Bioplastics in California

Economic Assessment of Market Conditions for PHA/PHB Bioplastics Produced from Waste Methane

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Executive Summary

In 2010, approximately 31 million tons of plastic waste was generated in the United States, which accounted for approximately 12.4 percent of total municipal solid waste in that year.[1] The environmental challenges associated with the production and disposal of conventional plastics are significant and substitution of such plastics with biobased alternatives may help mitigate some of these impacts.

Bioplastics, including biobased plastics (polymers made from renewable resources such as corn), have been introduced into the world market as an alternative to oil-based plastics. Although bioplastics currently represent a small proportion of aggregate plastic consumption worldwide, the market share of biobased polymers is increasing. According to some estimates, global bioplastic production was approximately 890,000 metric tons in 2012 and is forecasted to grow at a compound annual growth rate of 25 percent through 2017 reaching more than 2.5 million metric tons.[2]

In addition to existing production methods for manufacturing plastics from non-petroleum feedstocks, a new technology under development by Stanford University may provide yet another means of creating plastic products – from waste. This method would not rely on natural resources or food crops. Researchers at Stanford University have developed a process by which methane (CH_4), captured at solid waste landfills or wastewater treatment facilities (WWTFs), can be utilized as a feedstock to produce a polyhydroxybutyrate (PHB) polymer resin. The *Stanford Process*, if optimized at a commercial scale, has the potential to create a market in California for closed-loop plastic production made from waste. In this report we assess the market outlook for these plastics and the economic feasibility of a small-scale PHB production facility in the state, co-located at an existing waste treatment site.

The database and model developed for this study included 118 California solid waste landfills and 144 WWTFs. We find that of these, 49 landfills and 10 WWTFs already have, or could likely attain, sufficient methane capture to produce at least 1,000 metric tons of PHB polymer resin per year.

Certain characteristics of landfill and WWTF locations will be critical when assessing locations for the construction of a PHB production facility. The five most critical characteristics are:

- Facility size (measured in total waste in place or average dry weather flow for landfills and WWTFs, respectively).
- Current generation status (whether CH_4 is currently used for power production and if so, what percentage of total CH_4 available is used).
- Location and installed power transmission infrastructure.
- Current CH_4 capture and power generation contract status.
- Volume of excess CH_4 currently captured and flared.

Optimal sites are likely to be mid-sized facilities that may or may not currently capture CH_4, but do not generate electricity and thus are not subject to contractual agreements with local utilities for power generation. PHB resin production may offer an alternative means by which to utilize waste methane and turn it into a value-added product that can easily be transported, for facilities that have limited access to power transmission infrastructure,

We conducted an analysis to determine the economic viability of a 1,000 metric tons annually (kt p.a.) PHB production facility located at a California landfill or WWTF. The results of our model suggest that such a facility could be economically viable within a range of conditions. Using the baseline parameters explained in this report, we find that a production facility has a positive net present worth (NPW)[*] for any PHB resin price above $1.17/kg ($0.53/lb). This value is highly sensitive to our modeling assumptions and we have carried out a variety of sensitivity analyses in order to determine the degree to which our assumptions will affect the NPW of a facility.

Sensitivity analyses were performed to assess the impact of the following parameters on the project NPW:

- The Stanford estimated PHB yield and energy requirements.
- Energy procurement method and landfill gas (LFG) collection status.
- Equipment capital costs and annual operating and maintenance (O&M) costs (including labor).
- Polymer extraction and nutrient costs.
- PHB price.

Our model suggests that the greatest sensitivity lies in the costs associated with PHB price and the extraction process. Researchers at Stanford University are working to determine the most economically viable method of extraction; however, within the context of this modeling methodology, we can determine the effect of extraction costs on a dollars-per-unit PHB basis. With our baseline parameters, we find that if extraction costs are below $1.68/kg PHB the production facility may be economically viable.

Subject to process assumptions included in this report we find that implementation of such a PHB production facility could potentially be economically viable. However, this analysis should not be used in the absence of a rigorous site-specific engineering assessment, which would be required to determine a detailed cost estimate of a PHB production facility.

[*] Net present worth is the present value of the net cash flow for each year of the project summed over the project lifetime. This calculation is sensitive to the selected discount rate. Discount rate definition and assumptions in the model created for this report are discussed below.

Abbreviations and Acronyms

ABS	Acrylonitrile Butadiene Styrene
ADM	Archer Daniels Midland
cfm	Cubic feet per minute
CH_4	Methane
DOE	United States Department of Energy
EPA	United States Environmental Protection Agency
FTC	Federal Trade Commission
HDPE	High-density polyethylene
LDPE	Low-density polyethylene
LFG	Landfill gas
MSW	Municipal Solid Waste
Mt	Million metric tons
NIR	Near infrared
NPW	Net present worth
PE	Polyethylene
PET	Polyethylene terephthalate
PHA	Polyhydroxyalkanoates
PHB	Polyhydroxybutyrate
PLA	Polylactic Acid
PP	Polypropylene
PS	Polystyrene
USDA	United States Department of Agriculture
WWTF	Wastewater Treatment Facility

Introduction

Report outline and scope

This report focuses on the opportunities for bioplastic[†] market growth in California. In particular, we will discuss the potential for establishing a small-scale bioplastic resin production facility produced from a waste methane feedstock, which is present at California's many wastewater treatment facilities (WWTFs) and solid waste landfill facilities. The report is divided into three sections. Section 1 is a market review of bioplastic resins, producers, product categories, and production cost factors. It also includes a discussion of the barriers and opportunities faced by the bioplastics industry. Section 2 introduces the waste methane-to-PHB process and offers an assessment of the production potential for California WWTFs and landfills. Finally, Section 3 offers an economic feasibility model for a small-scale PHB production facility co-located with a methane source and description of the methodology, assumptions, results, and sensitivity analyses employed. It should be noted that estimates in this report indicate the authors' best estimates given current data available for the purposes of this generalized analysis. Before undertaking the installation of methane capture systems at landfills or WWTFs, it would be necessary to consult a gas capture engineering specialist in order to perform a more detailed assessment of the particular site conditions, cost considerations, and methane capture potential.

Background on plastic production and disposal

Production and consumption of conventional polymers has grown rapidly in recent decades. According to a recent estimate, more than 75 billion pounds of plastics are produced every year globally. The worldwide annual growth rate of plastic production averaged 5.9 percent from 1971 to 2006, reaching 245 million metric tons (Mt) by the end of this period.[3] This is much higher than the growth rate of 0.7 percent for all bulk materials from 1971 to 2004.[4]

From disposable goods such as water bottles and product packaging to durable goods such as electronics housing, plastics are a staple in the day-to-day life of people around the world. Large-scale adoption of plastics has offered significant benefits to consumers by providing a wide array of low-cost goods and has yielded global economic benefits through the establishment of new industries.

However, the benefits derived from so many plastic products also come at a cost. Petroleum-based plastics account for a significant amount of the raw materials used to produce consumer products worldwide. Daily use and disposal of plastics is of particular concern in the U.S., where per capita plastic consumption is approximately 80 kg (176 lbs) per year, compared to the

[†] There is no universally accepted definition of "bioplastic." However, bioplastic resins generally are either bio-based (sourced from renewable materials) or degradable (capable of degrading reasonably quickly in a natural environment), or both. A full discussion of the technical issues surrounding these terms is beyond the scope of this report.

European average of 60 kg (132.3 lbs) per year. In addition, a large portion of plastic products find their way into waterways and oceans. Perhaps the most conspicuous example, known as the “Great Pacific Garbage Patch,” is an area of the Pacific Ocean that includes thousands of square miles and contains high concentrations of plastic materials. [5]

In 2011, 32 million tons of plastic wastes were generated in the United States. The U.S. Environmental Protection Agency (EPA) estimates that plastics account for more than 12 percent of the municipal solid waste stream winding up in landfills (rising from less than 1 percent in 1960).[6] Of this, almost 14 million tons were in the form of containers and packaging, nearly 11 million tons were durable goods, and the rest were nondurable goods such as plates and cups.[7] In other words, the U.S. throws away about 22 billion pounds of plastic packaging each year, which amounts to 66 million pounds per day.[8]

Though many plastic products can be collected and recycled, infrastructure and consumer access varies across the country. The overall recycling rate of plastics in the U.S. is estimated at 8 percent; however, some plastics are recycled at much higher rates than others.[9] For example, the EPA reports that in 2011, 29 percent of HDPE bottles and 29 percent of PET bottles and jars were recycled.[10] In 2011, the recycling rate for PET beverage containers subject to the California redemption program was 67 percent.[11]

This report focuses on the potential adoption of a new process under continuing development by researchers at Stanford University, which we will refer to as the *Stanford Process*. This process uses waste methane produced by the biodegradation of organic materials in solid waste landfills and wastewater treatment facilities to produce PHB bioplastic resin. One advantage of this type of process is that the feedstock is a waste product rather than a non-renewable oil resource or a high-value food crop. Another promising aspect of the PHB biopolymer is that it can be broken down to its methane constituent and recycled. We will discuss the Stanford Process and its potential deployment in California in more detail in Sections 2 and 3, following a discussion of the current state of affairs surrounding bioplastics in Section 1.

Section 1: Bioplastics Market Review

Bioplastic categories

Commercial bioplastics can be produced from a variety of sources including corn, potatoes and bacteria. Table 1 provides a brief overview of bioplastic categories and the production methods used to create them.

Table 1 - Categories of Bioplastics

Bioplastic Type	Polymer Type	Production Method
Polyhydroxyalkanoates (PHA)	Polyester	Direct production of PHA by fermentation
Polylactide (PLA)	Polyester	Biobased monomer (lactide) by fermentation, followed by polymerization
Starch Plastics	Polysaccharides	Partially fermented starch; Thermoplastic starch (TPS); Chemically modified starch blends; Starch composites
Cellulose Polymers	Polysaccharides	Organic cellulose esters; Regenerated cellulose
Polytrimethylene Terepthalate (PTT)	Polyester	Biobased 1,3-propanediol (1,3-PDO) by fermentation plus petrochemical terephthalic acid (or DMT)
Polyamides (PA)	Polyamide	Biobased monomer 11-aminoundecanoic acid from castor oil or fermentation of acid
Polyethylene (PE)	Polyolefin	Biobased monomer ethylene obtained from ethanol; ethanol is produced by fermentation of sugar.
Polyvinylchloride (PVC)	Polyvinyls	Monomer vinyl chloride can be obtained from biobased ethylene (from ethanol).
Polyurethanes (PUR)	Polyurethanes	React polyol with isocyanate. Biobased polyol can be produced from vegetable oils.
Thermosets	Cross-linked Polymers	Condensation polymerization of polyols, organic acids and fatty acids or triglyceride oils.

Source: Shen (2009)[12]

Selected bioplastic resins and applications

Some of the most innovative plastics research in recent years has been bioplastic synthesis via microbial fermentation of polysaccharides. These efforts have resulted in the development of polylactic acid or polylactide (PLA, produced in the U.S. by NatureWorks) and polyhydroxyalkanoates (PHAs, until recently produced in the U.S. primarily by Metabolix).

PLA

PLA is a compostable, thermoplastic polyester derived from lactic acid. This lactic acid source of PLA is itself produced from the fermentation of agricultural byproducts such as cornstarch or other starch-rich substances like maize, sugarcane or wheat. PLA can be produced in a high-molecular-weight form through ring-opening polymerization of lactide using a (stannous octoate) catalyst. The resulting thermoplastic film material offers good moisture-barrier properties and is able to withstand the rigors of injection molding and blow- or vacuum-forming processes.

PLA is currently utilized in the production of loose-fill packaging, food packaging, beverage containers, and disposable foodservice tableware items.[13] PLA can also be used for products such as plant pots and disposable napkins. It has been commercially available since 1990, and certain blends have proven successful in medical implants, sutures, and drug delivery systems because of their capacity to dissolve away over time (this is also true of most PHAs). However, even though PLA plastics are generally less expensive to produce than PHAs, they are still significantly more expensive than conventional plastics like PET and have thus far failed to win widespread consumer acceptance.[14]

Polyhydroxyalkanoates (PHAs)

PHAs have gained major importance due to their structural diversity and structural similarities to traditional plastics. PHAs are potentially non-toxic, biocompatible, biodegradable thermoplastics that can be produced from renewable resources. PHAs are often degraded upon exposure to soil, compost, or marine sediment. However, there is some uncertainty about these properties. The rate of biodegradation of PHAs is dependent on factors such as exposed surface area, moisture, temperature, pH and molecular weight.[15] Initially PHAs were used in packaging films, mainly in bags, containers and coatings. More recently, other applications such as pharmaceuticals, razor handles, bottles and cups have utilized the material.[16] PHAs are estimated to cost at least $1.50 per pound to produce.[17]

The family of PHA polymers, including polyhydroxybutyrate (PHB) and PHB-related copolymers, is very versatile and thus presents significant opportunities for marketability. A wide range of properties can be achieved through the manipulation of their crystallinity which can make the resins suitable for both rigid and flexible plastics.[18] One of the primary benefits of PHA polymers is that their properties are such that it is not only suitable for injection molding, but it can be processed in conventional injection molding equipment.[19] Unlike some other bioplastics, PHAs are biodegradable and will biodegrade in a marine environment under certain conditions. One study found, depending on the conditions, they may degrade in 45 days to eight weeks.[20]

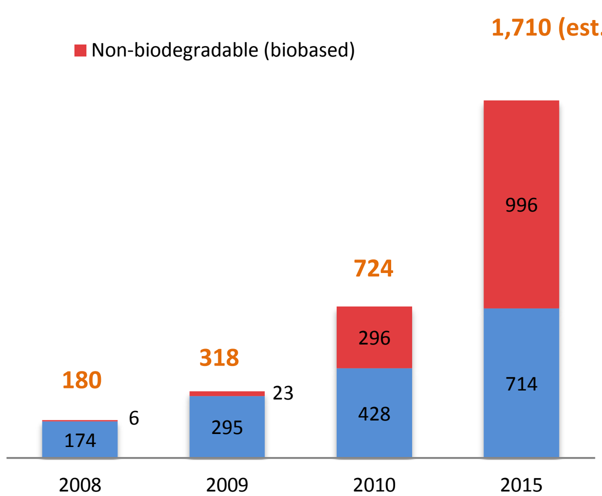
If properly managed, substitution of conventional petroleum-based plastics with biobased alternatives potentially offers significant environmental benefits. Some studies estimate that cradle-to-cradle life cycles for bioplastics such as PHB will range from one to 10 years, which would be a substantial benefit when compared with conventional plastics created from fossil feedstocks.[21]

World demand

Worldwide bioplastics demand has grown tremendously over the past several years, albeit still representing a small fraction of global plastics demand. As of 2007 it was estimated that worldwide production of bioplastics amounted to approximately 360,000 metric tons (890,000 metric tons by 2012) and was projected to reach 1.5 to 4.4 million metric tons (Mt) by 2020.[22]

Another report by the European Bioplastics Association determined global bioplastic production reached 725,000 metric tons in 2010 and forecast production of 1.7 million metric tons by 2015.[23] The Society of the Plastics Industry (SPI) Bioplastics Council estimates the bioplastics industry will grow more than 20 percent annually through 2015.[24] The expected trend of global bioplastic production capacity to 2015 is depicted below in Figure 1.

