PG&E GAS R&D AND INNOVATION

WHITEPAPER

Biomass

9/18/2018

Together, Building
a Better California

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Summary: Biomass

Definition: Biomass is living or recently living plants, animals or waste and is often referred to as “Biomass” or “feedstock”. Biomass is considered a renewable source of energy due to regrowth and carbon capture of plant matter, continuous production of human or animal waste, and the displacement of fossil fuels. It is by far the oldest source of energy humans have ever used, (starting a fire with wood for example), but modern techniques have made this source of energy scalable to today’s needs. Biomass is generally processed by one or several technologies into fuel or electric power and is generally broken down into the following categories:

1. Woody Biomass
2. Agricultural Residue
3. Municipal Solid Waste
4. Animal Manure
5. Wastewater
6. Landfills
7. Energy Crops

The definitional aspect of Biomass in the value chain is that it is the original source for biogas or syngas and subsequent clean fuels or gases. Generally speaking, Biomass is waste from human activity or is purposely grown and then harvested. Once collected, aggregated, and in some cases pre-processed, Biomass moves to the conversion or processing step in the low-carbon gas/fuel value chain.

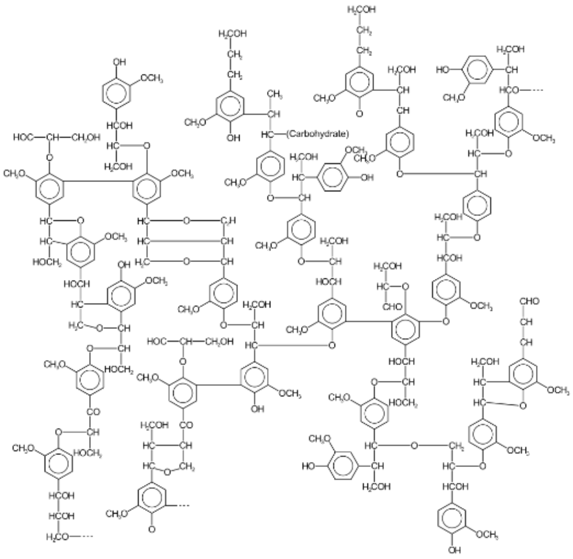


Figure 1 Lignin Polymer (Liquefied Wood, 2011)

Lignocellulosic Biomass: This is a term for Biomass that is plant-based, like trees, bushes, or grass, and also for agricultural waste like corn stover or sugarcane bagasse, forestry residues, or energy crops like switchgrass or sugarcane. It would NOT include wastes like dairy manures or wastewater. Lignocellulose is the scientific term for plant dry matter, composed primarily of Lignin, which is a rigid polymer that is found in wood and bark, and carbohydrate polymers (like cellulose).

Most Biomass can be categorized as lignocellulosic Biomass. This is important because lignocellulosic Biomass has only one effective, commercialized form of conversion into energy in the form of gas – pyrolysis (which is itself a step within gasification). *All non-lignocellulosic Biomass can be effectively converted to energy through biochemical means in an anaerobic digester.

**Note: one of the very earliest and most effective forms of energy conversion for lignocellulosic Biomass is actually* fermentation through a multi-step process, involving pre-treatment and hydrolysis of the lignocellulose to release fermentable simple sugars*, which produces liquid biofuels like ethanol and biodiesel* (Wisconsin Biorefining Development Initiative)*. However, for PG&E's purposes as a gas utility, this conversion technology is not applicable.*

More Introductory-level Resources on Biomass:

US Energy Information Administration: Biomass Explained (Text)
US Energy Information Administration: Biomass and the Environment (Text)
California Energy Commission, UC Davis: Assessment of Biomass Resources in CA (Report)

Quantitative Sizing of Biomass Potential

PG&E Internal Analysis (Oldham, 2017):

- **Total**: 89 bcf by 2030, 202 bcf by 2040, 205 bcf by 2050
- Animal Manure
    - Carbon intensity: -50 to -250 gCO_2/MJ (but without credits for avoided methane, 35-55)
    - Supply from dairy farms, primarily.

10 BCF (2030)	19 BCF (2040)	19 BCF (2050)

- Landfill Gas
    - Carbon intensity: 20-50gCO_2/MJ

  - Most facilities already producing energy in long-term PPAs, so some of these numbers are higher than when can be added in new potential supply. They're already counted.
  - Supply from Waste Management companies, landfill owners, municipalities that own landfills.

42 BCF (2030)	54 BCF (2040)	56 BCF (2050)

- Agricultural Residues:
  - Carbon intensity: 20-50gCO_2/MJ

3 BCF (2030)	31 BCF (2040)	24 BCF (2050)

- MSW
  - Carbon intensity: 15-35gCO_2/MJ
  - Supply from Waste Management companies, municipalities that own facilities.

26 BCF (2030)	51 BCF (2040)	52 BCF (2050)

- Wastewater Treatment
  - Carbon intensity: 15-35gCO_2/MJ
  - Same Suppliers as Landfills.

4 BCF (2030)	4 BCF (2040)	7 BCF (2050)

- Woody Biomass
  - Carbon intensity: 30-40gCO_2/MJ
  - Suppliers – timber companies

4 BCF (2030)	43 BCF (2040)	47 BCF (2050)

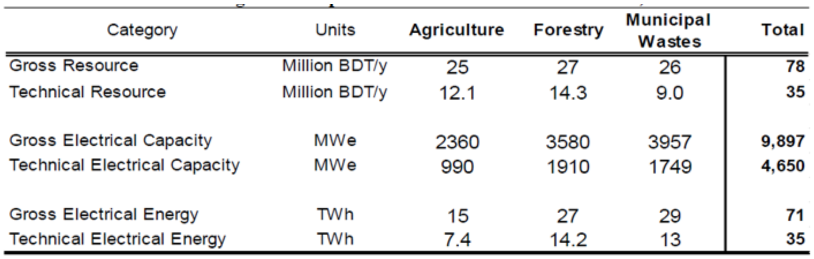
Assessment of Biomass Resources in California (California Biomass Collaborative, University of California, Davis, 2015):

Summary: Within the resource categories considered here, total or gross estimated Biomass is 78 million bone dry tons (BDT) per year. Technical (recoverable) resource is estimated at 35 million BDT/y (see Table 1 and Figure 2 below).

Roughly 45% of the gross Biomass resource is considered to be technically available for conversion or other uses. The remainder occur in sensitive habitat areas, on steep slopes not suitable for harvesting, are needed to maintain soil tilth and fertility, or are unrecoverable by harvesting and recovery equipment (Kaffka, 2014).

- Total: 78M BDT per year
- Technically recoverable resource 35M BDT/y (roughly 45% gross Biomass resource) (about 600 trillion BTU, or 0.6 Quad)
- Total Biogas potential: 93 bcf methane/year
    - Animal Manure: 3.4MM BDT - 19.7 bcf
        - 66M Agricultural animals in CA – 5.3M cattle
        - Total manure production from animals is 11.7M BDT/y – 10.9M BDT of that is from cattle
    - Landfill Gas: 106 BCF – 53 bcf
    - MSW: 1.2MM BDT – 12.6 bcf
    - Waste Water Treatment: 11.8 BCF – 7.7 bcf
    - Woody Biomass?
        - Main categories are logging slash, mill residues, Biomass from forest thinning and stand improvement operations, chaparral.
        - Gross Forest Biomass: 26.8M BDT
        - Technically available 14.3M BDT

Table 1 Resources and Generation Potentials from Biomass in California, 2013 (California Biomass Collaborative, University of California, Davis, 2015)



Category	Units	Agriculture	Forestry	Municipal Wastes	Total
Gross Resource	Million BDT/y	25	27	26	**78**
Technical Resource	Million BDT/y	12.1	14.3	9.0	**35**
Gross Electrical Capacity	MWe	2360	3580	3957	**9,897**
Technical Electrical Capacity	MWe	990	1910	1749	**4,650**
Gross Electrical Energy	TWh	15	27	29	**71**
Technical Electrical Energy	TWh	7.4	14.2	13	**35**

