PG&E GAS R&D AND INNOVATION

WHITEPAPER

Conversion and Processing of Biogas and Syngas

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Together, Building
a Better California

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Summary: Processing and Conversion to Biogas and Synthetic Gas (Syngas)

Definition: The process of turning biogas feedstock or biomass into energy carriers (such as biogas or syngas) is generally called "conversion" or "processing". These technologies are the "power plants" of the biogas value chain. Generally, they can be bucketed into two major categories:

1. Thermochemical Conversion
   These include technologies like gasification and pyrolysis that produce syngas. The macro-molecules contained in the organic feedstock are cracked into smaller molecules by the effect of high temperature.
2. Biochemical Conversion
   This process leverages bacteria enzymes and microorganisms to convert biomass to biogas through anaerobic digestion, or ethanol and other liquid biofuels through fermentation.

Of these, several technologies are mature and can be used in the generation of biogas or syngas which can be effectively upgraded to biomethane of high enough quality to inject into gas utility pipeline. The most common conversion technologies that are applicable to biomethane are **Gasification**, **Pyrolysis**, and **Anaerobic Digestion**. However, in order to understand why certain technologies are most beneficial in certain applications, one must understand the concept behind *lignocellulosic biomass,* which is described in the Biomass whitepaper.

THERMAL CONVERSION TECHNOLOGIES

Pyrolysis and gasification are the most common ways to convert biomass into syngas. Pyrolysis is a purely thermal process in absence of oxygen, it results in a range of organic compounds and the formation of solid carbon residue called char. Gasification includes additional stages of oxidation and reduction that further crack organic components down to carbon monoxide and Hydrogen.

Biomass feedstock must be prepared and dried (the "wetter" biomass is, the more that the energy in the heating stage is used simply to vaporize the water in the biomass, which is wasteful. In some cases, the technology cannot handle wet feedstock.). The feedstock is then heated in a no- or low-oxygen environment which produces bio-oils, and biochar, and syngas. Syngas is the gaseous results of reconstituting the molecules of heated biomass into a synthetic gas that is comprised primarily of Carbon Monoxide (CO) and of Hydrogen (H_2) gas. This mixture is usually scrubbed to remove impurities or particulates. The resulting, cleaner syngas is often combusted to generate electricity, but can also be methanated to generate biomethane. (Friends of the Earth, 2009)

For an introduction on how Gasification works at a high level, this is a good resource: NETL.DOE.gov

Pyrolysis

Pyrolysis is the thermochemical decomposition of biomass in the absence of oxygen, where heat is applied to break down the biomass into its constituent molecules. Usually the temperatures of the system are range from between 350-550^{o}C up to 700-800^{o}C. Products are a combination of syngas (typically hydrocarbons C_nH_m), biochar, and bio-oil.

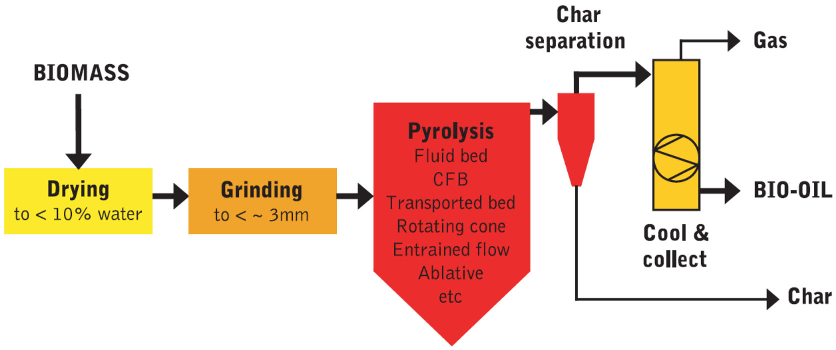


Figure 1 Flow Diagram of Pyrolysis (PG&E R&D and Innovation, 2018)

Why care about Pyrolysis?

Pyrolysis is an interesting process because of the many ways to produce renewable energy, pyrolysis (alone or as a step in gasification) is one of the few processes that has the potential to be *carbon negative.* Assuming the feedstock is from a renewable source (like waste, or dead bark-beetle trees), pyrolysis not only generates syngas, but also biochar, a carbon rich solid that effectively contains a significant amount of carbon. If that biochar is applied to soil in agricultural or other applications, then that carbon is effectively sequestered – a GHG reduction above and beyond the syngas' original renewable sources.

However, there is an inherent tradeoff to using biomass to produce biochar for carbon sequestration and to produce energy. You can only produce one at the cost of the other. Biochar's effectiveness as an agricultural additive are also disputed, though experts acknowledge that there does not seem to be any negative repercussions to its use. *For more on Biochar, please see the section below on Byproducts of Thermal Conversion.*

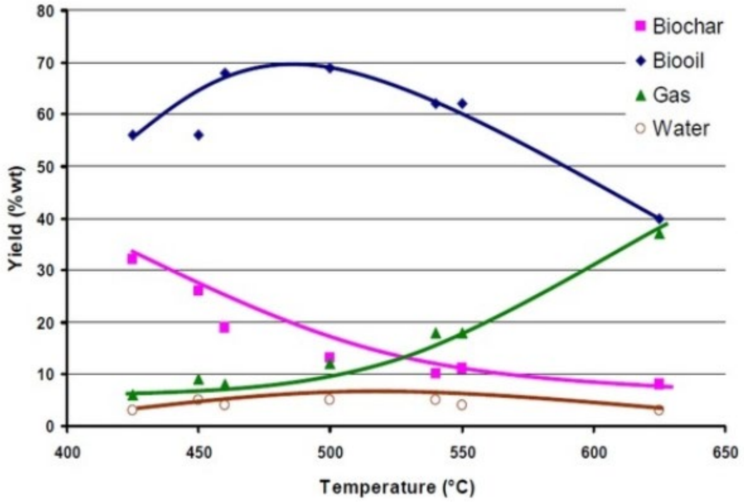


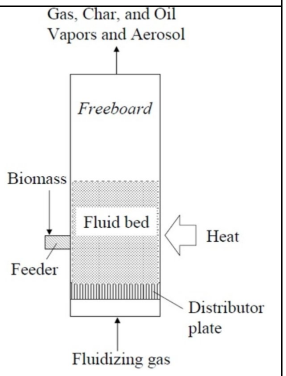
Figure 2 Relative proportions of end products in pyrolysis of biomass (Jahirul, 2012)

