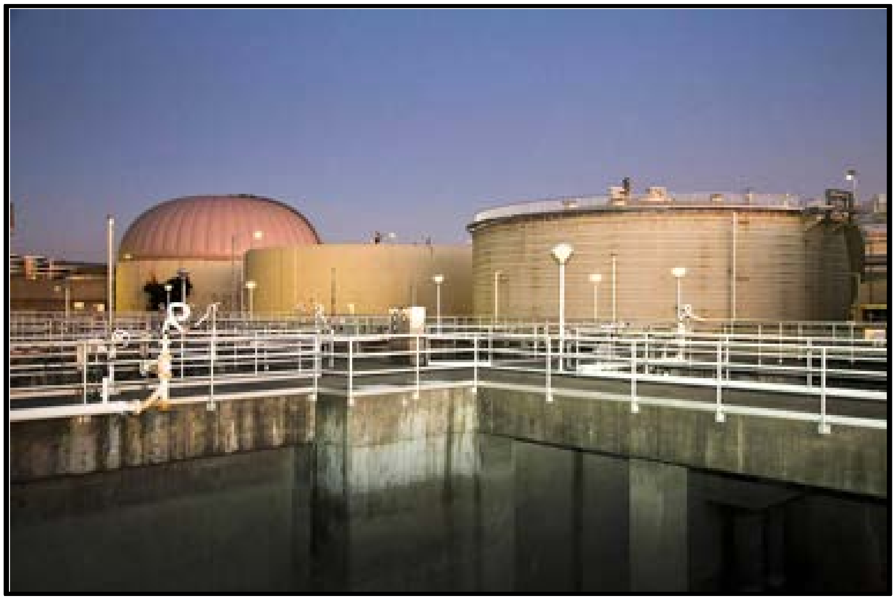
California Environmental Protection Agency

Air Resources Board

Low Carbon Fuel Standard (LCFS) Pathway for the Production of Biomethane from the Mesophilic Anaerobic Digestion of Wastewater Sludge at a Publicly-Owned Treatment Works (POTW)



Industrial Strategies Division
Fuels Evaluation Section

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State of California
AIR RESOURCES BOARD

Low Carbon Fuel Standard (LCFS) Pathway for the Production of Biomethane from the Mesophilic Anaerobic Digestion of Wastewater Sludge at a Publicly-Owned Treatment Works (POTW)

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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 kamal.ahuja@arb.ca.gov.

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ADDENDUM

PATHWAY CARBON INTENSITY UPDATES

At its February 2015 hearing, the California Air Resources Board will consider re-adopting the California Low Carbon Fuel Standard (LCFS). Among the regulatory items it will be considering will be updated carbon intensity (CI) values for the LCFS Tier 2 Lookup Table fuel pathways. The CIs for those pathways must be calculated using the CA-GREET 2.0 model. Under the proposed regulation, CA-GREET 2.0 will replace CA-GREET 1.8b as the required LCFS fuel pathway direct CI model. The pathways described in this document will be among that group of Lookup Table pathways.

The Production of Biomethane from the Mesophilic Anaerobic Digestion of Wastewater Sludge at a Publicly-Owned Treatment Works (POTW) pathway was published on September 8, 2014, and consists of two sub-pathways; biomethane produced at a Small-to-Medium POTW (Alternative Case 1), and biomethane produced at a Medium-to-Large POTW (Alternative Case2). This update contains the text of the original document, but appends the following updated CI information to that text.
As such, the qualitative description of the fuel pathways contained in the original text remains valid and accurate. However, the quantitative, CI-related information in that original text is replaced with the information presented in Table A-1.
In Alternative Case 1, the anaerobic digestion, digestate management, and biogas upgrading processes are largely dependent upon grid-based electrical generation and a parasitic thermal load for digester heating purposes. In Alternative Case 2, part of the biogas produced in the digester is used to derive electrical power in the combined heat and power (CHP) unit for process electrical purposes, and the remainder of the biogas is allocated to transportation fuel uses.

The carbon intensities for biomethane are being re-calculated based upon the change in the electricity mix from California Marginal to California-Average (CAMX) portfolio of electrical generating assets in CA-GREET 2.0. This change results in slightly higher GHG emissions estimates for pathways dependent upon grid-based electrical power for their process needs, and a correspondingly higher GHG emissions credit if surplus cogenerated power is displacing grid-based electrical generation (co-product credit).
While the Alternative Case 1 is largely dependent upon grid-based electrical energy, Alternative Case 2 generates surplus electricity which is assumed to be exported to the public grid and displace grid-based electrical generation. With a change in the calculation methodology from California Marginal to California Average portfolio of electrical generating assets, a slightly higher CI estimate is obtained for biomethane produced under Alternative Case 1, and correspondingly a slightly higher electricity co-product credit and a lower CI estimate for biomethane produced under Alternative Case 2 is obtained.

The CIs for biomethane also reflect higher tank-to-wheels (TTW) estimates for biomethane combustion in medium and heavy-duty natural gas vehicles, and a minor correction for overestimating fuel cycle emissions associated with digestate transport. The changes for the pathway are summarized in the Table A-1 below.

Table A-1: Carbon Intensities for Pathways CNG020 and CNG021

Parameter	**CNG020 Medium-to-Large POTW (Alternative Case 2)**	**CNG021 Small-to-Medium POTW (Alternative Case 1)**
Total WTT GHG Emissions Impacts (g CO_2e/day)	(10,075,546.74)	2,760,570.56
Total TTW GHG Emissions Impacts (g CO_2e/day)	19,762,298.71	4,936,190.14
Total WTW GHG Emissions Impacts (WTT + TTW) (g CO_2e/day) **(A)**	**9,686,751.97**	**7,696,760.70**
Digester Biomethane Yield (m^3/day)	34,656.77	6,931.35
Digester Biomethane Yield Fueling (scf/day)	1,223,754.81	133,366.58
Net Biomethane Available for Vehicle Fueling (scf/day)	319,857.30	79,893.36
Biomethane LHV (Btu/scf)	962.00	962.00
Biomethane Energy Value (MJ/day) **(B)**	**1,242,071.63**	**248,414.33**
Proposed Biomethane CI (g CO_2e/MJ) (A/B)	**7.80**	**30.98**

I. Executive Summary

This document describes a Low Carbon Fuel Standard (LCFS) pathway for the production of biomethane from the mesophilic anaerobic digestion of wastewater sludge at a wastewater treatment plant (WWTP) located at a publicly-owned treatment works (POTW). The biomethane produced would be used for vehicle fuel and could be dispensed on-site through a compressed gas vehicle fueling station (for example, a CNG fueling station for transit buses or refuse hauling vehicles), or may be injected into the natural gas pipeline system ("common carrier pipeline") for dispensing at an off-site compressed gas vehicle fueling station.

Wastewater sludge is generated from the primary and secondary treatment processes designed for the municipal wastewater that flows into the WWTP. California State and local laws require further treatment of the wastewater sludge prior to discharge or disposal of the material as an effluent, or disposal in a landfill or in a land application site. Since the content of the wastewater sludge is primarily organic material, one of the most common processes for its treatment is by the anaerobic digestion of the sludge under mesophilic operating conditions (35 degrees Celsius). Anaerobically digesting the wastewater sludge destroys part of the organic matter and produces biogas, a mixture comprised of methane (CH_4) and carbon dioxide (CO_2), along with some trace impurities such as hydrogen sulfide, siloxanes, and vinyl chloride. Since both major components of biogas are heat-trapping greenhouse gases (GHG), the biogas produced is further destroyed by flaring (methane capture and destruction), or used in a device that generates electricity from the combustion of the biogas.

An alternative fate for the biogas, which is comprised of approximately 58 percent methane by volume, is to further refine the biogas to remove the carbon dioxide, and other trace impurities to produce near-pure biomethane (greater than 99 percent CH_4). This biomethane could then be compressed and sold as a vehicle fuel either on-site, or injected into the common carrier pipeline for fueling at an off-site location. Some POTWs may continue to use part of the biogas or biomethane in compliant energy-producing devices for the production of renewable power, and only allocate a fraction of their biogas produced toward transportation fuel uses. These alternate fates for the biogas produced from the mesophilic anaerobic digestion of the wastewater sludge at a POTW are the basis for the LCFS fuel pathways in this report.

This document presents the results of a life cycle analysis (LCA) of energy use and GHG emissions impacts performed on the wastewater sludge-to-biomethane pathway described above. Those impacts are then presented per unit of fuel energy as the carbon intensity (CI) value of the biomethane transportation fuel produced. In order to estimate the GHG impacts of these pathways, staff utilized two versions of the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) life cycle analysis model: CA-GREET version 1.8b and GREET1 (2012).[1] For wastewater sludge treatment processes that include anaerobic digestion, digestate and supernatant management, biogas cleaning, refining, compression, dispensing and distribution, staff found that worksheets available in the GREET1 Model closely estimated the energy use and material flow rates, and therefore the GREET1 Model was used as a basis to estimate the material and energy use for the pathways. Emission factors in CA-GREETv1.8b were used to estimate the actual GHG emissions associated with the material and energy use obtained from the GREET1 Model.

Based on a survey administered to over 250 California POTWs by the California Association of Sanitation Agencies (California Association of Sanitation Agencies, 2013), staff determined that over 150 POTWs operate anaerobic digesters to destroy part of the organic component of wastewater sludge. Of those found to be digesting wastewater organics, the majority of them (more than 90 percent) were found to be operating at mesophilic temperatures. Approximately 90 percent of those facilities digesting wastewater sludge were also using the biogas to produce renewable power for plant consumption or for export to the public grid, or both. Approximately half of those POTWs producing power were doing so by use of internal combustion engines (ICE) and generators. The ICEs have come under increasing regulatory scrutiny, subject to more stringent emissions standards for stationary sources by local air districts in order to attain air quality standards. The production of a transportation fuel, however, presents a viable solution to the regulatory constraints facing the POTWs. Detailed results of the CASA survey can be found in Appendix A of this report.

Staff has estimated the CIs for biomethane produced under two alternative scenarios. The first is an estimate for biomethane produced at a Small-to-Medium POTW (Alternative Case 1) with wastewater inflows of 5 to 20 million gallons per day (MGD). In this model, only a small parasitic load on the biogas produced is used to heat the digesters. Grid-based electricity, using the California marginal mix of electrical generating assets, is assumed to power the wastewater sludge treatment, and biogas cleaning, compression, and fuel dispensing processes. The second is an estimate for a Medium-to-Large POTW (Alternative Case 2) with wastewater inflows of 21 to 100 MGD. In this model, the majority of the biogas is allocated to the production of renewable power using a compliant device (such as a gas-fired turbine with an exhaust heat recovery system). The balance of the biogas produced in the digesters is allocated to an “application” which may include on-site vehicle fueling, or compression and distribution through the natural gas grid for purposes of off-site vehicle fueling. Heat recovered from the exhaust of the combustion gases produced by the compliant device is adequate to sustain the mesophilic thermal

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[1] The CA-GREET model (Version 1.8b, December 2009) and the GREET1 Model (Revision 2, December 2012) were developed by Argonne National Laboratory (ANL). The CA-GREET model has been adapted for use in California (Life Cycle Associates and ARB Staff). Some emission factors listed in GREET1 and not available in CA-GREET were incorporated by reference.

requirements of the anaerobic digesters. The electrical demand for the wastewater sludge treatment and biogas cleaning, compression, and dispensing processes is provided by the renewable power generated on-site by the compliant device. This alternative scenario also predicts that surplus electrical power[2] will be generated, and that this power will be exported, displacing California marginal electricity on the electrical grid. Therefore, this model accrues an additional LCFS credit for lowering the GHG impacts of grid-based California marginal electrical generation.

Common to both models (Alternative Cases 1 and 2) is a credit for avoided flaring emissions. Staff assumes that due to regulatory and air quality non-attainment considerations, flaring of the biogas to achieve near complete destruction of the volatile components in the biogas with high global warming potentials is the only available option for the reference case. Therefore, any productive use of the biogas, such as for vehicle fuel or the production of renewable electrical power, avoids the emissions and energy loss caused by flaring of the biogas. The avoided flaring emissions accrue as an LCFS credit in the pathway CI analyses.

The modeled CI results that estimate the life cycle impacts of GHG emissions from energy use (Alternative Cases 1 and 2), along with the applicable avoided flaring emissions credit (Alternative Cases 1 and 2), and the credit for displaced grid-based electrical generation (Alternative Case 2 only) are presented in Table ES-1 below. The CI estimate for each alternative case presented is obtained by first estimating the total well-to-tank (WTT) GHG impacts, which arise from the anaerobic digestion, digestate management and transport, biogas conditioning and refining, renewable power production, and biomethane compression, distribution, and dispensing. To this estimate is added the tank-to-wheels (TTW) GHG impacts, which arise when the finished fuel is combusted in a vehicle to derive motive power. This results in the total well-to-wheels (WTW) GHG emissions impacts, which, when expressed per unit of transportation fuel energy produced, represents the CI of the fuel.

As shown in Table ES-1, the resulting CIs are 30.51 g CO_2e/MJ, and 7.89 g CO_2e/MJ for Alternative Cases 1 and 2, respectively. In both cases, staff estimated the CIs for compressing biomethane for on-site vehicle fueling. The CIs are also applicable to biomethane produced and injected into the common carrier pipeline.[3]

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[2] The GREET1 Model estimates that electrical power surplus to the electrical energy requirements of the process units in the pathway for Medium-to-Large POTWs will be available for export. This amount of power is then considered to displace grid-based electrical generation.

[3] In most cases, the compression pressure required for pipeline injection (600-800 psi) is lower than the compression pressure required for on-site, high-speed vehicle fueling (3,600 psi). This determination was made during the analysis of the pathway for biomethane derived from high solids anaerobic digestion of food and green wastes (California Air Resources Board, 2012).