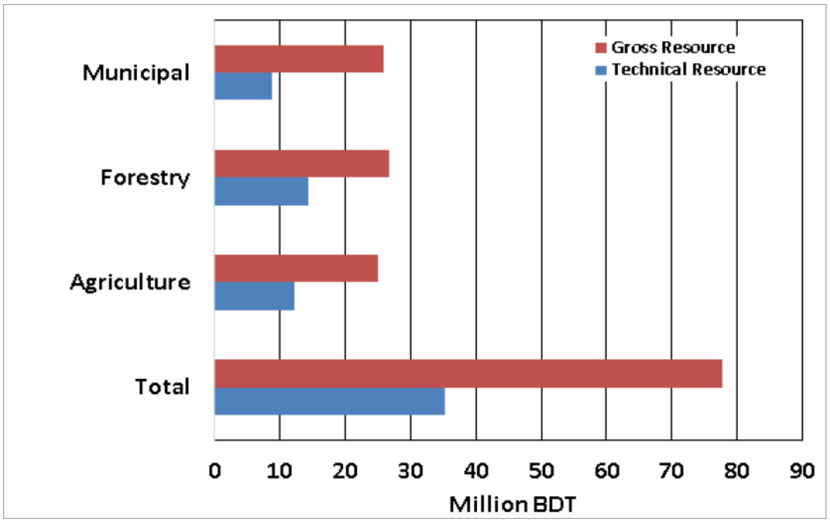
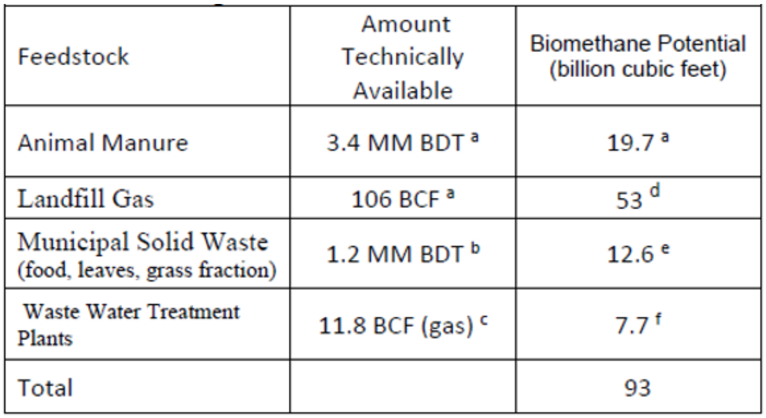
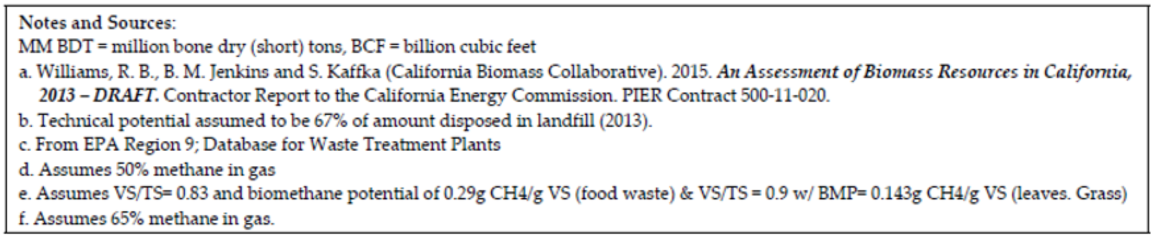


Figure 2 Resources and Generation Potentials from Biomass in California, 2013 (California Biomass Collaborative, University of California, Davis, 2015)

Table 2 Biogas Technical Potential from California Resources (California Biomass Collaborative, University of California, Davis, 2015)



Feedstock	Amount Technically Available	Biomethane Potential (billion cubic feet)
Animal Manure	3.4 MM BDT [a]	19.7 [a]
Landfill Gas	106 BCF [a]	53 [d]
Municipal Solid Waste (food, leaves, grass fraction)	1.2 MM BDT [b]	12.6 [e]
Waste Water Treatment Plants	11.8 BCF (gas) [c]	7.7 [f]
Total		93



Notes and Sources:
MM BDT = million bone dry (short) tons, BCF = billion cubic feet
a. Williams, R. B., B. M. Jenkins and S. Kaffka (California Biomass Collaborative). 2015. ***An Assessment of Biomass Resources in California, 2013 – DRAFT.*** Contractor Report to the California Energy Commission. PIER Contract 500-11-020.
b. Technical potential assumed to be 67% of amount disposed in landfill (2013).
c. From EPA Region 9; Database for Waste Treatment Plants
d. Assumes 50% methane in gas
e. Assumes VS/TS= 0.83 and biomethane potential of 0.29g CH4/g VS (food waste) & VS/TS = 0.9 w/ BMP= 0.143g CH4/g VS (leaves. Grass)
f. Assumes 65% methane in gas.

Macro Challenges (High Level):

- ***There isn't enough Biomass to meet our needs*** – With 0.6 Quad of energy before conversion there isn't enough Biomass in the state to make enough biogas to replace PG&E's gas throughput of 822,655 MMSCF (about 0.8 Quad) (PG&E Corporation, 2016). Assuming a conversion efficiency of 70%, California Biomass would potentially displace about 0.4 Quad, i.e. half of Natural Gas delivered by PG&E. In some cases, like sources from the human waste stream, the goal is actually to *reduce* the amount of waste generated. This is a constraint that can be alleviated by the *production* of sources of purpose grown, environmentally-friendly Biomass. This is normally associated with elephant grass, prairie switchgrass or corn for ethanol, but one particularly promising technology is algaes (specifically, micro-algaes) that can be grown to meet demand for PG&E's green gas customers.
- ***Biomass/Biogas is more expensive than alternatives*** – At the moment, Biomass is generally generating biogas at the price of $14 - 42/MMBTU (The Oxford Institute for Energy Studies, 2017). Natural Gas is currently at around $3/MMBTU. Moreover, assuming a conversion rate of 30% for electricity generation, it leads to a cost greater than $140/MWh). While PG&E doesn't necessarily expect to see comparable pricing (given low-carbon credits and the positive environmental value of biogas), projects that offer significantly lower prices will be more likely to garner investment.
- ***It's challenging and expensive to get feedstock to processing or conversion facilities*** - Currently, it costs a between $14 – 42 per MMBTU (depending on the feedstock) to source Biomass from where it is produced or grown and centralize it for conversion or processing (The Oxford Institute for Energy Studies, 2017). That cost goes directly to the bottom line because biogas is not yet cost competitive with other sources of energy (electric and gas) sourcing or generation.
- ***Especially within California, diversity of geography, industry, settlement work against us*** – The incredible diversity of land, ecosystems, biomes, and human settlement is usually considered one of California's greatest assets. However, with less standardization comes higher cost. Therefore, solutions California develops for Biomass may be even more effective and affordable when implemented in states with greater homogeneity of economic activity or territory.
- ***Water to grow the Biomass is an issue*** – Especially in California, water is a critical resource. Biomass and biogas feedstock by definition require water for production, and the most efficient forms of biogas conversion (anaerobic digestion) require higher water content for optimal processing. This creates a conflict that outstanding technology solutions will address.

Key Challenges in Leveraging Biomass as a Low-Carbon Fuel Source (Medium Level)

The major categories of problems related to current technically recoverable Biomass sources generally fall within one of four categories:

1. **Dispersed nature of Biomass**
2. **High costs for aggregation**
3. **Low energy density**
4. **Heterogeneity**
5. **Pilot Facilities for new technology are capital intensive upfront**

Generally speaking the sources of Biomass (i.e. trees, animal manure, crop residuals, trash from our houses, etc.) are by nature not all concentrated in one place. This leads to physical and technical barriers to accessing the Biomass to collect it, and higher costs to centralize that Biomass in one place for processing. These costs are exacerbated by the low-energy density of these sources of fuel since much of what trucks bring to processing facilities is air or water, which is not useful for, or detrimental to the conversion to fuel. Finally, the fact that all sources of Biomass are different even within the same category also makes standardization (and therefore cost efficiencies) difficult to obtain (Williams, 2013).