Outputs from the pyrolysis process depend on the temperature of the heat applied, as well as the length of time that the biomass is subject to the pyrolysis process.

- Slow Pyrolysis enhances char production at low temperatures and heating rates.
- Fast Pyrolysis are characterized by high heat transfer and heating rates, and rapid cooling, which produces high bio-oil yield. This technology can often have fairly low investment costs and good energy efficiencies on a small scale.
- Flash Pyrolysis involves rapid devolatilization in an inert atmosphere, a high heating rate, high reaction temperatures and ultra-short gas residence time (about 1 second) to form bio-oil, but often is limited because of its high oxygen content -- meaning it has a tendency to become corrosive and unstable. The product also contains metals and nitrogen that can harm refinery catalysts.

Pyrolysis Reactors often fall within several popular types, the most common of which are profiled below. *For more information about types of pyrolysis reactors, please refer to the technical analysis of pyrolysis with Gas Operations R&D and Innovation* (PG&E R&D and Innovation, 2018).

Table 1 Pyrolysis Reactor Types (PG&E R&D and Innovation, 2018)

Reactor Type	Description
Fixed bed	Solids flow down a vertical shaft and contact a counter-current upward moving product gas stream. Made of firebricks, steel or concrete with a fuel feeding unit, ash removal unit and gas exit. Operating parameters include high carbon conversion, long solid residence time, low gas velocity and low ash carry over. **Benefits:** Simple & reliable technology for fuels uniform in size with low content of fines. For small scale heat and power applications **Limitations:** Tar removal
Bubbling fluidized bed	Heated sand is used as the bed material. **Benefits:** Simple to construct and operate. Provide better temperature control, solids-to-gas contact, heat transfer and storage capacity due to high solids bed density. Bio-oil yield is between 70-75% weight of biomass on a dry basis. Char doesn't accumulate. **Limitations:** Very small biomass particle size (< 2-3 mm) is needed 
Circulating fluidized bed	Similar features as bubbling fluidized beds.

	Benefits: For large throughputs, despite more complex hydrodynamics. **Limitations:** Shorter residence times for chars and vapors, resulting in higher gas velocity and char content in bio-oil.
Ablative	Mechanical pressure presses biomass against the heated reactor wall, causing the material to “melt”, allowing the residual oil to evaporate away as a vapor. **Benefits:** Feed material doesn’t require excessive grinding. Larger biomass particle sizes (< 20 mm) are accepted. **Limitations:** More complex configuration. Scaling is a linear feature of the heat transfer (surface area controlled system) – lacking economies of scale.
Plasma	Cylindrical quartz tube surrounded by two copper electrodes. Biomass is fed into the middle of the tube using a variable-speed screw feeder at the top of the tube. Electrodes are coupled with electrical power sources to produce thermal energy to gas flows through the tube. Inert gas removes oxygen from the reactor and is used to produce plasma. The vapors are evacuated by a variable speed vacuum pump. **Benefits:** Tar formation is eliminated due to the cracking effects from plasma with electron, ion, atom and activated molecule species. **Limitations:** Consumes high electrical power – high operating costs. Large amount of heat from thermal plasma is released to the environment via radiation and conduction.

Gasification:

Like Pyrolysis, Gasification is a thermochemical process by which biomass is heated to break it into its constituent molecules. Unlike pyrolysis, gasification does expose this process to some oxygen – which does cause some combustion/incineration within a certain part of the reactor. The process uses partial oxidation at high temperatures (>1300 °F) with oxygen, air or steam. Like pyrolysis, gasification also produces syngas as its primary output. (Harris, 2009)

Gasification is usually either *autothermal* (involves direct heating and partial combustion of biomass) or *allothermal* (indirect heating from an external source). However, most gasifiers follow a similar 4-step process starting with dehydrating feedstock, then pyrolysis, combustion and reduction. Gasification, like pyrolysis relies on heat, and also includes some combustion, so if feedstock has a high moisture content, energy would go towards both vaporizing the water in the feedstock and heating the feedstock itself, possibly using more energy overall than if a pre-treatment drying stage was used.