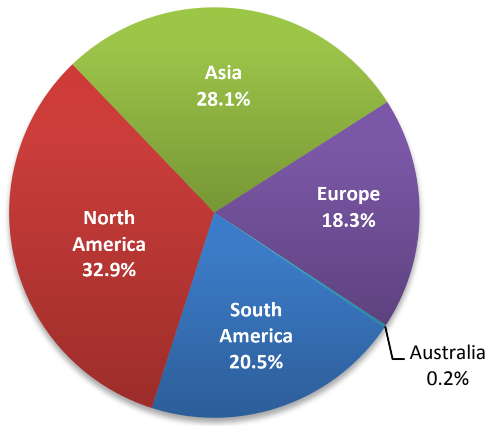
Figure 1 - Worldwide Bioplastic Production Capacity
Thousands of metric tons



Source: Darby (2012)[25]

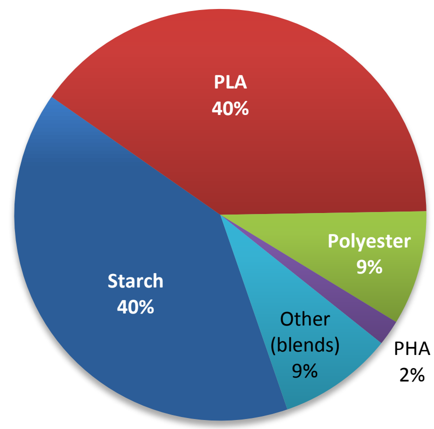
Figure 2 below illustrates the shares of global bioplastic production on a regional basis, while Figure 3 displays the shares of global demand accounted for by resin type.

Figure 2 - Worldwide Bioplastic Production Capacity by Region



Source: Darby (2012)[26]

Figure 3 - Worldwide Bioplastic Demand by Resin Type



Source: Darby (2012)[27]

The dominant market for bioplastics traditionally has been Europe, where organics are increasingly being diverted from landfills to compost facilities.[28] In fact, recent European forecasts predict 30 percent per year growth in the industry there.[29] In comparison, the United States has much more limited composting infrastructure, thus such diversion of organics is more problematic. Regardless of the slower overall growth of bioplastics in North America, the Freedonia Group reported in its World Bioplastics Report, released in November 2011, that North American demand for bioplastics will reach 267,000 metric tons by 2015.[30]

Despite the lag behind Europe, one study identified four areas of demand for bioplastics as having significant growth potential in the U.S. in the near future:

- Compostable single use bags and films.
- Fibers (degradable and non-degradable).
- Plastic foam cushioning blocks.
- Bioplastic molded products (degradable and non-degradable). [31]

Moreover, bioplastics maintain some key advantages. For example, the biocompatibility and absorbability in human tissue characteristic of certain bioplastics, enables these products to be suitable in the medical field for applications such as tissue engineering, wound healing, cardiovascular uses, orthopedics, and drug delivery. In fact, PHA sutures, artificial esophagi and artificial blood vessels are already offered as commercial products.[32 33]

The increasing demand for bioplastics translates into growing economic value for U.S. manufacturers. Table 2 below indicates biobased polymer production value in the U.S. by product category.

Table 2 - Biobased polymer production in the U.S. (2006)

Product	Value (Billion $)	Volume
Pharmaceutical Products	11.3	--
Plastic Coatings	19.5	1.6 Billion Gallons
Plastic Films	17.8	--
Plastic Containers	12.2	14 Billion Pounds

Source: USDA (2006)[34]

Price and performance are the largest influencing factors in driving market growth of bioplastics in the U.S. A study by Bohlmann expects major expansion in the bioplastics market as production costs continue to decrease, noting volatility in feedstock prices for both petroleum-based and food crop-based resins make future production costs somewhat uncertain.[35] Avoiding reliance on sometimes-volatile feedstock prices is another reason processes which utilize waste as inputs are appealing. For all processes, Bohlmann notes that improved coordination between stages of production is causing increases in efficiency and lowering costs of distribution.

Bioplastic producers

Many bioplastic production plants are small compared to production facilities of conventional, petroleum-based plastics. For example, China's TianAn PHA plant has a capacity of approximately 2,000 metric tons per year —quite small by traditional standards. However, as bioplastics gain traction in various end-use sectors, a handful of producers have emerged as leaders in biopolymer production worldwide. Notable producers with a North American presence include NatureWorks, Braskem, and Metabolix.[36] [37] [38]

NatureWorks

NatureWorks LLC began in 1989 as a Cargill research project focused on production of sustainable plastics using carbohydrates from plants. NatureWorks is now an independent company that is invested in by Cargill and PTT Global Chemical, which recently invested $150 million in NatureWorks.[39]

NatureWorks operates the world's largest bioplastics facility in Blair, Neb., which produces PLA at a capacity of 350 million pounds per year. Its primary product, Ingeo™ PLA resin, is used in apparel, bottles, cards, durable goods, films, fresh food packaging, polymers, polymer additives, adhesives, and coatings. The company grew more than 20 percent in 2011, both in sales dollars and volume in pounds.[40] The Blair plant is expected to be at full output by 2015. Within the same year, NatureWorks plans to open another facility with a capacity of 300 million pounds a year in Rayong, Thailand.[41]

Metabolix recently licensed a patent covering production of PLA blended with polybutylene succinic (PBS) polymers and similar materials to NatureWorks. It will use the Metabolix license to make materials through AmberWorks, a joint venture it formed recently with biochemical firm BioAmber Inc. of Montreal.[42] The benefits of blending these different resins include a product that will "exceed PLA in flexibility, toughness, and heat resistance—resembling polypropylene (PP) and polyethylene (PE), while PLA is more like PS or PET."[43] This new product will allow NatureWorks to explore new markets and further diversify the use of its resins. Dr. Marc Verbruggen, company president and CEO, said, "When you combine PLA with other resins, you can broaden the properties of the resin and broaden your product portfolio. It is the best way to get into broader categories."[44]

Metabolix

Metabolix, Inc. is a bioscience company founded in 1992. Its primary focus is designing sustainable alternatives to plastics and chemicals. In 2006, Metabolix and Archer Daniel Midland (ADM) formed a joint venture called Telles. ADM used its corn processing complex to produce Telles' signature product, Mirel™, which belongs to the PHA family of biopolymers. The production process utilizes plant derived sugars to produce "Mirel" plastic. Metabolix targets five areas of demand for selling its products: compost bag producers; marine and aquatic companies; consumer product manufacturers; business equipment producers; and packaging companies. Metabolix CEO Richard Eno estimated these segments comprise more than 2 billion pounds of demand for their product.[45]

With ADM, Metabolix became the largest PHA producer in the U.S.[46] The $300 million Telles production facility in Clinton, Iowa was ramping up to produce 50,000 metric tons per year. However, in January, 2012 ADM announced it would exit the joint venture. Mark Bemis, president of the corn sector at ADM, stated, "The fermentation technology performed well at our facility. Unfortunately, uncertainty around projected capital and production costs, combined with the rate of market adoption, led to projected financial returns for ADM that are too uncertain.''[47]

Metabolix shares plummeted 54 percent, to $2.74 per share shortly after this news was released.[48] ADM has taken ownership of the 110 million pound per year facility, which opened in 2010. Metabolix began actively searching for a new facility to produce Mirel, ending its search in July, 2012 when it signed a letter of intent with Antibióticos SA to manufacture Mirel at an Antibióticos plant in Leon, Spain.[49]

Metabolix has struggled financially, losing nearly $40 million in 2011, with gross revenue of less than $1.5 million. Almost two-thirds of the firm's revenue came from grants in 2011.[50] In order to recover, CEO Rick Eno said, "The company will soon relaunch with a more profitable business model, smaller-scale manufacturing facility, and an expanded product slate integrating biopolymers and biobased chemicals."[51]

The termination of the agreement with ADM allowed Metabolix to open discussion with alternative manufacturing and commercialization partners for PHA bioplastics.[52] These new partnerships grant the ability to integrate PHA polymers and biobased chemicals into downstream processing.[53] But one analyst noted, "Developing applications and markets for a new-to-the-world resin like PHA is a lengthy process, and the investment is difficult to justify on strictly financial grounds."[54] For this reason, the future of Metabolix may rest in its renewable C4 chemicals agreement with CJ CheilJedang, a global food and biotechnology company.

Braskem

Braskem was created in 2002 in a merger among six Brazilian companies. The company has 35 factories—28 located in Brazil and five in the United States. In total, the factories produce 16 million metric tons of thermoplastic resins and other chemical products annually.[55] One major customer of Braskem is Coca-Cola, which uses the company's biobased resin for its PlantBottle™ packaging.

The biopolymer that Braskem has specialized in producing is Green Polyethylene (PE). Its feedstock is ethanol made from sugarcane grown in Brazil. Braskem claims that for every ton of its Green PE that is produced, 2.5 tons of CO_2 are removed from the atmosphere.[56] The first Green PE plant located in Brazil has a capacity of 440 million pounds and it is already operating at more than half of its capacity. The firm is considering a second plant there, as well.[57]

"Bioplastics originally were different polymers from those of the traditional market, demanding investments and adjustments in the plastic supply chain," said Rodrigo Belloli, marketing and market intelligence manager for renewable chemicals at Braskem.[58] However, renewable PE is a drop-in polymer, which means it can replace traditional PE without additional investment or equipment adjustment from plastic customers.[59]

While São Paulo-based Braskem has had much success, the company has felt the impact of the global financial crisis on its bottom line.[60] Two new ethanol-based plastics plants in Brazil and a naphtha-based polypropylene plant originally planned for 2012 have been delayed until 2013, due to a global slowdown for the petrochemical industry.[61]

Other bioplastic producers

In the U.S., Meridian, Inc. produces a PHA bioplastic from plant-based oils (fatty acids) which are metabolized by bacteria in a fermentation tank. End uses for the resins include films, non-woven fabrics, and food-contact packaging. The company's facility, located in Bainbridge, Ga, produces 15,000 tons of PHA per year. When built to full capacity, it will be able produce more than 300,000 tons of PHA per year.[62]

Mango Materials, a Redwood City, Ca. startup company founded in 2010, is developing a PHB bioplastic using technology based on intellectual property licensed from Stanford University. The company seeks to convert waste methane from landfills and wastewater treatment facilities into plastic by feeding the gas to methane-eating bacteria, known as methanotrophs, which metabolize it through fermentation into PHB. The PHB is then extracted from the cell biomass and converted to bioplastic pellets, ready to be made into a plastic product. As of this writing, Mango Materials is producing only research-grade materials and hopes to have trial samples within the next year.[63]

Newlight is another California company producing bioplastics in the PHA family, using carbon dioxide and methane sourced from wastewater treatment facilities, landfills, anaerobic digesters, and energy-generating facilities. Based in Irvine and in operation since 2003, Newlight uses a proprietary biocatalyst derived from microbes, rather than fermentation, to convert the gases into plastic. Newlight added new production capacity in late 2012 that will enable it to produce more than 100,000 pounds per year of gas-to-plastic material.[64]

Micromidas, a startup established in 2008 in West Sacramento, originally focused on developing a PHA bioplastic using wastewater sludge as the feedstock. However, the company changed course in 2010 to develop a chemocatalytic process to produce paraxylene, a building-block chemical for PET. The process uses cellulosic biomass such as corrugated cardboard and rice hulls as feedstock.[65] Micromidas recently received additional funding to build a pilot-scale plant, which it hopes to have operational in 2014.[66]

A number of companies in Europe and Asia are increasing bioplastic production as well. For example, in Italy, Novamont is working with Coldiretti (an Italian association of farmers) to build a biorefinery at Terni. When at full capacity, the Terni biorefinery will produce 60,000 tons per year of compostable bioplastics.[67] Increasingly, bioproduct producers are setting up joint ventures with agricultural companies in order to secure low cost inputs to production.[68] This is important because of the quantities of food crops needed to produce significant quantities of bioproducts.

