DRAFT Lifecycle Assessment Greenhouse Gas Calculator Brief

The Bioenergy Market Adjusting Tariff (BioMAT) is a Feed-in-Tariff program created by Senate Bill (SB) 1122 (Rubio, 2012) and implemented by the California Public Utilities Commission (CPUC or Commission). The program is currently undergoing review, pursuant to Decision (D).14-12-081. As such, in October 2018, Energy Division issued its draft BioMAT Program Review and Staff Proposal. Among other things, that document observed that whether individual projects reduce net lifecycle emissions depends on project-specific factors, and asked stakeholders if the Commission should establish a requirement that facilities reduce net emissions as a condition for BioMAT eligibility. In response to recommendations by several commenting parties to further explore this topic, this document discusses Energy Division's efforts to develop a lifecycle greenhouse gas (GHG) emissions calculator that could be applicable to the BioMAT program. Staff is not proposing that this tool be used to determine project eligibility at this time. Rather, staff is developing this tool to inform the discussion about bioenergy GHG emissions. This brief is intended to describe the components and approaches within the model.

Lifecycle Assessment Calculator

The Life Cycle Assessment (LCA) Calculator[1] (model or tool) can apply a consequential LCA approach to BioMAT project operations, analyzing the impacts of project emissions relative to an alternate baseline scenario by employing project-specific inputs, industry and literature supported emission factors and resource characterization, and carbon balances. The LCA model estimates the net impact of emissions from GHGs[2], and can estimate the net emissions of nitrogen oxides, sulfur dioxides, and particulate matter attributed to most fuel resource categories.[3]

Feedstocks considered in the model are based on those utilized in BioMAT, which are considered in the model as true wastes or residues that exist as a by-product of other primary operations and processes that would occur in the absence of a project. This is an important assumption that excludes the complex and significant effects of forest treatment, ecological management, market incentives, and wildfire risk mitigation within the LCA boundary. This does not imply that those lifecycle stages are insignificant or do not warrant inclusion in other assessments. The ecological effects of landscape management may have significant impacts that are not captured in this tool.

Considering Biogenic Emissions

Many emissions accounting methodologies consider CO_2 from organic waste to be de facto "carbon neutral" because, in contrast to fossil carbon that is extracted from the ground, the combustion of contemporary organic material emits no more carbon than was originally absorbed from the atmosphere during the initial formation of the feedstock. In other words, "biogenic" CO_2 is sometimes considered carbon neutral, and its impact on radiative forcing is ignored, because it does not change net atmospheric carbon levels over the organic material's lifecycle. However, that understanding of carbon neutrality within

[1] "Calculator," "model" and "tool" are used interchangeably to describe the DRAFT LCA Calculator throughout this document

[2] The model only considers greenhouse gas emissions of carbon dioxide, methane, and nitrous oxides, and uses the global warming potential (GWP) with climate carbon feedback for these gases as defined in the Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, pg. 714. http://www.climatechange2013.org/images/report/WG1AR5_Chapter08_FINAL.pdf.

[3] Criteria pollutant emissions are estimated for transportation, power generation operations, and applicable flaring. Criteria pollutants are not estimated within the model for Category 1 – Co-Digestion and Category 2-Dairy due to current limitations in incorporating other agencies calculators into the LCA model.

the context of addressing climate change is shifting in response to concerns around when carbon is released (immediately or over time).

For example, under natural conditions, wood releases carbon slowly as it decays. When woody biomass is burned to produce energy, carbon is released instantaneously. Woody biopower accelerates the carbon emissions process and increases the short- to medium-term climate impacts.[4] This temporal aspect of when biomass carbon emissions occur is relevant to current climate discussions because California has committed to achieving net zero carbon emissions by 2045. Even if the carbon emitted from bioenergy facilities is eventually returned to the forest, it is being emitted now, during a period when emissions need to be reduced.[5] The time-scale of the emissions matter as the burning of woody biomass to create energy creates a "carbon debt" that can take years or decades to repay.[6]

This model accounts for all biogenic carbon emissions and compares them to an alternative emissions baseline. To accurately assess the impacts of GHG emissions from sources that may decay over decades, the model incorporates time-explicit accounting of GHGs within the BioMAT LCA boundaries. The LCA calculator incorporates biogenic and anthropogenic emissions as it models the flow of carbon throughout the fuel resource lifecycles of both the BioMAT and baseline scenarios.

LCA Calculator Overview

The scope for consequential emissions is limited to five primary functions within each applicable fuel resource category pathway to estimate project emissions: upstream transportation, feedstock processing, power generation, and downstream transportation, and by-product fate.[7] Further detail and examples of sub-levels within each of the stages described above are shown in Table 2.

The baseline emissions are estimated assuming there are five possible alternate processes that could occur absent the BioMAT project. The appropriately applied baseline processes vary dependent on the fuel resource category, but they may include transportation, landfilling, open pile burning, decay, and flaring. The only scenario to employ the flaring alternate scenario is the wastewater treatment category, which assumes the same amount of biogas is generated, but entirely flared instead of utilized for energy. The baseline scenario for the remainder of category 1 fuel resource categories and category 2-other agriculture is that residual digestate is sent to the landfill. The dairy alternate scenario is described in the California Department of Food and Agriculture's quantification methodology.[8] For category 3 and category 2: other agriculture, baseline scenarios include open pile burning or decay.

---

[4] Walker et al., "Biomass Sustainability and Carbon Policy Study."
[5] Science Advisory Board (SAB), "SAB Review of EPA's Accounting Framework for Biogenic CO2 Emissions from Stationary Sources."
[6] Walker et al., "Biomass Sustainability and Carbon Policy Study."
[7] Processing may include anaerobic digestion, gasification, fugitive emissions from gas cleaning and upgrading, and applicable flaring or combustion associated with BioMAT project operations. By-product fates of digester processes include, for all but category 2-dairy, that residual digestate is sent to the landfill or sent to compost. For non-digester category 3 and category 2-other agriculture projects, by-product fates may include that of bio-char and bio-oil.
[8] CDFA Dairy Digester Research and Development Program. [Quantification Methodology.]