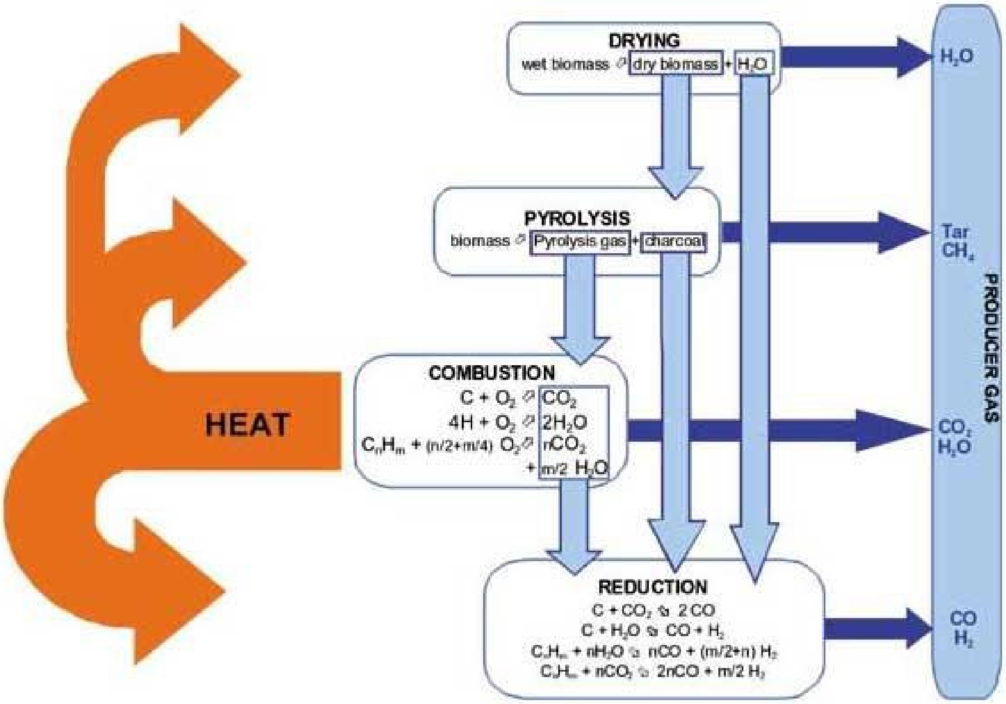


Figure 3 Four step gasification process (PG&E R&D and Innovation, 2018)

Why care about Gasification?

Gasification is a stable, commercially available technology that is *already* being used to generate electricity though most gasification technologies are frequently used to process coal and coal-products. The electricity that is generated from these facilities by burning syngas is not flexible and dispatchable,. If these plants can be retrofitted to generate syngas that can then be *upgraded* to biomethane, the resulting natural gas will be dispatchable, flexible, storable, renewable (if generated from renewable biomass) and contribute positively to gas throughput, a veritable stack of positive benefits over burning syngas for electricity.

Table 2 Gasification Reactor Types (PG&E R&D and Innovation, 2018)

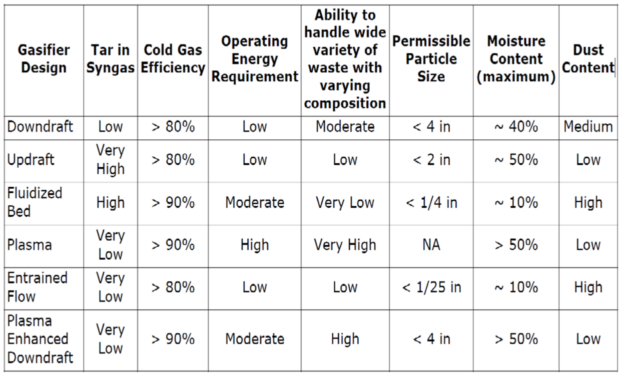
Gasifier Type	Description
Fixed bed (updraft)	Feedstock: injected at the top Gasifying agent (e.g. air/O_2 and/or steam): injected at the bottom Flow: counter-current Feedstock goes through different temperature levels in the reactor Product gas flows from reactor with little interactions with rest of biomass/char regions

Fixed Bed (downdraft)	Feedstock: injected at the top Gasifying agent: drawn in by suction blower via an air jacket or down through the top Fire at the bottom Incoming gasifying agent allows partial combustion in the lower earth area. The resulting heat produces pyrolysis above and reduction below.
Fluidized Bed	Feedstock: injected at side Gasifying agent: injected near the bottom Feedstock is suspended in the gasifying agent, within the bed that acts as a fluid Back-mixing (new feedstock particles mix with gasified particles) **Two types**: bubbling & circulating. In circulating, the bed particles can be removed using a cyclone separator, then recirculated. In addition, a gas vortex is created in the gasifier and separator, creating a long path of high temperature for the solids.
Entrained-Flow	Feedstock + gasifying agent: fed co-currently The gasifying agents entrain the feedstock particles as they flow into the gasifier in a dense cloud Operation at high temperature, pressure and turbulent flow, causing rapid feed conversion and high throughput Syngas is tar-free Ash melts into vitreous inert slag
Plasma	Feedstock: injected at side Gasifying agent: injected at side Uses plasma energy to convert feedstock to syngas. Plasma is an electrically charged gas (fourth state of matter). Process is can achieve temperatures close to the temperature of the surface of the sun (through a plasma torch). Due to the high temperatures, a wide range of feedstock is accepted e.g. biomass, MSW. No tar/char products are present.

	Two configurations: plasma assisted & plasma coupled with traditional thermal gasification. Plasma assisted has the plasma torch inside the gasification chamber.