Customization for each form of Biomass, and even customization within the same category to account for seasonality, sourcing, or individuality of the source increases costs dramatically. Some of these problems might be solved by new technology, but its development is heartbreakingly slow due to the enormous upfront capital it takes to build, fund, permit, and begin operations on demonstration processing facilities. *(Discussed more at length in "Processing")*

Dairy Example: One would expect cow manure to be a relatively consistent and concentrated form of Biomass. However, different consistencies and chemical makeup of manure from cows changes based on what they eat, the season, the temperature, or the health of each cow etc. All of these variables increase the cost to administer a facility that uses manure as a fuel source…and in some disastrous cases, lack of or improper customization kills the bacteria that are the key element of anaerobic digestion, dooming the entire facility. In addition, only the very largest 43% of dairies have enough concentrated cows (and manure) to provide a consistent stream of Biomass to a nearby anaerobic digester. Smaller dairies, though willing, would have to pay more to transport the manure long distances to aggregate enough Biomass to feed a centralized biogas plant. Most of what they end up transporting is actually water, which can be up to 90% of the weight of manure, and is why manure is not as energy dense as fossil fuels (California Dairy Statistics Annual , 2017). All of this complicates and intensifies the expense of using dairy manure in biogas development.

SUCCESSFUL TECHNOLOGIES WILL:

1. Reduce capital costs and size of potential facilities to reduce the need for aggregation
2. Increase the energy density, or reduce the amount of land needed for Biomass generation
3. Introduce homogeneity in otherwise diverse forms of Biomass
4. Reduce the water or air content of sources of Biomass before transport
5. Centralize the production/growth of Biomass where a processing facility can be co-located
6. Enable the processing or partial processing of Biomass to travel cheaply *to* sources of Biomass
7. Drive costs down for the growth of purpose-grown energy crops such as micro-algaes

Technical Challenges: Tech with Potential to Reduce Costs and Scale the Use of Biomass in California (Technical Level)

There are 3 major categories of Biomass technology that address the aforementioned challenges associated with using Biomass affordably and at scale. While many of these technologies have implications for conversion and processing later in the supply chain, those will be addressed in a separate paper.

1. Purpose-Grown Crops & (Micro) Algaes

Eliminates many constraints on scaling up Biomass resources, the Biomass itself is homogenous, and can offer productive means of consuming waste heat, CO_2, waste water and otherwise problematic outputs from conversion facilities.
Cost reduction technologies to take existing stationary densification methods and making them more efficient.

2. Cheap Mobile Biomass Densification

For some Biomass, the cost of aggregation over long-distances is too high to justify harvesting it (i.e. dead bark beetle trees up in the mountains). In these cases, having a mobile densification technology may increase the number of energy units carried per truckload. Since people pay for energy, this reduces time, money and energy spent in recovering these sources of Biomass.

3. Pre-treatment of Biomass/Quality Improvement

There are a few other means of pre-treating Biomass so that it makes I higher quality energy fuel. In addition, some types of Biomass can be made into significantly more productive fuel sources when pre-processed before conversion. This is especially useful where Biomass is already aggregated (like Rice Straw at Rice processing plants) but the Biomass is unusable or inefficient (Satlewal, 2017).

PURPOSE GROWN CROPS

While not widely practiced in California, growing energy crops that are purposefully produced as a source of biogas feedstock is common in Europe where biogas production is a thriving market, in the US Midwest and in South America where corn and sugar beets are grown for fermentation into bio-fuel ethanol. One major challenge with purpose growing crops of any kind is the inevitable conflict with the use of land. If land can be used to grow food, it's hard to make the case that that land can or should be economically used for energy generation purposes. Secondly, monocultures of energy crops are desirable because of their uniformity and efficiency – but often presents environmental problems and introduces high risks. Finally, energy crops run into the same problem of costly aggregation as many other forms of biogas feedstock or Biomass.

Which energy crops are best?

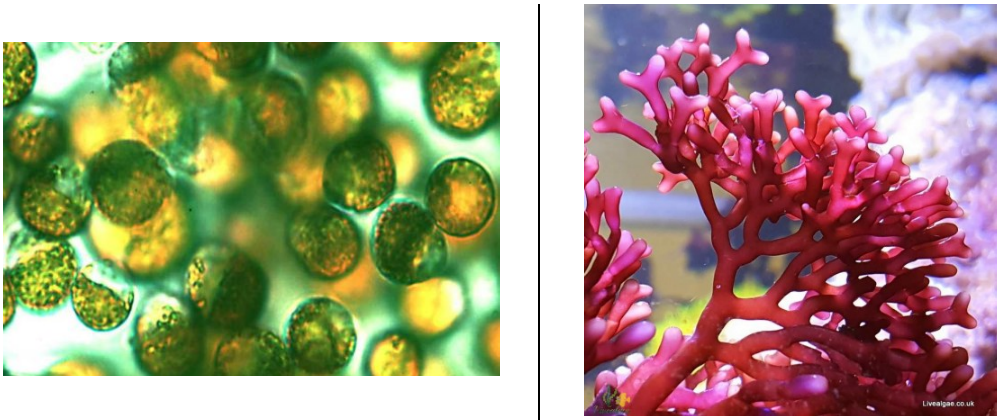
The suitability of a particular crop for methane production is described by the following equation:

Methane Potential * Crop Yield = Methane Yield per Hectare

Additionally, qualitative and financial factors contribute to the overall suitability of energy crops for a particular location or conversion method (labor, pesticides, fertilizer, machinery, etc). While corn is globally the most popular energy crop, it is also used for food (University of Illinois at Urbana-Champaign, 2017). Crops that can be used in rotation like rapeseed, sunflower, Biomass sorghum, or hemp (Zegada-Lizarazu & Monti, 2011) that can be used in fallow fields or in soil rotations may actually be best suited for energy generation in an agricultural powerhouse state like California. It is not a huge surprise that this research was conducted in Germany. In 2000, the Renewable Energy Sources Act kicked off a steep increase in the use of energy crops as a feedstock for biogas plants in Germany (primarily for electric generation). The number of biogas plants soared to 5,000 in 2009, with energy crops topping out at 4.4% of arable land in the country (Bioenergy Crops LTD, n.d.). The Leibniz Institute for Agricultural Engineering and Bioeconomy (ATB) did a study evaluating 403 silages of 43 crop species and found that for methane generation, lignin is an important Biomass constituent that determines specific methane yields. Traditional energy crops valued for their high sugar content (like sugar beets and potatoes) actually had lower methane content than crops like alfalfa clover grass, and miscanthus which can be used in crop rotations in fallow fields. For 30 out of 43 investigated crop species the average methane content laid between 54% and 57% of the produced biogas (Herrmann, 2016). However, one particular energy crop, algaes, does offer additional benefits explored below.

ALGAES

Algaes have long been considered among the most promising sources of Biomass for future energy needs for many reasons that seem nearly too good to be true. Algae is an incredibly fast-growing source of Biomass, it captures and sequesters CO_2, and can be cultivated in oceans or ponds that don't force a tradeoff between energy crop growth, arable land for food production and potable water. Why then are algae not already in common usage in the global energy system? The short answer is that the amount of energy it takes to mix, harvest, and convert microalgae into biogas is so significant that it nearly negates its own total energy production. As a result of this, the commercialization of algaes is unlikely without additional innovation.



(NORD University, 2018)

(Livealgae UK)

Figure 3 Pictures of Various Algae

What are algaes?

Macroalgaes are better known simply as seaweed. Microalgaes are usually uni- or multi-cellular plant organisms that form colonies. Generally speaking algae are considered very efficient, since they can devote more of their energy into photosynthesis (trapping light and CO_2) because they don't have to spend energy maintaining elaborate support and reproductive structures. Microalgae photosynthetic efficiency is 4.5% of solar energy again less than 1% for other crops. (Bolton, 2017).

Why could they be so good as a feedstock for biomethane?

Algae is tempting because of the complementary nature of its feedstocks and of algae *as* a feedstock. Algae consumes CO_2 during photosynthesis, and requires heat and water, all inputs that are considered waste for power plants or contaminants from the anaerobic digestion process. The algae itself is then used in an anaerobic digester to generate biomethane. Finally, digestate, the high nutrient waste product from anaerobic digestion, is like a super fertilizer, and can in turn be used to stimulate the growth of algaes. In some ways, the perfect complementarity of the system mirrors a self-contained ecosystem, where each step uses the waste of another step to fuel growth. For these reasons:

- Algae production may be very well suited to co-production with wastewater treatment plants. This is open water near gas pipelines that can easily be repurposed to algae use. Algaes used in anaerobic digestion don't require purity, so harvesting can be done more cheaply and in conjunction with existing wastewater treatment steps.
- Algae is a massive consumer of CO_2, a notable greenhouse gas, and as this feedstock scales to meet demand, it may provide a carbon market that makes use of sequestered carbon from other industries or from elsewhere in the energy generation system.
- Open cultivation systems clearly make the most sense for investment especially in temperate California, but seasonal changes in light and temperature still offer challenges to algae production on a larger scale.