There are several bioplastic producers in Asia, although less information about them is available. Japan’s Showa Highpolymer and Korea’s SK Chemicals both have small plants producing different types of polyesters. These resins are marketed in the U.S. under the trade name Bionelle.[69] The Dutch chemical company DSM announced a plan to invest in a PHA plant together with a Chinese biobased plastics company—Tianjin Green Bio-Science Co. The company is now producing PHA resin with an annual capacity of 10,000 metric tons.[70] The Japanese company Kaneka planned to produce 50,000 metric tons annually of PHB in 2010.[71]

Bioplastics as viable alternatives to conventional plastics

As more companies seek to be perceived as environmentally conscious, or “green,” the use of bioplastics may bolster the corporate image of companies that use them. However, a major impediment to the greater adoption of bioplastic is the cost premium. One significant cost component in the production of biobased alternatives to conventional plastics is the cultivating, harvesting, and transporting of feedstocks such as corn in order to enter the production cycle.

In addition, the lack of widespread ability for bioplastic products to enter conventional recycling streams (with potential impacts to recycled-content products and machinery) has thus far prevented a major shift toward biobased or degradable plastics.

Bioplastics generally and PHAs in particular offer significant potential for the replacement of conventional plastics in a wide variety of applications and product sectors. Many bioplastics perform comparably (or even superior) to conventional plastics. Bioplastics are now present in many industries and are replacing conventional plastics in many use sectors. Use of waste methane may offer the significant advantage of a low-cost feedstock for the production of bioplastics.[72]

Bioplastic packaging applications

Packaging is one of the fastest growing sectors for bioplastic consumption. Growing at a rate faster than the aggregate bioplastics market, packaging accounts for more than 25 percent of bioplastic production.[73] Bioplastic packaging consumption was estimated to be 125,000 metric tons in 2010 with an estimated market value of $454 million.[74] It is forecast that PHA and bio-derived polyethylene (PE) will make up a large share of bioplastic resins used in the packaging industry. The two together will account for more than 25 percent of bioplastic packaging consumption by 2020, according to one estimate.[75]

Despite this predicted growth, the market for PHA packaging is still very small and the market remains dominated by conventional plastics. Strong growth in this sector is expected as new capacity comes online; however, the degree to which PHAs are adopted will depend largely on pricing.[76] Despite relatively rapid growth PHAs still represent a small proportion of the bioplastic packaging market, accounting for an estimated 1.4 percent of total tonnage in 2010.[77] PLA represents the largest share of this market, accounting for approximately 42.5 percent of bioplastic packaging in the same year.[78]

Analysts expect the global bioplastic packaging market to grow from an estimated 125,000 metric tons in 2010 to approximately 884,000 metric tons by 2020.[79] Market research firm Pira International forecasts a 41 percent growth in demand for PHAs over this ten-year period.[80]

Besides single-use applications, producers of PHA also may be able to aim at products that require more durability.[81] For example, commercially available PHA can be used for injection molding, extrusion, and paper coating. The injection molded and/or extruded PHA products cover a wide range of applications, such as cutlery, packaging (bags, boxes and foams), agriculture mulch films, personal care (razor and tooth brush handles), office supplies (pens), golf tees, and toys. PHAs can also be extruded into fibers. For instance, the company Biocycle offers PHA fibers that can be used for automobile carpets, dental floss and cigarette filters; Green Bio offers PHA fibers that can be used in non-woven applications.[82]

Bioplastic products on the market today

There are several recent examples of large-scale substitution of conventional plastics with bioplastic alternatives. For instance, Stonyfield Farms replaced its conventional polystyrene (PS) yogurt containers with PLA plastic. This change reportedly allowed a 26 percent thickness reduction while providing greater strength, improved lid adhesion, and less breakage relative to the previous PS cups.[83] Target's in-house brand, Archer Farms, has also incorporated NatureWorks' Ingeo biopolymer in its snack packaging.[84] In addition, NatureWorks created the first iPhone covers manufactured entirely using plant-based material, using its IngeoT biopolymer.[85]

Coca-Cola has also incorporated biopolymers in certain plastic bottles. The PlantBottle™ is composed of 30 percent biobased PET and also is able to enter conventional recycling streams, unlike most other 100 percent biobased polymers. Coca-Cola Co. has stated a goal of producing PlantBottles™ that are composed of 100 percent biobased PET. [86]

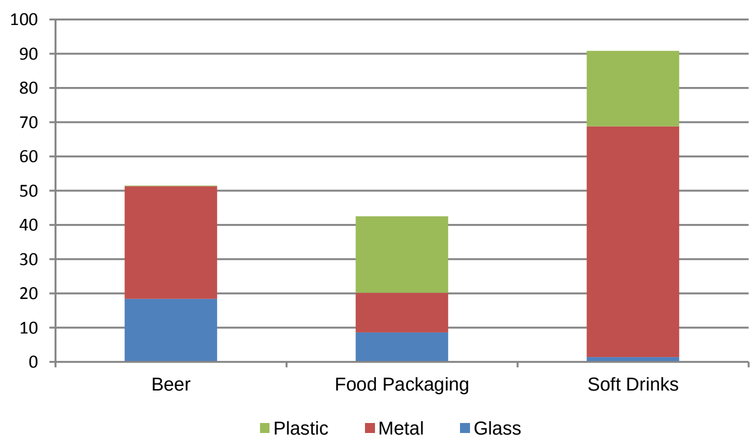
The greatest opportunity for substitution of conventional plastics by PHA in particular includes replacing polyvinyl chloride (PVC), high-density polyethylene (HDPE), low-density polyethylene (LDPE) and polypropylene (PP) resins.[87] Injection molding grade Mirel PHA can be processed on existing equipment built for conventional plastics, thus making a switch to bioplastics less costly for manufacturers. It is suitable for a variety of products, including durable goods such as electronic components, and has a cycle time similar to traditional plastics.[88]

Another possible area of demand is plastic bags. In the U.S., the plastic bag market has been estimated to be 68 million metric tons in 2007. According to a report by Mel Schlechter (2007), one of the biodegradable products of most interest in the U.S. is bags used for compostable materials (i.e. yard waste).[89] With increasing composting activities, the cost of degradable bags is expected to decrease but it is not known what composting volume is needed to make this a viable economic choice.

Potential markets for PHA-based products

The U.S. beverage sector plays a highly significant role in the container market. Much of this demand comes from soft drinks (Figure 4). Beer, the other major product in beverage containers in the U.S., is much more commonly packaged in metal or glass, and seems to pose less potential as a bioplastic application. Nonetheless, demand for plastic containers exceeded 165 billion units in 2008, requiring more than 14 billion pounds of resin.[90]

Figure 4 - Food and Drink Containers by Material in the U.S.
(Number of units)



Source: Shen et al (2009)

In recent years there has been increasing interest in more "environmentally friendly" plastics from the major soft drink manufacturers in the United States. In fact, Pepsi and Coke are now competing over their "green credentials" in their use of alternative plastics.[91] Recently, Pepsi announced an intended shift towards PET bottles derived 100 percent from organic materials. The company is marketing the change as a way to use less petroleum, comparing its plastic to PET used by Coke's PlantBottle™, which contains 30 percent biobased material.

Though bio-based plastics have proven to be a sufficient alternative to oil-based plastics for retail beverage container applications, PHA would most likely be limited to water packaging, since (like PLA) its barrier properties are not ideal for longer-term storage of acidic or carbonated liquids. The lack of clarity of PHA resins further limits their use in beverage containers. PHA and PLA may be more viable as single-use cups where the time period for their use is limited and the integrity of the containers would not be compromised. This could also lend to efficient collection of postconsumer containers at public events.

Pricing of PHA/PHB resin

The price of producing PHAs depends on the substrate cost, PHA yield on the substrate, and the efficiency of product formulation in downstream processing.[92] Depending on which bacterial producer is used to generate PHA, the cost of production can range from $4-$16 per kg.[93] However, the price should be $3-$5 per kg to be commercially viable.[94] Consequently, a great deal of effort has been devoted to reducing the production cost by the development of better bacterial strains and a more efficient extraction process.[95]

Minimization of the PHA production cost can only be achieved by considering the design and a complete analysis of the entire process.[96] Choi et al evaluated alternative PHB processes and found the cost of production depends largely on the cost of carbon substrate.[97] Consequently, they concluded, production costs for PHB processes can be considerably lowered when agricultural wastes are used as inputs and recommend that these options be more fully explored. This may indicate that waste methane from other sources could also be a potentially attractive option as a low-cost feedstock for PHB production. Sections 2 and 3 in this investigate that option, utilizing the waste byproducts of the degradation of organic materials in landfills and wastewater treatment facilities through implementation of the Stanford Process.

The PHA resin produced by Telles, known as Mirel, sold for approximately $2.49 per lb ($5.50 per kg) in 2010 (before the Telles joint venture broke up). At this price Mirel resin was significantly more expensive than conventional and other biobased alternatives.[98] Company representatives claimed this was due to Mirel's superior performance compared to other biobased plastics.[99]

By comparison, PLA was selling in bulk at approximately $0.90/lb. in the last quarter of 2011. With PS and PET selling at $1.00/lb. and $0.80/lb., respectively, NatureWorks CEO Marc Verbruggen claimed that PLA has become increasingly cost competitive.[100]

Challenges of PHA/PHB as an alternative to conventional plastics

Past concerns that have inhibited broader adoption of bioplastics include physical limitations such as poor tear propagation (the force required to tear film plastics), moisture sensitivity for starch-based products, controlled degradation times for mulch films, and lower temperature resistance.[101] Some of the disadvantageous properties of PHA resins include brittleness, lack of clear transparency, a narrow processing window, slow crystallization rate, and higher sensitivity to thermal degradation than conventional plastics. Similar to PLA, these shortcomings can potentially be overcome by blending PHA resins with other polymers or other additives.[102] Unfortunately this blending approach can negatively impact biodegradation of the plastics, reducing environmental benefits and increasing the difficulty of sorting in postconsumer waste streams.

Furthermore, the lack of curbside collection and municipal composting infrastructure for bioplastics has provoked strong resistance to their adoption from the recycling and composting industries. During the biodegradation process PHAs produce can produce a biogas composed of 40-70 percent methane and 30-60 percent CO_2.[103] To create a closed-loop cycle for methane-based PHB it would be necessary to retrieve PHB plastics in postconsumer waste disposal streams to be sent to facilities with bioplastic recycling capability, or ensure that PHB plastics are disposed of in facilities with appropriate anaerobic digestion or landfill gas (LFG) collection systems. (See further discussion of end-of-life management for bioplastics later in Section 1.)

Market demand factors

There are significant barriers to entering any market, particularly one where the perception of biobased production—especially if they come from waste products—is not always positive, and there have been past problems maintaining the quality level required for certain uses. In fact, one report claims the primary obstacle to market expansion is consumer perception.[104] However, the report goes on to suggest that if new biobased plastic producers live up to expectations for traditional plastics, they will have the benefit of belonging to an increasingly popular category of natural, high-tech products perceived as “environmentally friendly.”

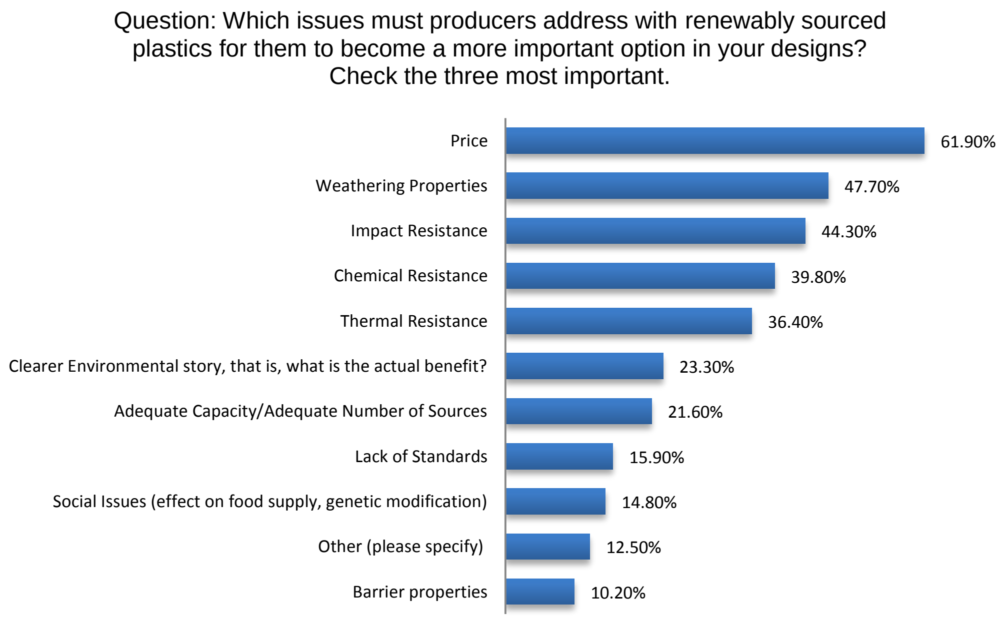
Ottman et al argue strongly that green appeal alone is not enough to attract most consumers to a given product and highlight important lessons from past successes and failures of “green” products.[105] In order to create a successful green product, they argue, marketing of the product must satisfy two objectives: improved environmental quality and customer satisfaction. Misjudging either or emphasizing the former at expense of the latter is what they term “green marketing myopia.” In fact, the authors assert, the marketing of successfully established green products requires establishing the benefits of the product regardless of its environmental friendliness. These non-green consumer values are what make these technologies sustainable in the long run.

Ottman et al go on to highlight five desirable benefits that are commonly associated with successful “green” products: efficiency and cost-effectiveness; health and safety; performance; symbolism and status; and convenience. Finally, the authors advise green marketers to focus on “the three C’s”: consumer value positioning, calibration of consumer knowledge, and credibility of product claims. They claim companies that have successfully addressed these issues have had much higher success rates in having their product adopted.