Table 1: Project and Baseline Lifecycle Components

Project Scenario Lifecycle Stages	Baseline Scenario Lifecycle Stages
Upstream Transportation of Feedstock	Transportation of feedstock from product origin to destination (if applicable)
Processing	Landfill Emissions (if applicable)
Power Generation	Decay (if applicable)
Downstream Transportation	Open Pile Burning (if applicable)
By-Product Fate	Flaring

Table 2: Fuel Resource LCA Pathway Summary

Fuel Resource Category	Upstream Transport	Processing	Power Generation	By-Product	Downstream Transport	By-Product Fate	Alternate Scenario	Output
Wastewater Treatment	No	Anaerobic Digester	Reciprocating Engine, Gas Turbine Engine, Boiler, Fuel Cell (RE, GTE, B, FC)	Digestate	Yes	Landfill, Compost	Same as Project Scenario except digester gas is flared	Net Annual Emissions
Food Processing		Anaerobic Digester	RE, GTE, B, FC	Digestate	Yes	Landfill, Compost	Total incoming feedstock is sent to landfill	Net Annual Emissions
Municipal Organic Waste	Yes	Anaerobic Digester	RE, GTE, B, FC	Digestate	Yes	Landfill, Compost	Total incoming feedstock is sent to landfill	Net Annual Emissions
Co-Digestion	Embedded Tool. Same Process as described by the California Climate Investments (Agency: California Department of Resources Recycling and Recovery. Project Type: Waste Diversion Waste Diversion, Organics Composting, Anaerobic Digestion/Co-Digestion)							
Dairy[9]	Embedded Tool. Same Process as described by the California Climate Investments (Agency: California Department of Food and Agriculture (CDFA). Project Type: Dairy Digesters)							
Dairy – (Energy Division tool)[10]	Yes	Anaerobic Digester	RE, GTE, B, FC	Digestate	Yes	Landfill, Compost	Manure would decompose in a lagoon and emit CH_4	N/A
Other Agriculture - AD	Yes	Anaerobic Digester	RE, GTE, B, FC	Digestate	Yes	Landfill, Compost	Decay in Field, Open Pile Burned	Net Annual Emissions
Other Agriculture - Non-AD	Yes	Collecting, Chipping, Gasifier/Pyrolysis/ Boiler	RE, GTE, B, FC	Biochar & bio-oil, None	Yes	Carbon in oil becomes CO2; Carbon biochar is sequestered.	Decay in Field, Open Pile Burned	Net Annual Emissions
Wood - AD	Yes	Collecting, Chipping, Anaerobic Digestion	RE, GTE, B, FC	Digestate	Yes	Landfill, Compost	Decay in Forest, Open Pile Burned	Net Emissions (Annual -Open Pile Burning; Payback Period[11]-Decay)
Wood – Non-AD	Yes	Collecting, Chipping, Gasifier/Pyrolysis/ Boiler	RE, GTE, B, FC	Biochar & bio-oil, None	Yes	Carbon in oil becomes CO2; Carbon biochar is sequestered.	Decay in Forest, Open Pile Burned	Net Emissions (Annual -Open Pile Burning; Payback Period-Decay)

[9] California Climate Investments: https://ww2.arb.ca.gov/resources/documents/cci-quantification-benefits-and-reporting-materials

[10] A new, Energy Division-customized Dairy LCA calculator is not currently included in the model. The CDFA tool has been incorporated into Energy Division's LCA model for now.

[11] Payback period is a term used to describe the length of time estimated before GHG emissions attributed to a Category 3 BioMAT project and wood decay are equal with respect to extant emissions in the atmosphere.

The model assesses individual projects using project-specific inputs. The assumed processes within each scenario are described in the flowcharts in Appendix A. Project emissions include all emissions from the point of waste generation through power generation and by-product fate. Baseline emissions are evaluated from the same starting point and are assessed through the appropriate assumed fate. Offset emissions are determined by evaluating the useful thermal output and electric power generation that displaces energy that would have been used in the baseline scenario. Project emissions (PE), baseline emissions (BE), and offset emissions (OE) are described in further detail throughout this document. The objective of the tool is to estimate the net emissions (NE) by the following equation:

$$[Net\ Emissions]\ \{MT\ CO_2e, NO_x, SO_x, PM\} = [Project\ Emissions] - [Baseline\ Emissions] - [Offset\ Emissions]$$

Project Emissions (PE):

Project Emissions may be considered to be a sum of

$$PE = Transport + Processing + Power\ Generation + By - Product$$

Transport:

Transport emissions describe the amount of GHG and other emissions generated as a result of two generalized operations: transporting the feedstock from its origin to the project site and from transporting by-products from the project site to its destination (e.g. landfill; composting facility). Transport emissions are evaluated using project-provided inputs and default assumptions regarding vehicle fuel efficiency, [12] fuel type, carrying capacity, trip distance, and emission factors from the "California Greenhouse gases, Regulated Emissions, and Energy use in Transportation model" (CA-GREET3.0).[13]

Processing:

Anaerobic Digestion

All of the fuel resource categories may undergo anaerobic digestion (AD). AD is assumed to take place within either type "Covered Anaerobic Lagoon" or "Complete mix, plug flow, or fixed film digester."

Each digester type provides a different biogas collection efficiency. It is assumed that project developers can provide the amount of incoming feedstock (tons) the project will utilize to maintain the necessary levels of AD and power generation.[14] For AD processes, the amount of generated biogas and carbon in the biogas is estimated by working backwards from the project provided fuel input (MMBtus), using the lower heating value of methane (m^3 / MMBtu), estimated methane processing losses, and an assumption that 65% of anaerobically digested biogas is methane.[15]

The LCA model assumes that, for any feedstock and digester, the Volatile Solids Reduction (%VSR) in an AD process has a strong positive correlation with the volatile carbon reduction in that feedstock.[16] This means

---

[12] A fuel efficiency for all truck types of 6.1 miles per gallon of diesel fuel is assumed, similar to that used by the CCI CDFA DDRDP tool https://ww2.arb.ca.gov/resources/documents/cci-quantification-benefits-and-reporting-materials.

[13] CA-GREET Model. https://ww3.arb.ca.gov/fuels/lcfs/ca-greet/ca-greet.htm

[14] The model requires the incoming feedstock amount (tons dry solids) for all but category 2 dairy.

[15] Digester gas is assumed to comprise of 65% methane, 35% carbon dioxide. Total fuel input (MMBtus) are used to estimate the amount of methane entering power generation equipment for gas combustion. Gas leakage amounts are evaluated and may vary based on AD type and biogas handling processes. The total amount of gas that is generated by the digester can then be assumed, and the molar weight of both gases can be used to estimate the amount of carbon generated in the biogas

[16] Per communications with faculty of civil and environmental engineering at Bucknell University.

the proportion of total carbon that is estimated to be digested and converted to biogas, as either CO_2 or CH_4, is used as an approximation for the proportion of volatile solids that are digested.

Non-Anaerobic Digestion Processes (Applicable to Category 2 Other Agriculture and Category 3 Projects)

Biomass projects are asked to select whether they utilize gasification, pyrolysis, or direct combustion (boiler) processes. Default assumptions are made regarding the product yield of gasifier processes, or the proportion of fuel weight that is allocated to biochar, bio-oil and gas.[17] Direct combustion of biomass via boiler processes are assumed to consume all the available biomass.

Biogas / Syngas Handling

The developer has an option to enter if upgrading of biogas occurs as an operation for their project. If so, the following upgrade types are provided as options, each with an associated methane loss as a percentage of volume: pressure swing adsorption, membrane separation, water scrubbing, chemical scrubbing, absorption, organic physical scrubbing, and other, which allows the project to specify the expected methane losses. Cleaning losses, with an assumed 0.5-1% losses by volume, are expected to occur for any operation that utilizes and handles gas. Any applicable flared gas emissions are evaluated using the natural gas flaring emissions factor from CA GREET 3.0**.**

Collecting and Harvesting: (Applicable to Category 2 Other Agriculture and Category 3 Projects)

An emission factor used from the Stockholm Environment Institute is used to estimate the emissions associated with collecting and grinding wood.[18] The same emission factors are being considered for use to represent emissions from collecting and processing agriculture residues.