A summary of some of the advantages and disadvantages of each gasifier type, as well as their efficiency (how much energy they use in order to generate this fuel) is summarized in the figures below:

Table 3 Approximate composition of raw syngas from gasified biomass (PG&E R&D and Innovation, 2018)



Gasifier Design	Tar in Syngas	Cold Gas Efficiency	Operating Energy Requirement	Ability to handle wide variety of waste with varying composition	Permissible Particle Size	Moisture Content (maximum)	Dust Content
Downdraft	Low	> 80%	Low	Moderate	< 4 in	~ 40%	Medium
Updraft	Very High	> 80%	Low	Low	< 2 in	~ 50%	Low
Fluidized Bed	High	> 90%	Moderate	Very Low	< 1/4 in	~ 10%	High
Plasma	Very Low	> 90%	High	Very High	NA	> 50%	Low
Entrained Flow	Very Low	> 80%	Low	Low	< 1/25 in	~ 10%	High
Plasma Enhanced Downdraft	Very Low	> 90%	Moderate	High	< 4 in	> 50%	Low

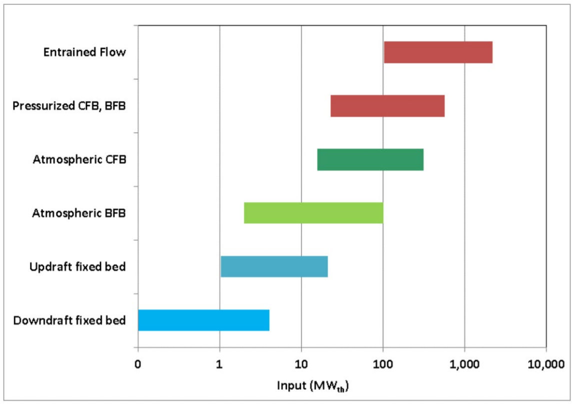


Figure 4 Gasifier Capacity Ranges (fuel energy input basis) (PG&E R&D and Innovation, 2018)

Steam Hydrogasification

One relatively new type of gasifier has been pioneered by Viresco Energy, called steam hydrogasification (SHR) (PG&E R&D and Innovation, 2018). Unlike other forms of thermochemical conversion, SHR occurs in a hydrogen and *water* environment, instead of air or pure oxygen. A wet feedstock is pre-treated to create a pumpable slurry, which is fed into the 750 °C gasifier where it is transformed into a methane-rich syngas in presence of high pressure or a catalyst. The remaining steps are similar to typical thermochemical cleanup and methanation steps (NETL, 2018). The chemical process is outlined below:

$$C_xH_yO_z + H_2O + 2H_2 \rightarrow CH_4 + H_2O + CO + \textbf{Others} \ (CO_2,\ C_2H_6,\ \text{etc})$$

There are several notable benefits to this technology. It can handle wet feedstock, dramatically expanding the potential feedstock thermochemical processes can handle. It has a higher thermal efficiency, and uses hydrogen instead of oxygen. In a future where power-to-gas is a more pervasive process, and utilities are generating a large amount of hydrogen, this could be an effective and more efficient use of that hydrogen than simply trying to transform hydrogen into methane directly. However, Viresco itself was not able to overcome community antipathy to their pilot plant in 2015. Any initiative to resuscitate this technology would likely be challenging.

Hydropyrolysis or PyroCatalytic Hydrogenation

G4 Insight's developed another variation of thermochemical process by pyrolyzing biomass in a Hydrogen rich atmosphere. The generated vapors and aerosols are separated from the solid phase mixture of char and media and catalytically converted into methane and steam in the presence of hydrogen gas. The general chemical transformation is: $C_6H_9O_4 + 11.5\ H_2 \rightarrow 6\ CH_4 + 4\ H_2$

Funded by the California Energy Commission successfully demonstrated the production of transportation grade bio-methane from forestry residue in 2014. G4 Insight is currently developing a new pilot funded by the Canadian Government and the Canadian Gas Association to be hosted by ATCO in Edmonton, Alberta, Canada.

While syngas is the primary output of both gasification and pyrolysis processes, there are several other byproducts that offer an additional potential revenue stream that can offset the costs of the system. Below is a summary of the major byproducts of Thermochemical Conversion and their potential.

BYPRODUCTS OF THERMOCHEMICAL CONVERSION

Syngas

Syngas, also known as 'synthetic gas', is a gas derived from thermochemical conversion of biomass through pyrolysis or gasification, often comprised primarily of carbon monoxide (CO) and hydrogen (H_2) as well as some methane (CH_4) – up to around 85% of the mix on average. Syngas is the primary output of gasification and is used primarily to generate energy. It is also often used interchangeably with the term "biogas" especially if the feedstock is organic and not fossil-fuel based.

The remainder of syngas is often a mix of other gases that often do add much to the heating value, including steam (H_2O), hydrocarbon chains (C_2H_2+), carbon dioxide (CO_2), nitrogen (N_2) and other trace particulates and contaminants. Often these extra gases will need to be "cleaned" from the syngas mixture before the syngas is combusted for electricity in a combined heat and power facility (CHP) or before being methanated (chemically transformed) into biomethane for injection into the gas system.

Table 4 Syngas Compositions (Robert B. Williams, 2015)

	Air-blown Producer Gas (vol. %)	Oxygen-blown Synthesis Gas (vol. %)	Indirect-fired-steam gasification Synthesis Gas (vol. %)
CO	22	38	19
H_2	14	20	20
CH_4	5	15	8
C_2H_2 and higher	low	5	3
H_20	2	4	38
CO_2	11	18	11
N_2	46	trace	trace
	Plus tars, PM, and other		

Cleaning Syngas:
After the syngas leaves the gasifier it is often “cleaned” of particulates in a separate reactor by scrubbing with water, and then CO_2 removed for carbon sequestration. Sometimes, a chemical process called the water gas shift reaction is used to optimize the hydrogen to carbon monoxide molecules to 3:1 for the right outcome (i.e. natural gas, CH_4) down the line (This process uses the stoichiometric equation: $CO + 3H_2 \rightarrow CH_4 + H_2O$). *For more information about cleaning and upgrading syngas into pipeline-grade methane, please refer to the whitepaper on Biomethane Upgrading* (PG&E R&D and Innovation, 2018) *or find a comprehensive overview at the* National Energy Technology Laboratory website (NETL, 2018).