Table ES-1
Summary of Life Cycle GHG Impacts and CIs for Biomethane Derived from Anaerobic Digestion of Wastewater Sludge

Parameter	Small-to-Medium POTW (Alternative Case 1)	Medium-to-Large POTW (Alternative Case 2)
Total WTT GHG Emissions Impacts (g CO_2e/day)	2,933,446.73	(8,799,057.62)
Total TTW GHG Emissions Impacts (g CO_2e/day)	4,646,249.17	18,601,504.67
Total WTW GHG Emissions Impacts (WTT + TTW) (g CO_2e/day) **(A)**	**7,579,695.90**	**9,802,447.05**
Digester Biomethane Yield (m^3/day)	6,931.35	34,656.77
Digester Biomethane Yield (scf/day)	133,366.58	1,223,754.81
Net Biomethane Available for Vehicle Fueling (scf/day)	79,893.36	319,857.30
Biomethane LHV (Btu/scf)	962.00	962.00
Biomethane Energy Value (MJ/day) **(B)**	**248,414.33**	**1,242,071.63**
Proposed Biomethane CI (g CO_2e/MJ) (A/B)	**30.51**	**7.89**

II. Introduction to Life Cycle Analysis

The use of life cycle analysis (LCA) to estimate the carbon intensity (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 wastewater sludge digestion 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 (NGV).

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 (low solids or wet fermentation) of wastewater sludge at a publicly-owned treatment works (POTW). Under this pathway, the biogas produced is purified to biomethane, which could then be compressed and dispensed onsite or injected into the natural gas common carrier pipeline.

USE OF CA-GREETv1.8b AND GREET1 MODELS FOR LCA

A California-specific version of a 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 wastewater sludge-to-biomethane pathway. The California-specific version of the model, known as CA-GREETv1.8b, 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 the CA-GREETv1.8b model to calculate GHG emissions from the wastewater sludge-to-biomethane pathway whenever the necessary emissions factors were present in the model.

For wastewater sludge treatment processes which include anaerobic digestion, digestate, supernatant, and biosolids management and transport, biogas conditioning and refining, renewable power production, biomethane compression, distribution, and dispensing, staff found that the GREET1 Model (Argonne National Laboratory, 2012) closely estimated the energy use and material flow rates, and therefore the GREET1 Model was used as a basis to estimate the GHG emissions impacts for the fuel pathway.

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

- Some emission values in CA-GREETv1.8b are calculated recursively. This happens when a fuel is used in the process that produces that same fuel. Diesel fuel, for example, is used to extract and transport crude oil. This means that the CI of diesel contributes to the CI of crude oil. Since diesel is refined from crude, the CI of diesel plays a role in its own CI. The CIs of crude oil and diesel fuel are recursively calculated in CA-GREETv1.8b. If a new CI for diesel is entered into the model, that CI will be used to calculate a new CI for crude oil. The result of that calculation will be used to calculate a new CI for diesel. This iterative recalculation process will continue a fixed number of times.

- Btu/mmBtu is the energy input necessary in British Thermal Units or Btus, to produce one million Btus of a finished (or intermediate) product. This description is used consistently in GREET for all energy calculations.

- g CO_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 Intergovernmental Panel on Climate Change (Solomon et al, 2007) global warming potential (GWP) values and included in the total.
  The CA-GREETv1.8b model 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 CA-GREETv1.8b is defined as the ratio of energy output to the sum of the energy output and energy consumed.

- Note that rounding of values has been minimized in several tables in this document. This is to allow stakeholders executing runs to compare actual output values from the CA-GREETv1.8b or GREET1 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 is quantified. In the case of electrical generation, the energy needed to produce and transport the fuels used to generate the electrical energy is 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. In this pathway, the potential co-product produced from the low solids anaerobic digestion of wastewater sludge is renewable electricity, which is assumed to displace fossil-fuel based grid generation, and soil amendment or fertilizer if the biosolids produced by the process are deemed to be rich in inorganic nutrients and free of pathogens.

- 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, or estimated to be a fraction of the volume throughput.

The CI estimate for each scenario presented is obtained by first estimating the total WTT GHG impacts, which arise from the anaerobic digestion; digestate, supernatant, biosolids management and transport; biogas conditioning and refining; renewable power production; and biomethane compression, distribution, and dispensing. The application of credits for avoided flaring emissions, and for cogeneration and export of surplus electricity are also applied to the WTT estimates.

To this WTT estimate is added the TTW GHG emissions which arise when the finished fuel is combusted in a vehicle to derive motive power. This results is the total WTW GHG emissions impacts which, when expressed per unit of the transportation fuel energy produced, represents the CI of the fuel.

Section III of this report presents a system boundary within which the life cycle GHG impacts are assessed. A system boundary defines the universe of GHG emission increases and decreases (debits and credits) to be considered in the WTW analysis. Lastly, the production of transportation fuel is presented as alternative cases to the reference case which assumes that the purpose of the wastewater sludge treatment process is to destruct the organic matter in the sludge as much as possible. Section IV of this report presents the characteristics of the feedstock and the wastewater sludge-to-biomethane production process. Section V presents the derivation of the actual life cycle energy consumption and GHG emissions impacts. Section VI contains the compilation of the WTT and TTW estimates. Along with the applicable credits that lower these emissions impacts, staff then proposes the CIs for the alternative cases.

III. System Boundary, Reference and Alternative Cases, and System Credits

In traditional life cycle analysis, a system boundary around the pathway elements in which the transport of all material inflows and outflows, as well as energy inputs and outputs is established. The universe of energy and material flows to be considered in the life cycle analysis is defined by the establishment of this system boundary.

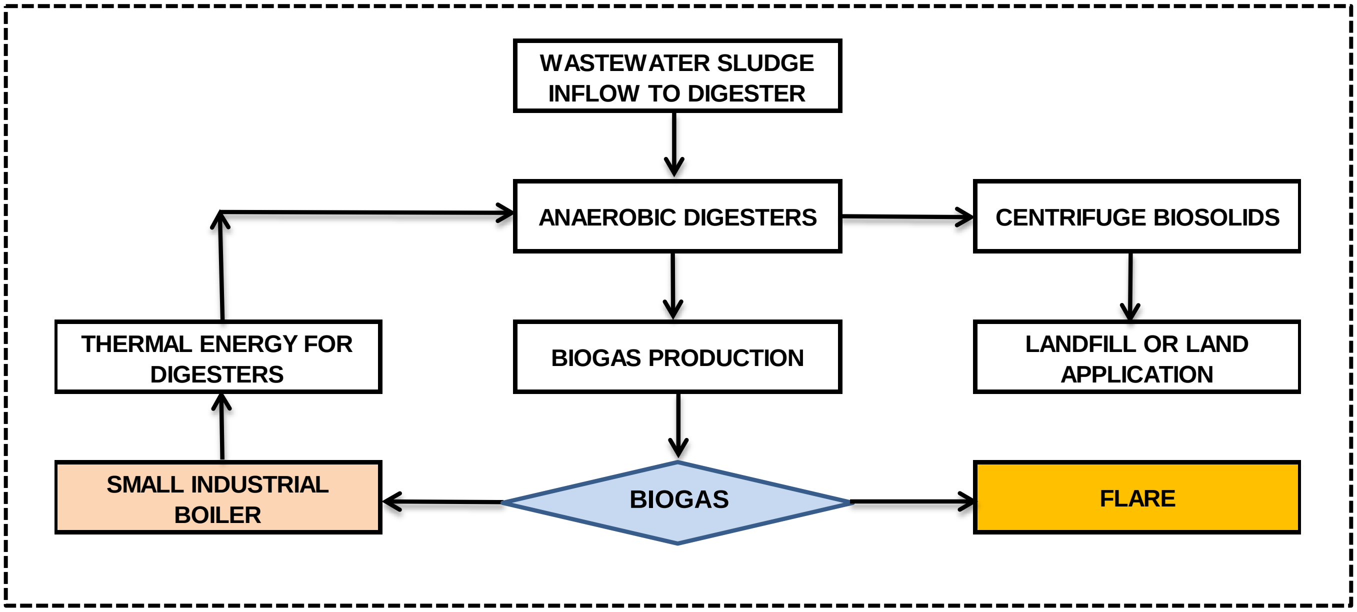
While the generation of wastewater sludge, the primary feedstock used for the production of biogas, commences at the influent channels and settling basins associated with the wastewater treatment plant (WWTP), all existing wastewater treatment processes are not considered to be within the wastewater sludge-to-biomethane system boundary because those processes are required for the effective treatment and discharge of the wastewater influent. Similarly, wastewater sludge treatment processes, such as anaerobic digestion, biogas conditioning and cleaning, biogas flaring, digestate management, and biosolids and supernatant transport and disposal, are also required for the effective treatment and discharge of the wastewater residuals. The question that arises is how do we measure the emissions impact of the pathway elements if all processes are attributable to existing regulations that require adequate treatment of the wastewater prior to discharge?

The life cycle analysis of greenhouse gas emissions impacts is therefore performed by assessing a change from the business-as-usual, baseline, or reference case to an alternative case that necessitates the production and consumption of the fuel for purposes of deriving motive power or renewable electricity. However, both reference and alternative cases still require the establishment of system boundaries around the appropriate set of life cycle pathway elements to be considered in the analysis.

a. Establishing a Reference Case for a POTW

Figure III-1 below depicts the Reference Case for the wastewater sludge-to-biomethane LCFS pathway. In this case, an assumption is made that wastewater sludge enters the anaerobic digesters after primary and secondary treatment processes have been implemented. In the digesters, biogas is produced from the anaerobic digestion of the wastewater sludge. The rate of biogas production, and correspondingly the rate of organic matter destruction, is dependent upon the operating temperature of the digesters. The biogas that is generated is collected in the digester header space. Part of the biogas may be combusted in a small industrial boiler for process thermal requirements (such as heating of the digesters to mesophilic operating temperatures), and the remainder of the biogas is assumed to be flared to achieve near complete destruction of the volatile components of the biogas and to reduce the global warming impacts of the gases produced to the environment. The digestate that remains in the digesters after the anaerobic digestion process is complete is sent to centrifuges where separation of the biosolids and the supernatant takes place. The dewatered biosolids are disposed off-site in a landfill, or they can be used for land application purposes (for example, alternative daily cover, or as soil amendment, or as non-food crop fertilizer). The end application of the biosolids is dependent upon the level of pathogen reduction achieved and the level of nutrients that remain in the biosolids.

Figure III-1
Schematic of the Reference Case for a POTW with System Boundary



In terms of assessing the “fate” of the wastewater sludge in the Reference Case, the end objective is to reduce the organic content of the wastewater sludge so that the material may be safely discharged, emitted, or recirculated into the process without causing any harm to the public health or the environment. Therefore, any use or treatment of the feedstock that achieves the same end goals while proactively capturing the energy value of the products and by-products from the treatment process is an Alternative Case to the established Reference Case.

b. Establishing an Alternative Case for a Small-to-Medium POTW with 5 to 20 MGD Average Daily Wastewater Inflows (Alternative Case 1)

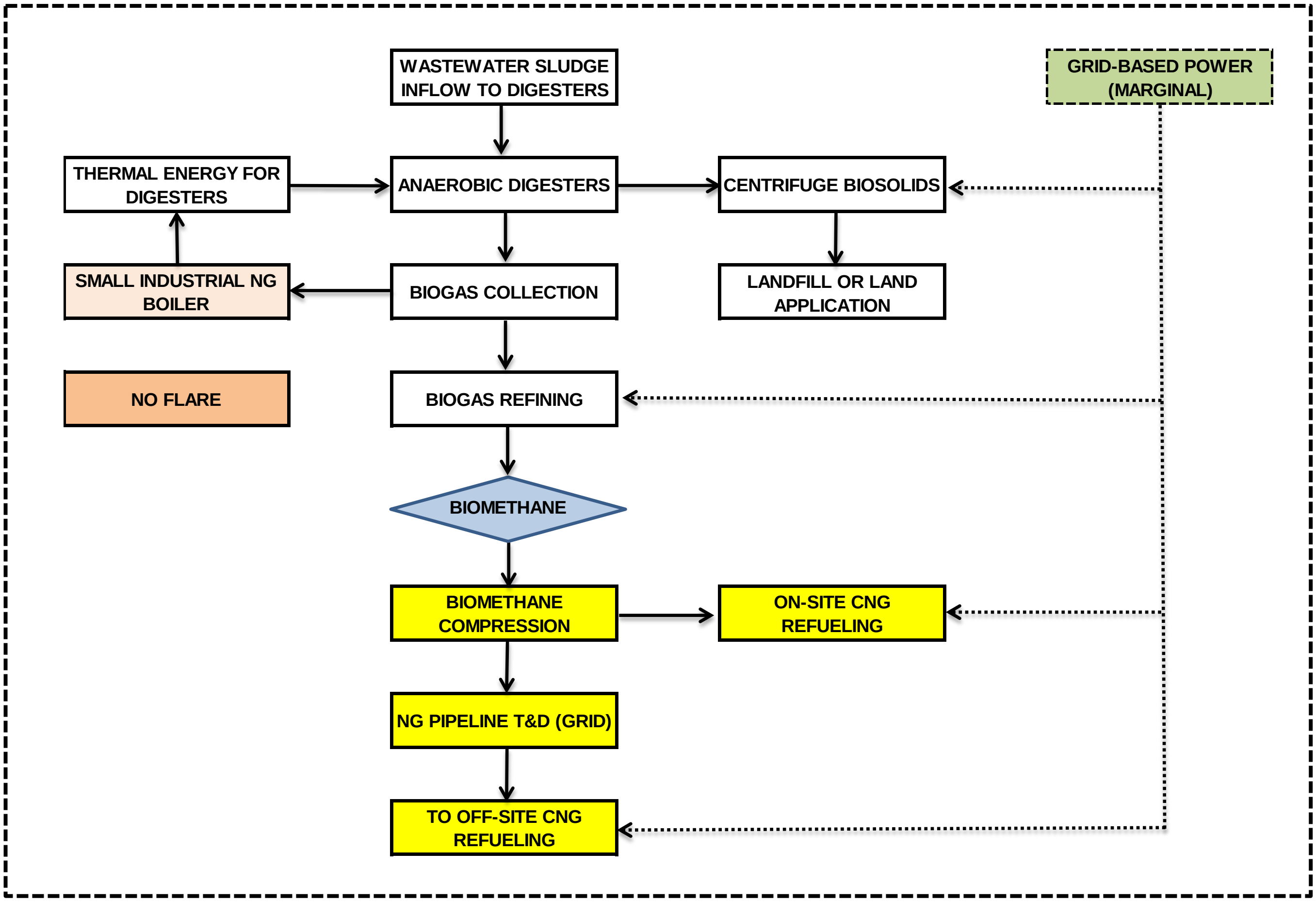
The Alternative Case for a Small-to-Medium POTW with 5 to 20 MGD wastewater inflows (Alternative Case 1) assumes that, due to regulatory constraints, the use of non-compliant combustion devices for the production of renewable electricity, or the flaring of the biogas that was generated in the anaerobic digesters is forbidden. A viable and sustainable project that achieves the same goals as the Reference Case (i.e., reduction or destruction of the organic matter to safely discharge, or emit the products of the treatment process without causing a public nuisance, or endangering human health, or the environment), while also capturing the latent energy value of the product gas, is the production of a transportation fuel to derive motive power.