Chipped Wood Storage: (applicable to Category 3 Projects)

Project developers are asked to indicate if wood is stored prior to use. If stored, the model's default assumption is that wood is stored for 60 days prior to use, and a corresponding amount of woody decay is assumed to occur. Decay modeling is discussed further in the Baseline Scenario Discussion.

Power Generation:

The project developer must provide the applicable power generation technology from the possible options described in table 2 which include boiler, reciprocating engine, gas turbine engine (single or combined cycle), and fuel cell. The emission factors for each of the stationary combustion application technologies are referenced from CA-GREET 3.0. The process for estimating direct emissions from fuel cell use is described in Appendix B. Potential upstream emissions attributed to steam generation for Steam Reformation of Methane (SRM) can be captured in the LCA model.

By-Product Fate:

The applicable by-products from project operations are digestate, biochar and bio-oil.

For gasification or pyrolysis processes, the applicable by-products are biochar and bio-oil. A carbon mass balance is applied to estimate what amount of carbon from the feedstock is allocated to each of its co-products. The composition of bio-oil and syngas are assumed to be known, and therefore the amount of

---

[17] Allocation assumptions are based on the IEA's Task 34 Booklet "Biomass Pyrolysis" https://www.ieabioenergy.com/publications/biomass-pyrolysis/

[18] Stockholm Environment Institute (SEI). "Greenhouse gas and air pollutant emissions of alternatives for woody biomass residues." Page 46.

carbon can be determined based on the apportioned mass.[19] The amount of carbon in the feedstock is assumed to be known based on the feedstock characteristics. The amount of carbon allocated to biochar is determined by evaluating the difference.

$$Carbon_{char} = Max\left[\ Carbon_{feedstock} - \left(Carbon_{gas} + Carbon_{oil}\right),\ 0\ \right]$$

The carbon in bio-oil is assumed to become CO_2, and the carbon in char is assumed to be sequestered.[20] The model does not account for any subsequent offsets or emissions due to the biochar.

For AD processes, the applicable by-product is digestate. Digestate is assumed to be transported to a landfill, composting facility, or allocated to both fates. Landfill emissions accounting is discussed in the baseline emissions section. Composting emission factors, referenced from California GHG Inventory documentation, are based only on feedstock amount, and do not consider feedstock type.[21]

The carbon in digestate is estimated via a carbon mass balance, similar to the method estimating the carbon in biochar. The amount of carbon in the feedstock and generated biogas is assumed to be known based on project inputs, feedstock characteristics, and processing losses. The amount of carbon in the digestate is determined by evaluating the difference.

$$Carbon_{digestate} = Max\left[\ Carbon_{feedstock} - Carbon_{gas},\ 0\ \right]$$

Baseline Emissions (BE):

Baseline emissions for each fuel resource category may be assumed to be the sum of emissions from any applicable transportation and assumed fate. Transportation emissions are estimated similarly to that described in the transportation section. Baseline fuel resource fates are described in this section.

$$BE = Transport + Baseline\ Fate$$

Landfill:

Landfill emissions are currently evaluated based on the methods of CARB's staff report, "Proposed LCFS Pathway for the Production of Biomethane from High Solids Anaerobic Digestion of Organic Wastes"[22] The model assumes landfill emissions should be attributed to the single operation year described by the model.

Decay:

The fuel resource decays in place and carbon is assumed to decay into CO_2, soil organic carbon, and methane (CH_4).[23] It is assumed that 2% of the carbon gets sequestered as soil organic carbon and 0% to 2% of carbon in the fuel resource may be assumed to decay into CH_4.[24]

---

[19] The project developer may have an option to provide an estimate for the syngas composition. Default estimates are based on the 2019 paper "Pyrolysis of wood sawdust: Effects of process parameters on products yield and characterization of products" by Anil Kumar Varma, Lokendra Singh Thakur, Ravi Shankar and Prasenjit Mondal. Gasification estimates are from "Bioenergy: Principles and Applications," by authors Li and Khanal through Wiley Blackwell Publishing.

[20] Assumption based on communications with CARB LCA staff and Placer County Air Quality Control District Staff.

[21] GHG Inventory Page. https://ww3.arb.ca.gov/cc/inventory/doc/doc_index.php Accessed June 20, 2019.

[22] Methods presented in Figure 8, page 50. "Proposed LCFS Pathway for High Solids Anaerobic Digestion." https://www.arb.ca.gov/fuels/lcfs/2a2b/internal/hsad-rng-rpt-062812.pdf June 2012.

[23] 2% of carbon to soil; 0-2% of carbon to methane; remainder to carbon dioxide.

[24] Aerobic organic decay is generally considered to generate CO_2, however, some reports and existing LCA studies suggest methane may be a by-product of wood decay, such as Placer County Air Pollution Control District's "Biomass Waste for Energy Project Reporting Protocol" (https://www.placer.ca.gov/DocumentCenter/View/2115/Biomass-

Agricultural biomass is assumed to decay within a year. The model does not currently consider variations across agriculture subcategories, including different emissions and characteristics of residues from orchards, thinnings, row crops, etc.

Woody decay is unique from other baseline scenarios because it cannot be assumed that woody decays within a year. Wood decay is modeled with a first order exponential decay equation that estimates the amount of remaining biomass over 100 years. County-specific exponential decay constants are applied and include spatially dependent characteristics such as wood species, forest residue density, historical temperature, and moisture content.[25]

Open Pile Burning:

Open pile burning emissions for agriculture residues and forest residues are assigned emission factors reviewed in literature.[26] The model may assume less than 100% of the fuel resource is fully burned, and that the remaining charred biomass contains sequestered carbon.

Special Consideration of Category 3 Emissions:

Category 3 fuel resources were extensively discussed in comments to the BioMAT program review proposal. This section addresses a few key items that are relevant to the use of an LCA tool.

Externalities of Woody Biomass

The LCA calculator does not include several potentially significant GHG impacts of woody biomass utilization from upstream processes within its scope because for most Category 3 resources—fire threat reduction, fire safe clearance activities, and infrastructure clearance projects—the sustainable forestry definition precludes any non-residue from being utilized. For the remaining category 3 eligible resources—other sustainable forest management and high hazard fuel—there are existing restrictions on what may qualify. In addition, it is widely considered to be financially prohibitive to log and harvest forest wood for the sole purpose of electric power generation. [27]

Due to economic limitations, it is assumed that BioMAT projects will likely support forestry operations occurring for reasons other than energy generation by utilizing residues. This rationale leads staff to assume that BioMAT is not the primary driver of forest management operations, and thus the effects of forest management with respect to carbon sequestration, forest health and management, and wildfire mitigation are not attributed to BioMAT projects. That residues are uneconomical to collect also supports the assumption that, if unutilized, residues would otherwise be open pile burned or left to decay.[28]

Waste-For-Energy-Project-Protocol-PDF?bidId=). Energy division staff is considering a range of values to assume for CH_4 emissions from decay.

