**2.1-3.0**	11.4-14.7	**3.0-3.9**	14.7-18.5	**3.9-4.9**
950K Tier 4i	7.3-10.6	**1.9-2.8**	10.6-13.8	**2.8-3.7**	13.8-17.4	**3.7-4.6**
962H*	9.4-12.0	**2.5-3.2**	12.0-15.1	**3.2-4.0**	15.1-19.2	**4.0-5.1**
962K Tier 4i	8.7-11.1	**2.3-2.9**	11.1-14.2	**2.9-3.8**	14.2-18.1	**3.8-4.8**
966H*	9.1-13.4	**2.4-3.5**	13.4-16.9	**3.5-4.5**	16.9-20.5	**4.5-5.4**
966K Tier 4i	8.8-12.7	**2.3-3.4**	12.7-16.0	**3.4-4.2**	16.0-19.9	**4.2-5.2**
972H*	12.3-17.1	**3.3-4.5**	17.1-21.0	**4.5-5.5**	21.0-25.5	**5.5-6.7**
972K Tier 4i	11.6-15.7	**3.1-4.1**	15.7-19.3	**4.1-5.1**	19.3-24.0	**5.1-6.3**
980H*	15.6-20.6	**4.1-5.4**	20.6-26.0	**5.4-6.9**	26.0-32.9	**6.9-8.7**
980K Tier 4i	14.8-19.6	**3.9-5.2**	19.6-24.9	**5.2-6.6**	24.9-31.6	**6.6-8.3**
988H*	28.0-40.1	**7.4-10.6**	40.1-52.6	**10.6-13.9**	52.6-65.1	**13.9-17.2**
990H*	42.0-58.3	**11.1-15.4**	58.3-75.0	**15.4-19.8**	75.0-91.6	**19.8-24.2**
992K*	53.0-75.7	**14.0-20.0**	75.7-98.4	**20.0-26.0**	98.4-121.0	**26.0-32.0**
993K*	61.3-87.4	**16.2-23.1**	87.4-113.6	**23.1-30.0**	113.6-140.0	**30.0-37.0**
994F*	87.0-123.0	**23.0-32.5**	123.0-160.0	**32.5-42.2**	160.0-197.0	**42.2-52.0**

*The Medium and Large Wheel Loader (i.e. 938H through 980H) and Large Wheel Loader (i.e. 988H through 994F) hourly fuel rates are taken directly from customer machines registered on Product Link worldwide. Data from the top and bottom 5% of these customer machines has been excluded from the tables because it varies widely (15-60% from the extremes shown) and therefore is not considered representative of what the remaining 90% of customers experience. Hourly fuel consumption for the 90% of machines in the tables also varies depending upon geographical region, load factor variation between units, etc. Cat machines are often used in more demanding applications which can account for differences between competitive models used in lighter duty applications. Consult your local Cat dealer for ways to more accurately estimate hourly fuel consumption for specific applications.

[a] Front-End Loader Specified for HSAD operations was the Caterpillar 966K Tier 4i or equivalent model.