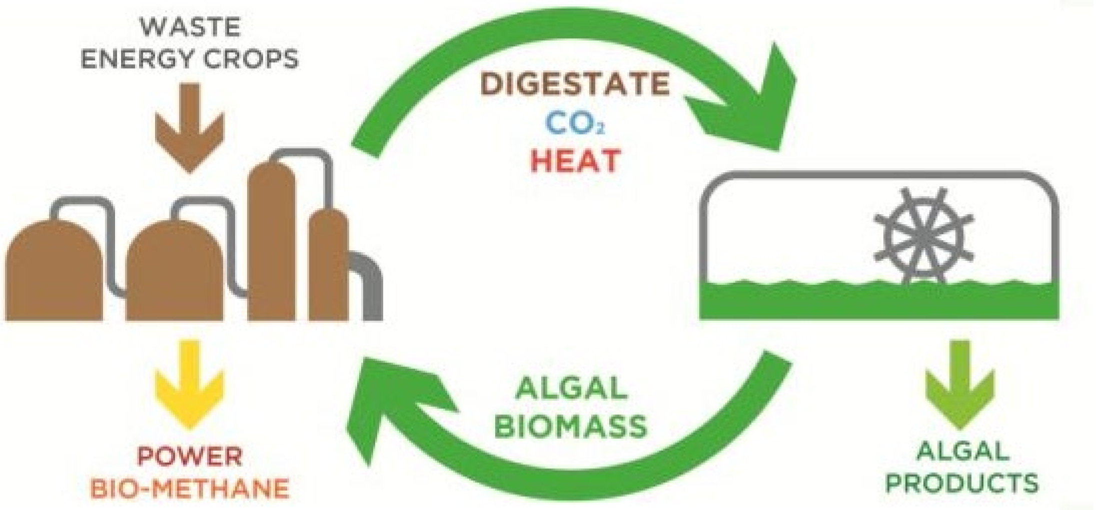


Figure 4 Lifecycle of Algal Product Production (AlgaeBioGas, 2017)

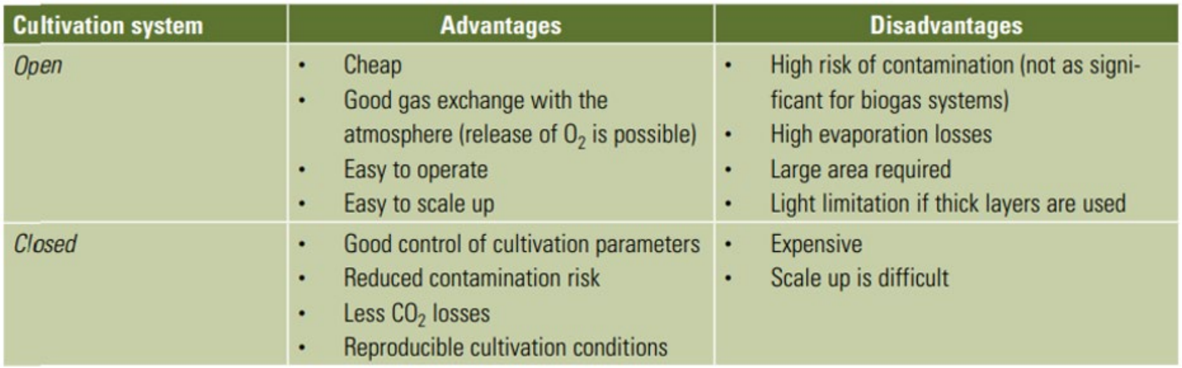
There are three major steps in leveraging microalgae. Cultivation, Harvesting, and Pre-Treatment. (AlgaeBioGas, 2017)

Cultivation: Microalgae cultivation can generally be broken down into indoor and outdoor systems, open and closed cultivation systems, and immobilized and free-floating species. Open systems (usually outdoor) are significantly cheaper, easier to build and manage, and much of their disadvantages (cross-contamination, etc) are not relevant for their application in generating biogas.

Harvesting: The key challenge with harvesting is that microalgaes are often dispersed in the water, very small, and only slightly denser than water. Separating the algae entirely from water is difficult and energy intensive. Pure microalgae cultures aren't necessary for biogas processing, so when used as a feedstock for biogas, retaining some of that water is less important, so harvesting can be done more economically. Several forms of harvesting have been developed including chemical, mechanical, electrical, and biological separation.

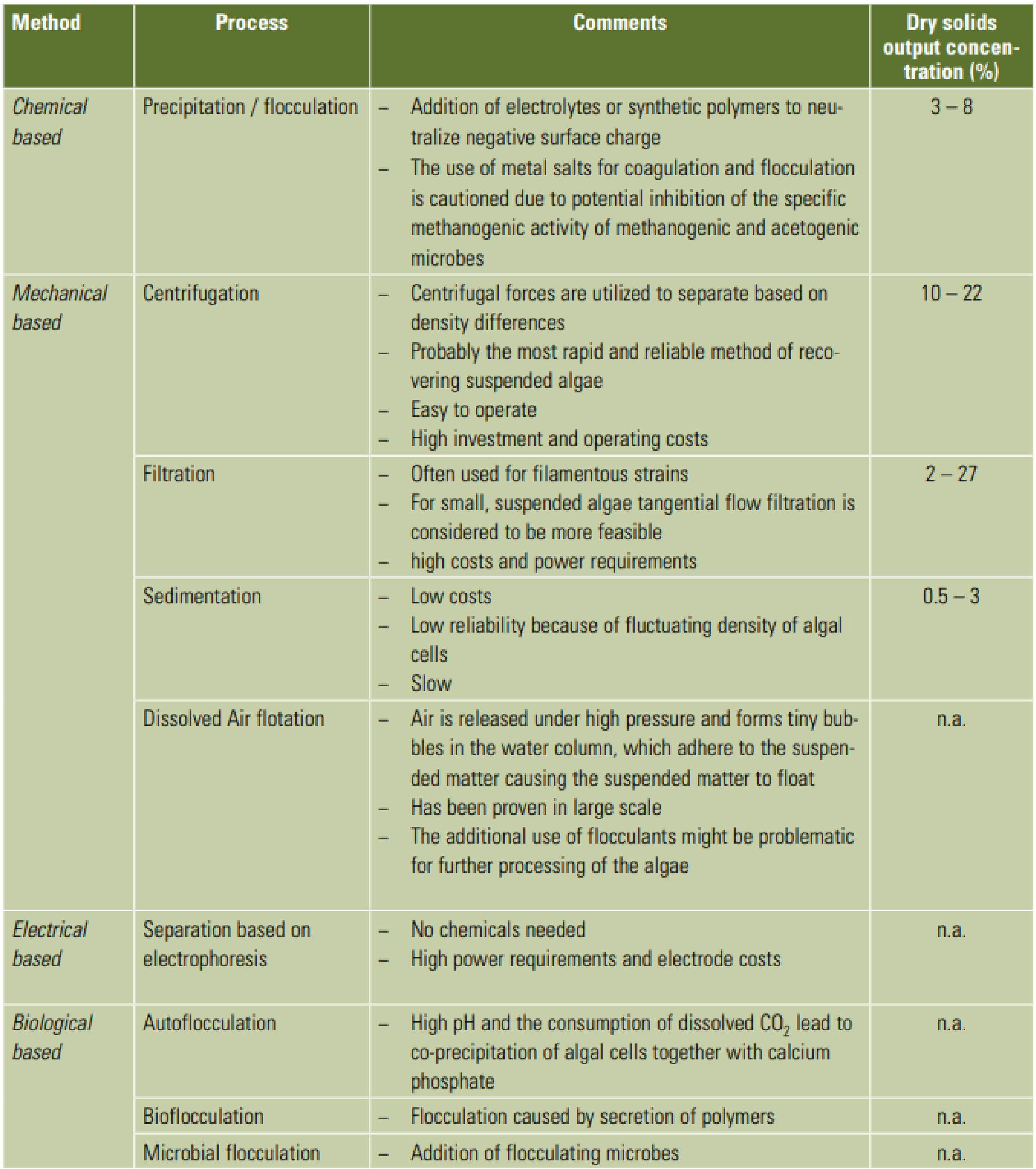
Pre-Treatment: There are some things that can be done once algae are harvested to make them better suited to anaerobic digestion. Productivity can vary widely based on species and cultivation – with a maximum Biomass yield of 13-15 g m^{-2} d^{-1} (Murphy, 2015). Some technologies such as thermal hydrolysis have been successfully applied to algae to increase that methane yield by up to 24%. However, pre-treatment is something of a double edge sword. If we are using more energy to generate more energy, the net energy benefit would have to be worth the cost and effort of the pre-treatment.