[25] The Schatz Energy Resource Center (SERC) at Humboldt State University provided Energy Division staff with raster files describing location-specific decay constant values for the entire state of California (for fine woody debris and coarse woody debris, each raster contained applicable decay constant values for every 30 x 30 square meter that considered woody species composition and climatic factors such as historical temperature and soil moisture). More information on SERC's California biopower impacts project can be found at http://schatzcenter.org/cbip/.

[26] "Emission Factors for open and domestic burning for use in atmospheric models." Akagi, et al. Atmospheric Chemistry and Physics. https://www.atmos-chem-phys.net/11/4039/2011/

[27] High Hazard Fuels Availability Study (HHZ Study). Prepared for the CA Forest Management Task Force. https://fmtf.fire.ca.gov/

[28] HHZ Study. Prepared for the CA Forest Management Task Force.

Category 3 Time-Dependent Emissions Assessment

To assess Category 3 emissions, the LCA model evaluates the applicable GHG emissions from forest residue decay each year, for 100 years. The tool accounts for the atmosphere's retention of each year's GHG emissions using persistence functions and parameters supported in the Fifth IPCC Assessment Report (AR5).[29] The total emissions remaining in the atmosphere are evaluated using a discretized impulse response function. The tool then compares the annual amount of decay emissions in the atmosphere to the emissions remaining in the atmosphere from a single year of BioMAT project operations, using IPCC supported persistence functions to describe the retention of CO_2, CH_4 and N_2O. For each year, the appropriate global warming potential (GWP) of existing project and decay GHG emissions are evaluated using AR5 GWPs that include climate carbon feedback.

	GWP 20 Y	**GWP 100 Y**
CO2	**1**	**1**
CH4	**86**	**34**
N2O	268	298

Offset Emissions

BioMAT projects may receive credit, or offset emissions, related to electricity generation and useful thermal output. Each project exports electricity to the grid. Some projects may also generate on-site electricity and utilize waste heat to further reduce fossil carbon emissions that may have otherwise occurred. The LCA model prompts projects to indicate, for electricity and thermal energy, what percentage of on-site consumption is attributed to operations and processes that would have occurred in the absence of the BioMAT project. For on-site fuel use, the model only calculates displaced energy consumption that would have occurred regardless of the BioMAT project as an offset. The LCA model estimates displaced grid electricity emissions using project generation information and an average grid emissions factor. The emissions factor is evaluated similarly to the method described in the Low Carbon Fuel Standard program's 2019 update to its pathway for grid electricity consumption, but with AR5 GWP values applied to methane and nitrous oxide.[30] The deemed amount of useful thermal energy output the facility may receive credit for as offset is estimated to be emissions that would have occurred for an equivalent amount of MMBtus, assumed to be natural gas unless otherwise specified, to undergo combustion in a small industrial boiler.

Model Inputs:

The model allows for projects project-specific inputs, to be provided by the developer, to produce estimates of project-specific annual emissions. The table below describes the inputs that the tool requires. Inputs may be designated as either "Must Enter" or "Optional to Enter." The required input is indicated as a yellow cell in the tool if the information is required. The optional input, for which the model assumes a default, is indicated as a light blue cell.

[29] Methane and nitrous oxide are assumed to persist according to a first order exponential decay approximation with perturbation lifetimes provided by the IPCC. The carbon dioxide persistence function and parameters utilized are supported by the IPCC and can be found in F. Joos et al., "Carbon dioxide and climate impulse response functions for computation of greenhouse gas metrics: a multi-modal analysis," *Atmospheric Chemistry and Physics.*

[30] Low Carbon Fuel Standard (LCFS) Annual Updates to Lookup Table Pathways. California Average Grid Electricity Used as a Transportation Fuel in California AND Electricity Supplied under the Smart Charging or Smart Electrolysis Provision. 2019. https://www.arb.ca.gov/fuels/lcfs/fuelpathways/comments/tier2/elec_update.pdf

A goal of this tool is to be easily utilized by project developers and aims to use information that is already currently required to be reported. Items indicated by the checkmark reflect inputs that are already required to be reported by BioMAT projects to establish program eligibility.

Developer Provided Input	Information currently provided? [31]	Must Enter (ME) or Optional (O)
Fuel Attestation	✓	ME
Total Fuel Input	✓	ME (Digester Processes)
Energy Exported	✓	ME
Biomass or Biogas	✓	ME
Annual Input of Fuel Resource (dry weight)		ME
Anaerobic Digestion Type	✓	ME
Biogas Upgrade Process		ME
Useful Thermal Output (MMBtus)	✓	ME (if applicable)
County	✓	ME
MMBtus of gas that is expected to be flared that is incremental to gas that is flared during normal operation		O
Anaerobic Digestion / Not Anaerobic Digestion	✓	ME
If applicable, a Secondary Heating Process (MMBtus, fuel type, and Technology)		ME
% of Useful Thermal Energy Output that is utilized for BioMAT specific operations		ME
Amount of Residual Material Sent to Landfill (Co-Digestion Only)		ME, if applicable
Is woody feedstock chipped? On site?		ME, if applicable
Methane Composition of Biogas[32]		O
Fate of methane losses from digester and upgrading (flare/fugitive)		ME
% of Digestate to Compost[33]		O
Transportation Inputs (Fuel, Vehicle Type, Distance)		O

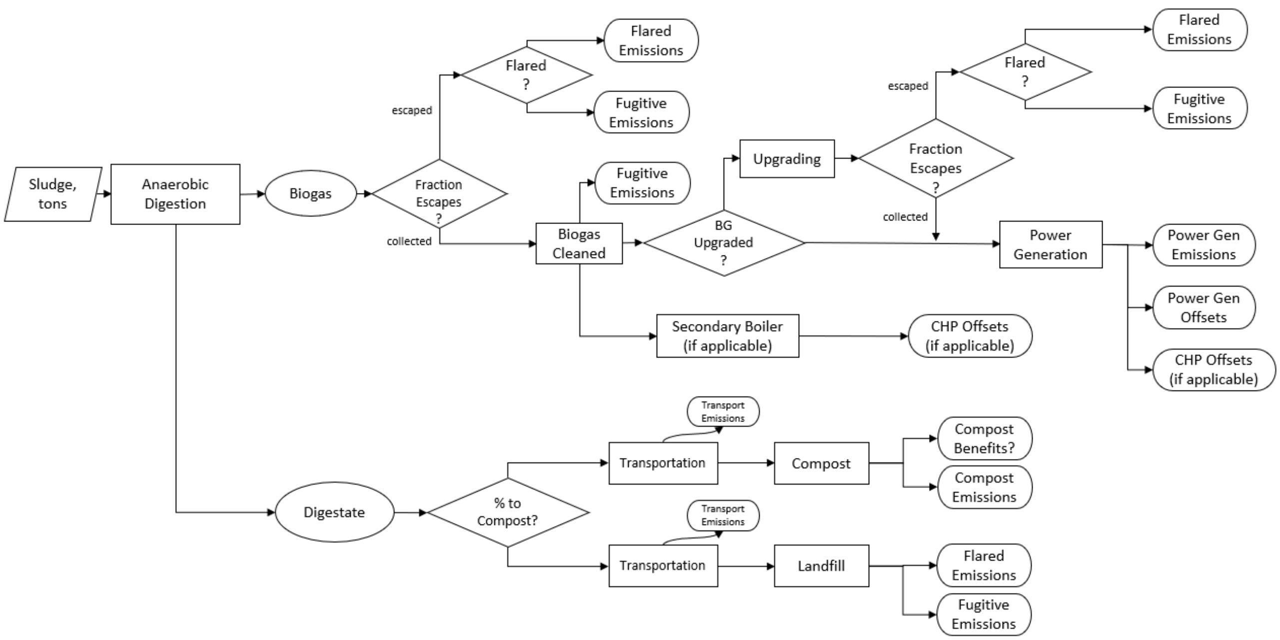
[31] Currently, items indicated with a checkmark are already provided by project developers.
[32] A default value of 65% is used in the model for category I fuel resources, category II dairy resources, and any biogas generated from anaerobic digestion.
[33] A default value of 0% is used to estimate the proportion of by-product that is composted.