Biogas production processes are assumed to be identical to the Reference Case, with the thermal energy demand of the digesters being supplied by a small parasitic load on the digester biogas output used in a small industrial gas-fired boiler to produce steam. Since the biogas must be conditioned and refined prior to use in a vehicle, the system boundary includes an additional biogas refining unit for biomethane production, compression, and on-site vehicle fueling, or for direct injection into the natural gas grid for purposes of distributing the biomethane to an off-site vehicle fueling station. Electrical energy requirements for wastewater sludge treatment process operations are assumed to be provided by the public grid.

The Alternative Case for a Small-to-Medium POTW accrues a credit for avoiding flaring emissions of the Reference Case. This credit manifests itself by lowering the total GHG emissions impacts from energy use by the wastewater sludge-to-biomethane production processes.

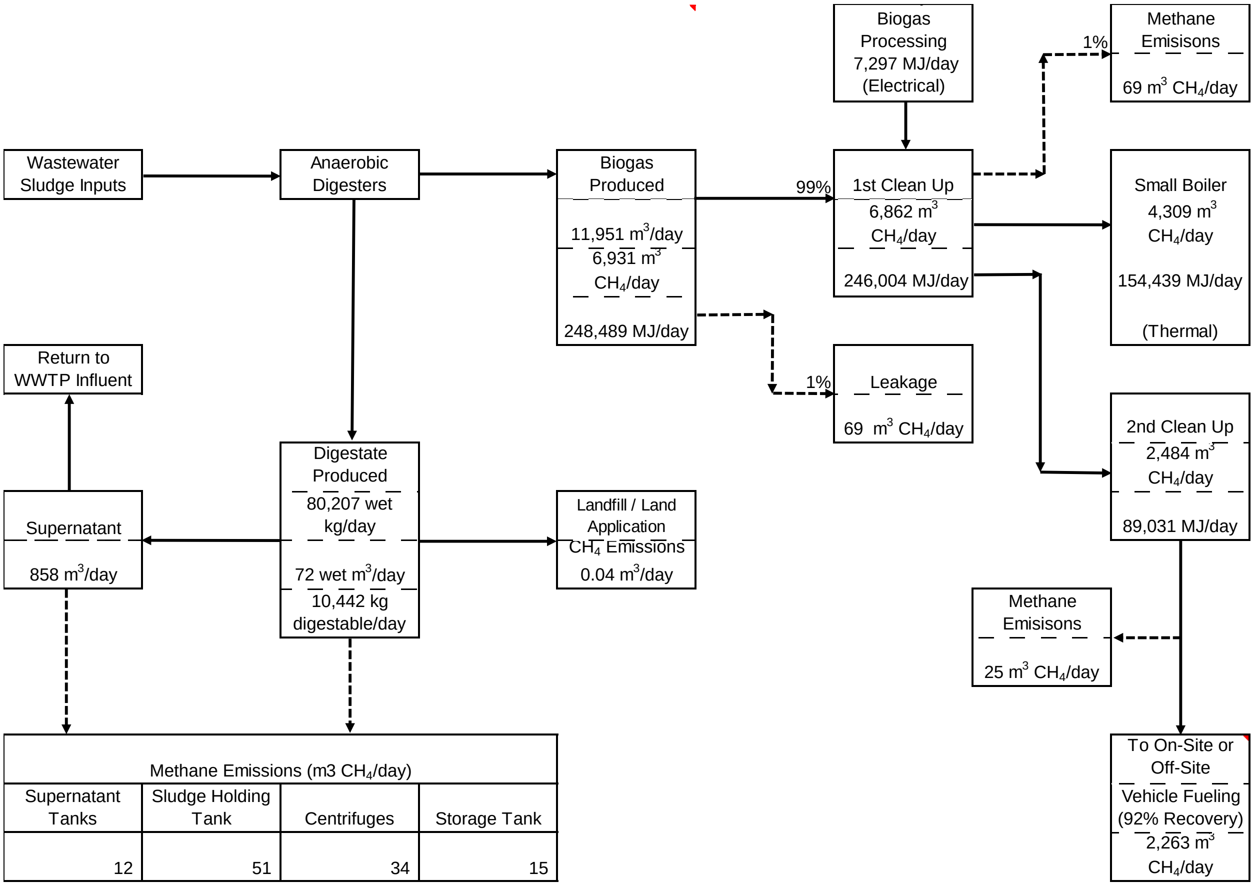
The system boundary for the Alternative Case for a Small-to-Medium POTW (Alternative Case 1) is depicted in Figure III-2 below:

Figure III-2
Schematic of the Alternative Case for a Small-to-Medium POTW with System Boundary



A schematic of the methane flows within the system boundary established for the Alternative Case for a Small-to-Medium POTW (Alternative Case 1) is presented in Figure III-3 below:

Figure III-3
Methane Balance for a Small-to-Medium POTW (Alternative Case 1)



Methane Emissions (m3 CH_4/day)			
Supernatant Tanks	Sludge Holding Tank	Centrifuges	Storage Tank
12	51	34	15

c. Establishing an Alternative Case for a Medium-to-Large POTW with 21 to 100 MGD Wastewater Inflows (Alternative Case 2)

The Alternative Case for a Medium-to-Large POTW with greater than 20 MGD and up to 100 MGD wastewater inflows (Alternative Case 2) assumes a more complex scenario than the Alternative Case for Small-to-Medium POTWs (Alternative Case 1). The large amount of biogas generated in the digesters presents additional options for use of the biogas, and an allocation between uses is made.

The Alternative Case 2 also assumes that due to regulatory constraints, the production of electricity with non-compliant combustion devices powering generators, or the flaring of the biogas generated in the anaerobic digesters is forbidden. A viable and sustainable use of the biogas under Alternative Case 2 is the production of renewable electrical power from a compliant combustion device such as a natural gas-fired turbine with generator. The amount of biogas allocated to the production of renewable electrical power is a quantity that allows enough heat to be recovered from the combustion exhaust to meet the thermal energy demand of the digesters. The remaining quantity of biogas is then allocated to the production of transportation fuel. This use constitutes Alternative Case 2.

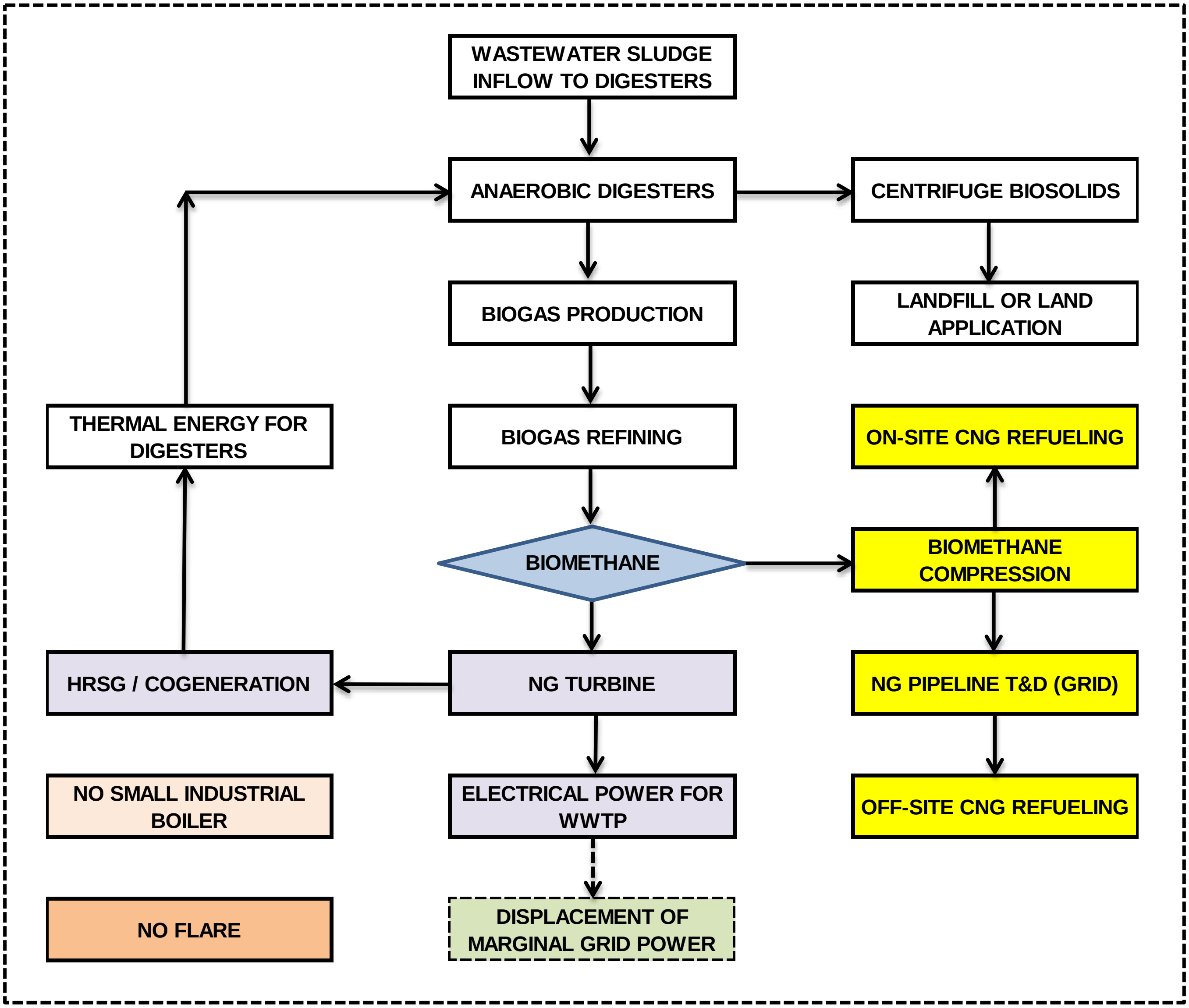
Biogas production processes are assumed to be identical to the Reference Case, except that there is no need for a digester parasitic load as an adequate amount of heat is recovered from the combustion gases that exit the compliant fuel combustion source. Since the biogas must be conditioned and refined prior to use in a vehicle, the system boundary includes an additional biogas refining unit for biomethane production, product compressors, and either an on-site vehicle fueling station, or a system to directly inject the biomethane into the natural gas grid for purposes of distributing transportation fuel to an off-site vehicle fueling station.

Electrical energy requirements for both the wastewater sludge treatment process operations and the biogas conditioning, refining, and compression are assumed to be provided by the on-site biogas/biomethane-fueled compliant device (for example, a gas-fired turbine) with generator. For the case of establishing the system boundary for Alternative Case 2, the life cycle model also predicts that, based on the quantity of biogas generated in the digesters and the electrical energy requirements of the process units in the pathway, surplus electrical power produced by the gas-fired device and generator would be available for other wastewater treatment plant operations, or would be available for export to the public grid. Therefore, the Alternative Case 2 accrues an LCFS credit for displacing grid-based electrical generation. This credit manifests itself by lowering the total WTT GHG emissions impacts from energy use by the wastewater sludge-to-biomethane production processes.

In addition, the Alternative Case 2 also accrues a credit for avoiding flaring emissions that occur in the Reference Case. This credit manifests itself by lowering the total GHG emissions impacts from energy use by the wastewater sludge-to-biomethane production processes.

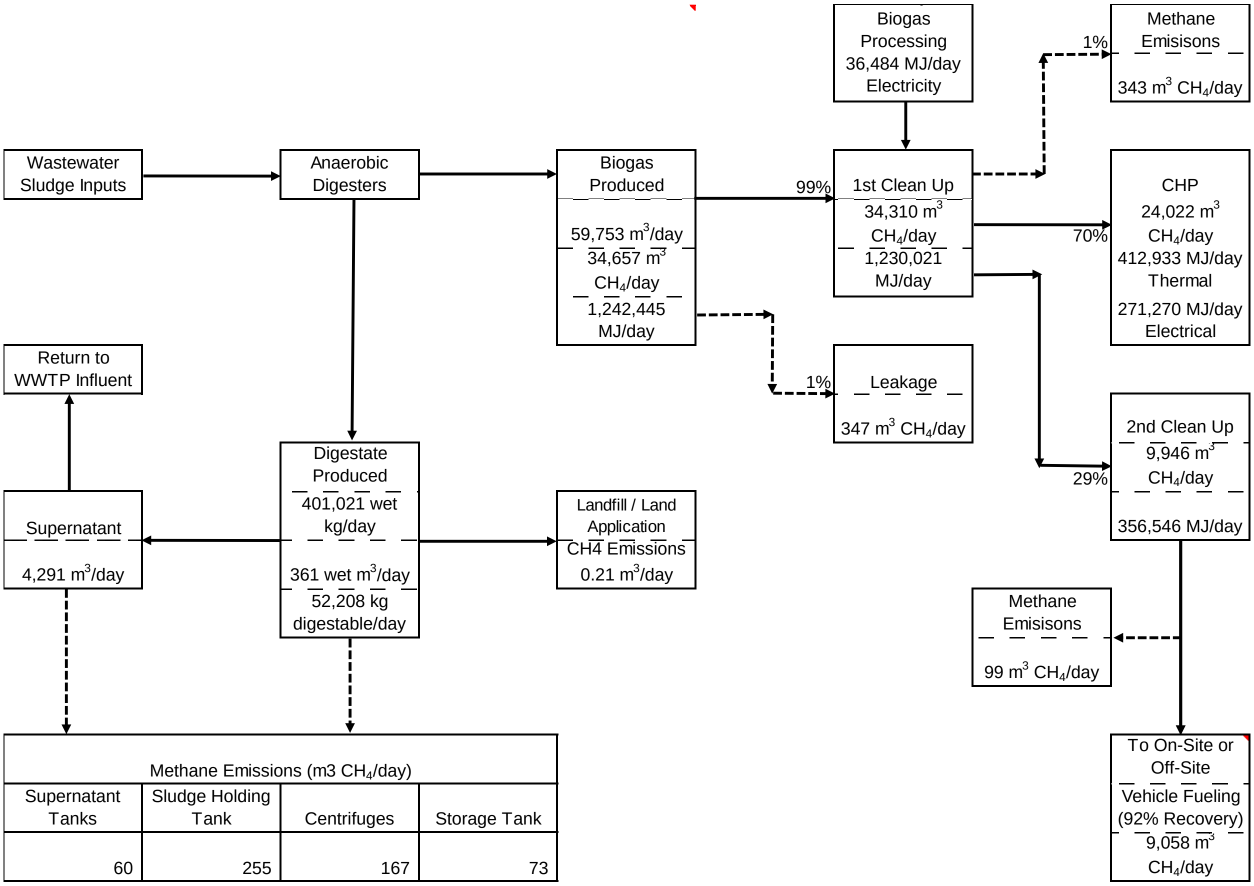
A schematic of the system boundary for the Alternative Case for a Medium-to-Large POTW (Alternative Case 2) is depicted in Figure III-4 below:

Figure III-4
Schematic of the Alternative Case for a Medium-to-Large POTW with System Boundary



Staff notes that the Biogas Refining unit shown in the schematic above may not need to refine biogas for combustion in a gas-fired turbine to the same level as is required for producing biomethane for motor-fuel or pipeline injection specifications. A schematic of the methane flows across and within the system boundary established for the Alternative Case for a Medium-to-Large POTWs (Alternative Case 2) is presented in Figure III-5 below:

Figure III-5
Methane Balance for a Medium-to-Large POTW
(Alternative Case 2)



Staff notes that the material throughput, biogas production, point source and fugitive methane emission rates depicted above were obtained from the GREET1 Model for Alternative Case 2. The second stage biogas refining efficiency (92 percent) is the estimated typical capture efficiency for a biogas refining unit employing pressure swing adsorption (PSA) technology (California Air Resources Board, 2012).

IV. Feedstock and Process Characterization

The wastewater sludge that is generated from the primary and secondary treatment processes at the POTW is the only feedstock for biomethane production. As discussed previously, the system boundary for the proposed pathway is established where the wastewater sludge enters the anaerobic digesters. The question that arises is whether the chemical and physical properties of all municipal wastewater sludges used as feedstock for the production of biomethane can be considered to be equal.

Staff understands that the physical and chemical properties of municipal wastewater sludge are more or less identical across treatment plants. However, their characteristics may be influenced by factors such as process design, or co-digestion of energy-rich wastes such as pre-consumer industrial food wastes, fats, oils, and greases (FOGs), and other high-strength wastes. Staff will therefore attempt to characterize the wastewater sludge in terms of some commonly measured parameters. These characteristics were obtained from the GREET1 Model (Argonne National Laboratory, 2012) for test cases of 20 MGD and 100 MGD municipal wastewater inflows, and up to 2-stage mesophilic anaerobic digestion of wastewater sludge. For the purposes of this pathway, co-digestion of the wastewater sludge with food wastes was not assumed to be occurring. The material and energy balances presented in Section III of this report, therefore, reflect the physical and chemical characteristics defined in Table IV-1 below.

Although the pathways developed in this document assume that the dewatered digestate (biosolids) are disposed off or used as an alternative daily cover in a landfill, use of the digestate as a marketable fertilizer or soil amendment can potentially earn a co-product credit. These uses are not assumed in this document because most POTWs do not currently manage their biosolids for these applications. Concerns about the pathogen content in the biosolids have generally prevented their application on soils where food crops are cultivated. POTWs that do manage their biosolids as a fertilizer or soil amendment are however invited to apply under the LCFS Method 2 process for a pathway in which the application of biosolids earns a GHG credit for displacing synthetically produced fertilizers. This credit is normally calculated on the basis of the nutritional content of the biosolids relative to the synthetically produced fertilizer. The biosolids are assumed to displace an amount of fertilizer having equivalent available nitrogen, phosphorous, and potassium content. In such cases, the displacement effect is assumed to accrue a credit in the proposed pathway by lowering the GHG impacts from producing synthetic fertilizer.
The GREET1 Model can calculate the GHG credits from this displacement effect.

Table IV-1
Wastewater Sludge Feedstock and Digestion Characteristics

Anaerobic Digester Characteristics	**Units**	**Small-to-Medium POTW (20 MGD)**	**Medium-to-Large POTW (100 MGD)**
Total Sludge Entered to Digester	(kg/day)	37,220.83	186,100.00
Volatile Solid Loading Rate	(kg VS/day)	23,720.00	118,600.00
Volatile Solid Reduction	(VSR, %)	0.56	0.56
Biogas Production Rates	(m^3 biogas / kg VS destroyed)	0.90	0.90
Methane Share in Biogas	(% vol.)	0.58	0.58
Daily Biogas Production Rate	(m^3/day)	11,950.61	59,753.05
Total Electrical Energy Requirement	(MJ/day)	8,709.00	43,546.00
Total Thermal Energy Requirement	(MJ/day)	86,486.00	412,933.00
Digestate Characteristics	**Units**	**Small-to-Medium POTW (20 MGD)**	**Medium-to-Large POTW (100 MGD)**
Inert Solids Inputs	(m^3/day)	13,500.83	67,500.00
Solids in the Digestate	(kg/day)	23,942.38	119,707.72
Digestible Solid in Digestate	(kg/day)	10,441.54	52,207.72
Required Polymer for Dewatering	(kg/day)	119.71	598.54
Centrifuge Energy Demand	(MJ/day)	8,739.93	43,698.11
Total Dry Biosolids to be Disposed	(kg/day)	24,062.09	120,306.26
Total Volume of Generated Sludge	(m^3/day)	72.19	360.92
Digestate Fate		Landfill or Land Application	Landfill or Land Application
Amount of N in Digestate Disposed*	(kg/day)	-	-
Amount of P in Digestate Disposed*	(kg/day)	-	-
Amount of K in Digestate Disposed*	(kg/day)	-	-
Digestate Transportation Distance	(miles)	40.00	40.00
Supernatant Characteristics	**Units**	**Small-to-Medium POTW (20 MGD)**	**Medium-to-Large POTW (100 MGD)**
Solids Generation Rate	(m^3/day)	930.46	4,652.30
Supernatant Flow Rate	(m^3/day)	858.27	4,291.38

*Staff assumes that the digestate is only being landfilled or used as Alternative Daily Cover.

When operated under the conditions specified in this pathway, biogas yields from the mesophilic anaerobic digestion of municipal wastewater sludge should be fairly consistent across POTWs.

Other factors that can influence the biogas yield rates include, for example, co-digestion of food and FOG wastes, as well as digester operation under thermophillic operating conditions. This pathway however, does not consider the impacts of co-digestion or higher temperature digestion. Staff expects that co-digestion of food and FOG wastes with wastewater sludge would only have the impact of increasing the biogas yields and correspondingly reducing the proposed CI for the pathway. And while thermophillic digestion can dramatically increase biogas yield rates, the energy requirements to operate the digesters under thermophillic operating conditions can also be significantly higher.

Table IV-2 below presents some characteristics of the fugitive biogas and biomethane emissions from wastewater sludge digestion.

Table IV-2
Biogas and Biomethane Emissions Rates

Biomethane Emission Rates	**Units**	**Small-to-Medium POTW (20 MGD)**	**Medium-to-Large POTW (100 MGD)**
From Digester due to Leaks and Maintenance	(m^3 CH_4/m^3 Total Biogas Production)	0.0100	0.0100
From Digested Sludge Holding Tank:	-	-	-
- Holding Duration: 5 days	(m^3 CH_4/m^3 Net Biogas Production after Leakage)	0.0328	0.0328
- Holding Duration: 1 day	(m^3 CH_4/kg digestible solid in digestate)	0.0049	0.0049
From Operation of Centrifuges	(m^3 CH_4/m^3 Net Biogas Production after Leakage)	0.0082	0.0082
From Dewatered Biosolids Storage Tank:	-	-	-
- Storage Duration: 10 days	(m^3 CH_4/m^3 Net Biogas Production after Leakage)	0.0164	0.0164
- Storage Duration: 1 day	(m^3 CH_4/kg digestible solid in digestate)	0.0014	0.0014
From Soil Applied Biosolids	(m^3 CH_4/m^3 digestate disposed)	0.0129	0.0129
From Landfilled Biosolids	(m^3 CH_4/m^3 digestate disposed)	0.0006	0.0006
From Supernatant	(m^3 CH_4/m^3 Supernatant)	0.0139	0.0139

V. Life Cycle Analysis of Energy Consumption and GHG Emissions Impacts

The wastewater sludge that is sent to the anaerobic digesters is generated from primary and secondary treatment processes at the wastewater treatment plant (WWTP). This sludge consists of volatile and other inert solids which must be decomposed before the plant can discharge the solid material and effluent. WWTPs provide heat energy to large anaerobic digestion vessels to break down the solids in the wastewater sludge.

Digestion of the wastewater sludge requires bacteria that feed on the organic matter in the absence of oxygen, as well as thermal energy. The amount of heat supplied to the tanks dictates whether the digestion occurs under mesophilic (~ 35 deg C) or thermophillic (~ 55 deg C) conditions. Most POTWs in California[4] practice mesophilic anaerobic digestion. The anaerobic digestion process is also a function of the amount of time the wastewater sludge spends in the digesters. The time spent in the digesters is called the "residence time," and it may last from 14 to 21 days. The by-product of the anaerobic digestion process is called biogas, a mixture of approximately 60 percent methane, and 40 percent carbon dioxide, along with some other impurities. In addition to the biogas, the wastewater sludge digestion process produces a digestate which is sent through centrifuges for dewatering. The dewatered biosolids are then typically sent off-site for land application, landfilling, or used as alternative daily cover (ADC). If the biosolids are completely free of pathogens and found to be rich in inorganic nutrients, they may be used as a soil amendment or crop fertilizer. Lastly, the biogas that accumulates in the digester header space is collected and processed to remove impurities, and then either used as fuel, or to provide process energy, or flared to reduce the GHG impacts the biogas may have on the environment. The biogas may also be further refined to remove the carbon dioxide, yielding near pure (99 percent) biomethane, which could be used as a transportation fuel.

In this section, staff will address the life cycle energy requirements for the production of biomethane from the mesophilic anaerobic digestion of wastewater sludge in a low solids (wet fermentation) process, as well as determine the life cycle GHG impacts for the proposed biomethane pathway. The GHG impacts are assessed based on the electrical and thermal energy demands of the individual operational processes which include anaerobic digestion, digestate management, supernatant management, first-stage biogas refining, and second-stage biogas refining along with biomethane compression, and on-site vehicle fueling. The wastewater sludge-to-biomethane pathway has been developed for two scenarios:

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[4] See Appendix A, results of the California POTW Survey conducted by the California Association of Sanitation Agencies (CASA).

Small-to-Medium POTWs with wastewater inflows of 5 to 20 MGD referred to as Alternative Case 1; and Medium-to-Large POTWs with wastewater inflows of 21 to 100 MGD referred to as Alternative Case 2. Both scenarios assume that up to a two-stage mesophilic anaerobic digestion process will dictate the production of biogas in the digesters.

In the case of the Small-to-Medium POTW (Alternative Case 1), it is assumed that a fraction of the biogas is expected to be consumed by the boilers for process thermal needs and to provide thermal energy for the digesters to operate under mesophilic operating conditions. The majority of the biogas produced would be allocated to the production of biomethane for transportation use purposes. This model also assumes that grid-based electrical power will be obtained for the electrical energy needs of the WWTP.

In the case of the Medium-to-Large POTWs (Alternative Case 2), it is assumed that a majority of the biogas produced would be cleaned and conditioned for use in compliant combustion devices, such as gas-fired turbines with generators, to produce renewable power. Since such devices emit exhaust with high heat potential (in excess of 1,000 degrees F), a heat recovery steam generator (or heat exchanger with a steam boiler) would be used to recover the heat from the exhaust and produce steam to meet the thermal energy demands of the digesters. The remainder of the biomethane is then assumed to be allocated to transportation applications (such as on-site compressed natural gas or CNG vehicle fueling, or injection into the natural gas grid for off-site CNG vehicle fueling). This model does not depend upon external grid-based electrical power to operate the treatment processes at the WWTP since power is produced internally by the compliant combustion device and generator. Any electrical power produced and not consumed by the process units of the wastewater sludge digestion process is considered to be surplus electrical energy, which may be exported to the public grid, or may displace an equivalent amount of grid-based electrical generation.

An analysis of the process energy (electrical and thermal) requirements and life cycle GHG emissions impacts of each operational unit of the biomethane production cycle is presented below:

a. Mesophilic Anaerobic Digestion

Anaerobic digesters operating under mesophilic conditions require thermal energy and electrical energy inputs.

For Small-to-Medium POTWs with 5 to 20 MGD of wastewater inflows, Alternative Case 1 assumes that the digester thermal energy demand is met by a parasitic load on the biogas generated in the digesters. This biogas is consumed in a small industrial boiler that produces steam used to bring the digesters into the mesophilic temperature range.

The GREET1 Model predicts that 86,486 MJ per day of thermal energy (output) will be required for 2-stage mesophilic anaerobic digestion of wastewater sludge. Assuming a steam boiler efficiency of 80 percent, and a heat exchanger efficiency of 70 percent is applicable, the net thermal demand of the digesters is estimated to be 154,439 MJ per day. This thermal demand produces a draw of 152,163 scf biomethane per day. The GHG emissions impacts from biogas combustion in a small, industrial boiler (10 – 100 mmBtu/hr) are presented in Table V-1 below:

Table V-1
GHG Emissions from Thermal Energy Demand for Anaerobic Digestion Small-to-Medium POTW (Alternative Case 1)

Pollutant	Emissions Factors for Small Industrial Boiler * (g/mmBtu)	GHG Emissions Impacts for Alternative Case 1 (g/day)
VOC	2.42	**353.80**
CO	28.82	**4,218.95**
CH_4	1.10	**161.02**
N_2O	0.31	**46.11**
CO_2	58,176	**8,515,714.84**

* See Spreadsheet "ca_greet1.8b_dec09.xls," Worksheet "EF," (10-100 mmBtu/hr Input).