Biochar

Biochar is charcoal (a rigid amorphous carbon matrix made of carbon, hydrogen and various inorganic species) generated from biomass during thermal conversion as a byproduct of both pyrolysis and gasification. It is produced artificially during the thermochemical decomposition of biomass in an oxygen-limited environment (in gasification, the biochar is produced in the pyrolysis zone). It is also a naturally occurring phenomenon in some areas of the world, particularly in the Amazon basin where it was termed “Amazon Dark Earth” or “Terra Pretas” (Blakeslee, 2009). It is a stable solid that is rich in Carbon. Biochar generates a great deal of excitement due to the fact that by sequestering carbon in a stable solid, biochar is the reason why thermal conversion technologies are the only type of energy generation that has the potential to be inherently *carbon negative*.

Biochar is good for carbon sequestration in soil, and also helps reduce nitrogen emissions and water losses. These are all great for California, with the caveat that biochar production increases can only come at the cost of producing less biogas. However, claims made about agricultural benefit, such as increased crop yield, nutrient retention, pH stabilization, disease and pest resistance, etc, are at best cherry picked from highly inconsistent data, and sometimes are not applicable given biochars diverse potential chemical and biological makeup.

For more information about biochar and the validity of the many claims made about it, please see the Biochar Whitepaper analysis (PG&E R&D and Innovation, 2018).

Bio-Oil

Bio-oil is a liquid that can be used as a substitute for gasoline, produced from the condensation of vapor of a pyrolysis reaction. It has a heating value of 40-50% of that of hydrocarbon fuels. It is a mixture of oxygenated compounds, with the functional groups of carbonyl, carboxyl, and phenolics. Because of its high oxygen levels, bio-oil has many issues that make it difficult to be an effective substitute for other liquid fuels like gasoline – it often experiences problems with fuel quality, phase separation, stability, and fouling on thermal processing. Like gasoline, this 'crude' bio-oil often requires refining before it can be used effectively as a biofuel.

ANAEROBIC DIGESTION:

Anaerobic Digestion (AD) is a natural process where microorganisms break down organic material in the absence of oxygen to create a gas mixture commonly described as biogas. Biogas feedstock is generally organic material like animal manures, food waste, or sewage, since the bacteria that digest the feedstock generally do well in the presence of water, and often struggle with breaking down lignocellulosic biomass. The resulting biogas is usually methane (CH_4) and carbon dioxide (CO_2) with traces of water, other gases and some particulates. In addition, AD also produces a nutrient rich liquid mixture called *digestate*, which is a very effective natural fertilizer for agriculture.

Figure 5 Illustration of an AD on a farm (Michigan State University, 2013)

Anaerobic Digestion is a natural, efficient, and mature technology. That makes it one of the best tools for generating renewable natural gas in the modern conversion arsenal. It also is the best way to deal with biomass that has a high moisture content, like dairy manure, municipal solid waste, or waste water. These also happen to be the types of waste that contribute the most fugitive methane emissions in California. While challenges remain to implementing AD technology economically in real life applications, it is already widely used in Europe and Asia to generate renewable natural gas.

Roughly 10,000 biogas plants in agriculture, industry and waste water treatment were in operation in Europe in 2016 to produce 16 MTOE (0.6 Quad) (European Biogas Association, 2011).

Most AD systems require some infrastructure (tanks, mixers, covers, and heating systems), as well as the microorganisms that are the basis for the process of anaerobic digestion (fermenting bacteria, syntrophs, or methanogens). Once constructed, a typical biodigester will break down the feedstock through a process of liquefaction or bacterial hydrolysis – adding water (the opposite of thermal conversion). Next, *Acidogenic Bacteria* convert sugars and amino acid chains into CO_2, H_2, ammonia, and other organic acids, which *Acetogenic bacteria* convert part of this material into a substrate used by *Methanogens* to convert all of these molecules into methane (CH_4) and carbon dioxide (CO_2). The remaining mixture is a methane-rich gas, and a nutrient-rich liquid (digestate).

Key attributes of Anaerobic Digesters:

Anaerobic Digestion systems harness a naturally occurring process, and are well-developed. They offer much more customization that many other conversion technologies in part because of this. Most biodigesters are distinguished by (1) heat, (2) moisture content, or (3) whether the digester handles feedstock in batches or in a continuous flow.

(1) Since bacteria are living organisms, they require heat to survive. There are a few different heating levels that have a significant impact on the productivity of biodigesters (TheEcoAmbassador.Com, 2017):

- Thermophylic (120-140°F) - Typical of large-scale digesters leading to higher efficiency. Reduces digester retention times to 3-5 days. Also requires more heat energy from external heat exchangers. Kills more pathogenic bacteria, but cost to maintain higher operating temperature is high. This temperature also develops “Class A Bio-solids” which is designated as dewatered and heated sewage sludge that meets US EPA guidelines for land application with no restrictions.
- Mesophylic (95-105°F) - Typically require digestion times longer than 20 days. Common for smaller, midsized operations.
- Psychrophylic (60-75°F) - Common for small-scale operations and landfills where production rates and retention times are less important. It is the least efficient system, but it is the simplest and least-expensive digester. Digestion slows down or stops completely below 60 or 70°F, so these digesters do not produce methane all of the time (TheEcoAmbassador.Com, 2017).

(2) Similarly, biodigesters can often differ on the level of moisture content in their feedstock. While all anaerobic digesters are best suited to conversion of biomass with a high moisture content, there are two general categories of biodigesters:

- Wet digesters (low solids) generally have feedstocks with less than 15% solids content. It is more common to have a wet digestion system compared to a dry digester system. One of the advantages of having a wet digester is that the feedstock is usually in a slurry form, so it can be pumped for easier handling.
- Dry digesters (high solids) are systems that take in feedstocks greater than 15% solids content.