Table 3 Advantages and disadvantages of common cultivation systems (Murphy, 2015)



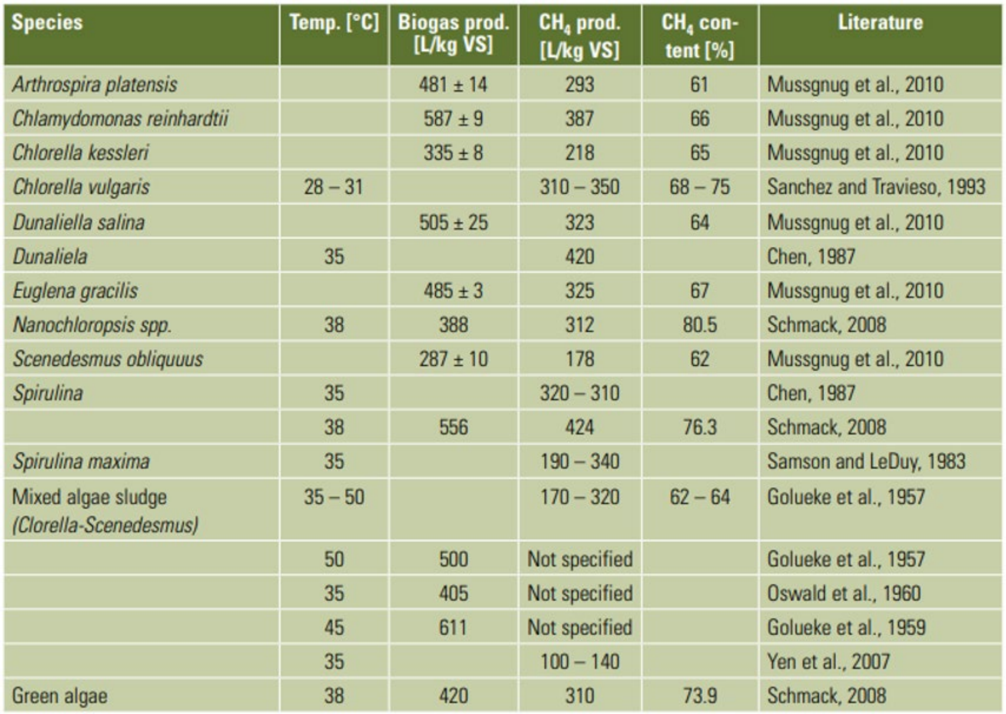
Cultivation system	Advantages	Disadvantages
Open	Cheap Good gas exchange with the atmosphere (release of O_2 is possible) Easy to operate Easy to scale up	High risk of contamination (not as significant for biogas systems) High evaporation losses Large area required Light limitation if thick layers are used
Closed	Good control of cultivation parameters Reduced contamination risk Less CO_2 losses Reproducible cultivation conditions	Expensive Scale up is difficult

Table 4 Methods and Processes of cultivation systems (Murphy, 2015)



Method	Process	Comments	Dry solids output concentration (%)
Chemical based	Precipitation / flocculation	– Addition of electrolytes or synthetic polymers to neutralize negative surface charge – The use of metal salts for coagulation and flocculation is cautioned due to potential inhibition of the specific methanogenic activity of methanogenic and acetogenic microbes	3 – 8
Mechanical based	Centrifugation	– Centrifugal forces are utilized to separate based on density differences – Probably the most rapid and reliable method of recovering suspended algae – Easy to operate – High investment and operating costs	10 – 22
	Filtration	– Often used for filamentous strains – For small, suspended algae tangential flow filtration is considered to be more feasible – high costs and power requirements	2 – 27
	Sedimentation	– Low costs – Low reliability because of fluctuating density of algal cells – Slow	0.5 – 3
	Dissolved Air flotation	– Air is released under high pressure and forms tiny bubbles in the water column, which adhere to the suspended matter causing the suspended matter to float – Has been proven in large scale – The additional use of flocculants might be problematic for further processing of the algae	n.a.
Electrical based	Separation based on electrophoresis	– No chemicals needed – High power requirements and electrode costs	n.a.
Biological based	Autoflocculation	– High pH and the consumption of dissolved CO_2 lead to co-precipitation of algal cells together with calcium phosphate	n.a.
	Bioflocculation	– Flocculation caused by secretion of polymers	n.a.
	Microbial flocculation	– Addition of flocculating microbes	n.a.

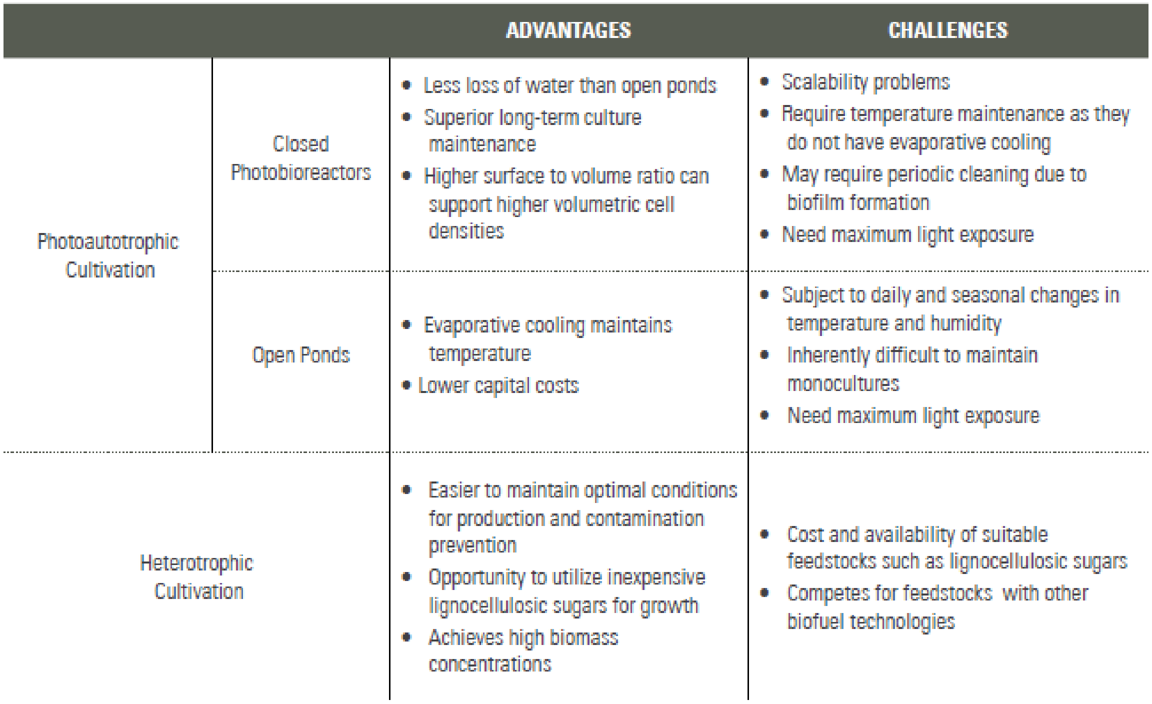
Table 5 Methane and biogas production from different microalgae species measured by BMP tests (Murphy, 2015)



Species	Temp. [°C]	Biogas prod. [L/kg VS]	CH_4 prod. [L/kg VS]	CH_4 content [%]	Literature
Arthrospira platensis		481 ± 14	293	61	Mussgnug et al., 2010
Chlamydomonas reinhardtii		587 ± 9	387	66	Mussgnug et al., 2010
Chlorella kessleri		335 ± 8	218	65	Mussgnug et al., 2010
Chlorella vulgaris	28 – 31		310 – 350	68 – 75	Sanchez and Travieso, 1993
Dunaliella salina		505 ± 25	323	64	Mussgnug et al., 2010
Dunaliela	35		420		Chen, 1987
Euglena gracilis		485 ± 3	325	67	Mussgnug et al., 2010
Nanochloropsis spp.	38	388	312	80.5	Schmack, 2008
Scenedesmus obliquuus		287 ± 10	178	62	Mussgnug et al., 2010
Spirulina	35		320 – 310		Chen, 1987
	38	556	424	76.3	Schmack, 2008
Spirulina maxima	35		190 – 340		Samson and LeDuy, 1983
Mixed algae sludge *(Clorella-Scenedesmus)*	35 – 50		170 – 320	62 – 64	Golueke et al., 1957
	50	500	Not specified		Golueke et al., 1957
	35	405	Not specified		Oswald et al., 1960
	45	611	Not specified		Golueke et al., 1959
	35		100 – 140		Yen et al., 2007
Green algae	38	420	310	73.9	Schmack, 2008

Cultivation of algae can either use solar energy (photoautotrophic) or bio-reactions using other Biomass (heterotrophic). It seems at this point that heterotrophic cultivation has been abandoned and research focuses on photoautotrophic cultivation.