Tanner and Kast surveyed the determinants for successful green marketing in Switzerland.[106] They found green purchases are facilitated by positive attitudes of consumers toward environmental protection, fair trade, local products, and availability of action-related knowledge. On the other hand, green marketing success was negatively correlated with perceived time barriers and frequency of shopping in super markets. They did not find the decision to purchase green products to be correlated with moral thinking, monetary barriers, or the socioeconomic status of consumers. While this study is specific to Swiss consumers, some of the findings have been argued elsewhere as well, in studies from Spain and the Organization for Economic Co-operation and Development (OECD).[107] [108] Yet other studies have concluded American consumers are less likely to be swayed by appealing to environmental sensitivities. However, this largely depends on the region of the United States where products are being marketed.[109] [110]

A 2011 article that appeared in *Design News* claims that less than 10 percent of design engineers currently use plastics made from renewable sources such as plants and algae.[111] However, a majority claims they expect to consider the use of biobased plastics within five years.[112] One survey of design engineers referenced in this report asked, “Which issues must producers address with renewably sourced plastics for them to become a more important option in your designs?”[113] The most often noted concern was price, followed by weathering properties and impact resistance. The results of the survey are displayed below in Figure 5.

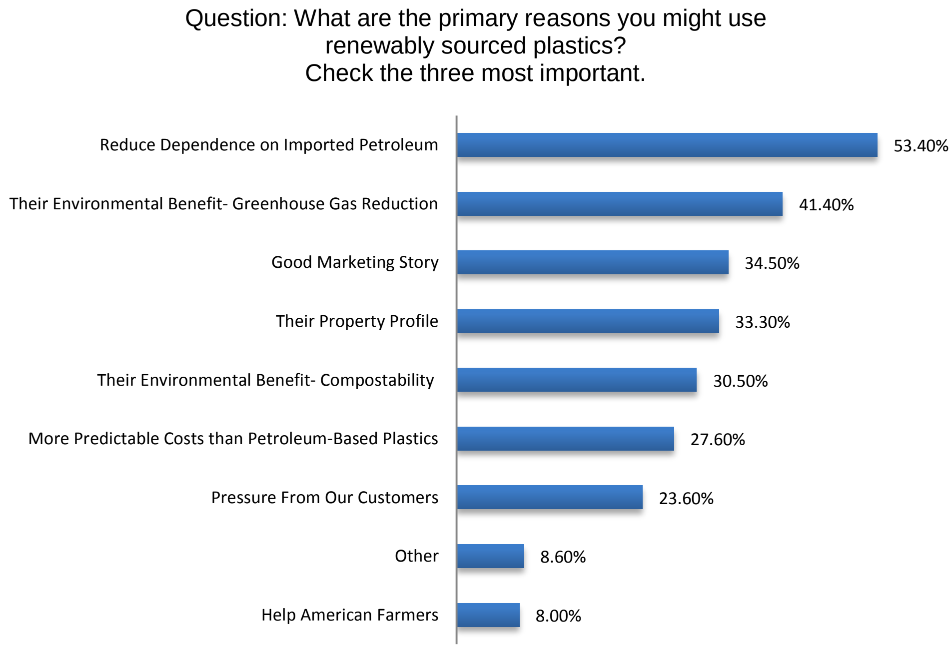
Figure 5 - Survey of Design Engineers 1



Source: Smock (2011)

Another survey question asked, “What are the primary reasons you might use renewably sourced plastics?” Perhaps surprisingly, the most commonly selected answer was to reduce U.S. dependence on imported oil. The results of this survey are displayed below in Figure 6.

Figure 6 - Survey of Design Engineers 2



Land use and feedstock costs

In comparison to competing bioplastics, PHB production from waste methane may have significant cost advantages. Costs associated with the feedstock, land use, and energy requirements for production of other biobased plastics are high. Using waste methane to produce PHB may avoid many of these costs; however, there are additional costs associated with nutrients and extraction. These issues will be explored in greater detail in Section 3.

Using feedstocks such as corn may impact food prices and thus can be controversial. In countries such as the U.S., low prices of many agricultural products depend on federal support. Furst notes that although non-food biobased feedstocks, such as switchgrass, are perhaps a decade away from commercial viability, this is "the clear direction of the industry." [114] Another analyst notes non-food plant waste sources present difficulties in the breaking down of cellulose, which is more easily done with food-based plant materials.[115]

End-of-life management of postconsumer bioplastics

Recycling-related economic issues

In California, plastic recycling infrastructure is fairly well developed and there is additional capacity for materials. Currently, PET is the most commonly used plastic for beverage bottles and the most recycled plastic. One reason it dominates the market is that there is so much of it—largely due to its superior performance in bottle and container applications. Current levels of bottle production and recycling are high enough to render business operations in PET recycling economically feasible.

PET bottles are recycled because the business of bottle recycling is sufficiently profitable to attract investment capital, the supply of uniform bottles is large enough and growing fast enough to support investment, the technology is available to convert used bottles into a number of value-added products, and the products are profitable.[116] In addition, there is added market incentive through the California Redemption Value (CRV) system, which adds a five- or ten-cent deposit to each CRV-eligible bottled product sold in the state. Thus, there exists an established infrastructure for the recycling of specific products and it may be difficult for new products to break into this system.

When bioplastics enter conventional plastic recycling streams they can contaminate the collected PET feedstock (potentially impacting recycled-content products) and cause problems with recycling machinery. Recyclers are concerned that bioplastics pose a threat to the current system by complicating the process of sorting PET and other plastics.

Improvements to near infrared (NIR) sensors may make the sorting of bioplastics from postconsumer plastics more feasible. However, this process is costly and must be widely adopted for effective implementation. Widespread use of NIR technology would require significant investment by waste and recycling operators.

In order for such investment to be economically viable there must be 1) a large and growing amount of bioplastic in the postconsumer recycling stream, and (2) a market for the secondary raw materials resulting from the NIR sorting process.[117, 118] Sustained recycling of PHA/PHB products would require an established manufacturing operation and end use for the material. Today there are a few startup PHA/PHB operations in California, but resin production is minimal.

As discussed in Sections 2 and 3, existing waste disposal sites may provide a sufficient supply of methane to support a PHB manufacturing operation in California utilizing the Stanford Process. But until recycling is a viable end-of-life option, the most optimal solution may be limited use of bioplastic food service products in specific locations or at special events, where the used bioplastics can be collected efficiently. Such locations include universities, hotels, restaurants, and even Congress and the U.S. Department of Agriculture. [119] (A full discussion of the recycling challenges related to bioplastics is beyond the scope of this report.)

Composting-related economic issues

There are two main factors that make a material compostable: the material itself and the microorganisms in the compost. A compostable plastic is a plastic that undergoes degradation by a biological process during composting to yield carbon dioxide, water, inorganic compounds, and biomass at a rate consistent with other known compostable materials, and leaves no visually distinguishable or toxic residues. The material must degrade as a result of naturally occurring microorganisms (such as bacteria, fungi, and algae) that consume the plastic as food. Consequently, all compostable plastics are biodegradable, but the reverse is not true.[120] In any case, most commercial composters in California do not currently accept “compostable” bioplastics. These products are treated as contaminants and screened out because they do not degrade rapidly enough, among other reasons.

Rynk reviewed case studies about the contamination of compost as a result of plastics and other foreign particles.[121] In one study, samples of municipal solid waste compost were inspected after repeated sieving, drying, and weighing. It was found that, on average, about 1.9 percent compost dry weight of plastics remained even after repeated sieving with sieve sizes of 1 to 4 mm. For larger compost size ranges (4 mm to <25 mm), the plastics contamination percentage ranged from 3.5 percent to 6.6 percent of the compost dry weight.

Goldstein argues the main benefit of bioplastics is just green marketing based on pseudo-environmental qualities, since at present there is no system in place for the collection and composting of these materials. She believes a new packaging waste problem has been created, rather than a sustainable packaging solution. However, she concludes compostable packages can be a valuable alternative if we are willing to formally address the challenge of clearly understanding the cradle-to-grave life of these materials. Including compostable polymers in existing food, manure, or yard waste composting facilities is a promising approach.[122]

Regardless of the properties of compostable products, new Federal Trade Commission (FTC) guidelines require companies to provide “competent and reliable scientific evidence” that their product is appropriately labeled, to ensure claims such as “compostable” are not misleading. Moreover, it appears the FTC is serious about enforcing these guidelines. It recently sought action against a company for claiming paper plates are biodegradable, when in reality most plates go to landfills where the conditions make biodegradation difficult.[123]

If bioplastic producers want to label their products as compostable or make other claims of “environmental friendliness,” the burden is on the company to back the claims scientifically. Consequently, the distinctions producers need to understand and anticipate include not only the lab-tested decomposition characteristics of their products, but also how the products will be post-processed at the end of their lives.

Source-separated composting, in which the waste is separated by consumers at the residential level, has gained attention in the U.S., Canada and Europe. For example, in San Francisco, a residential three-cart collection model is employed, which consists of organics, single-stream recyclables, and trash. In this case, bioplastics could potentially be discarded with food waste in the organics bin, as opposed to the recycling or trash bins where traditional plastics would be placed. However, residential compost collection currently is extremely limited in California. Whether this arrangement is desirable or even widely feasible is still under debate.

Factors impacting commercialization

NatureWorks states on its website that 2.5 kg of corn are required per kg of PLA plastic produced. Therefore, to produce 300 million lbs. of PLA (the capacity of the company’s Nebraska plant) requires 750 million pounds of corn. The company put out a solicitation requesting a contract for corn to be provided at $260/ton. This implies that corn costs them $0.13/lb. of plastic produced. These figures illustrate the importance of low cost inputs for bioplastic production.

For PLA and other bioplastics, food crops are a major input. The net production cost of making bioplastics also incorporates a number of other elements, including additional raw materials, value derived from byproducts, waste disposal, utilities, labor, maintenance materials, plant overhead, taxes and insurance, depreciation, and corporate overheads.[124]

Managing entire supply chains is not straightforward, and transitioning from the development stage to commercialization of a material requires an immense amount of coordination. For example, Hamelinck et al examined existing supply chains for biofuels and discussed the complications involved in managing the complex networks required to grow, process, and distribute these types of products.[125] The authors developed a tool for comparing dissimilar supply chains, concluding the optimal production method depends largely on the means of transportation used for distribution.

Other authors have hypothesized an optimal supply chain for bioplastics to be commercialized. Eksioglu et al offered an analysis of the design and management of biomass-to-bioproduct-refinery supply chains from a systems engineering perspective.[126] The authors provided a mathematical model for designing a supply chain and managing the logistics of a biorefinery. The model coordinates decisions between stages of the supply chain and determines the number, size, and location of biorefineries needed to produce bioproducts. The model also determines the amount of biomass shipped, processed and inventoried over a specific time period. Consequently, their framework can be used to evaluate efficiency levels for currently-in-place supply chains; the authors analyzed a bioenergy supply chain in Mississippi. They concluded the current geographical distribution of biorefineries is suboptimal, and better planning with respect to the location of infrastructure investments can greatly increase the overall efficiency of the supply chain.

Others argue bioplastics will need to be recycled on an industrial scale to be commercialized successfully. Cornell developed four fundamental requirements he argues are necessary for bioplastics to be viable for postconsumer recyclable goods in the U.S.:[127]

1. Enough capital investment to secure equipment and operate the business.
2. Enough raw material of sufficient quality at rational cost.
3. Adequate technology to transform raw material to valuable products at a cost that allows for profit.
4. Products of sufficient value that customers pay prices that allow for profit.

The last point, profitable product, is particularly critical for products made from postconsumer plastics. The public image of recycled goods is often that of inferior quality. To be successful, Cornell contends, postconsumer plastics must not only have a total cost lower than sales price, but also have physical and aesthetic properties commensurate with price, be consistent in attributes, and be available in adequate quantities. He argues that absent these features, biopolymers do not have a chance to be commercially recycled successfully.[128]

Funding

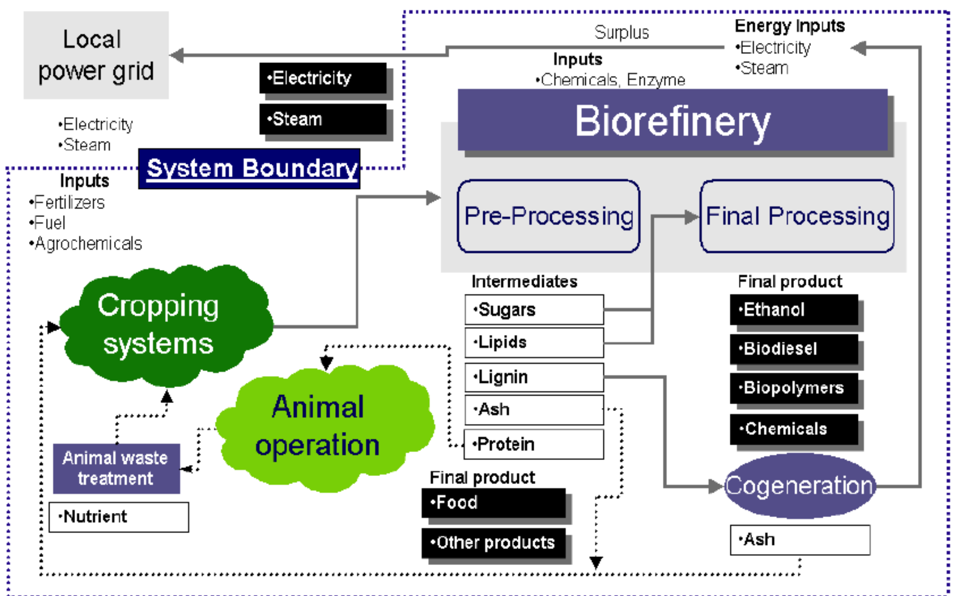
Another challenge facing bioplastic producers is securing funding for the difficult transition from research and development to commercialization. In fact, even promising young companies with waste-to-bioplastic processes like Micromidas and Mango Materials, both in California, are having trouble securing the capital they need to scale up to commercial sizes. Micromidas' owner was quoted as saying "We're stuck in between development and full-scale production. It's tough to find lenders who will invest in a first plant." Micromidas previously estimated the cost of building its first commercial size plant to be $10 million.[129]

Biorefinery conversion process

An overview of the economics of biorefineries describes the role of the biorefinery in the bioplastics supply chain.[130] The term biorefinery describes the processing complexes that use renewable agricultural residues, plant-based starch and other materials as feedstocks to provide a wide range of chemicals, fuels, and biobased materials.[131] Biorefineries use a variety of conversion technologies to produce such bioproducts.