Example Calculation for Estimating Methane Emissions

Thermal Energy Demand for Anaerobic Digestion (Output) = $\frac{86{,}486\ MJ}{day}$

Steam Boiler Efficiency: = *80%*
Heat Recovery Efficiency: = *70%*

Thermal Energy Demand for Anaerobic Digestion (Input) = $\frac{154{,}439\ MJ}{day}$

Methane Emissions Factor for Small Boiler = $\frac{1.10\ g\ CH_4}{mmBtu}$

Therefore, Methane Emissions = $\frac{154{,}439\ MJ}{day} \times \frac{1\ Btu}{1055.06\ J} \times \frac{1.10\ g\ CH_4}{mmBtu}$

Methane Emissions = $\frac{161.02\ g\ CH_4}{day}$

For Medium-to-Large POTWs with 21 to 100 MGD of wastewater inflows, Alternative Case 2 assumes that the digester thermal energy demand is met by the heat recovery operations from the exhaust of the gas-fired combustion device. The GREET1 Model predicts that 412,933 MJ per day of thermal energy will be required for 2-stage mesophilic anaerobic digestion of wastewater sludge. The recovered heat then producers more steam for the purpose of providing heat energy to the digesters. Therefore, in Alternative Case 2, no additional fuel or biogas is required to provide the thermal energy needed to bring the digesters into the mesophilic temperature range. Since no additional combustion is needed to heat the digesters, the GHG emissions from this operation are assumed to be zero.

The GREET1 Model estimates that for Alternative Case 1, 8,709 MJ of electrical energy output per day is required for the mesophilic anaerobic digestion process. This represents 29.7 percent of the total electrical demand for the wastewater sludge-to-biomethane pathway. As illustrated in the schematic for Alternative Case 1 (Figure IV-2), the electrical energy is assumed to be provided by the grid. Staff assumes that the applicable regional portfolio of electrical generating assets is the California marginal mix. The GHG emissions impacts for fuel-cycle energy use and emissions from electric generation is presented in Table V-2 below:

Table V-2
GHG Emissions from Electrical Energy Demand for Anaerobic Digestion Small-to-Medium POTW (Alternative Case 1)

Pollutant	Feedstock* (g/mmBtu)	Fuel* (g/mmBtu)	Sum (g/mmBtu)	GHG Emissions Impacts of Electrical Energy Demand** (g/day)
VOC	10.19	5.67	15.86	130.94
CO	18.44	39.68	58.12	479.73
CH_4	212.37	7.04	219.42	1,811.18
N_2O	0.10	2.48	2.58	21.33
CO_2	8,276.83	96,249.68	104,526.51	862,814.77

*See Spreadsheet “ca_greet1.80b_dec09.xls,” Worksheet “Electric,” Feedstock and Fuel factors for stationary applications (Fuel-Cycle Energy Use and Emissions of Electric Generation: Btu or Grams per mmBtu of Electricity Available at User Sites (wall outlets)).

Example Calculation for Estimating VOC Emissions

Electrical Energy Demand for Anaerobic Digestion

$$= \frac{8{,}709\ \text{MJ}}{\text{day}}$$

VOC Emissions Factor for Grid Power

$$= \frac{15.86\ \text{g VOC}}{\text{mmBtu}}\ \text{(Fuel Cycle Emissions)}$$

Therefore, VOC Emissions

$$= \frac{8{,}709\ \text{MJ}}{\text{day}} \times \frac{1\ \text{Btu}}{1055.06\ \text{J}} \times \frac{15.86\ \text{g VOC}}{\text{mmBtu}}$$

VOC Emissions

$$= \frac{130.94\ \text{g VOC}}{\text{day}}$$

For Medium-to-Large POTWs with inflows of 21 to 100 MGD, the GREET1 Model estimates that for Alternative Case 2, 43,546 MJ of electrical energy output per day is required for the mesophilic anaerobic digestion process. This quantity represents approximately 30.7 percent of the total electrical demand for the wastewater sludge-to-biomethane pathway. The electrical energy demand is met by a high-efficiency on-site gas-fired micro-turbine or turbine (simple or combined cycle) with generator. The GREET1 Model assumes a cogeneration efficiency of 31.5 percent is applicable for such devices, therefore the net fuel input requirement for the energy generating device is 138,241 MJ per day. The GHG emissions impact of fuel combustion for stationary applications (grams per mmBtu of fuel burned) is presented in Table V-3 below:

Table V-3
GHG Emissions from Electrical Energy Demand for Anaerobic Digestion Medium-to-Large POTW (Alternative Case 2)

Pollutant	Simple Cycle or Combined Cycle Gas Turbine (g/mmBtu of fuel input)*	GHG Emissions Impact of Electrical Energy Demand (g/day)
VOC	3.43	**449.29**
CO	24.00	**3,144.65**
CH_4	4.26	**558.17**
N_2O	1.50	**196.54**
CO_2	58,171	**7,622,004.15**

* See Spreadsheet “ca_greet1.80b_dec09.xls,”, Worksheet “EF” (Emission Factors of Fuel Combustion for Stationary Applications (grams per mmBtu of fuel burned)).

Example Calculation for Estimating CO Emissions

Electrical Energy Demand for Anaerobic Digestion $= \frac{43{,}546\text{ MJ}}{\text{day}}$

CHP Generator Electrical Efficiency $= 31.50\%$

Fuel Input Required for Combustion $= \frac{43{,}546\text{ MJ}}{\text{day}} \times \frac{1}{31.50\%} = \frac{138{,}241\text{ MJ}}{\text{day}}$

CO Emissions Factor for SC / CC Gas Turbine $= \frac{24.00\text{ g CO}}{\text{mmBtu}}$ *(Fuel Combustion for Stationary Applications)*

Therefore, CO Emissions $= \frac{138{,}241\text{ MJ}}{\text{day}} \times \frac{1\text{ Btu}}{1055.06\text{ J}} \times \frac{24.00\text{ g CO}}{\text{mmBtu}}$

CO Emissions $= \frac{3{,}144.65\text{ g CO}}{\text{day}}$

In addition to the GHG emissions impacts that arise from the thermal and electrical energy demand for the mesophilic anaerobic digestion process, the GREET1 Model additionally estimates fugitive methane losses from the digesters to be approximately one percent.

For Alternative Cases 1 and 2, a one percent fugitive methane loss equates to 69 and 347 m^3 per day, respectively. These losses are added to the overall GHG emissions impacts for determining the total well-to-tank (WTT) emissions.

b. Digestate Management

Once the minimum residence time for the batch of wastewater sludge in the digesters has been achieved and the biogas collected, the remaining residue (called digestate) is transported to the centrifuges for dewatering. Electrical energy is consumed by the pumps used to transport the digestate from the digesters to the centrifuges, as well as by the centrifuges themselves. This process produces dewatered biosolids. The transport of the dewatered biosolids to an off-site land application site or landfill consumes fossil fuel energy.

The GHG emissions impact of both electrical energy and fossil fuel consumption for digestate management activities is presented in Tables V-4 and V-5 below. The GREET1 Model estimates that, for Alternative Case 1, 8,740 MJ of electrical energy per day is required to transport and dewater the digestate. This quantity represents approximately 29.8 percent of the total electrical energy demand of the wastewater sludge–to-biomethane pathway. As illustrated in the schematic for Alternative Case 1 (Figure IV-2), the electrical energy is assumed to be provided by the grid. Staff assumes that the applicable regional portfolio of electrical generating assets is the California marginal mix. The GHG emissions impacts for fuel-cycle energy use and emissions from electric generation is presented in Table V-4 below:

Table V-4
GHG Emissions from Electrical Energy Demand for Digestate Management (Small-to-Medium POTW)

Pollutant	Feedstock* (g/mmBtu)	Fuel* (g/mmBtu)	Sum (g/mmBtu)	GHG Emissions Impacts of Electrical Energy Demand (g/day)
VOC	10.19	5.67	15.86	**131.41**
CO	18.44	39.68	58.12	**481.43**
CH_4	212.37	7.04	219.42	**1,817.61**
N_2O	0.10	2.48	2.58	**21.41**
CO_2	8,276.83	96,249.68	104,526.51	**865,878.60**

*See Spreadsheet “ca_greet1.80b_dec09.xls,” Worksheet “Electric,” Feedstock and Fuel factors for stationary applications (Fuel-Cycle Energy Use and Emissions of Electric Generation: Btu or Grams per mmBtu of Electricity Available at User Sites (wall outlets)).

For Medium-to-Large POTWs with wastewater inflows of 21 to 100 MGD, the GREET1 Model estimates that for Alternative Case 2, 43,698 MJ of electrical energy output per day is required for digestate transport and dewatering operations. This quantity represents approximately 30.8 percent of the total electrical energy demand for the wastewater sludge-to-biomethane pathway. This electrical energy demand is met by a high-efficiency on-site gas-fired micro-turbine or turbine (simple or combined cycle) with generator. The GREET1 Model assumes a cogeneration efficiency of 31.5 percent is applicable for such devices, therefore the net fuel input requirement for the energy generating device is 138,724 MJ per day. The GHG emissions impact of fuel combustion for stationary applications (grams per mmBtu of fuel burned) is presented in Table V-5 below:

Table V-5
GHG Emissions from Electrical Energy Demand for Digestate Management (Medium-to-Large POTW)

Pollutant	Simple Cycle or Combined Cycle Gas Turbine (g/mmBtu of fuel input)*	GHG Emissions Impact (g/day)
VOC	3.43	**450.86**
CO	24.00	**3,155.63**
CH_4	4.26	**560.12**
N_2O	1.50	**197.23**
CO_2	58,171.00	**7,648,627.80**

* See Spreadsheet “ca_greet1.80b_dec09.xls,” Worksheet “EF” (Emission Factors of Fuel Combustion for Stationary Applications (grams per mmBtu of fuel burned)).

The GREET1 Model predicts that the total amount of dry biosolids produced in the digestate dewatering stage will be 24,062 kilograms per day by the Small-to-Medium POTW (Alternative Case 1), and 120,306 kilogram per day by the Medium-to-Large POTW (Alternative Case 2). Staff assumes that the dewatered biosolids would be transported to a land application site or landfill 40 miles away from the Small-to-Medium POTW or the Medium-to-Large POTW using a heavy, heavy-duty diesel truck (HHDDT) that travels 5 miles per gallon of fuel, and has a cargo payload of 23 short tons.

Staff estimates that 2.40 mmBtu per day and 12.02 mmBtu per day of ultra-low sulfur diesel will be consumed by the HHDDT at the Small-to-Medium and the Medium-to-Large POTWs, respectively.

Example Calculation for Estimating ULSD Fuel Use for Biosolids (Dewatered Digestate) Transport

	Small-to-Medium POTW	***Medium-to-Large POTW***
Total Dry Biosolids to be Disposed (kg / day) (A1)	*24,062.09*	*120,306.26*
Total Dry Biosolids to be Disposed (tons / day) (A2)	*26.53*	*132.64*
Vehicle Cargo Carrying Capacity (tons) (B)	*22.5*	*22.5*
Number of Truck Trips Per Day (C = A1 or A2 / B)	*1.18*	*5.90*
Distance to Landfill or Land Application Site (miles) (D)	*40*	*40*
Total Distance Covered with Back-Haul (miles) (E = C x 2 x D)	*94.32*	*471.60*
Vehicle Fuel Economy (miles per gallon) (F)	*5*	*5*
Total ULSD Fuel Consumed (gallons / day) (G)	*18.86*	*94.32*
ULSD Lower Heat Value (LHV) (Btu / gallon) (H)	*127,464*	*127,464*
ULSD Energy Consumption (mmBtu / day) (I = G x H)	***2.40***	***12.02***

A summary of GHG emissions impacts from the production and use of ultra-low-sulfur diesel (ULSD) fuel in California is presented in Table V-6 below. These emissions represent the well-to-tank (WTT), or fuel-cycle GHG emissions associated with the production and transport of ULSD from petroleum crude for use in California. In addition to fuel cycle emissions, actual GHG emissions that ensue from transport of materials (dewatered digestate to landfill) must also be estimated. Together, the fuel cycle emissions and the GHG emissions from actual fuel use for transport operations represent the total GHG emissions impacts from diesel fuel use in California.

Table V-6
GHG Emissions from ULSD Fuel Use in California
(Fuel Cycle Emissions)*

	Feedstock	**Fuel**		**Alternative Case 1**	**Alternative Case 2**
	Crude for Use in CA Refineries (g/mmBtu)	**Ultra Low Sulfur Diesel (g/mmBtu)**	**Total Well-to-Tank (WTT) Emissions** (g/mmBtu)**	**Small-to-Medium POTW WTT Emissions (g/day)**	**Medium-to-Large POTW WTT Emissions (g/day)**
Loss Factor		1.0000441			
VOC	5.43	4.37	9.80	**23.56**	**117.79**
CO	19.71	7.16	26.88	**64.63**	**323.15**
CH_4	90.34	10.94	101.29	**243.55**	**1,217.70**
N_2O	0.11	0.11	0.23	**0.55**	**2.73**
CO_2	6,743.50	12,175.11	18,918.91	**45,491.78**	**227,451.00**

*Summary of Energy Consumption and Emissions: Btu or Grams per mmBtu of Fuel Throughput at Each Stage.