Table 6 Advantages and Disadvantages of Photoautotrophic and Heterotrophic Cultivation (Ferrell & Sarisky-Reed, 2010)



		ADVANTAGES	CHALLENGES
Photoautotrophic Cultivation	Closed Photobioreactors	• Less loss of water than open ponds • Superior long-term culture maintenance • Higher surface to volume ratio can support higher volumetric cell densities	• Scalability problems • Require temperature maintenance as they do not have evaporative cooling • May require periodic cleaning due to biofilm formation • Need maximum light exposure
	Open Ponds	• Evaporative cooling maintains temperature • Lower capital costs	• Subject to daily and seasonal changes in temperature and humidity • Inherently difficult to maintain monocultures • Need maximum light exposure
Heterotrophic Cultivation		• Easier to maintain optimal conditions for production and contamination prevention • Opportunity to utilize inexpensive lignocellulosic sugars for growth • Achieves high biomass concentrations	• Cost and availability of suitable feedstocks such as lignocellulosic sugars • Competes for feedstocks with other biofuel technologies

Algae can be used to produce a broad range of bio-fuel through different thermochemical, biochemical or chemical processes:

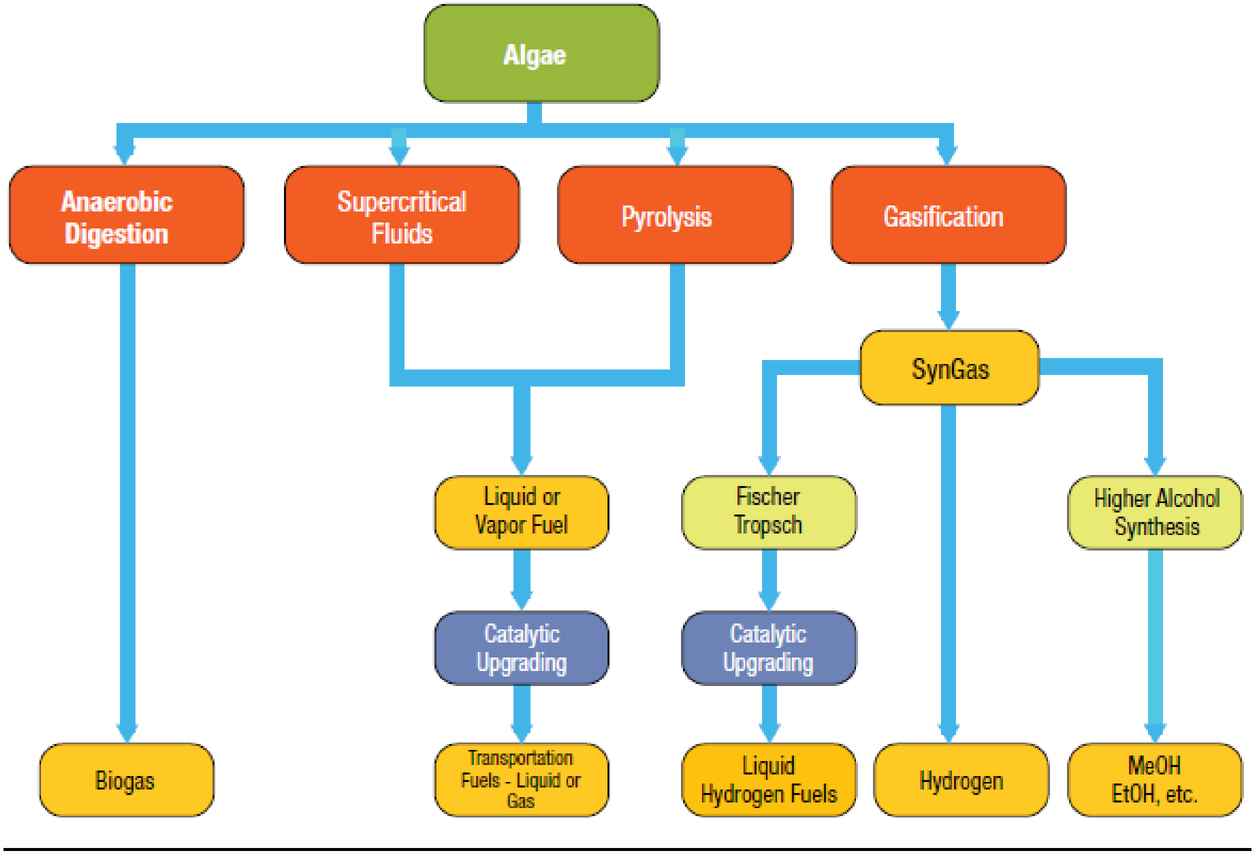


Figure 5 Pathways for Algae Use (Ferrell & Sarisky-Reed, 2010)

CHEAP MOBILE DENSIFICATION

The chief barrier to using more Biomass is densification. Densification offers several advantages to current practice. They include: improving the efficiency of transportation from the source of Biomass to where it will be consumed, molding feedstock into a uniform size and shape, improved energy density, and conformance to the specifications of destination technologies used to convert the feedstock into energy. Densification is most effective with lignocellulosic Biomass (woody Biomass) partially because lignin improves the process, the need for uniform and dry feedstock for gasification technologies, and also due to the distributed nature of much of the woody Biomass resource in California. Making this process cheaper, or more mobile is the next key hurdle.

Densification: The most common forms of densification are the pellet mill, the briquette press, and screw extruder.

As the name implies, the Pellet Mill takes in finely ground ingredients, and turns them into dense pellets. This technology is usually classified either as "ring die" or "flat die" and generally consists of a hard steel die with 1-2 rollers. By heating, softening, and spreading the feedstock over the rotating die and rollers, the Biomass is "forced through the perforations to form densified [material]" which are then cut off into pellets. (Tumuluru, 2011)

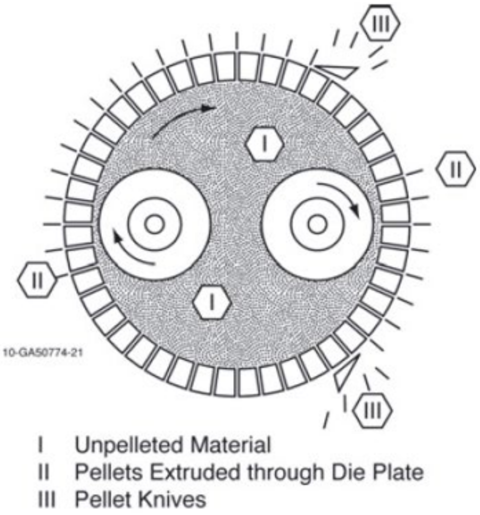


Figure 6 Working processes of a pellet mill die (Tumuluru, 2011)

Briquette Presses can handle larger feedstock particles and higher moisture. They generally work by creating steam under high pressure, hydrolyzing the material, then subjecting that material to high heat and pressure, which binds the particles together. Hydraulic Piston Presses can be used as briquetting machines (production at 50-400kg/hr, with higher moisture content >15%). The other alternative is the Mechanical Piston Press, which is often used for larger scale production as it is energy efficient, has a long operating life (production 200-2500 kg/hr) (Tumuluru, 2011).