Figure 7 illustrates the inputs and outputs of a hypothetical biorefinery. In this case, the figure diagrams horizontal flows for a biorefinery that produces biofuels. However, many of the inputs would be the same for a producer of bioplastics.

Figure 7 - Biorefinery Process



Source: Dale (2009)

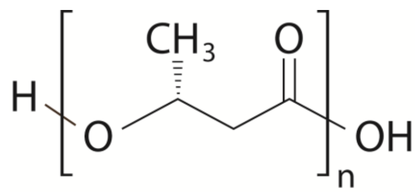
Section 2: Overview of CH_4-to-PHB Process and California Resource Potential

Overview of the CH_4-to-PHB Process

PHB bioplastics – Stanford's research

Researchers at Stanford University have developed a process by which waste methane is used as a feedstock for the production of polyhydroxybutyrate (PHB), referred to in this report as the Stanford Process. Figure 8 below depicts the molecular structure of PHB.

Figure 8 - The PHB Molecular Structure[132]



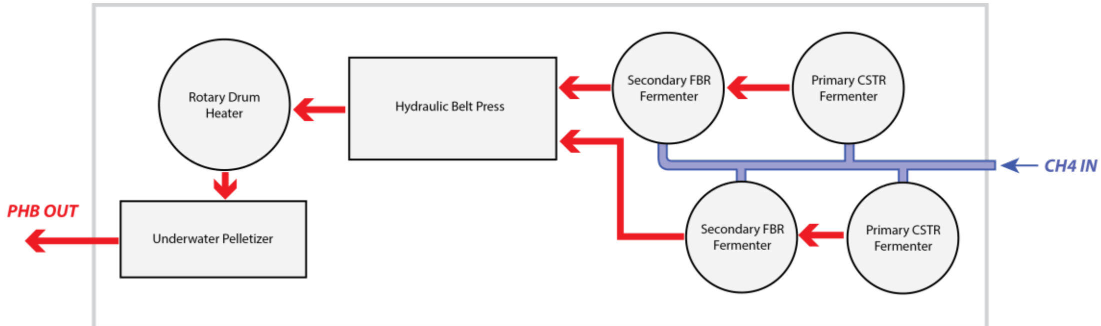
Waste methane emitted during the biodegradation process of organic material can be captured and utilized as a feedstock for the production of PHB bioplastic. In particular solid waste landfills and wastewater treatment facilities (WWTFs) have the potential to capture large amounts of methane to produce PHB as a value added product. At landfill facilities methane is created and emitted as organic material biodegrades underground. A network of pipes with holes to allow the inflow of methane can be laid as solid waste is introduced. As the organic material biodegrades the methane can be directed through the network of pipes and can be captured and flared or used for power generation. At WWTFs methane is emitted in anaerobic digesters as part of the water treatment process. Here also it can be captured and used for power generation or be flared.

Stanford Process overview

Once methane is captured it is introduced into a primary fermenter where the PHB accumulation phase begins. Methanotrophs are bacteria that feed on the carbon in methane and store it in their cells as cytoplasmic granules to be used as an energy source when needed. The methanotrophs multiply during this first phase which may last approximately 48 hours, after which they are moved to a secondary fermenter to begin the growth phase.[133] During this second phase, lasting an estimated 24 hours, the bacteria cells grow under nutrient-starved conditions. Following this process, the material is sent to a hydraulic belt press. Next is processed in a rotary drum heater, resulting in a powder form of the polymer. The powder then goes to an underwater pelletizer, where it is formed into marketable resin pellets.[134]

Figure 9 below depicts an example of a PHB production facility using waste methane as a feedstock. Although currently performed at a research scale, the Stanford Process theoretically could be deployed on a small, commercial scale with varying production capacity options.

Figure 9 - Diagram of a Hypothetical PHB Production Facility



Source: Criddle et al.

Biogas feedstock and energy requirements

Many landfills and WWTFs use waste methane for power generation. Stanford researchers estimate 18 to 26 percent of captured methane will be sufficient to meet the energy requirements for the PHB production process, allowing the remaining 74 to 82 percent of CH_4 to be used as feedstock for polymer production.[135] Therefore, it may be possible for captured methane to be used as both the feedstock for PHB production and as the power source for facility operation. Potentially this could reduce costs for PHB production, compared to facilities that must purchase corn or other organic feedstocks.

California waste methane and bioplastic production potential

California landfill and wastewater treatment facilities

California's solid waste disposal and wastewater treatment facilities hold the potential to provide large amounts of carbon feedstock for the production of PHB bioplastic. Methane is produced naturally during the decomposition process that occurs in anaerobic conditions underground at solid waste disposal facilities and in the anaerobic digesters at many WWTFs. If allowed to escape into the air, CH_4 is an extremely potent greenhouse gas with a global warming potential some 25 times greater than CO_2.[136] Many facilities, rather than allow the CH_4 to escape, burn (or "flare") the captured methane, greatly reducing the detrimental effect the gas has in the atmosphere.

In recent years, increased attention has been paid to this escaping gas, as it not only represents an environmental hazard but also a valuable, recoverable carbon source. Many facilities capture this gas and burn it to generate electricity. But using this methane to produce bioplastics also may offer significant environmental and economic benefits. The low cost of the feedstock potentially could give the PHB producer an economic advantage over competing resins. For conventional plastics, the uncertain prices of fossil feedstocks represent long-term challenges for the industry. When these feedstocks become more expensive, bioplastics may become increasingly competitive, particularly if costs of production for bioplastics decline.

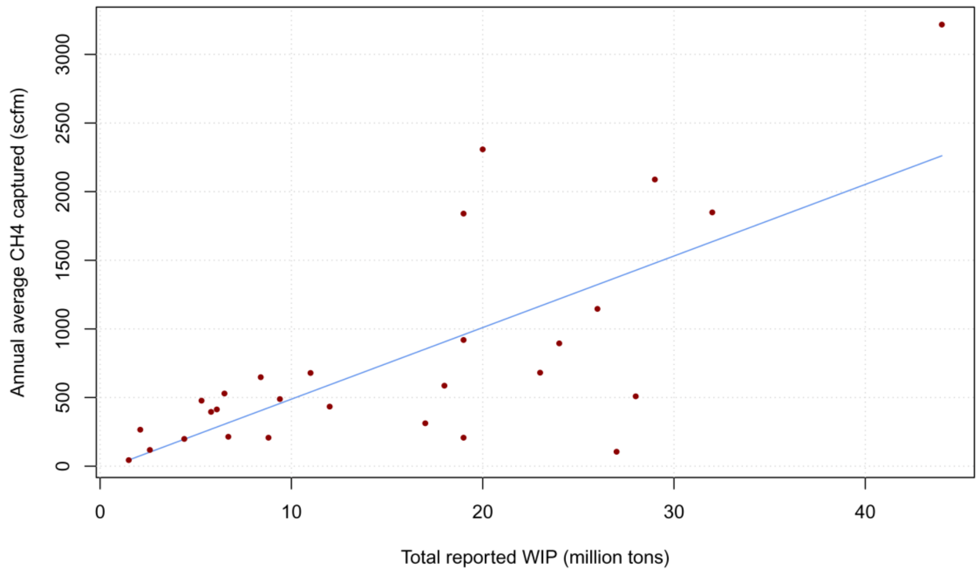
PHB bioplastics produced from waste methane also may enjoy an economic advantage compared to bioplastic competitors like PLA producers, whose feedstock depends on the price of corn. Moreover, use of corn as a feedstock for non-food products is controversial both for its potential impact on global food security and, particularly in the United States, for corn's heavy dependency on agricultural subsidies.[137]

California solid waste disposal facilities

The California state Solid Waste Information System (SWIS) database holds information about the waste disposal and methane capture at California landfill facilities as reported to CalRecycle. Using Equation 1, it is possible to determine the PHB production potential of facilities for which methane capture data are available.

For those facilities which do not capture methane, it is necessary to estimate the amount of landfill gas (LFG) generated and thus the amount of usable CH_4 available if such facilities were to implement an LFG capture system. Through linear regression analysis (a statistical technique used to determine the best predictor of a dependent variable), we determined total waste in place (WIP) was the best indicator of methane capture at facilities for which data were available. WIP is defined as the total amount of waste placed in a landfill, reported in tons. We find average CH_4 for a given facility reasonably can be estimated as a linear function of total reported WIP. Figure 10 shows the relationship between methane capture and WIP.

Figure 10 - Approximation of Annual Average CH_4 Capture by Total Waste in Place‡



The linear approximation equation is given below in Equation 1.

Equation 1 - Linear Approximation of Annual Average CH_4 Capture by Total Waste in Place

$$AVGCH4 = -33.369 + 52.148 \cdot WIP$$

Adjusted $R^2 = 0.5$, P-value = 1.56×10^{-5}

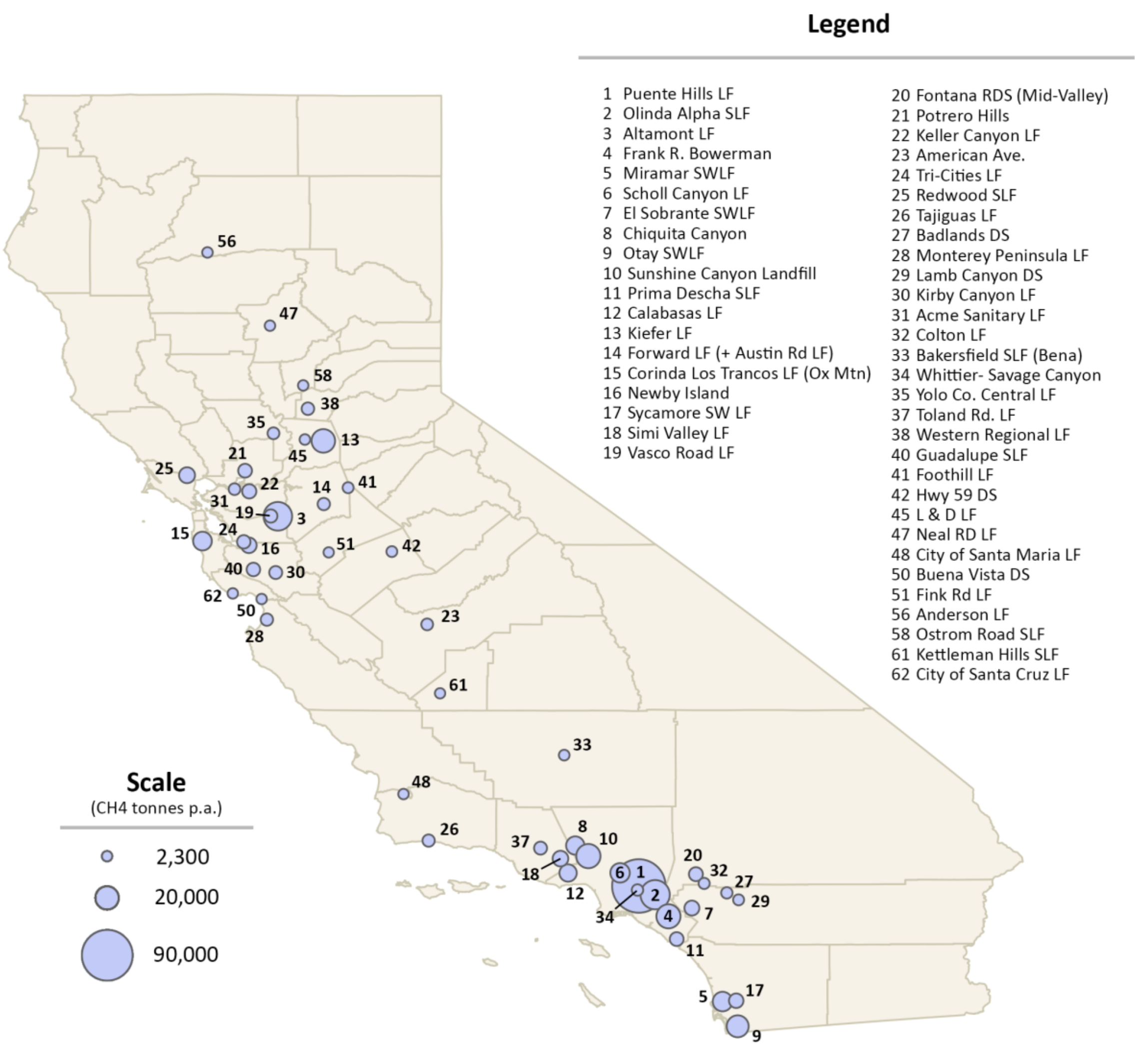
We estimate a landfill will require approximately 2,300 metric tons annually of captured CH_4 to produce 1 kt annually of PHB resin, while simultaneously generating power onsite. (In Section 3 we model the economic feasibility of a production facility of this size.)

Figure 11 below displays the locations and sizes of the 49 landfill facilities in the State that are projected to meet this capacity.