Appendix A: Flowcharts of Project and Baseline Pathways

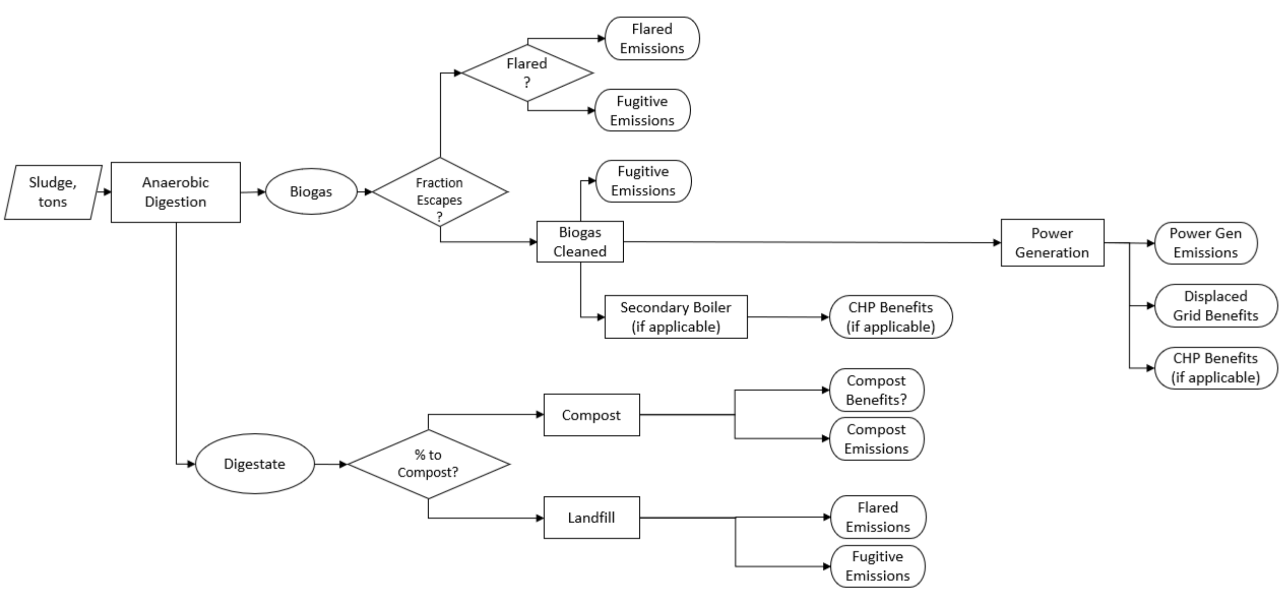
Category I

Wastewater Treatment

Project

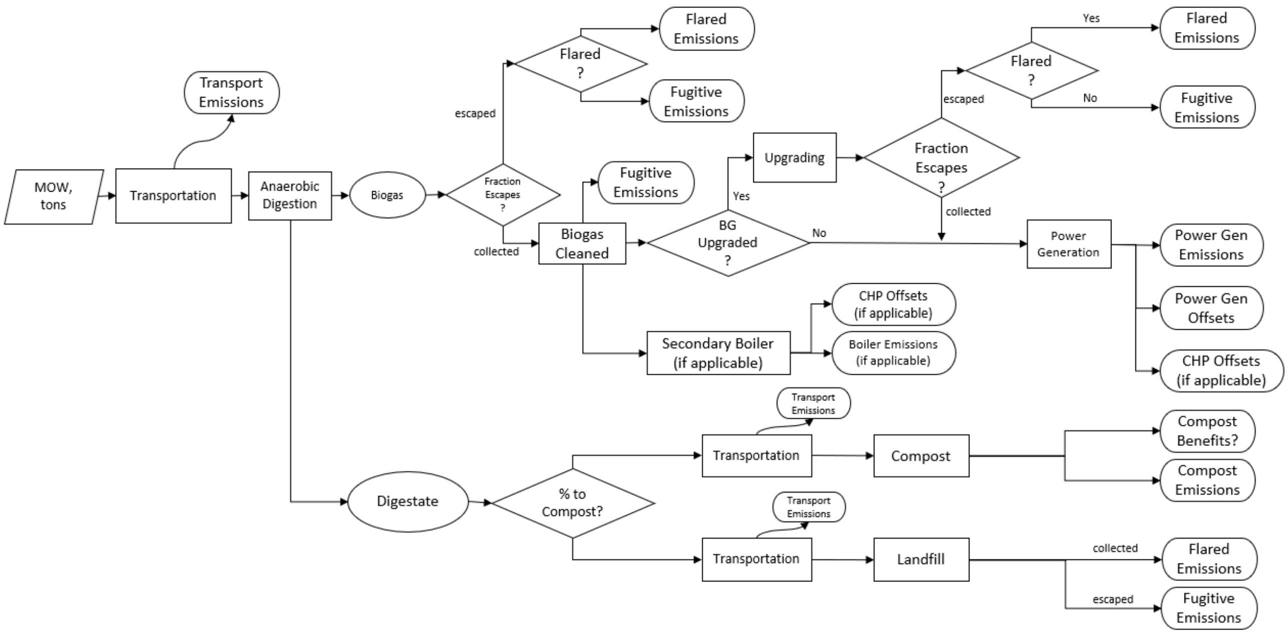


Baseline

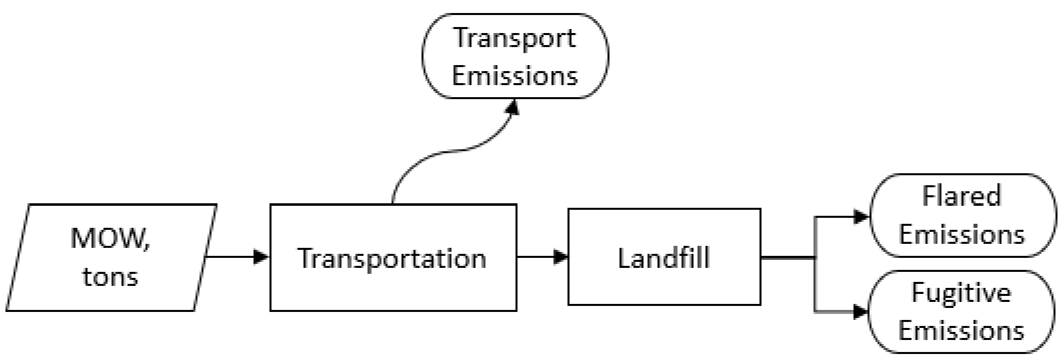