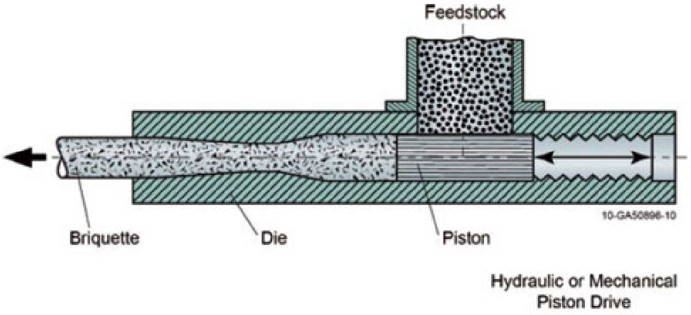


Figure 7 Mechanical or hydraulic piston press (Tumuluru, 2011)

Screw Extruders work in four stages: input Biomass, initial compression, final compression, and discharge. Generally, the Biomass is ground up so it can be fed into the extruder, where it is heated to 200+° C which helps bind the material together. During final compression, the material enters a tapered die at high temperature (again reducing moisture). After cooling small extruded log are produced, more ideally suited for burning or co-firing technologies.

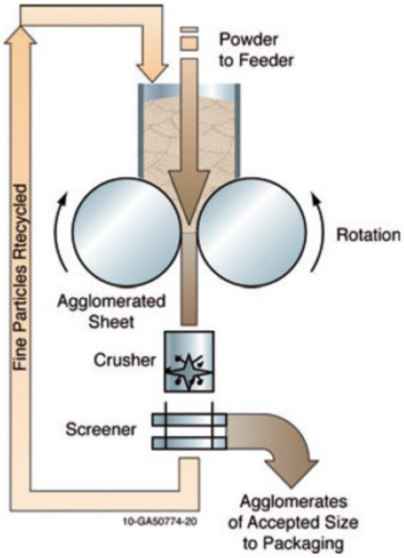


Figure 8 Roller press mill (Tumuluru, 2011)

Efficiency: Since this feedstock is the source of gas and therefore energy generation, how much energy the densification process *consumes* is important in the overall energy efficiency of biogas. That efficiency is affected by temperature and pressure used by the technology. It is also affected by the moisture content, particle size and distribution of feedstock, and biochemical composition like starches, proteins, fats, and other lignocellulosic components. Generally, extrusion requires more energy due to compression and pushing. Pellet mills are usually the most energy efficient.

Some elements of the technology might have more impact when improved than others. Pressure is a key input that determines the quality of the pellets or briquettes. Die geometry can influence desirable outcomes like moisture content, durability and density of the final product. All of these outcomes are dependent on the feedstock, and higher levels of protein and lignin are considered assets (often associated with woody Biomass).

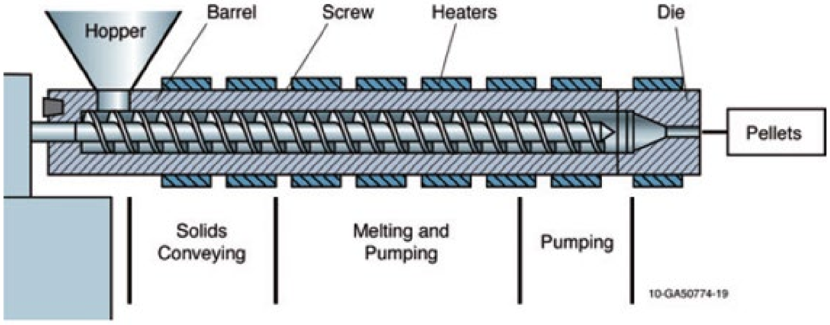


Figure 9 Extruder for Biomass or polymer processing (Tumuluru, 2011)

Cheap and Mobile: The technologies above are well established, but Biomass sourcing remains expensive because of its dispersion – these technologies need to be small enough to be portable while also running continuously and efficiently. Mobile pelleting plants exist today primarily for consumer home use application. However, in order to unlock the constraints around harvesting woody Biomass, this mobile technology must be cheaper to use in the field, accommodate a wide variety of Biomass, and process the Biomass at industrial speeds. Accomplishing this could unlock as-of-now technically and economically un-recoverable Biomass in California.

Real World Example: Pelleting in Europe is quite common and is used primarily for heating (64% of the market) and the remainder for power production (36%) (AEBIOM, 2018). Wood pellets are already being used in the production of renewable biogas through woody Biomass gasification. In Luxembourg, LuxEnergie opened its Kirchberg Power Plant in 2017 after retrofitting the plant to run on Biomass from natural gas (Luxembourg: Wood Gasification Plant Opened, 2017). The facility processes 2.5 tons of wood pellets to serve Kirchberg's district heating network. Luxembourg likely imports these pellets from Germany or Sweden (AEBIOM, 2018), and is only able to do so economically because of the energy dense nature of the Biomass pellets.

Summary (European Biomass Industry Association, 2018)

- An increased bulk density (from 80-150 kg/m^3 for straw or 200 kg/m^3 for sawdust to 600-700 kg/m^3 after densification), resulting in lower transportation costs, reduced storage volume and easier handling.
- A lower moisture content (humidity <10%), favoring a long conservation and minor losses of product during the storage period.
- An increased energy density and more homogeneous composition, resulting in better combustion control possibilities and thereby higher energy efficiency during combustion.

For more information:

- European Biomass Industry Association (European Biomass Industry Association, 2018)

PRE-TREATMENT BIOMASS

While densification is a form of pre-treatment, additional processing options such as Torrefaction, can offer other value-added advantages throughout the Biomass/biogas value chain. Pre-treatment of Biomass can improve chemical and physical elements of the Biomass to increase the heating value, the efficiency of energy conversion, or even make some currently unusable Biomass eligible for processing. This process that be applied to all types of Biomass, but is currently most applicable to Biomass that is intended for gasification, anaerobic digestion or for particularly challenging forms of Biomass (like rice straw).

Torrefaction: The most common form of pre-treatment, Torrefaction is the thermal process that converts Biomass into a more energy dense material similar to coal. Its greatest advantage is the ability to reduce the amount of water or biological activity in the Biomass.

It is commonly used in conjunction with palletization in woody Biomass and often offers similar advantages – in essence increasing the units of energy per truckload of Biomass, since the energy is what conversion technologies pay for. However, Torrefaction also offers other advantages besides energy density such as homogenous composition, hydrophobia, improved conversion efficiency due to grindability, and finally it also stops biological activity like rotting, which has applications for organic forms of Biomass.

Step 1

Receiving and storage

Wood chips are collected and stored so they can be used as biomass fuel.

Step 2

Drying

The wood chips are dried using a closed-loop belt dryer before undergoing torrefaction.

Step 3

Torrefaction

The wood chips are heated using microwave technology within a rotating drum reactor, creating a charcoal-like substance.

Step 4

Grinding and pelletizing

The torrefied wood is ground up and made into pellets that produce up to 10% more energy than untreated wood.

Figure 10 Steps for preparing Biomass (Word of the Day: Torrefaction, 2016)

Other Pre-Treatment Options: Torrefaction is just one of several options for pre-treating Biomass. Several others are listed below. However, their relevance to the eventual production and cost of generating biomethane is minimal.

- Pre-Heating
- Grinding
- Steam Explosion
- Torrefaction
- Ammonia Fiber Explosion
- Alkali Pre-treatment

Call out: Alkali Pre-Treatment

Water leaching, also called rain leaching, is an interesting process by which agricultural silage like rice straw (silage is the term for agricultural residual waste) is exposed to water which leaches potassium and chlorine and changes the properties of lignin and hemicelluloses from the Biomass. The result is a *dramatic* increase in the effectiveness of rice straw as a gasification or pyrolysis feedstock (Satlewal, 2017). In general, rice straw is underutilized as Biomass in the agricultural residues category in California and can be subject to open burning or other expensive disposal mechanisms. Cultivating this technology might expand the technically and economically recoverable amount of Biomass available for biogas production in California.

Rice is a staple food, and after sugar products is the highest produced agricultural commodity in the entire world. California is the second largest producer with 26% market share in the United States (Miller, Tapping the hidden value of farm waste, 2017). However, rice is arguably the most important agricultural product in Asia where its use as a source of Biomass or bio-oil has been studied extensively by local researchers especially in Korea, Indonesia, and Vietnam. MIT was recently profiled for its work developing a mobile torrefaction and pre-treatment technology to address agricultural residues in India primarily for rice. Some of these technologies, and global research have potential application in California and any progress in leveraging rice straw/silage for energy production could have a global impact (Miller, Mobile Torrefaction Technology that can Convert Biomass into Clean-Burning Fuel, 2017) (Jenkins, 1999).