‡ Here three outliers have been removed. These include: Puente Hills Landfill in Whittier, Olinda Alpha Landfill in Brea, and Frank R. Bowerman Landfill in Irvine.

Figure 11 - California Landfill Facilities by Reported or Estimated CH4 Production Potential

Facilities of 2,300 metric tons annually and greater are pictured



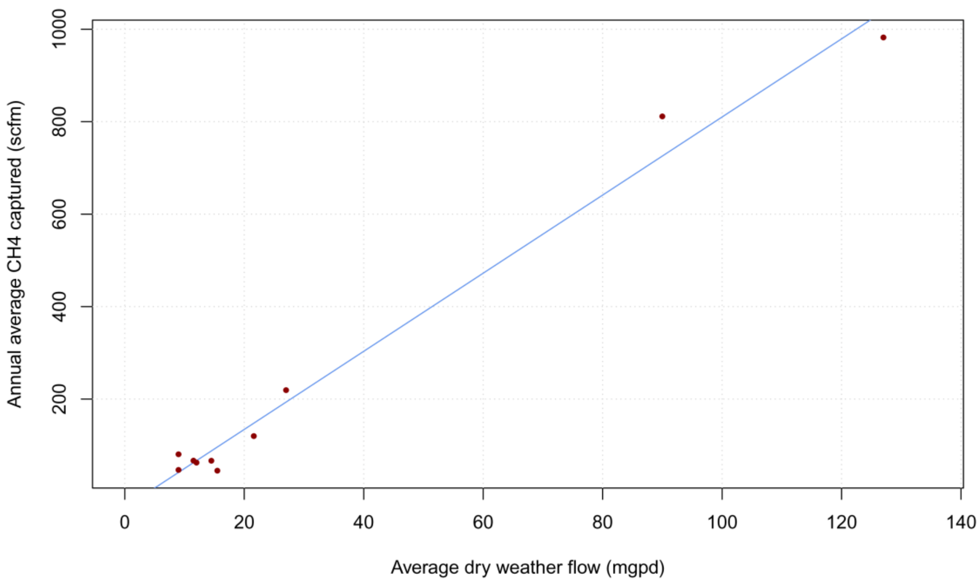
California wastewater treatment facilities

California's many wastewater treatment facilities also produce large amounts of CH_4 and similarly hold great PHB production potential.

Our research found that average dry weather flow, measured in million gallons per day (mgpd) was the most reliable predictor of average CH_4 capture. Unlike landfills, which are required to report certain statistics with regard to their operations, no such database exists for waste water facilities and thus such statistics are not readily available. Data used to forecast CH4 collection throughout the State were collected from materials published online and through direct contact with individual facilities.

Figure 12 displays the data collected for WWTFs in California and the linear approximation of CH_4 capture.

Figure 12 - Approximation of Annual Average CH_4 Capture by Average Dry Weather Flow§



Annual average CH_4 capture may thus be reasonably estimated as a linear function of average dry weather flow (Equation 2).

Equation 2 - Linear Approximation of Annual Average CH_4 Capture by WWTF Average Dry Weather Flow

$$AVGCH4 = -34.734 + 8.449 \cdot ADWF$$

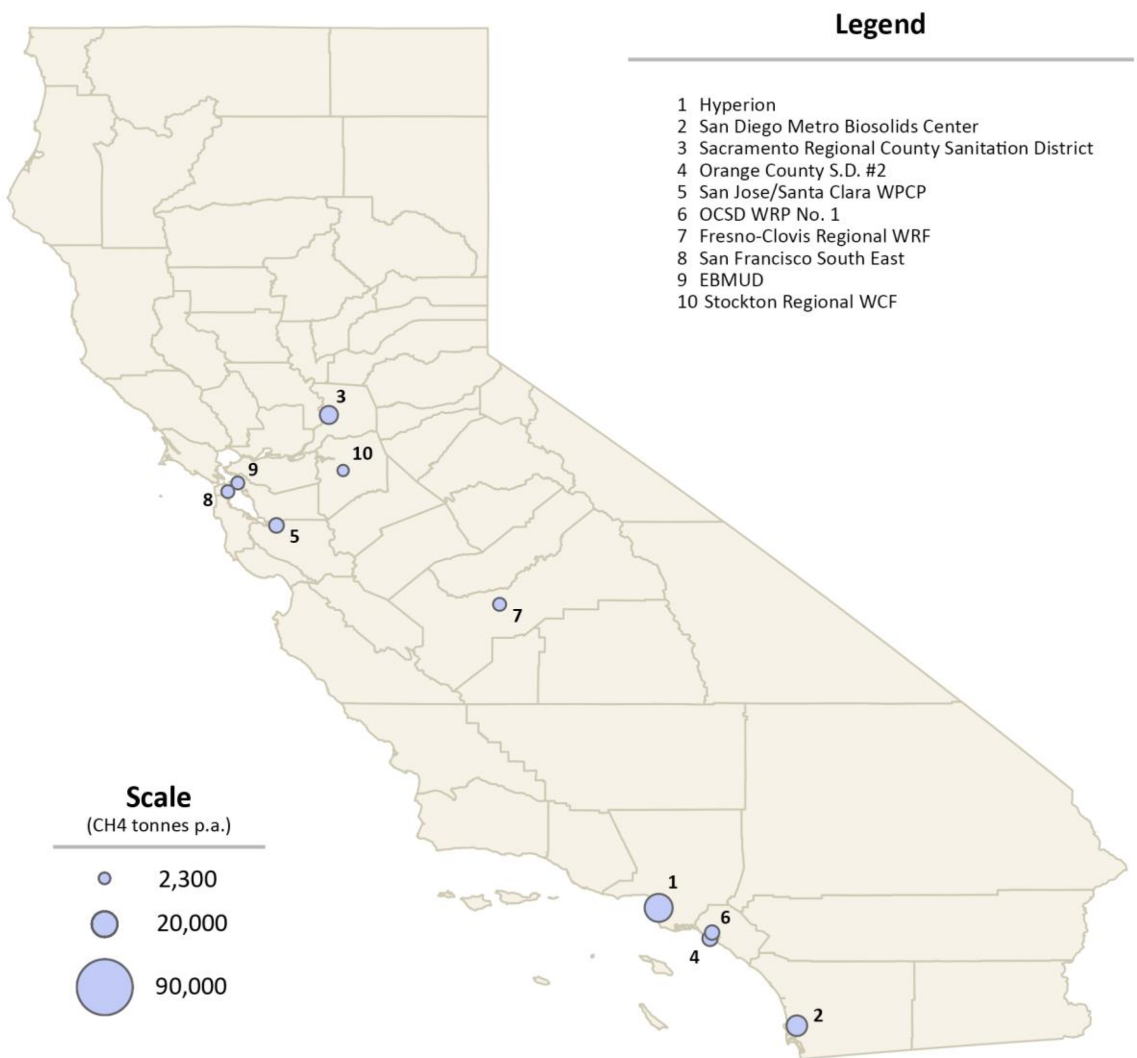
Adjusted $R^2 = 0.98$, P-value = 1.52×10^{-8}

§ Here two outliers have been removed due to extremely high average dry weather flow values. These include: Hyperion WWTF (Playa Del Rey) and JWPCP (Carson)

Figure 13 below displays the locations and sizes of the ten wastewater treatment facilities in the State that are projected to meet the 2,300 metric tons of captured CH_4 required to produce1 kt of PHB per year, while generating power onsite.

Figure 13 - California Wastewater Treatment Facilities by Reported or Estimated CH4 Production Potential

Facilities of 2,300 metric tons annually and greater are pictured



Identifying optimal conditions for small-scale PHB production sites

The use of waste methane at landfills and wastewater treatment facilities offers a significant opportunity for such facilities to turn a byproduct of the disposal and treatment process into a value-added product. However, there exist barriers to the implementation of such production facilities. As discussed above, waste methane is currently used as a fuel for power generation at many California landfills and WWTFs – particularly the larger ones – offering significant environmental and economic benefits. Such facilities are unlikely to cease this production to begin bioplastic production for two reasons: 1) the capital investment required for electricity generation is high and will be lost if such facilities turn to bioplastics, and 2) many such facilities are in medium- or long-term contracts which require them to continue providing electricity to the local utility for many years into the future.

But within these limitations, it is possible to identify facilities that will be optimal for small-scale locations for bioplastic production. The following characteristics help assess the suitability of California landfills and WWTFs for this purpose.

- *Facility size*

  Landfill and WWTF sites to be considered for the implementation of a bioplastic production facility must be capable of enough methane capture to consistently produce the planned volume of PHB resin. At a production level of 1,000 metric tons annually, we estimate 49 California landfill sites and 10 WWTFs have sufficient levels of CH_4 generation to produce this level of polymer resin while generating power onsite.

- *Current generation status*

  Current generation status of landfill facilities and WWTFs should be considered when planning a site for a small-scale PHB production facility. Sites that do not have CH_4 capture implemented will incur higher startup costs.

- *Location and power transmission infrastructure*

  Facilities in areas without adequate power transmission infrastructure may be more interested in a bioplastic production facility, as they may not have the option to generate power for sale to the local utility. There will be a lower opportunity cost for these facilities to devote captured CH_4 to polymer production instead of power generation. This may offer such facilities an option to create a value-added product with CH_4 that is currently escaping or being flared.

- *Current power generation contract status*

  Many facilities that utilize captured CH_4 to generate electricity are subject to multi-year contracts with local utilities. For example, the Kiefer Landfill near Sacramento is contracted to sell generated power to the Sacramento Municipal Utility District for a 10-year period. Facilities subject to such contracts are unlikely to have CH_4 available for a small-scale facility.

- *Amount of excess CH4 currently flared*

  Certain facilities that currently generate power onsite capture significantly more CH_4 than can be used for power generation, due to capacity constraints. Excess CH_4 is generally flared. On average, larger landfills tend to flare approximately 50 percent of the methane that is captured. For example, the Otay Solid Waste Landfill in San Diego reported flaring approximately 57 percent of its total captured methane in 2010. A PHB production facility may offer a means by which to take advantage of this value that is currently being lost.

Based on these criteria, the optimal facilities for a PHB production facility in the state would be mid-size facilities that may or may not currently capture waste methane, but do not currently generate electricity. These facilities would not be under contract to provide electricity to a local utility company and would not have invested the capital required to install equipment for that purpose. A facility located far from adequate transmission capacity would be a more likely candidate to exhibit these characteristics and therefore more optimal for PHB production. The incentive may be great for such utilization of methane at these facilities, as it offers the potential to turn a waste byproduct into value-added resin pellets, a product more easily transported than electricity, which requires expensive transmission infrastructure.

Section 3: Economic Feasibility Model of a Small-Scale Facility

Methodology and assumptions

Facility size and CH_4 requirements

For the purposes of this model, we have assumed that the small-scale facility will have a production capacity of 1,000 metric tons annually. This scale was deemed appropriate due to the estimated amount of available CH_4 at California landfill and wastewater treatment facilities. There are 49 landfills and 10 WWTFs in our database that are projected to have sufficient CH_4 production to be potential sites for a small-scale facility. A sensitivity analysis of this assumption will be discussed below.

According to Stanford University, the estimated yield of PHB from captured CH_4 (gPHB/g CH_4) is 0.56. Thus, a facility producing 1,000 metric tons PHB annually will require 1785.71 annually metric tons of exploitable CH_4. As discussed in Section 2, researchers further estimate 18-26 percent of captured CH_4 will be sufficient to meet onsite energy requirements for PHB plant operations, thus leaving 74-82 percent of captured CH_4 as feedstock for PHB production.[138]

In the current facility model we will assume the small-scale PHB production facility will in fact generate power onsite. If we also take the Stanford assumption of 0.5 percent fugitive loss of CH_4, we then find that to produce PHB at this level a minimum of 2300.9 metric tons CH_4 must be captured per year. This is equivalent to an annual average 226.67 cubic feet per minute (cfm).

Process equipment

The California Department of Toxic Substances Control (DTSC) undertook a study that approximated equipment costs for a 125 million pound (56.7 kt) annually facility producing PHB by the same process. The equipment costs found by the DTSC can be found in Appendix A. The current model scales this estimate to reflect the smaller scale of the small-scale facility. Certain equipment requirements for the Stanford process may differ from the equipment referenced in the DTSC study. At the time of the writing of this report the Stanford process was still under development and final equipment requirements are uncertain. The process is still at laboratory scale and specific equipment costs and sizes for production scale are highly uncertain. The DTSC study provides detailed equipment cost information for PHB plastic production at production scale and was found to be the most accurate estimate available. In order to overcome this uncertainty we have performed a sensitivity analysis of this assumption to assess the impact that variance in equipment costs will have on the economic viability of the facility. Results of this sensitivity analysis are provided at the end of Section 3. The methodology for scaling this estimate is illustrated below in Equation 3.

Equation 3 – Process Equipment Scaling Formulation

$$C_B = C_D \left(\frac{L_B}{L_D}\right)^k$$

Here, C_D denotes the equipment cost estimate provided by the DTSC, $6,097,000. L_B denotes the plant capacity in our baseline scenario, 1,000 metric tons annually. L_D indicates the capacity of the plant in the DTSC estimate, 125 million pounds (56.699 kt) annually. Finally, the exponent k indicates a scaling parameter for which a value of 0.7 is used. This is a commonly accepted value in chemical engineering cost estimation applications.

In addition to scaling this estimate, we employ a multiplier to revise this estimate upward to adjust for underestimation of equipment costs and provide a more conservative estimate of profitability in the model. In our *baseline* scenario we scale this estimate upward by 50 percent. Sensitivity analyses relative to these assumptions will be discussed at the end of Section 3.