(3) Finally, biodigesters can be built to accommodate either batches of feedstock or a continuous flow of feedstock into the system:

- Batch Flow: The feedstock is loaded into the digester all at once. Once a batch has been loaded, there is a set period of time for the digestion process to occur before the digester is emptied and reloaded with a new batch.
- Continuous Flow: The feedstock is constantly fed into the digester while digested material is continuously removed.

Table 5 Anaerobic Digester Types (PG&E R&D and Innovation, 2018)

Digester Type	Description
Single Stage System	All anaerobic process reactions take place inside a single reactor. **Benefits**: Cheaper to construct and operate. **Limitations**: Will not be optimal for the various trophic groups of microbes, lower gas production and organic conversion rate.
Multi-Stage System	Multiple reactors (usually two of them) are designed in series to optimize the process and enhance gas production. **Benefits:** Greater biological stability, greater ability to cope with fluctuations in feedstock type and amount, potential for higher output due to optimal conditions, higher volume reduction by volatile solids destruction, better odor control. **Limitations:** More complex requirements to control and operate, and higher capital costs.
Plug Flow Digester	Plug flow digesters are long, narrow concrete enclosures with either a rigid or flexible cover that pushes manure from one end to the other as more manure is introduced on the front end. Common inputs include drier (11-13% solids content) and thicker organic matter such as manure. The final output is biogas, compost, and liquid digestate. Typical components include a mix tank, a digester tank with heat exchangers a biogas recovery system, an effluent storage system, and a biogas utilization system. One main benefit is the ability to optimize energy production in any climate.
Complete Mix Digester	Complete Mix Digesters, typically constructed from steel or concrete, are technologically advanced systems designed to maximize the quantity and the quality of biogas that is produced. These are also known as continuously stirred tank reactors (CSTR). Some of the main benefits are biological stabilization of the effluent and odor control. The feedstocks, which are mainly slurry form, will be mixed with bacteria. The incoming feedstock will displace an equal amount of output. The typical components of a complete mix system are a sealed mix tank, a digester tank with mixing, heating and biogas recovery systems, an effluent storage structure, and a biogas utilization system. Dozens of complete mix digesters have been constructed globally.
Covered Lagoon	Covered Lagoon anaerobic digesters produce biogas at ambient temperatures from diluted manure with less than 3% solids. In order to trap biogas, an impermeable cover floats on top of a lagoon filled with flush manure. These systems are typical in warmer climates. The components of the system include a solids separator, one or more lagoons, a floating lagoon cover, and a biogas utilization system. Often a variable volume one-cell lagoon designed for both treatment and storage will be utilized to recover biogas. A second lagoon can be used for variable volume storage to receive effluent from the primary lagoon and

contaminated runoff which will be stored and used for irrigation, recycle flushing, or for other purposes. Dozens of covered lagoon anaerobic digestion systems have been implemented globally. Lagoon cover materials should be ultraviolet resistant, hydrophobic, tear and puncture proof, non-toxic to bacteria, and have a bulk density near that of water.

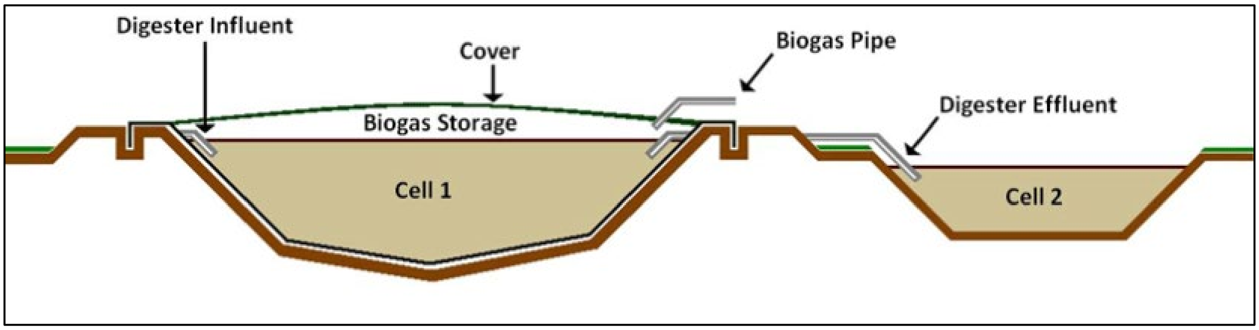


Figure 6 Covered Lagoon schematic

A Note on Efficiency: These technologies are generally quite efficient to thermochemical conversion, but the range is wide, and can vary from 20-70% (Narihiro, 2016). For every 1 kg of waste that is converted by anaerobic digestion, 0.35 m^3 of CH_4 is produced, generally with a lower thermal value (22 MJ m^{-3}) than conventional methane (36 MJ m^{-3}) because of the presence water (Narihiro, 2016). Finally, anaerobic digestion can be painfully slow, occurring over months compared to thermal conversion's seconds. Thus, measuring the amount of time that the biomass/sludge remains in the digester is an important facet of efficiency, called "hydraulic retention time" or HRT. That time can be shorted when using a small digester, but it often involves compromising on the optimal outcome for biogas. The table below is a comparison of the most commonly used biodigesters, their efficiency, and production of methane (AgSTAR, 2011):

Table 6 Comparison of Commonly Used Biodigesters (AgSTAR, 2011)