**Total Well-to-Tank Emissions = (Feedstock Factor) x (Loss Factor) + (Fuel Factor)

<u>Example Calculation for Estimating ULSD Fuel Use Fuel Cycle CH_4 Emissions</u>

Total Well-to-Tank (WTT) Emissions = *(Feedstock Factor) x (Loss Factor) + (Fuel Factor)*

Total Well-to-Tank (WTT) CH_4 Emissions $= \frac{90.34 \text{ g } CH_4}{\text{mmBtu}} \times 1.0000441 \text{ (Loss Factor)} + \frac{10.94 \text{ g } CH_4}{\text{mmBtu}}$

Total Well-to-Tank (WTT) CH_4 Emissions $= \frac{101.29 \text{ g } CH_4}{\text{mmBtu}}$

ULSD Fuel Consumed - Medium HDDT $= \frac{4.63 \text{ mmBtu}}{\text{day}}$

Therefore, ULSD Fuel Use in California
(Fuel Cycle CH_4 Emissions)
(Small-to-Medium POTW) $= \frac{101.29 \text{ g } CH_4}{\text{mmBtu}} \times \frac{2.40 \text{ mmBtu}}{\text{day}}$

ULSD Fuel Use Fuel Cycle CH_4 Emissions
(Small-to-Medium POTW) $= \frac{243.55 \text{ g } CH_4}{\text{day}}$

Similarly,

ULSD Fuel Consumed - Heavy HDDT $= \dfrac{12.02 \text{ mmBtu}}{\text{day}}$

Therefore, ULSD Fuel Use in California
(Fuel Cycle CH_4 *Emissions)*
(Medium-to-Large POTW) $= \dfrac{101.29 \text{ g } CH_4}{\text{mmBtu}} \times \dfrac{12.02 \text{ mmBtu}}{\text{day}}$

ULSD Fuel Use Fuel Cycle CH_4 ***Emissions***
(Medium-to-Large POTW) $= \dfrac{1{,}217.70 \text{ g } CH_4}{\text{day}}$

GHG emissions also arise from the actual combustion of ULSD in heavy-heavy duty diesel-fueled vehicles (for both Small-to-Medium, and Medium-to-Large POTWs) when the dewatered biosolids are transported to a land application site or landfill. A transport distance of 40 miles is assumed (one-way). To simulate the GHG impacts of transporting the material, staff assumed that the physical properties of the dewatered digestate (dry biosolids) would be similar to transporting calcium carbonate ($CaCO_3$), a compound for which the energy consumption and emissions from feedstock and fuel transport are present in CA-GREETv1.8b.

Table V-7
GHG Emissions from Distribution of Biosolids
(Dewatered Digestate)

	Material Transport	**Alternative Case 1**	**Alternative Case 2**
Pollutant	**Total Emissions (g/mmBtu)**	**Small-to-Medium POTW TTW Emissions (g/day)**	**Medium-to-Large POTW TTW Emissions (g/day)**
VOC	3.61	**8.67**	**43.36**
CO	16.33	**39.27**	**196.35**
CH_4	10.46	**25.14**	**125.70**
N_2O	0.21	**0.50**	**2.52**
CO_2	8,508.17	**20,458.46**	**102,288.74**

Example Calculation for Estimating ULSD Fuel N_2O Emissions from Biosolids Transport

	Small-to-Medium POTW	***Medium-to-Large POTW***
ULSD Energy Consumption (mmBtu / day) (A)	2.40	12.02
N_2O Emissions Factor (g / mmBtu) (B) (Staff assumes that dry Biosolids transport by truck can be simulated with $CaCO_3$ Transport)	0.21	0.21
Therefore, N_2O Emissions (g / day) (C = A x B)	**0.50**	**2.52**

The total impact of GHG emissions from dewatered digestate (biosolids) transport from the POTW to the land application site or landfill is the sum of the well-to-tank emissions (Table V-6) and the tank-to-wheels emissions (Table V-7). A summary of the total GHG emissions impact from transport and distribution of biosolids is presented in Table V-8 below:

Table V-8
Total GHG Emissions from ULSD Fuel Use

	Alternative Case 1	**Alternative Case 2**
Pollutant	**Small-to-Medium POTW WTW Emissions (g/day)**	**Medium-to-Large POTW WTW Emissions (g/day)**
VOC	**32.23**	**161.15**
CO	**103.90**	**519.50**
CH_4	**268.69**	**1,343.40**
N_2O	**1.05**	**5.25**
CO_2	**65,950.24**	**329,739.73**

In addition to the GHG emissions impacts that arise from digestate management, the GREET1 Model estimates fugitive methane losses from the digestate management system, which includes the sludge holding tanks, centrifuges, and the storage tanks. For Alternative Cases 1 and 2, fugitive methane losses are estimated to be 99 m^3 and 495 m^3 per day, respectively. These losses are added to the overall GHG emissions impacts for determining total well-to-tank (WTT) emissions for wastewater sludge-to-biomethane pathways.

Additional methane losses predicted by the GREET1 Model after the dewatered digestate has been disposed in a landfill or land application site (0.042 m^3/day) are assumed to be negligible after application of a landfill gas capture efficiency of 75 percent applicable to a typical landfill (California Air Resources Board, 2012).

c. Supernatant Management

Once the digestate has been dewatered, the biosolids that remain in the centrifuge are transported to a land application site or landfill. The fluid that is separated from the biosolids is called the supernatant. This fluid is returned to the wastewater treatment plant influent as a recycle stream. The electrical energy demand for returning the supernatant fluid to the influent channels is assumed to be insignificant.

The GHG emissions impacts of supernatant return to wastewater influent channels, however, are not zero. The GREET1 Model estimates that, supernatant storage tanks and return lines will emit an additional 12 m^3 and 60 m^3 CH_4 per day, for Small-to-Medium POTWs and Medium-to-Large POTWs (Alternative Cases 1 and 2), respectively. These losses are added to the overall GHG emissions impacts for determining total well-to-tank (WTT) emissions for the biomethane pathway.

d. Stage-1 Biogas Refining Process

Once the biogas is generated in the anaerobic digesters by the decomposition of the wastewater sludge under mesophilic operating conditions, it collects in the digester header space. The GREET1 Model suggests that the composition of the biogas is estimated to be approximately 58 percent methane (by volume), with the balance consisting of carbon dioxide and impurities. Blowers are employed to send the biogas in the digester header space to the Stage-1 biogas refining unit, where impurities such as siloxanes, vinyl chloride, hydrogen sulfide, and moisture are removed so that efficient combustion of the biogas in an engine or turbine is possible. Removal of the impurities also minimizes buildup on engine parts and turbine blades.

Stage-1 biogas refining is assumed to consume only electrical energy. The GREET1 Model specifies that Small-to-Medium POTWs (Alternative Case 1) consume 7,297 MJ of electrical energy output per day. This represents 24.9 percent of the total wastewater sludge-to-biomethane pathway electrical energy demand. The energy is assumed to be supplied by grid-based electrical power. The applicable regional portfolio of electrical generating assets is the California marginal mix. The GHG emissions impacts for fuel-cycle energy use and emissions from electric generation are presented in Table V-9 below:

Table V-9
GHG Emissions from Electrical Energy Demand for Stage-1 Biogas Refining (Small-to-Medium POTW)

Pollutant	Feedstock* (g/mmBtu)	Fuel* (g/mmBtu)	Sum (g/mmBtu)	GHG Emissions Impacts of Electrical Demand (g/day)
VOC	10.19	5.67	15.86	**109.71**
CO	18.44	39.68	58.12	**401.93**
CH_4	212.37	7.04	219.42	**1,517.48**
N_2O	0.10	2.48	2.58	**17.87**
CO_2	8,276.83	96,249.68	104,526.51	**722,899.21**

*See Spreadsheet “ca_greet1.80b_dec09.xls,” Worksheet “Electric,” Feedstock and Fuel factors for stationary applications (Fuel-Cycle Energy Use and Emissions of Electric Generation: Btu or Grams per mmBtu of Electricity Available at User Sites (wall outlets)).

The GREET1 Model also indicates that approximately 69 m^3 CH_4 per day will be emitted from the Stage-1 biogas refining process as fugitive methane losses. These losses are added to the overall GHG emissions impacts for determining total well-to-tank (WTT) emissions.

For Alternative Case 2 (Medium-to-Large POTW), the GREET1 Model estimates that 36,484 MJ per day of electrical energy output will be required for Stage-1 biogas refining. This represents 25.7 percent of the total wastewater sludge-to-biomethane pathway electrical energy demand. The electrical energy is assumed to be supplied by an on-site gas-fired micro-turbine or turbine (simple or combined cycle) with generator. The GREET1 Model assumes a cogeneration efficiency of 31.5 percent is applicable for such devices, therefore the net fuel input requirement for the energy generating device is 115,821 MJ per day.

The GHG emissions impact of fuel combustion in the on-site gas-fired turbine (grams per mmBtu of fuel burned) is presented in Table V-10 below:

Table V-10
GHG Emissions from Electrical Energy Demand for Stage-1 Biogas Refining (Medium-to-Large POTW)

Pollutant	Simple Cycle or Combined Cycle Gas Turbine (g/mmBtu of fuel input)*	GHG Emissions Impact (g/day)
VOC	3.43	**376.42**
CO	24.00	**2,634.64**
CH_4	4.26	**467.65**
N_2O	1.50	**164.67**
CO_2	58,171.00	**6,385,859.96**

* See Spreadsheet "ca_greet1.80b_dec09.xls," Worksheet "EF." (Emission Factors of Fuel Combustion for Stationary Applications (grams per mmBtu of fuel burned)).

In addition to the GHG emissions impacts that arise from the electrical energy demand for Stage-1 biogas refining, the GREET1 Model estimates that this operation will produce approximately 343 m^3 per day in additional methane losses. These losses are added to the overall GHG emissions impacts for determining total well-to-tank (WTT) emissions.

e. Stage-2 Biogas Refining, Compression, and On-Site Vehicle Fueling

The Stage-2 biogas refining process primarily includes removal of the carbon dioxide in the biogas to produce near pure biomethane. This is required to meet motor fuel specifications, or to inject biomethane into the common carrier natural gas pipeline. Several technologies may be employed to achieve this separation. These may include technologies such as pressure swing adsorption (PSA), water scrubbing, chemical scrubbing, or membrane separation. For PSA, methane recovery efficiencies from the biogas can be in the low to mid-90 percent range, with near pure biomethane present in the product gas (99 percent biomethane). The unrecovered methane in the tail gas when PSA is employed is typically flared or sent to a thermal oxidizer for methane destruction. Alternatively, technologies such as membrane separation may achieve lower methane recovery efficiencies near 75 percent (Unison Solutions, 2014), but produce a tail gas that is rich in methane content that brings energy value when it is re-directed to the combined heat and power plant (CHP) as an alternative to flaring.

Electrical compressors are required to compress the biogas before it enters the Stage-2 biogas refining process, as well as to compress the biomethane. Vehicle fueling options may include an on-site low-speed or high-speed biomethane fueling station, or the direct injection of the biomethane into the natural gas distribution grid. For on-site high speed vehicle fueling, compression pressures of up to 3,600 psi may be required. If injection of biomethane into the natural gas grid is desired, then biomethane compression pressures of 600-800 psi (California Air Resources Board, 2012) may be required. For simplicity, this analysis assumes that vehicle fueling occurs on-site.

The GREET1 Model estimates that the primary energy input for the Stage-2 biogas refining process is electrical energy. For Small-to-Medium POTWs (Alternative Case 1), the GREET1 Model estimates that 2,671 MJ of electrical energy output per day is required for the Stage-2 biogas refining process. This represents 9.1 percent of the total electrical demand for the total wastewater sludge-to-biomethane pathway. An additional 1,870 MJ per day of electrical energy output is required for on-site biomethane compression and vehicle fueling. This represents 6.4 percent of the total electrical demand for the pathway.

The energy is assumed to be supplied by grid-based electrical power. Staff assumes that the applicable regional portfolio of electrical generating assets is the California marginal mix. The fuel cycle GHG emissions from electric energy use are presented in Table V-11 below:

Table V-11
GHG Emissions from Electrical Energy Demand for Stage-2 Biogas Refining (Small-to-Medium POTW)

Pollutant	Feedstock* (g/mmBtu)	Fuel* (g/mmBtu)	Sum (g/mmBtu)	GHG Emissions from Electrical Energy Demand (g/day)
VOC	10.19	5.67	15.86	**68.27**
CO	18.44	39.68	58.12	**250.11**
CH_4	212.37	7.04	219.42	**944.29**
N_2O	0.10	2.48	2.58	**11.12**
CO_2	8,276.83	96,249.68	104,526.51	**449,841.32**

*See Spreadsheet "ca_greetv1.80b_dec09.xls," Worksheet "Electric," Feedstock and Fuel factors for stationary applications (Fuel-Cycle Energy Use and Emissions of Electric Generation: Btu or Grams per mmBtu of Electricity Available at User Sites (wall outlets)).

For Alternative Case 2 (Medium-to-Large POTW), the GREET1 Model estimates that 10,693 MJ of electrical energy output per day will be required for the Stage-2 biogas refining process. This amount of energy represents 7.5 percent of the total electrical energy demand. An additional 7,485 MJ of electrical energy output per day, representing 5.3 percent of the total electrical energy demand, will be required for biomethane compression and on-site vehicle fueling. The electrical energy is assumed to be supplied by an on-site gas-fired micro-turbine or turbine (simple or combined cycle) with generator. The GREET1 Model assumes a cogeneration efficiency of 31.5 percent is applicable for such devices, therefore the total net fuel input requirement for the energy generating device is 57,709 MJ per day (Stage-2 biogas refining and biomethane compression for on-site CNG fueling).

The GHG emissions from fuel combustion for stationary applications (grams per mmBtu of fuel burned) are presented in Table V-12 below:

Table V-12
GHG Emissions from Electrical Energy Demand for Stage-2 Biogas Refining (Medium-to-Large POTW)

Pollutant	Simple Cycle or Combined Cycle Gas Turbine (g/mmBtu of fuel input)*	GHG Emissions Impact (g/day)
VOC	3.43	**187.56**
CO	24.00	**1,312.74**
CH_4	4.26	**233.01**
N_2O	1.50	**82.05**
CO_2	58,171.00	**3,181,826.97**

* See Spreadsheet “ca_greet1.80b_dec09.xls,” Worksheet “EF.”