Energy use

According to Stanford estimates, if electricity is generated onsite at a small-scale facility, 18 to 26 percent of the CH_4 captured will be sufficient to meet the energy demands of the PHB production process.[139] Thus as described above, this implies that at a PHB yield rate of 0.56 g/1 g CH_4 a 1,000 metric ton annually facility will require approximately 1,786 metric tons CH_4 per year for PHB production and another 515 metric tons CH_4 annually to meet the energy needs of the PHB production process. This is equivalent to 2,433 megawatt hours (MWh) on an annual basis.

This model assumes that the small-scale facility will not have a gas collection system in place and the costs of implementing this are included in the model. The U.S. EPA provides detailed estimates of costs associated with the implementation of such systems at typical solid waste landfill locations. These data are used for the cost estimation portion of this model.[140]

Sale price of PHB

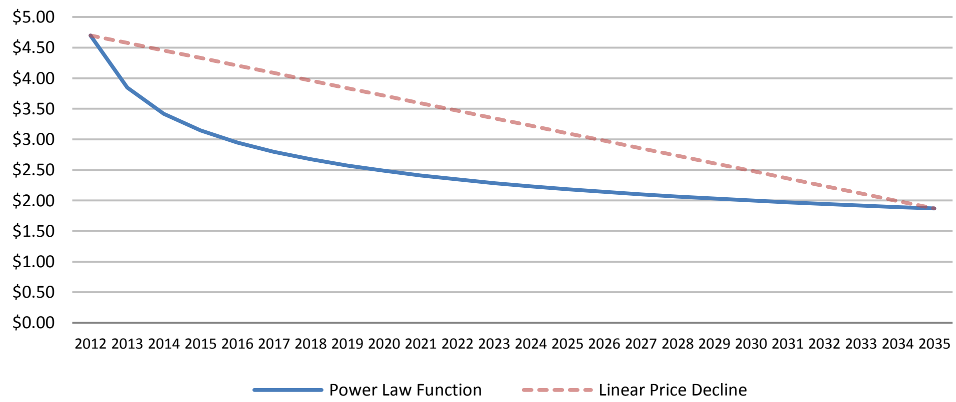
According to estimates by Stanford University, the current price of PHB resin is approximately $4.70 per kg. As prices of bioplastic resins have generally followed a downward trend, we anticipate that the trajectory of this downward movement will follow a power law function reaching maturity by 2035. Here we assume that the price will be near the current price for conventional (PET) resin at this time. Thus, we assume a value of $1.87/kg by the end of this timeframe. The power law function as used in the model is below in Equation 4.

Equation 4 - Power Law Price Estimator

$$f(x) = ax^k$$

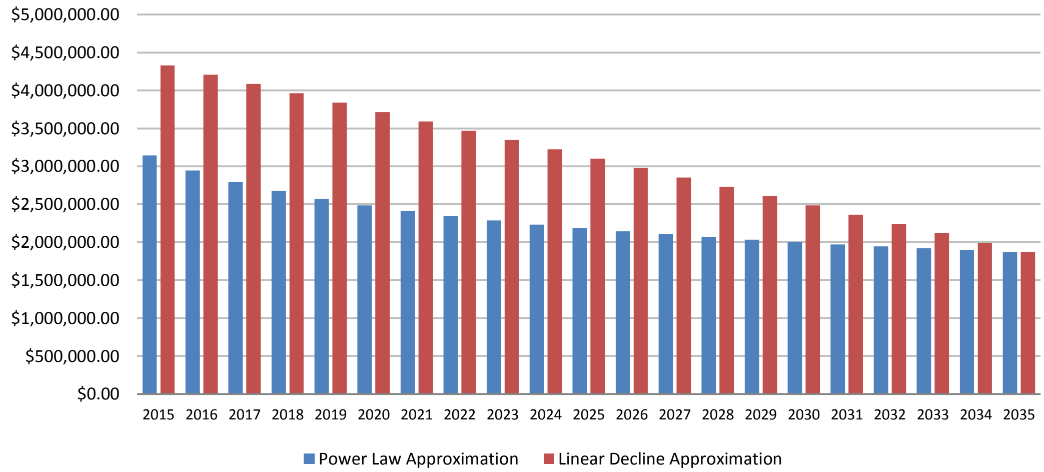
Here $f(x)$ represents the price of PHB per kg in year x where 2012 is year 1. The coefficient a is the estimated price of PHB in year 1. The exponent k takes a value of -0.29 in our baseline scenario. This value yields our estimated price level of PHB at maturity of $1.87/kg at year 2035. This approach of price forecasting results in a more conservative and more probable price trajectory over time. Prices of products in nascent industries tend to experience more rapid price decline in early years with the rate of decline decreasing over time. An estimate of linear price decline over time would likely overestimate expected revenue. Figure 14 below displays both the assumed trajectory of the PHB price over this time horizon according to this power law approximation (as used in our baseline scenario) and the price trajectory as would be estimated under a linear price decline approximation.

Figure 14 - Estimated Price of PHB Resin Over Time



As noted above, a linear approximation would likely overestimate sales revenue particularly in the early years of the project. This is illustrated in Figure 15 which displays annual sales revenue for both the power law and linear decline assumptions.

Figure 15 - PHB Sales Revenue by Year



The trajectory of future prices of PHB is highly uncertain. This model predicts a price decline based on reasonable assumptions about a young product in a nascent industry. However, due to the uncertainty of the market and the large impact this factor will have on the potential revenue of a PHB production facility, sensitivity analyses were conducted with respect to this variable. Such analyses will be discussed at the end of Section 3.

Extraction and nutrient costs

The cost of chemicals necessary for the PHB extraction process is an extremely important parameter in the cost estimation of a PHB production facility of this type. Additionally, nutrients necessary for the growth and accumulation phases of the process also must be taken into consideration. Our current best estimates for these costs are displayed below in Table 3.

Table 3 - Extraction and Nutrient Costs

Extraction method	Cost $/kg PHB	Annual extraction chemical cost
SDS-Sodium hypochlorite	0.34	$340,000

Nutrient	Cost $/kg PHB	Annual cost
Phosphate	0.09	$90,000
Nitrate	0.03	$30,000

There remains a high degree of uncertainty relative to these costs, thus uncertainty analysis with respect to these costs will be highly important. This will be discussed at the end of Section 3.

Labor costs and other inputs

In order to estimate the annual labor costs associated with operating a 1 kt PHB production facility, the authors have reviewed various studies that have estimated these costs.[141] [142] Here we find an estimate of labor costs based on a percentage of the total initial capital investment. We have found a conservative estimate to be 27.3 percent of total capital costs. In our baseline scenario this amounts to $147,865 on an annual basis, which we find to be a reasonable estimate. Again, sensitivity analyses relative to this assumption will be discussed at the end of Section 3.

Landfill and WWTF data

As discussed in the previous section, data relative to available CH_4 at California landfills and WWTFs was obtained from the SWIS database and from the U.S. EPA Section 9 database for Wastewater Treatment Plants. These databases provided an array of data points with respect to these facilities. Facilities that are currently collecting CH_4 also report capture volumes enabling the forecasting of capture potential for remaining facilities. As previously discussed, we estimate 49 California solid waste landfills and 10 WWTFs currently have sufficient CH_4 generation (some have existing capture capacity while others do not) for a small-scale 1kt annually facility to produce PHB resin while generating power onsite.

Corporate tax rate

The corporate tax rate applied in our baseline scenario is 43.84 percent. This includes 35 percent federal tax and 8.84 percent California state tax and corresponds to the applicable tax given the profit calculated in the model. A complete tax table is available in Appendix B.

Net present worth and project lifetime

All three scenarios considered calculate net present worth (NPW) over a 20 year project lifetime with a discount rate[**] of 6 percent. The authors consider these reasonable assumptions and are widely used values in project evaluation in related industries.

[**] The discount rate is an annual percentage value that accounts for the fact that money in the base year is worth more than money in future years due to the opportunity cost of not having the money available to invest (time value of money), thus enabling the calculation of the "present value" of future money.

Model inputs and results

Model inputs

In this study we have used the assumptions above to provide a baseline scenario of the estimated economic feasibility of a 1,000 metric ton annually PHB bioplastic production facility. Due to the high degree of uncertainty associated with many of the assumptions in this model we provide here results of a *high scenario* and a *low scenario* in addition to the *baseline scenario*.

Many input parameters of the model are adjusted in these three scenarios. These include: PHB yield per unit CH_4, energy requirement, fugitive CH_4 loss, process equipment costs, power generation capital and O&M costs, PHB resin sale price, extraction and nutrient costs, and labor costs. Here the high scenario provides results under favorable conditions (low costs, high efficiency, and high sale price of PHB) while the low scenario provides results under unfavorable conditions (high costs, low efficiency, and low sale price of PHB). The input parameters that are varied between the three scenarios are displayed below in Table 4.

Table 4 – Input Parameter Variation in HIGH, BASELINE, and LOW Scenarios

Input	Values			Units
	HIGH	BASELINE	LOW	
PHB yield	0.62	0.56	0.48	g PHB/g CH_4
Energy Requirement	15%	22%	30%	Percent of CH_4 capture
Equipment Cost Multiplier	1.25	1.50	2.50	Multiplier applied to scaled DTSC cost estimate
O&M Cost Multiplier	1.25	1.50	2.50	Multiplier applied to scaled DTSC cost estimate
Labor Cost	19.30%	27.30%	39.30%	Annual labor costs estimated as a percentage of TCI
Current PHB market price	$4.70	$4.70	$3.25	$US/kg PHB
Market PHB price at maturity	$2.26	$1.87	$1.29	$US/kg PHB
Value of *k* in power law estimated price forecast	-0.23	-0.29	-0.29	Exponential parameter
SDS Cost	$0.29	$0.34	$0.44	Cost $/kg PHB
Phosphate	$0.07	$0.09	$0.14	Cost $/kg PHB
Nitrate	$0.02	$0.03	$0.05	Cost $/kg PHB

Model results

Table 5 below displays the results of the model's *low scenario*. Here the net present worth (NPW) on a 20-year time horizon is approximately negative $552,000. This scenario illustrates that under certain adverse conditions such a facility could potentially yield a net loss. It should be noted here that the assumptions in this scenario are meant to represent an extreme case with much higher than expected cost and lower than expected revenue due to low prices of PHB.

Table 5 - LOW Scenario Net Present Worth

Year	Revenue	Costs	Net Cash Flow
0			-$3,026,203.03
1	$2,174,132.28	$1,393,345.47	$476,249.29
2	$2,037,896.20	$1,393,345.47	$381,197.99
3	$1,932,945.01	$1,393,345.47	$310,133.09
4	$1,848,438.18	$1,393,345.47	$254,986.38
5	$1,778,227.26	$1,393,345.47	$211,088.47
6	$1,718,513.84	$1,393,345.47	$175,499.17
7	$1,666,799.50	$1,393,345.47	$146,250.15
8	$1,621,360.10	$1,393,345.47	$122,442.31
9	$1,580,959.70	$1,393,345.47	$105,925.76
10	$1,544,684.50	$1,393,345.47	$84,503.08
11	$1,511,841.39	$1,393,345.47	$66,543.19
12	$1,481,893.17	$1,393,345.47	$51,441.43
13	$1,454,415.74	$1,393,345.47	$38,718.35
14	$1,429,068.92	$1,393,345.47	$27,988.50
15	$1,405,576.00	$1,393,345.47	$18,938.46
16	$1,383,709.16	$1,393,345.47	$11,310.77
17	$1,363,278.74	$1,393,345.47	$4,892.18
18	$1,344,125.33	$1,393,345.47	-$495.29
19	$1,326,113.77	$1,393,345.47	-$5,001.10
20	$1,309,128.53	$1,393,345.47	-$8,751.51
Net Present Worth:			**-$552,342.36**

The results of the *baseline scenario* are displayed below in Table 6. These results indicate a NPW of more than $8 million over the 20-year lifetime of the project. Here we find that the revenue generated by PHB resin sales (given conservative price estimates) can indeed outweigh the associated costs.

Table 6 - BASELINE Scenario Net Present Worth

Year	Revenue	Costs	Net Cash Flow
0			-$2,171,468.56
1	$3,144,129.75	$915,699.66	$1,225,551.82
2	$2,947,111.43	$915,699.66	$1,057,706.87
3	$2,795,335.86	$915,699.66	$926,269.91
4	$2,673,125.98	$915,699.66	$819,475.72
5	$2,571,590.20	$915,699.66	$730,479.77
6	$2,485,235.39	$915,699.66	$654,943.49
7	$2,410,448.50	$915,699.66	$589,938.61
8	$2,344,736.15	$915,699.66	$533,391.79
9	$2,286,310.95	$915,699.66	$483,778.68
10	$2,233,851.43	$915,699.66	$439,943.96
11	$2,186,355.24	$915,699.66	$400,990.01
12	$2,143,045.50	$915,699.66	$366,204.81
13	$2,103,308.92	$915,699.66	$335,013.59
14	$2,066,653.51	$915,699.66	$306,945.49
15	$2,032,679.15	$915,699.66	$281,609.80
16	$2,001,056.33	$915,699.66	$258,678.71
17	$1,971,510.79	$915,699.66	$237,874.55
18	$1,943,812.02	$915,699.66	$218,960.14
19	$1,917,764.52	$915,699.66	$201,731.33
20	$1,893,201.26	$915,699.66	$186,011.32
Net Present Worth:			**$8,084,031.81**

The results of the *high scenario* are displayed below in Table 7. Here we find that under better than expected conditions a small-scale facility could attain a NPW of almost $12 million.