Who are Experts in this field?

Experts specific to individual types of Biomass or Biomass technologies:

Table 7 Individual and Technology Specific Experts

Industry Experts	**Expert**	**Alternative**
California	Stephen Kaffka, UC Davis	Robert (Bob) Williams, UC Davis
	Bryan M Jenkins, UC Davis	Biomass Laboratory, UC Davis
United States	US DOE, Biomass Research and Development Board	
International	Germany, Denmark (Europe)	India
Types of Biomass		
Woody Biomass	G4 Insights	
Agricultural Residue	UC Davis, Bryan M. Jenkins	MIT, Ahmed Ghoniem and Kevin Kung, PhD student
Municipal Solid Waste	California Integrated Waste Management Board	Sierra Energy, Advanced Plasma Power (APP)
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)
Technologies		
Torrefaction	Michael Wild, International Biomass Torrefaction Council	US Endowment for Forestry and Communities
Pelleting	Jaya Shankar Tumuluru (Idaho National Laboratory) Daniela Thran, IEA Bioenergy	University of California, Division of Agriculture and Natural Resources, IEA Bioenergy

Key technologies to investigate and Timeline?

There are few immediate and critical R&D opportunities from the utility perspective in the improvement of Biomass sourcing. However, some potential projects might include:

1. Investigation of algae potential in conjunction with a wastewater treatment plant for use in a co-located anaerobic digester. This project might determine whether algaes can be used as an economic feedstock for anaerobic digestion to biogas.
2. Rain or Water leaching of rice silage might be worthwhile to make this a potential feedstock for co-digestion in an anaerobic digester or for Biomass in a gasification plant. Rice silage/straw is often *already* aggregated for processing of rice for food, so many of the challenges associated with aggregation would not exist in this feedstock.
3. If a cheap, mobile densification or pre-treatment technology became available, it would be worth looking into funding a project creating Biomass from woody Biomass that would otherwise be at risk for fire.

References

AEBIOM. (2018). *A Focus on the Pellet Market (EPC)*. Retrieved from AEBIOM: European Biomass Association: http://www.aebiom.org/16250-2/

AlgaeBioGas. (2017, September 13). *Algal Treatment of Biogas Digestate*. Retrieved from AlgaeBioGas: https://algaebiogas.eu/

Bioenergy Crops LTD. (n.d.). *Sustainable energy crops for biogas*. Retrieved from Bioenergy Crops: http://bioenergycrops.com/blog/2013/02/27/energy-crops-for-biogas/

Bolton, J. R. (2017, October 19). *The Maximum Efficiency of Photosynthesis.* Retrieved from ResearchGate: https://www.researchgate.net/publication/229939005_The_maximum_efficiency_of_photosynthesis

California Biomass Collaborative, University of California, Davis. (2015). *An Assessment of Biomass Resources in California.* California: California Energy Commission.

California Dairy Statistics Annual . (2017). *California Dairy Statistics Annual 2017 Data.* Retrieved from California Dairy Statistics Annual: https://www.cdfa.ca.gov/dairy/pdf/Annual/2017/2017_Statistics_Annual.pdf

European Biomass Industry Association. (2018). *Biomass pelleting.* Retrieved from Eubia: http://www.eubia.org/cms/wiki-Biomass/Biomass-pelleting/

Ferrell, J., & Sarisky-Reed, V. (2010). *National Algal Biofuels Technology Roadmap.* Maryland: U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Biomass Program. Retrieved from https://www1.eere.energy.gov/bioenergy/pdfs/algal_biofuels_roadmap.pdf

Herrmann, C. (2016, April). Biogas Crops Grown in Energy Crop Rotations: Linking Chemical Composition and Methane Production Characteristics. *Elsevier Bioresource Technology, 206*, 23-35.

Jenkins, B. (1999). *Combustion of Leached Rice Straw for Power Generation.* Davis, CA: Department of Biological and Agricultural Engineering.

Kaffka, S. (2014). *TASK 5: Biomass Energy in California's Future: Barriers, Opportunities, and Research Needs.* Davis, CA: UC Davis California Geothermal Energy Collaborative.

Liquefied Wood. (2011). Retrieved from http://projekti.gimvic.org/2011/2a/utekocinjen_les/zgradbalesa.html

Livealgae UK. (n.d.). *Rhodopeltis Sp.* Retrieved from Livealgae: https://www.livealgae.co.uk/macroalgae/red-macroalgae-species/rhodopeltis-sp-red-marine-macro-algae

Luxembourg: Wood Gasification Plant Opened. (2017, October 30). Retrieved from EndsWaste&Bioenergy: https://www.endswasteandbioenergy.com/article/1448689/luxembourg-wood-gasification-plant-opened

Miller, B. (2017, January 26). *Mobile Torrefaction Technology that can Convert Biomass into Clean-Burning Fuel*. Retrieved from Phys.org: https://phys.org/news/2017-01-mobile-torrefaction-technology-Biomass-clean-burning.html

Miller, B. (2017, January 25). *Tapping the hidden value of farm waste*. Retrieved from MIT News : http://news.mit.edu/2017/tapping-hidden-value-of-farm-waste-0125

Murphy, J. D. (2015). *A Perspective on Algal Biogas.* IEA Bioenergy. Retrieved from http://task37.ieabioenergy.com/files/daten-redaktion/download/Technical%20Brochures/AD_of_Algae_ebook_end.pdf

NORD University. (2018, January 24). *Future Food and Feed from Microalgae.* Retrieved from Arctic Frontiers: https://www.arcticfrontiers.com/wp-content/uploads/downloads/2018/Arctic%20Frontiers%20Science/Presentations/24%20January%202018/Aquaculture%20in%20the%20High%20North%20in%20times%20of%20change/1010%20Wijffels_Rene.pdf

Oldham, M. (2017, November 3). Energy Policy & Planning Analyst, Principal. (L. Finnegan, Interviewer)

PG&E Corporation. (2016, December 31). *CORPORATE RESPONSIBILITY AND SUSTAINABILITY REPORT 2017*. Retrieved from PG&E: http://www.pgecorp.com/corp_responsibility/reports/2017/bu01_pge_overview.html

Satlewal, A. (2017). *Rice Straw as a Feedstock for Biofuels: Availability, Recalcitrance, and Chemical Properties.* Knoxville, TN: Biofpr. Retrieved from https://www.researchgate.net/publication/320454952_Rice_straw_as_a_feedstock_for_biofuels_Availability_recalcitrance_and_chemical_properties_Rice_straw_as_a_feedstock_for_biofuels

The Oxford Institute for Energy Studies. (2017, June). *Biogas: A Significant Contribution to Decarbonising Gas Markets?* Retrieved from Oxford Energy: https://www.oxfordenergy.org/wpcms/wp-content/uploads/2017/06/Biogas-A-significant-contribution-to-decarbonising-gas-markets.pdf

Tumuluru, J. S. (2011). A Review of Biomass Densification Systems to Develop Uniform Feedstock Commodities for Bioenergy Application. *Biopfr*, 683-707.

University of Illinois at Urbana-Champaign. (2017, June 20). *Corn better used as food than biofuel, study finds*. Retrieved from ScienceDaily: https://www.sciencedaily.com/releases/2017/06/170620142918.htm

Williams, R. B. (2013). *An Assessment of Biomass Resources in California.* Davis, CA: California Biomass Collaborative. Retrieved from http://www.energy.ca.gov/2013publications/CEC-500-2013-052/CEC-500-2013-052.pdf

Wisconsin Biorefining Development Initiative. (n.d.). *Fermentation of Lignocellulosic Biomass* . Retrieved from Biomass Innovation: http://www.Biomasssinnovation.ca/pdf/fermlig.pdf

Word of the Day: Torrefaction. (2016, April 28). Retrieved from sunshine hours: https://sunshinehours.net/2016/04/28/word-of-the-day-torrefaction/

Zegada-Lizarazu, W., & Monti, A. (2011). Energy crops in rotation. A review. *Elsevier Biomass and Bioenergy, 35*(1), 12-25. Retrieved from https://www.sciencedirect.com/science/article/pii/S0961953410002588