Municipal Organic Waste Diversion

Project

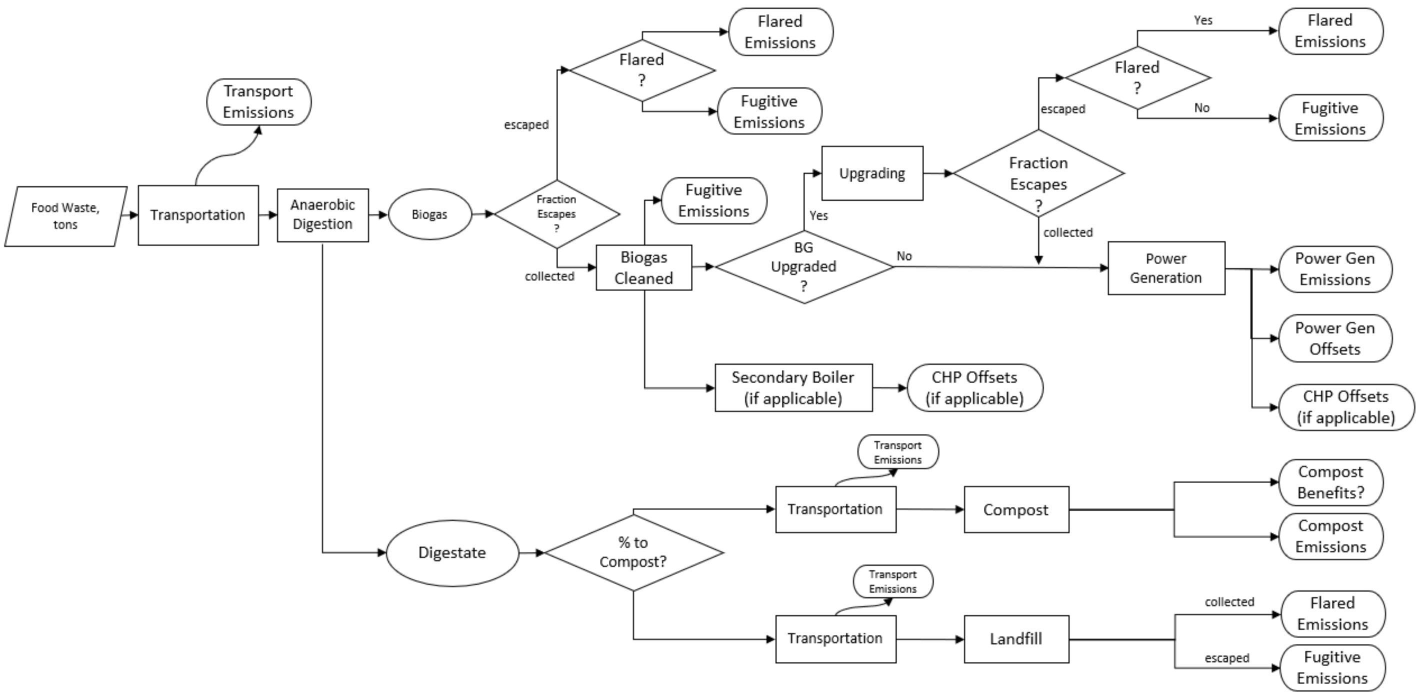


Baseline

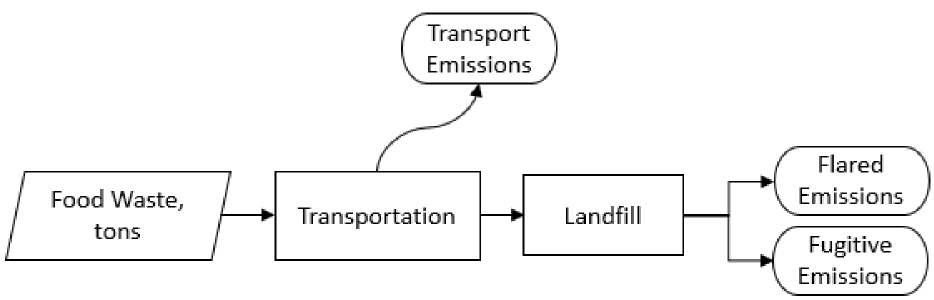


Food Processing Waste

Project:



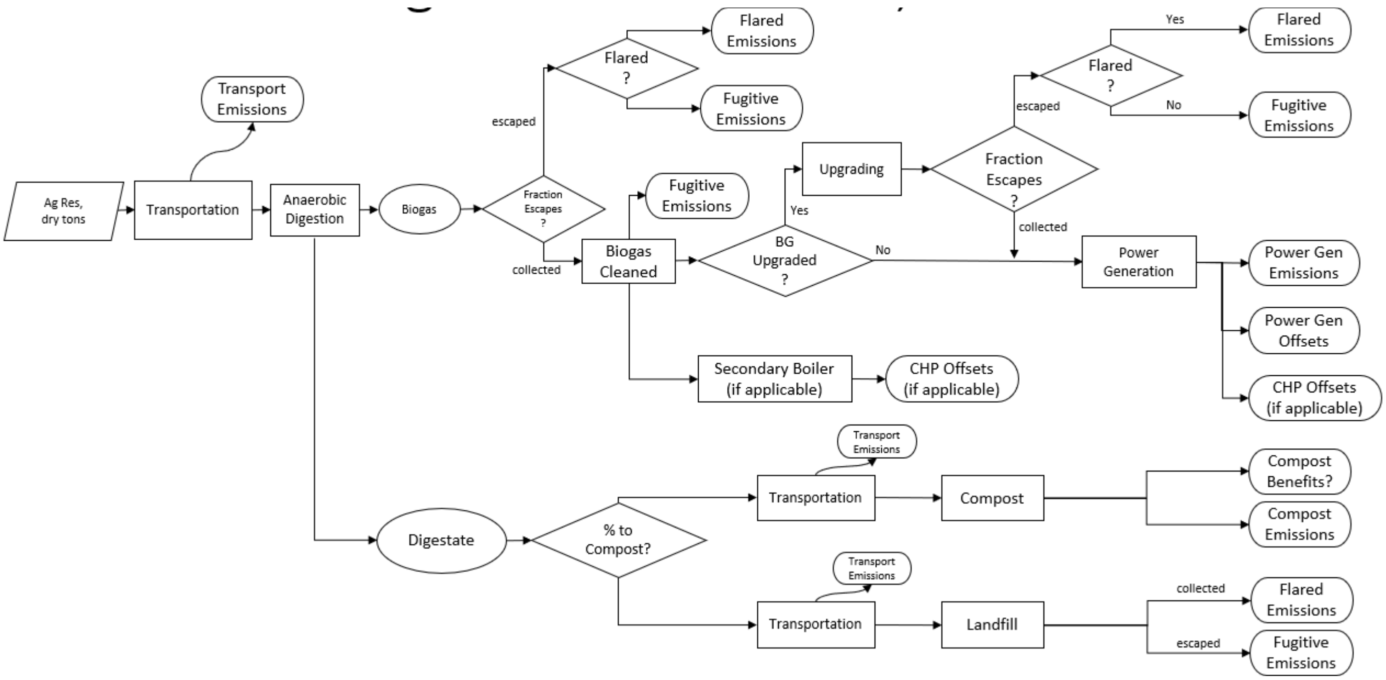
Baseline:



Category II

Other Agriculture

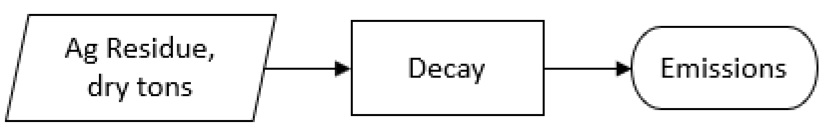
Project: Other Agriculture, Anaerobic Digestion



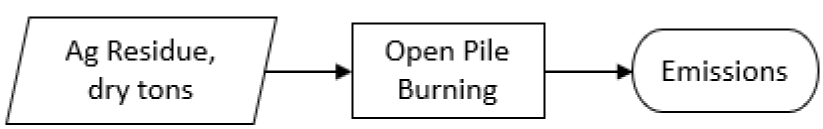
Project: Agriculture, Non-Anaerobic Digestion

**To Be Created

Baseline: Decay



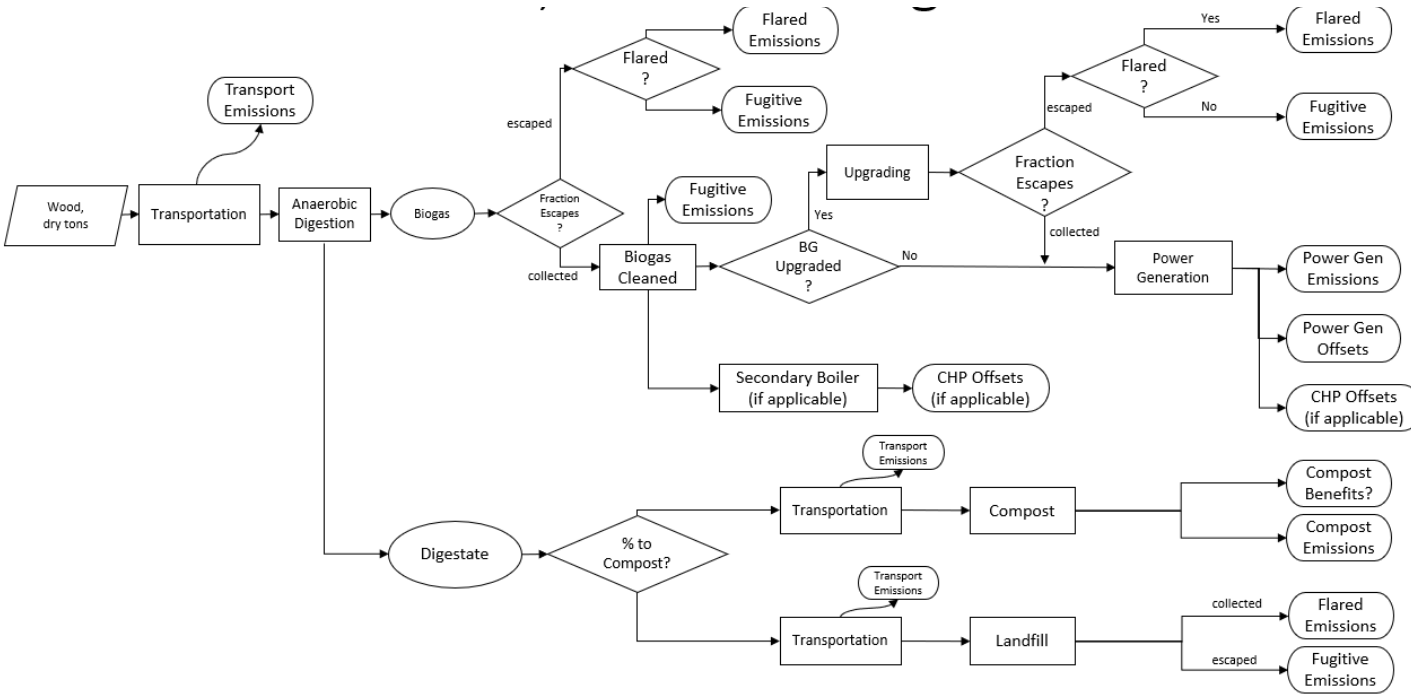
Baseline: Open Pile Burning



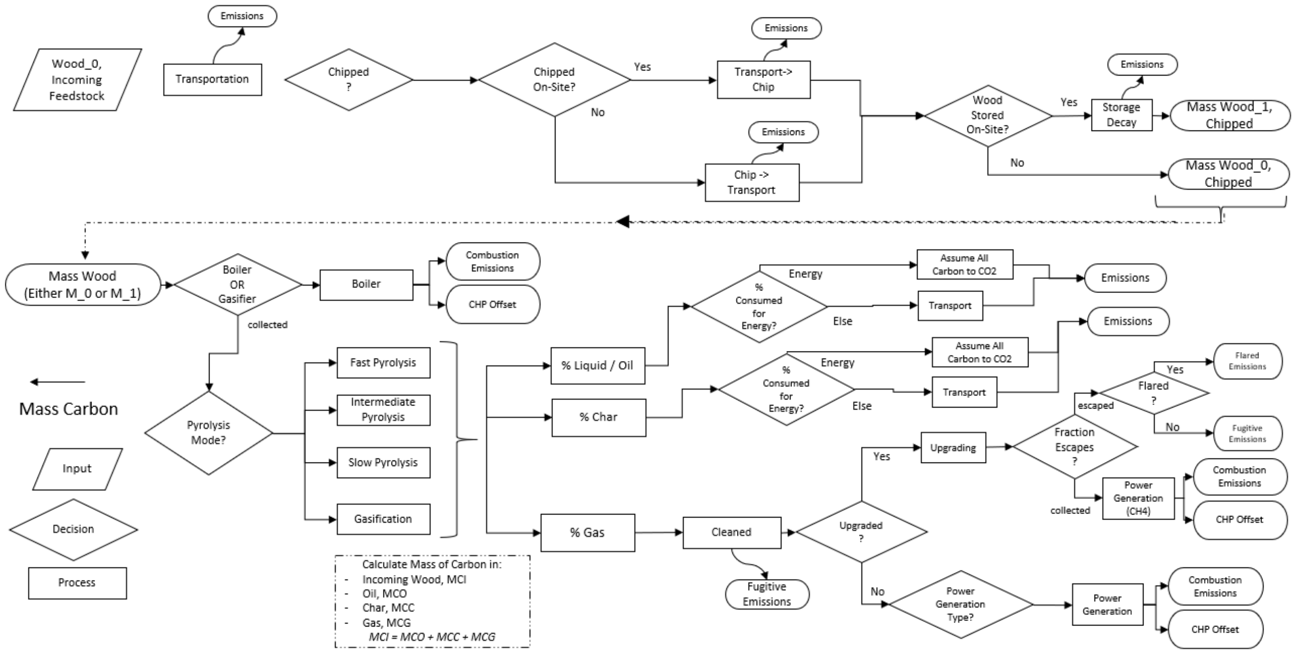
Category III

Wood

Project: Wood, Anaerobic Digestion



Project: Wood, Non-Anaerobic Digestion

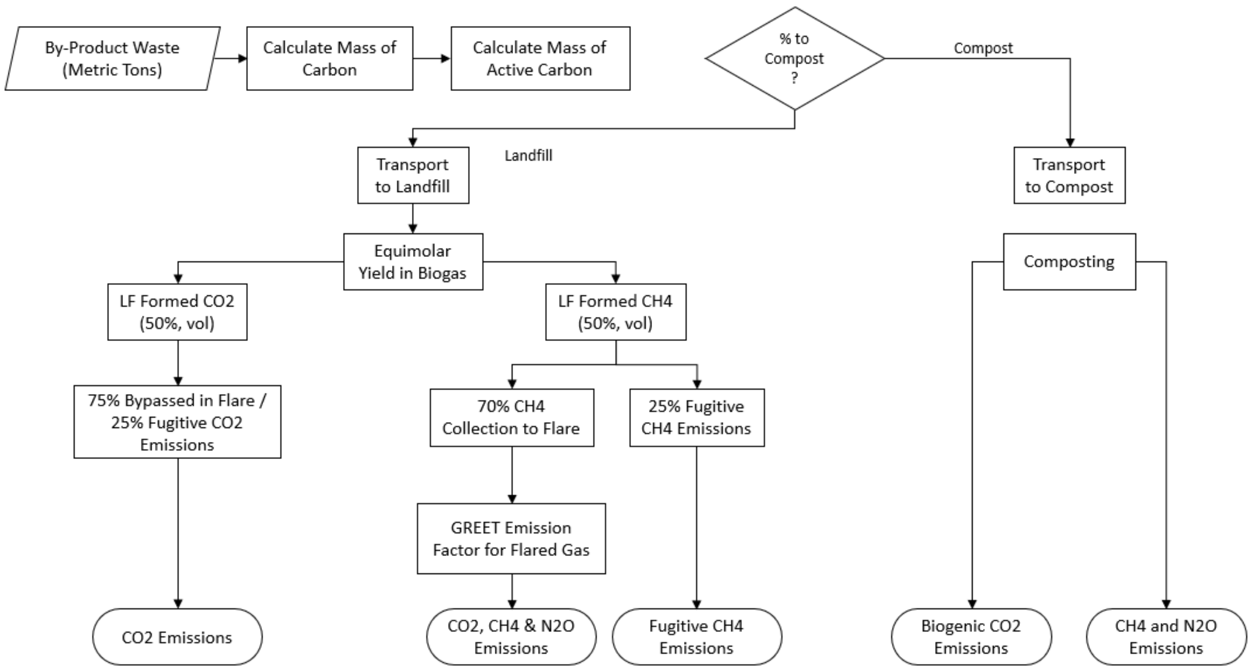


Baseline: Decay

Baseline: Open Pile Burning

Landfill / Composting

In the model, composting emissions have been deemed to yield a carbon neutral impact. Rather than provide composted residues with a net benefit (see CARB's Composting Emissions Reduction Factor), this model simply assumes all waste directed towards composting facilities yield a net zero emissions impact with respect to greenhouse gases.



Appendix B: Fuel Cell Emission Factor – by-product of Steam Reformation of Methane (SRM)

$$\mathit{Assumed\ Net\ Reaction\ of\ SRM}:$$

$$CH_4 + 2\ H_2O \ \rightarrow\ CO_2 + 4H_2$$

- Assume 99.9% of biogas is utilized (99.9% of methane is consumed)
- Assume the above process is applicable to all fuel cell plants
- 1 MMBtu of Methane is assumed as the fuel input
- Any Carbon Dioxide in the biogas is accounted for in the LCA model separate from the fuel cell emission factor.
- Upstream emissions associated with steam generation is account for in the LCA model separate from the fuel cell emission factor
- P=1 atm, T=60 deg F, 1 standard cubic foot (scf) = 31.1 m^3
- Assume 1 MMBtu of Methane has a Lower Heating Value of 910 BTU/scf (per CA GREET3.0)
- 31.1 m^3 = 31,100 Liters (1 m^3 = 1000 L)