	Optimal Feedstocks	**Percent Solids**	**Hydraulic Retention Time (HRT)**	**Co-Digestion**	**Temperature**	**Efficiency (VS reduced %)**	**% CH_4**
Plug Flow Digester	Dairy manure	11-13%	15+ days	Not Optimal	Mesophilic or thermophilic	68 - 72	68
Complete Mix Digester	Diluted manure – slurry, other slurry organic wastes	3-10%	15+ days	Yes	Mesophilic or thermophilic	50	58
Covered Lagoon	Manure from flush/pit recharge collection systems	0.5-3%	40-60 days	Not Optimal	Psychrophilic	Not available	40 – 80 (dependent on temp)

BYPRODUCTS OF ANAEROBIC DIGESTION

Biogas:

Biogas is distinguished from syngas by being the result of a biochemical process of breaking down biomass in the absence of oxygen, producing a methane-rich gas. Syngas is generally the product of gasification or thermochemical conversion and is comprised primarily of carbon monoxide and hydrogen. instead of a mechanical, thermal one, though some people may use them interchangeably in casual conversation. However, unlike syngas, biogas is *primarily* methane in its raw form, usually between 50-70% methane with 25-45% CO_2. The remaining 5-15% of biogas includes traces of steam (H_2O), oxygen (O2), Nitrogen (N2), ammonia, hydrogen sulphide (H_2S), and other elements. Because biogas is methane-rich, it does not generally need additional methanation, and instead only requires cleaning and upgrading (cleaning out non-methane constituents in the gas, and upgrading the gas to an acceptable heating value) to be pipeline-ready. However, some of those constituents, notably H_2S, are potent poisons, and must be removed carefully and disposed of. Similarly, CO_2 must be separated and sequestered for greatest greenhouse gas (GHG) reduction effect (PG&E R&D and Innovation, 2018).

Digestate:

The material that is left over after the anaerobic digestion is a wet mixture that can be separated into a solid and a liquid. It is composed of water, minerals, nitrogen, phosphorus, potassium, and the build of the residual carbon from the original organic material. Digestate (also known as anaerobic digestate effluent) is well-known as an effective and natural fertilizer for agriculture.

Macro Challenges:

- ***Conversion technologies are enormously expensive*** – Gasification and Pyrolysis facilities can cost in the range of hundreds of millions of dollars. Anaerobic digester facilities can range from $50k to $3M (Beddoes, 2007). Since this is an up-front capital requirement and financing for these projects can be challenging, there is an imperative to make these systems substantially cheaper.
- ***Owners of biodigesters need simplicity because energy is not their core business*** – Most of the owners and operators of biodigester facilities by definition will not be specialists in energy generation (such as dairy farmers and agricultural companies). They will need more process, product, and technical guidance than the average developer. Since anaerobic digestion relies on bacteria that require careful management it will be important to establish standards, make technical recommendations, and develop technology that can automate critical processes to simplify this process for them and increase the odds of success.
- ***Lack of a dominant standard in thermochemical conversion*** – While gasification and pyrolysis are generally considered mature technologies (gasification has been used in processing coal for decades), few thermochemical conversion facilities dedicated to producing biomethane exist world-wide. Additionally, while there are many technologies available, no one design has emerged as significantly more efficient, cheaper, or better than any other.
- ***Anaerobic digestion is the most efficient way to convert energy, but it's too limited*** – Anaerobic digestion uses the least energy of any method of converting biomass to energy. But AD uses living bacteria – they have limitations to what feedstocks they can process, their process is slow (months instead of hours!), and even small

changes can kill a whole digester. These problems are fixable, and eliminating current constraints on anaerobic digestion could have a huge positive impact on California's emissions.

KEY BARRIERS TO ADOPTION OF CONVERSION FACILITIES:

The major categories of problems related to conversion generally fall within one of four categories:

1. **Conversion facilities are capital intensive up front**
2. **Lack of universal standards for safety, feedstock, etc.**
   - **Lack of standards also results in a proliferation of different conversion technologies**
   - **Lack of standards make it harder for non-specialists to operate in the industry**
3. **Feedstock Interchangeability is limited**
   - **Lignocellulosic biomass cannot be processed well in a digester**
   - **Wet biomass cannot be processed well via thermal conversion**
4. **Conversion variable costs can be expensive, sensitive, or inefficient.**

Conversion technologies are relatively mature technologies compared to the rest of the biomethane and RNG industry. However, despite being long-established, there exists few common standards, which results in several challenges that will have to be fixed to hasten the adoption of these technologies on a more widespread basis. Having universal standards for safety (i.e. the disposal of hazardous by-products like H_2S or tars), how feedstocks are pre-treated, or processes for usage of bacteria in digesters – all of these will result in maximizing the efficiency and useful life of conversion technologies.

However, standards will also help to reduce the overwhelming number of variations that proliferate within any given category of conversion technology today. At the moment, there are so many versions of gasification and anaerobic digestion, that it can be difficult for potential owners to intelligently select, operate, and maintain a system. Add into this that many of these owners are often not industry veterans but specialists in other fields (dairy farmers, wastewater treatment plant operators, etc.) and that some of these variations often have large implications for the cost and effort to maintain and operate the system on an ongoing basis - and it becomes very challenging to successfully execute projects, secure financing, and keep these projects running to profitability.

Finally, one constraint with conversion technologies is their poor flexibility – specifically that woody and lignocellulosic biomass is most efficiently processed with thermal conversion, and wet biomass is most efficiently processed with anaerobic digestion. Since AD is by far the most efficient (and often cheaper) process, is there a way to process lignocellulosic biomass in a digester? Doing so might encourage additional standardization, use of a more efficient technology, and lower cost (and more competitive pricing) for the industry.