The GREET1 Model additionally estimates that the Stage-2 biogas refining process will produce 25 m^3 and 99 m^3 of fugitive CH_4 emissions per day under Alternative Cases 1 and 2, respectively. These losses are added to the overall GHG emissions impacts for determining total well-to-tank (WTT) emissions.

f. Tail Gas Emissions from Unrecovered Methane

Methane recovery efficiencies in the low to mid-90 percent range can be achieved when carbon dioxide separation technologies such as pressure swing adsorption (PSA) are employed for the Stage-2 biogas refining process. Staff has assumed that the unrecovered methane in the tail gas will be flared (with or without small amounts of added natural gas), or sent to a thermal oxidizer for further destruction. This results in further GHG impacts associated with the Stage-2 biogas refining process.

Conversely, if a carbon dioxide separation technology such as membrane separation is used, methane recovery efficiencies in the mid-70 to 90 percent range can be achieved (Unison Solutions, 2014). A membrane separation efficiency of 75 percent produces a tail gas that is rich in methane content. This tail gas can be consumed by the combined heat and power plant or CHP unit to recover additional energy (Unison Solutions, 2014).

From an emissions standpoint, staff assumes that selection of PSA represents a worst-case scenario, and has therefore included the GHG emissions impact from combustion of the unrecovered methane in the tail gas. These emissions are presented in Table V-13 below, and are based on a methane recovery efficiency of 92 percent (California Air Resources Board, 2012):

Table V-13
GHG Emissions from Combustion of Unrecovered Methane in Tail Gas

Biogas Refining Technology and Efficiency:		PSA, 92 Percent	
Biomethane in Tail Gas (m3/day):		197	788
Biomethane in Tail Gas (scf/day):		6,947	27,814
Pollutant	**Emissions Factor (g/mmBtu of Fuel Burned)**	**Small-to-Medium POTW (g/day)**	**Medium-to-Large POTW (g/day)**
VOC	2.50	**16.71**	**66.89**
CO	26.00	**173.76**	**695.68**
CH_4	49.00	**327.48**	**1,311.08**
N_2O	1.10	**7.35**	**29.43**
CO_2	58,048.00	**387,949.47**	**1,553,176.27**
Total GHG Emissions (g CO_2e/day)		**398,652.17**	**1,596,025.08**

Example Calculation for Estimating Methane Emissions from Tail Gas Flaring

		Small-to-Medium POTW	***Medium-to-Large POTW***
Biomethane in Tail Gas (m^3/day):		*196.75*	*787.68*
Biomethane in Tail Gas (scf/day):	**(A)**	*6,947.25*	*27,813.68*
Methane (CH_4) Emissions Factor (g/mmBtu of Fuel Burned)	**(B)**	*49.00*	*49.00*
Methane (CH_4) Lower Heat Value (LHV) (Btu/scf)	**(C)**	*962.00*	*962.00*
Fuel Burned in Flare / Thermal Oxidizer (mmBtu/day)	**(D = A x C)**	*6.68*	*26.76*
Therefore, Methane (CH_4) Emissions (g/day) =	**(B x D)**	**327.48**	**1,311.08**

VI. Applicable Credits, Well-to-Wheels GHG Emissions, and Proposed CI

In this section, staff will first present the LCFS credits that are applicable to the wastewater sludge-to-biomethane pathways presented under Alternative Cases 1 and 2. The credits are then combined with the life cycle GHG emissions of each alternative case to determine the net well-to-tank (WTT) GHG emissions for the fuel pathways presented. The final step for determining the overall carbon intensities of the Alternative Case 1 and Alternative Case 2 biomethane pathways consists of combining the total WTT with the tank-to-wheels (TTW) emissions from combustion of the biomethane fuel in the vehicle. The combined estimates for WTT and TTW GHG emissions produces the well-to-wheels (WTW) GHG emissions, which when divided by the fuel energy value yields the carbon intensity (CI) of the fuel.

a. Avoided Flare Emissions Credit

The reference case established in Section IV is driven by regulations requiring the organic content of the wastewater sludge to be reduced or destroyed before the treated effluent is discharged into the surface waters. Anaerobic digestion is the preferred method for destroying that organic content. Under the reference case, the biogas produced is flared to reduce the GHG and criteria pollutant emissions. In Alternative Case 1 and Alternative Case 2, that biogas is used instead for transportation fuel and the generation of renewable electrical power using compliant combustion equipment. The avoidance of flaring generates a credit under both alternative cases. Table VI-1 presents the GHG emissions associated with flaring at Small-to-Medium, and Medium-to-Large POTWs. These impacts translate into the flaring emissions avoided credits under Alternative Cases 1 and 2, respectively.

Table VI-1 below presents the avoided GHG impacts from flaring the digester gas (Reference Case).

Table VI-1
Avoided Biogas Flaring Emissions Credit for Alternative Cases 1 and 2

Digester Biomethane Generation Potential (m3/day):		6,931	34,657
Digester Biomethane Generation Potential (scf/day):		244,751	1,223,755
Pollutant	**Natural Gas Flare Emissions Factor (g/mmBtu of Fuel Burned)**	**Small-to-Medium POTW (g/day)**	**Medium-to-Large POTW (g/day)**
VOC	2.50	588.63	2,943.13
CO	26.00	6,121.71	30,608.56
CH_4	49.00	11,537.07	57,685.35
N_2O	1.10	259.00	1,294.98
CO_2	58,048.00	13,667,426.12	68,337,130.58
Total GHG Emissions (g CO_2e/day):		**14,044,481.14**	**70,222,405.70**

Example Calculation for Estimating Avioided Methane Emissions By Not Flaring

		Small-to-Medium POTW	*Medium-to-Large POTW*
Biomethane in Flare Gas (m^3/day):		*6,931.35*	*34,656.77*
Biomethane in Flare Gas (scf/day):	**(A)**	*244,750.96*	*1,223,754.81*
NG Flare Emissions Factor for Methane (g/mmBtu of Fuel Burned)	**(B)**	*49.00*	*49.00*
Methane (CH_4) Lower Heat Value (LHV) (Btu/scf)	**(C)**	*962.00*	*962.00*
Potential Amount of Fuel Burned in Flare (mmBtu/day)	**(D = A x C)**	*235.45*	*1,177.25*
Therefore, Avoided Methane (CH_4) Emissions (g/day) =	**(B x D)**	**11,537.07**	**57,685.35**

b. Cogenerated Electricity and Surplus Export Credit

Under Alternative Case 2 (Medium-to-Large POTWs), biogas or biomethane not allocated to transportation fuel would continue to be used in compliant power generating devices to produce renewable power.
A portion of the renewable power produced on-site would be utilized to meet the electrical demands of the wastewater treatment process units (for example, for the anaerobic digestion process, digestate management, biogas refining, compression, and dispensing units, etc.). The power not utilized by the treatment process units would be available for export.

Staff notes that the surplus available energy may still be consumed by other process units within the wastewater treatment plant (for example, by the primary or secondary wastewater treatment processes), but if the on-site produced power is not consumed within the plant, it would be considered to be surplus cogenerated power available for export.

Exported electricity would displace grid-based electricity. In California, surplus cogenerated electricity which is exported to the public grid, is assumed to displace the California marginal portfolio mix of electrical power generating assets.

The GREET1 Model estimates that, for Alternative Case 2 (Medium-to-Large POTWs), 271,270 MJ of electricity per day would be generated. The electricity required for process operations is estimated to be 141,906 MJ of electricity per day. Therefore the net electricity available for export (surplus) to the public grid or process units is estimated to be 129,364 MJ per day.

Table VI-2 below shows the GHG emissions that are produced from displacing surplus cogenerated electricity. These emissions are produced by generating 129,364 MJ per day of electricity less an estimated 8.1 percent distribution and transmission loss.[5] Therefore, the net amount of electricity displaced by exporting 129,412 MJ per day of electricity from the POTW is 118,885 MJ per day. The emissions avoided from displacement of California marginal electricity are presented in Table VI-2 below. These displaced emissions accrue as a credit to the pathway.

Table VI-2
GHG Emissions Displaced from Export of Surplus Cogenerated Electricity

Surplus Exported: 129,364 MJ/day	**Feedstock**	**Fuel**	**Total***	**Alternative Case 2 Displacement Credit (g/day)**
Pollutant	**(g/mmBtu)**	**(g/mmBtu)**	**(g/mmBtu)**	
VOC	10.19	5.67	15.86	**1,787.44**
CO	18.44	39.68	58.12	**6,548.68**
CH_4	212.37	7.04	219.42	**24,724.18**
N_2O	0.10	2.48	2.58	**291.21**
CO_2	8,276.83	96,249.68	104,526.51	**11,778,151.80**

*CA-GREETv1.8b, Worksheet "Electric," See #7 Feedstock and Fuel Factors for Stationary Application (g/mmBtu of of Electricity Available at User Sites (wall outlets)).

An example calculation for estimating the carbon monoxide emissions displaced from export of surplus cogenerated electricity produced on-site is presented below:

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[5] See CA-GREETv1.8b, Worksheet "Electric," Item #3, Cell D31.

Example Calculation for Estimating Carbon Monoxide Emissions Displaced from Exporting Surplus Cogenerated Electricity

Surplus Electrical Energy Available for Export = $\frac{129{,}363.68\ \text{MJ}}{\text{day}}$

Electrical Distribution and Transmission Losses = 8.1%

Net California Marginal Electricity Displaced = $\frac{118{,}885.22\ \text{MJ}}{\text{day}}$

Fuel Cycle CO Emissions Factor for Electrical Generation = $\frac{58.12\ \text{g CO}}{\text{mmBtu}}$

Therefore, CO Emissions = $\frac{118{,}885.22\ \text{MJ}}{\text{day}} \times \frac{1\ \text{Btu}}{1055.06\ \text{J}} \times \frac{58.12\ \text{g CO}}{\text{mmBtu}}$

CO Emissions = $\frac{6{,}548.68\ \text{g CO}}{\text{day}}$

The surplus 129,364 MJ per day of cogenerated electricity that is exported by the Medium-to-Large POTW is also associated with GHG emissions produced on-site by the CHP unit. These GHG emissions must be considered as a cost of surplus energy production and weighed against the GHG emissions benefit of displacing California marginal grid-based electrical generation.

The electrical energy is assumed to be produced by an on-site gas-fired micro-turbine or turbine (simple or combined cycle) with generator. The GREET1 Model assumes a cogeneration efficiency of 31.5 percent is applicable for such devices, therefore the total net fuel input requirement for the energy generating device is 410,678 MJ per day. The GHG emissions from fuel combustion for stationary applications (grams per mmBtu of fuel burned) are presented in Table VI-3 below:

Table VI-3
GHG Emissions from Surplus Cogenerated Electricity Production (Medium-to-Large POTW)

Pollutant	Simple Cycle or Combined Cycle Gas Turbine (g/mmBtu of fuel input)*	GHG Emissions Impact (g/day)
VOC	3.43	**1,334.73**
CO	24.00	**9,341.91**
CH_4	4.26	**1,658.19**
N_2O	1.50	**583.87**
CO_2	58,171.00	**22,642,964.03**

* See Spreadsheet “ca_greet1.80b_dec09.xls,” Worksheet “EF.”

An example calculation for estimating CO_2 emissions from the production of 129,364 MJ per day of surplus cogenerated electricity output on-site at the CHP unit is presented below:

<u>Example Calculation for Estimating Carbon Dioxide Emissions from Surplus Cogenerated Electricity Production On-Site</u>

Surplus Electrical Energy Available for Export $= \dfrac{129{,}464\ \text{MJ}}{\text{day}}$

CHP Generator Electrical Efficiency $= \underline{31.50\%}$

Fuel Input Required for Combustion $= \dfrac{129{,}464\ \text{MJ}}{\text{day}} \times \dfrac{1}{31.50\%} = \dfrac{410{,}678\ \text{MJ}}{\text{day}}$

CO_2 Emissions Factor for SC / CC Gas Turbine $= \dfrac{58{,}171\ \text{g}\ CO_2}{\text{mmBtu}}$ *(Fuel Combustion for Stationary Applications)*

Therefore, CO_2 Emissions $= \dfrac{410{,}678\ \text{MJ}}{\text{day}} \times \dfrac{1\ \text{Btu}}{1055.06\ \text{J}} \times \dfrac{58{,}171\ \text{g}\ CO_2}{\text{mmBtu}}$

CO_2 Emissions $= \dfrac{\mathbf{22{,}642{,}964\ \text{g}\ CO_2}}{\textbf{day}}$

The net GHG emissions displacement credit to the pathway for Alternative Case 2 from the export of surplus cogenerated electrical energy generated at the Medium-to-Large POTW is the difference in GHG emissions obtained from the production of electrical energy at the CHP unit of the POTW (Table VI-3), and the net-of-losses GHG emissions avoided from displacement of California marginal electricity (Table VI-2). These emissions are summarized in Table VI-4 below:

Table VI-4
Net GHG Emissions Credit for Surplus Electrical Energy Export

Surplus Exported: 129,464 MJ/day	GHG Emissions from Surplus Cogenerated Electricity Production On-Site	GHG Emissions Avoided from Displacement of CA Marginal	Net GHG Emissions Credit from Surplus Electricity Export (g/day)
Pollutant	**(g/day)**	**(g/day)**	
VOC	1,334.73	1,787.44	**(452.72)**
CO	9,341.91	6,548.68	**2,793.24**
CH_4	1,658.19	24,724.18	**(23,065.99)**
N_2O	583.87	291.21	**292.66**
CO_2	22,642,964.03	11,778,151.80	**10,864,812.23**

c. Total Well-to-Tank (WTT) GHG Emissions Estimates

The WTT GHG emissions impacts assessed in Section V for material transport, thermal and electrical energy use, digestate management, supernatant management, biogas refining, biomethane compression, and on-site vehicle fueling when combined with the applicable credits for avoided flaring, and electricity exported, yield the total WTT GHG emissions for the wastewater sludge-to-biomethane pathway. A summary of the total WTT GHG emissions estimate for Alternative Case 1 (Small-to-Medium POTW) is presented in Table VI-5 below.