- Moles in 31,100 Liters of Methane:

$$n = \frac{PV}{RT} = \left[\frac{atm * L}{\left[\frac{atm * L}{mol * K}\right] * K}\right] = \frac{1\ * 31{,}100}{.08206 * 288.7} = 1{,}313\ mol\ CH_4$$

$$1{,}313\ mol\ CH_4 \times 16\frac{g}{mol} = 21{,}000\ g\ CH_4$$

99.9% of methane is assumed to be consumed during fuel cell operations.

1 mole of CH_4 yields 1 mole of CO_2

$$0.999 \times 21{,}000\ g\ CH_4 \times \frac{44}{16} = 57{,}692\ g\ CO_2$$

0.1% of methane is assumed to leak into the atmosphere.

$$0.001 \times 21{,}000\ g\ CH_4 \times 86 = 1{,}806\ g\ CO_2(\mathrm{e})20\ \mathrm{Y\ GWP}$$

$$0.001 \times 21{,}000\ g\ CH_4 \times 34 = 714\ g\ CO_2(e)100\ Y\ GWP$$

$\boldsymbol{EF\ Fuel\ Cell\ 20\ Year\ GWP}$:	$\boldsymbol{EF\ Fuel\ Cell,\ 100\ Year\ GWP}$:
$\boldsymbol{59{,}506\ \frac{g\ CO_2}{mmBtu\ (CH_4)}}$	$\boldsymbol{58{,}414\ \frac{g\ CO_2}{mmBtu\ (CH_4)}}$

Appendix C: Key Modeling Assumptions

Category 3: Model excludes implications for forest health and regrowth

All qualifying fuel is a true waste that would have existed absent BioMAT

Anaerobic Digestion: volatile solids reduction is directly correlated to Carbon reduction in the feedstock

Landfill: Carbon in by-product decomposes similar to that described in the LCFS HSAD Pathway and in a timeframe comparable to one year of BioMAT operation

Total Fuel Input describes fuel that enters the primary power generation method (not necessarily raw feedstock or biogas generated)

All project and baseline emissions are assumed to occur within or near one year, except for the scenario assessing woody decay

Energy content in gas is solely attributed to Methane

Excludes project build / construction, end-of-life impact

Ash generation from biomass boilers is negligible