Potential R&D Projects for Conversion Technologies

These are the categories of technologies that are priorities in addressing some of the key challenges facing conversion technology adoption and usage in California.

1. CODIGESTION of WOODY BIOMASS IN DIGESTERS

Co-digestion is the process of including woody biomass feedstock in an anaerobic digester along with the wet biomass that is generally used. Sometimes this process can allow the digestion of otherwise un-digestible lignocellulosic biomass, and can often *increase* the efficiency of the whole process.

However, additional technologies might be available for processing woody biomass in an efficient manner, and any such technologies should be explored.

2. STANDARDS FOR BACTERIA TYPES AND MANAGEMENT

Bacteria are the key element to anaerobic digestion. There are many varieties of bacteria that can be used in AD, and often several different types must be used to produce methane effectively in any one system. Identifying the best (combination) of bacteria for applications for dairy, wastewater, and other feedstocks is critical.

Establish best practices for bacteria management (to prevent owners and operators from project-killing mistakes or mis-management of digester systems).

3. EXPAND ANAEROBIC DIGESTION PRODUCTIVITY WITH ENZYMES

Enzymes are a critical element of improving anaerobic digester productivity. With the right enzymes, AD systems can expand their capacity, expand the potential feedstocks that can be used in the system, and increase productivity.

4. PYROLYSIS AND GASIFICATION TECHNOLOGY EFFICIENCY IMPROVEMENTS

Thermochemical conversion requires heat to promote chemical reactions that break down the lignocellulosic molecules in woody biomass (or to breakdown otherwise challenging feedstock like batteries or waste materials), and therefore consumes a great deal of energy in order to generate syngas. It will be important to explore ways to make this process more efficient.

5. ESTABLISH PREFERRED PYROLYSIS TECHNOLOGIES

There is a proliferation of potential pyrolysis solutions on the market today. It will be important to evaluate current facility designs, and to support front-runners to reduce cost and complexity.

6. SMALLER and CHEAPER CONVERSION FACILITIES

Conversion systems that can significantly reduce costs or the size of their facilities (with the goal being a small, modular, and cheap system), will improve the economics of RNG projects considerably. Since the resulting biomethane is cost-prohibitive without GHG credits and subsidies, this will contribute significantly to the ability of the industry to becomes profitable without government support.

7. STEAM HYDROGASIFICATION

The potential for a hydrogen and steam environment for the thermochemical conversion of biomass is promising, but the only company licensed with the technology shuttered in 2015. It may be worthwhile to take a second look at this technology in the California economic and policy context to determine whether it might be a viable option for biomethane production.

8. CARBON CAPTURE SOLUTIONS

Thermochemical conversion is one of the few mechanisms for generating renewable energy that can be carbon *negative*. Part of the cleaning and upgrading process for syngas includes removing CO_2 and other carbon products such as tar and biochar. Technologies that can do this cheaper than existing solutions and in a form that can be repurposed to feed alternative carbon markets will be very valuable to PG&E's overall goals for GHG reduction, and could potentially feed an additional revenue stream as a supply for carbon based products.

Key Technologies to Investigate and Timeline

There are several projects that can be done within PG&E's R&D scope that will be beneficial from the utility perspective in the improvement of biomass sourcing. However, some potential projects might include:

1. Co-digestion project to measure the productivity of an anaerobic digester co-digesting woody biomass with dairy manure feedstock. There is also potential to use the same project to determine the potential and effectiveness of enzymes.
2. Evaluation of the many different technologies available for gasification for efficiency, ease and affordability of operating and maintaining the system, and cost. The purpose of such a project would be to understand what technology options are available and identify technologies that are demonstrably market leaders if there is one.
3. Establish standards for operating anaerobic digesters based on best practices in engineering, design, and digester management from mature projects in Europe in order to establish guidelines for California biogas project development, and bacteria maintenance.

WHO ARE EXPERTS IN THIS FIELD?

Experts specific to individual types of Conversion or Processing technologies:

Table 7 Individual and Technology Specific Experts

Industry Experts	Expert	Alternative
California	UC Davis Biomass Collaborative UC Riverside	Reginald E Mitchell, Professor, Stanford University Arun Raju Director, Center for Renewable Natural Gas
	Vann Bush, GTI	Daniel LeFevers, GTI
	Ronald Stanis, GTI	Prab Sethi, CEC
United States	Nicholas Nagle, National Renewable Energy Laboratory	
International	GoBiGas – Gothenburg Biomass Gasification Project GAYA project	
Conversion Technologies		
Woody Biomass	Edson Ng, Matt Babicki, G4 Insights	
	GTI	West Biofuels
	Daniel Dodd, Sierra Energy	

Agricultural Residue	Sierra Energy UC Davis, Bryan M. Jenkins	MIT, Ahmed Ghoniem and Kevin Kung, PhD Student
Municipal Solid Waste	California Integrated Waste Management Board	Advanced Plasma Power (APP), Sierra Energy
Animal Manure	Martha Krebs, CEC PIER	The California Department of Food and Agriculture
Wastewater	The Interagency Wastewater Biogas Working Group, California Association of Sanitation Agencies	State Water Resource Board
Landfills	Sierra Energy	Advanced Plasma Power (APP)
Algaes	Stephen Mayfield, California Center for Algae Biotechnology	IEA
Energy Crops	M.W Jenner, S.R Kaffka, (California Biomass Collaborative, CEC)	Leibniz Institute for Agricultural Engineering and Bioeconomy (ATB)
Steam Hydrogasification	Viresco Energy	UCR, College of Engineering, Center Environmental Research & Tech

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