Table VI-5
Summary of Total Well-to-Tank GHG Emissions Impact for Small-to-Medium POTW (Alternative Case 1)

Anaerobic Digestion	Thermal Load (g/day)	Electrical Load (g/day)	Fugitive Emissions (g/day)	Total Emissions (g/day)
VOC	353.80	130.94	-	**484.74**
CO	4,218.95	479.73	-	**4,698.68**
CH_4	161.02	1,811.18	49,255.42	**51,451.44**
N_2O	46.11	21.33	-	**67.44**
CO_2	8,515,714.84	862,814.77	-	**9,378,529.61**
Total CO_2e				**10,693,802.64**
Digestate Management	**Transport (g/day)**	**Electrical Load (g/day)**	**Fugitive Emissions (g/day)**	**Total Emissions (g/day)**
VOC	32.23	131.41	-	**163.64**
CO	103.90	481.43	-	**585.33**
CH_4	268.69	1,817.61	70,691.81	**72,778.12**
N_2O	1.05	21.41	-	**22.46**
CO_2	65,950.24	865,878.60	-	**931,828.84**
Total CO_2e				**2,759,403.78**
Supernatant Management	**Transport (g/day)**	**Electrical Load (g/day)**	**Fugitive Emissions (g/day)**	**Total Emissions (g/day)**
VOC	-	-	-	**-**
CO	-	-	-	**-**
CH_4	-	-	8,544.99	**8,544.99**
N_2O	-	-	-	**-**
CO_2	-	-	-	**-**
Total CO_2e				**213,624.76**
Biogas Refining (1st Stage)	**Thermal Load (g/day)**	**Electrical Load (g/day)**	**Fugitive Emissions (g/day)**	**Total Emissions (g/day)**
VOC	-	109.71	-	**109.71**
CO	-	401.93	-	**401.93**
CH_4	-	1,517.48	48,984.44	**50,501.92**
N_2O	-	17.87	-	**17.87**
CO_2	-	722,899.21	-	**722,899.21**
Total CO_2e				**1,991,746.85**
Biogas Refining (2nd Stage)	**Tail Gas-to-Flare or Thermal Oxidizer (g/day)**	**Electrical Load (g/day)**	**Fugitive Emissions (g/day)**	**Total Emissions (g/day)**
VOC	16.71	68.27	-	**84.98**
CO	173.76	250.11	-	**423.88**
CH_4	327.48	944.29	17,733.16	**19,004.93**
N_2O	7.35	11.12	-	**18.47**
CO_2	387,949.47	449,841.32	-	**837,790.80**
Total CO_2e				**1,319,349.84**

Table VI-5 (Continued)
Summary of Total Well-to-Tank GHG Emissions Impact for Small-to-Medium POTW (Alternative Case 1)

Avoided Biogas Flaring Emissions	Thermal Load (g/day)	Electrical Load (g/day)	Fugitive Emissions (g/day)	Total Emissions (g/day)
VOC	-	-	-	**(588.63)**
CO	-	-	-	**(6,121.71)**
CH_4	-	-	-	**(11,537.07)**
N_2O	-	-	-	**(259.00)**
CO_2	-	-	-	**(13,667,426.12)**
Total CO_2e				**(14,044,481.14)**
Surplus Electricity Export Credit	**Thermal Load (g/day)**	**Electrical Load (g/day)**	**Fugitive Emissions (g/day)**	**Total Emissions (g/day)**
VOC	-	-	-	**-**
CO	-	-	-	**-**
CH_4	-	-	-	**-**
N_2O	-	-	-	**-**
CO_2	-	-	-	**-**
Total CO_2e				**-**
Net WTT GHG Emissions	**Thermal Load (g/day)**	**Electrical Load (g/day)**	**Fugitive Emissions (g/day)**	**Total Emissions (g/day)**
VOC	-	-	-	**254.43**
CO	-	-	-	**(11.89)**
CH_4	-	-	-	**190,744.33**
N_2O	-	-	-	**(132.75)**
CO_2	-	-	-	**(1,796,377.65)**
NET WELL-TO-TANK (WTT) CO_2e EMISSIONS:				**2,933,446.73**

Staff notes that the well-to-tank GHG emissions stated in Table VI-5 above were adjusted for their respective global warming potentials to obtain the net well-to-tank carbon dioxide equivalent (CO_2e) emissions.

Similarly, a summary of the total WTT GHG emissions for Alternative Case 2 (Medium-to-Large POTWs) is presented in Table VI-6 below.

Table VI-6
Summary of Total Well-to-Tank GHG Emissions Impact for Medium-to-Large POTW (Alternative Case 2)

Anaerobic Digestion	Thermal Load (g/day)	Electrical Load (g/day)	Fugitive Emissions (g/day)	Total Emissions (g/day)
VOC	-	449.29	-	**449.29**
CO	-	3,144.65	-	**3,144.65**
CH_4	-	558.17	247,396.18	**247,954.36**
N_2O	-	196.54	-	**196.54**
CO_2	-	7,622,004.15	-	**7,622,004.15**
Total CO_2e				**13,885,770.99**
Digestate Management	**Transport (g/day)**	**Electrical Load (g/day)**	**Fugitive Emissions (g/day)**	**Total Emissions (g/day)**
VOC	161.15	450.86	-	**612.01**
CO	519.50	3,155.63	-	**3,675.13**
CH_4	1,343.40	560.12	353,459.06	**355,362.59**
N_2O	5.25	197.23	-	**202.47**
CO_2	329,739.73	7,648,627.80	-	**7,978,367.53**
Total CO_2e				**16,930,449.22**
Supernatant Management	**Transport (g/day)**	**Electrical Load (g/day)**	**Fugitive Emissions (g/day)**	**Total Emissions (g/day)**
VOC	-	-	-	-
CO	-	-	-	-
CH_4	-	-	42,725.08	**42,725.08**
N_2O	-	-	-	**-**
CO_2	-	-	-	**-**
Total CO_2e				**1,068,126.91**
Biogas Refining (1st Stage)	**Thermal Load (g/day)**	**Electrical Load (g/day)**	**Fugitive Emissions (g/day)**	**Total Emissions (g/day)**
VOC	-	376.42	-	**376.42**
CO	-	2,634.64	-	**2,634.64**
CH_4	-	467.65	244,922.22	**245,389.87**
N_2O	-	164.67	-	**164.67**
CO_2	-	6,385,859.96	-	**6,385,859.96**
Total CO_2e				**12,574,987.79**

Table VI-6 (Continued)
Summary of Total Well-to-Tank GHG Emissions Impact for Medium-to-Large POTW (Alternative Case 2)

Biogas Refining (2nd Stage)	**Tail Gas to Flare Emissions (g/day)**	**Electrical Load (g/day)**	**Fugitive Emissions (g/day)**	**Total Emissions (g/day)**
VOC	66.89	187.56	-	**254.45**
CO	695.68	1,312.74	-	**2,008.42**
CH_4	1,311.08	233.01	70,995.66	**72,539.76**
N_2O	29.43	82.05	-	**111.48**
CO_2	1,553,176.27	3,181,826.97	-	**4,735,003.24**
Total CO_2e				**6,585,664.91**
Avoided Biogas Flaring Emissions	**Thermal Load (g/day)**	**Electrical Load (g/day)**	**Fugitive Emissions (g/day)**	**Total Emissions (g/day)**
VOC	-	-	-	**(2,943.13)**
CO	-	-	-	**(30,608.56)**
CH_4	-	-	-	**(57,685.35)**
N_2O	-	-	-	**(1,294.98)**
CO_2	-	-	-	**(68,337,130.58)**
Total CO_2e				**(70,222,405.70)**
Net Surplus Electricity Export Credit	**Thermal Load (g/day)**	**Electrical Load (g/day)**	**Fugitive Emissions (g/day)**	**Total Emissions (g/day)**
VOC	-	-	-	**(452.72)**
CO	-	-	-	**2,793.24**
CH_4	-	-	-	**(23,065.99)**
N_2O	-	-	-	**292.66**
CO_2	-	-	-	**10,864,812.23**
Total CO_2e				**10,378,348.25**
Net Well-to-Tank GHG Emissions	**Thermal Load (g/day)**	**Electrical Load (g/day)**	**Fugitive Emissions (g/day)**	**Total Emissions (g/day)**
VOC	-	-	-	**(1,703.67)**
CO	-	-	-	**(16,352.48)**
CH_4	-	-	-	**883,220.30**
N_2O	-	-	-	**(327.16)**
CO_2	-	-	-	**(30,751,083.47)**
			NET WELL-TO-TANK (WTT) CO_2e EMISSIONS:	**(8,799,057.62)**

Staff notes that the well-to-tank GHG emissions stated in Table VI-6 above were adjusted for their respective global warming potentials to obtain the net well-to-tank carbon dioxide equivalent (CO_2e) emissions.

d. Tank-to-Wheel (TTW) GHG Emissions Estimates

Under both alternative scenarios, the biogas produced by the anaerobic digestion of wastewater sludge would be refined to near-pure or pipeline quality biomethane suitable for use as a fuel in a natural gas-fired heavy-duty vehicle. Such vehicles include transit buses and cargo delivery trucks. Staff assumes that all of the carbon in the biomethane fuel would convert to carbon dioxide during combustion (California Air Resources Board, 2009). The CH_4 and N_2O emissions from engines were estimated using emission factors for the combustion of natural gas in heavy-duty diesel trucks: 0.0375 gram per mile (for both pollutants) and global warming potentials of 25 and 298, respectively. Staff has also assumed that a natural gas vehicle (NGV) fuel economy of 4.8 MJ per mile is applicable.

The resulting TTW GHG emissions for the Alternative Cases 1 and 2 are summarized in Table VI-7 below:

Table VI-7
Tank-to-Wheels GHG Emissions from
Combustion of Biomethane in a Heavy-Duty Natural Gas-Fired Vehicle

Parameter	Small-to-Medium POTW (Alternative Case 1)	Medium-to-Large POTW (Alternative Case 2)
Net Biomethane Allocation for Vehicle Fueling (scf/day)	79,893.36	319,857.30
Net Biomethane Allocation for Vehicle Fueling (lb-mol/day)	222.54	890.97
Net Biomethane Allocation for Vehicle Fueling (g/day)	1,615,136.62	6,466,284.99
CO_2 Emissions from Biomethane Combustion (lb-mol/day)	222.54	890.97
CO_2 Emissions from Biomethane Combustion (gCO_2/day)	4,441,625.69	17,782,283.73
Biomethane Energy Value (MJ/day) (A)	**81,089.18**	**324,644.83**
CH_4 Emissions from Biomethane Combustion (g/day)	633.51	2,536.29
CH_4 Equivalent CO_2e Emissions (gCO_2e/day)	15,837.73	63,407.19
N_2O Emissions from Biomethane Combustion (g/day)	633.51	2,536.29
N_2O Equivalent CO_2e Emissions (g CO_2e/day)	188,785.75	755,813.75
Net GHG Emissions (g CO_2e/day) (B)	**4,646,249.17**	**18,601,504.67**
Net GHG Emissions (g CO_2e/MJ) (B / A)	**57.30**	**57.30**

e. Total Well-to-Wheels (WTW) GHG Emissions Estimates

The sum of the total WTT GHG emissions estimate and the TTW estimate results in the lifecycle well-to-wheels (WTW) GHG emissions estimate for the transportation fuel (biomethane) being produced. The WTT estimates for Alternative Cases 1 and 2 were summarized in Tables VI-5 and VI-6, respectively. The TTW estimates for Alternative Cases 1 and 2 were presented in Table VI-7 above. The WTW estimates are then the sum of the WTT and TTW GHG emissions for the biomethane produced by the wastewater sludge anaerobic digestion process. When the WTW GHG emissions impacts are presented per unit of fuel energy produced, the ratio represents the CI of the fuel. A summary of the WTW GHG emissions impacts for Alternative Cases 1 and 2, as well as the resultant CI of the fuel, is presented in Table VI-8 below.

Table VI-8
Total Well-to-Wheel (WTW) GHG Emissions and
Carbon Intensities for Biomethane Derived from Wastewater Sludge

Parameter	Small-to-Medium POTW (Alternative Case 1)	Medium-to-Large POTW (Alternative Case 2)
Total WTT GHG Emissions Impacts (g CO_2e/day)	2,933,446.73	(8,799,057.62)
Total TTW GHG Emissions Impacts (g CO_2e/day)	4,646,249.17	18,601,504.67
Net WTW GHG Emissions Impacts (g CO_2e/day) **(A)**	**7,579,695.90**	**9,802,447.05**
Digester Biomethane Yield (m^3/day)	6,931.35	34,656.77
Digester Biomethane Yield (scf/day)	244,750.82	1,223,754.81
Biomethane LHV (Btu/scf)	962.00	962.00
Biomethane Energy Value (MJ/day) **(B)**	**248,414.33**	**1,242,071.63**
Biomethane CI (g CO_2e/MJ) (A / B)	**30.51**	**7.89**

VII. References

Argonne National Laboratory and Life Cycle Associates LLC, 2009. California-Modified Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model (CA-GREET), Version 1.8b, Systems Assessment Section, Center for Transportation Research, ANL, December 2009. http://www.arb.ca.gov/fuels/lcfs/ca_greet1.8b_dec09.xls

Argonne National Laboratory, 2012. Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model (GREET1), Systems Assessment Section, Center for Transportation Research Version 2, December 2012.

California Air Resources Board, 2009. "Detailed California Modified GREET Pathway for Compressed Natural Gas," Appendix A, Section 5.1, February 2009.

California Air Resources Board, 2012. "Proposed Low Carbon Fuel Standard (LCFS) Pathway for the Production of Biomethane from High Solids Anaerobic Digestion (HSAD) of Organic (Food and Green) Wastes," June 2012.

California Association of Sanitation Agencies, 2013. Survey of Publicly-Owned Treatment Work (POTW) Facilities in the State of California, February 2013.

Solomon et al, 2007. “Climate Change 2007: The Physical Science Basis,” Technical Summary, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK, and new York, USA, 2007. http://www.ipcc.ch/publications_and_data/ar4/wg1/en/contents.html

Unison Solutions, 2014. BioCNG™ System Technical Specifications. http://www.unisonsolutions.com/products/biocng-vehicle-fueling-systems/

Unison Solutions, 2014. ARB Staff member email correspondence and telephone conversation with Adam Klaas of Unison Solutions on May 29, 2014.

Appendix A

(CALIFORNIA ASSOCIATION OF SANITATION AGENCIES POTW SURVEY)