Table 7 - HIGH Scenario Net Present Worth

Year	Revenue	Costs	Net Cash Flow
0			-$1,803,379.16
1	$3,416,835.42	$735,663.09	$1,457,807.97
2	$3,245,897.17	$735,663.09	$1,289,851.84
3	$3,112,598.26	$735,663.09	$1,153,986.90
4	$3,004,175.56	$735,663.09	$1,040,436.15
5	$2,913,313.09	$735,663.09	$943,412.18
6	$2,835,450.57	$735,663.09	$859,185.26

7	$2,767,565.18	$735,663.09	$785,197.21
8	$2,707,556.58	$735,663.09	$719,607.77
9	$2,653,909.88	$735,663.09	$661,042.54
10	$2,605,498.86	$735,663.09	$608,443.61
11	$2,561,464.90	$735,663.09	$560,976.23
12	$2,521,139.45	$735,663.09	$517,968.11
13	$2,483,992.40	$735,663.09	$478,868.34
14	$2,449,596.80	$735,663.09	$443,218.85
15	$2,417,604.09	$735,663.09	$410,633.94
16	$2,387,726.23	$735,663.09	$380,785.36
17	$2,359,722.64	$735,663.09	$353,391.09
18	$2,333,390.47	$735,663.09	$328,206.89
19	$2,308,557.21	$735,663.09	$305,019.68
20	$2,285,074.98	$735,663.09	$283,642.46
Net Present Worth:			**$11,778,303.21**

The respective annual cash flow for each scenario is plotted below in Figure 16. Cash flow is most positive in the initial years of the project and falls rapidly in all three scenarios. This is largely due to the assumed fall in price of PHB resin which results in reduced revenue in the later years of the project and the assumed discount factor.

Figure 16 - Annual Discounted Net Cash Flow

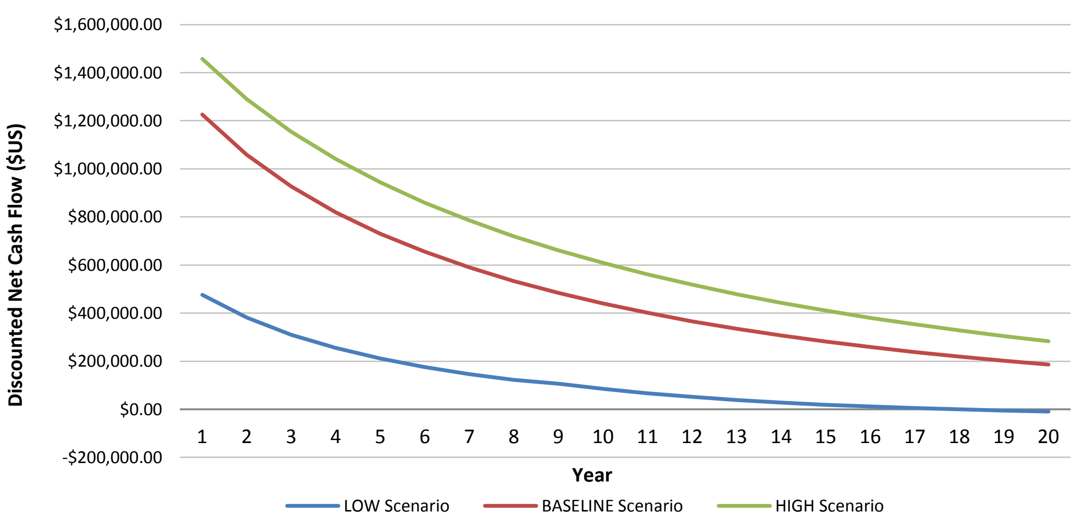
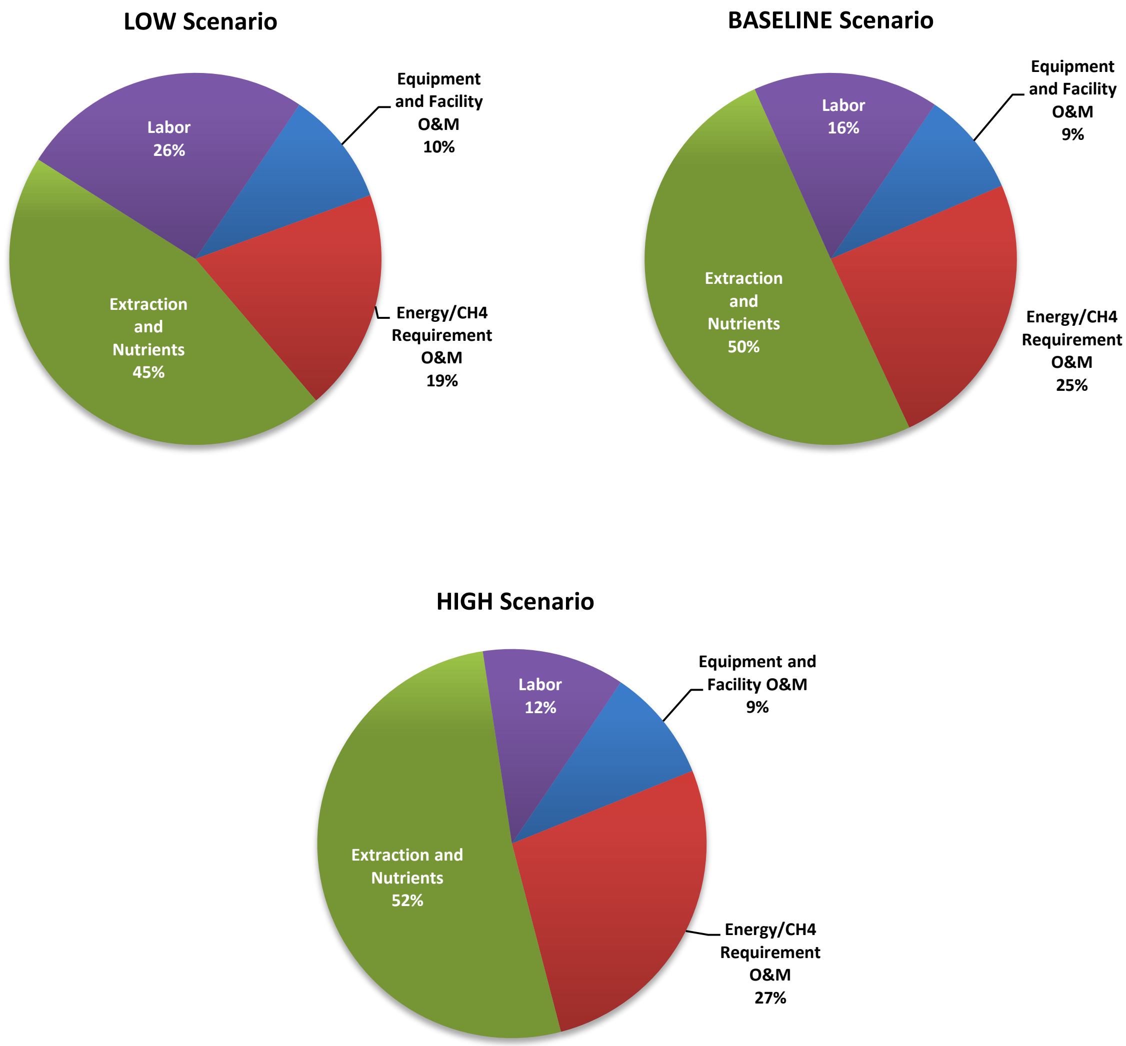


Figure 17 below displays the relative costs by category in all three scenarios. As can be seen here extraction costs represent an extremely large proportion of total costs and thus profitability of a PHB production facility will be highly sensitive to the prices of extraction chemicals and the amounts used to achieve extraction per g PHB. Sensitivity to this will be discussed below in the sensitivity analysis section.

Figure 17 - Average Annual Costs by Category



Although results of the model vary significantly with changes to the various input parameters these results illustrate that it is likely that under reasonable assumptions a small-scale facility such as this would be profitable. Given the baseline parameters of the model described in this report, with a constant sale price of PHB resin this model predicts that this project will have a positive NPW for any price above $1.17/kg PHB ($0.53/lb PHB).

Sensitivity analysis of model input parameters

Uncertainty in cost estimation and sensitivity analysis

The Stanford Process of converting waste methane to PHB plastics is a novel and unique process for which there is no substantial precedent. Many of the model parameters are subject to a relatively high degree of uncertainty, thus it is necessary to conduct some sensitivity analyses in order to determine the magnitude of the impact that such variables have on the final NPW of the project. In particular the parameters that will be discussed in this analysis include: (1) the Stanford estimated PHB yield and energy requirements, (2) energy procurement method and landfill gas (LFG) collection status, (3) equipment capital costs and annual O&M costs (including labor), (4) extraction costs, and (5) PHB price.

PHB yield and energy requirements

Values assumed for PHB yield and for process energy requirements are critical to the accurate forecasting of profitability of a production facility and also to the production potential of a given landfill or WWTF site. In our baseline scenario we use 0.56 g PHB/g CH_4 as an estimated value of PHB yield. We also assume that 22 percent of CH_4 capture will be sufficient to provide the energy needed for the PHB production process. Both values are based on estimates made by researchers at Stanford University.[143] Table 8 below displays the results of the baseline scenario as a function of changes in these estimates.

Table 8 - Net Present Worth as a Function of Estimated PHB Yield and CH_4 Required for Energy

PHB Yield (g PHB/g CH_4) – Baseline value in red

CH4 to meet energy requirement (% of total capture)	0.435	0.46	0.485	0.51	0.535	0.56	0.585	0.61	0.635	0.66
14%	$8,303,479	$8,337,962	$8,368,891	$8,396,787	$8,422,076	$8,445,108	$8,466,170	$8,485,507	$8,503,320	$8,519,785
16%	$8,195,571	$8,235,919	$8,272,108	$8,304,748	$8,334,338	$8,361,286	$8,385,931	$8,408,556	$8,429,399	$8,448,664
18%	$8,082,400	$8,128,898	$8,170,603	$8,208,220	$8,242,320	$8,273,376	$8,301,778	$8,327,852	$8,351,872	$8,374,073
20%	$7,963,569	$8,016,526	$8,064,024	$8,106,865	$8,145,702	$8,181,071	$8,213,417	$8,243,112	$8,270,469	$8,295,753
22%	$7,838,646	$7,898,392	$7,951,979	$8,000,312	$8,044,128	***$8,084,032***	$8,120,525	$8,154,027	$8,184,891	$8,213,417
24%	$7,707,147	$7,774,040	$7,834,036	$7,888,151	$7,937,208	$7,981,885	$8,022,744	$8,060,253	$8,094,809	$8,126,748
26%	$7,568,540	$7,642,966	$7,709,719	$7,769,927	$7,824,509	$7,874,218	$7,919,677	$7,961,411	$7,999,858	$8,035,393
28%	$7,422,233	$7,504,610	$7,578,495	$7,645,136	$7,705,549	$7,760,568	$7,810,885	$7,857,077	$7,899,632	$7,938,963
30%	$7,267,565	$7,358,348	$7,439,772	$7,513,214	$7,579,791	$7,640,424	$7,695,875	$7,746,781	$7,793,679	$7,837,023
32%	$7,103,799	$7,203,483	$7,292,889	$7,373,531	$7,446,636	$7,513,214	$7,574,101	$7,629,997	$7,681,493	$7,729,087

Here we can see that even extreme values of these estimates have a relatively small impact on the viability of this project.

Figure 18 and Figure 19 below indicate net present worth (NPW) as a function of each estimate individually. We can see here that as the necessary proportion of CH_4 needed for power generation *increases*, the NPW decreases. Conversely, as PHB yield *decreases*, the NPW of the project decreases. Again we can see that changes to these estimates do not result in drastic changes in the NPW of the project even at extreme values.

Figure 18 - NPW as a Function of CH_4 Required for Energy

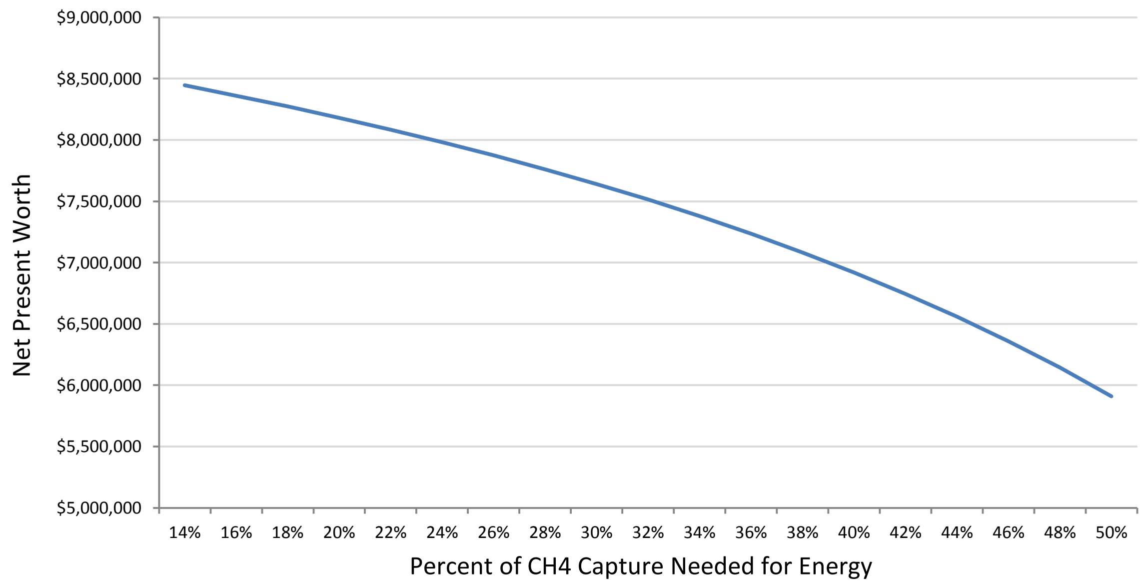
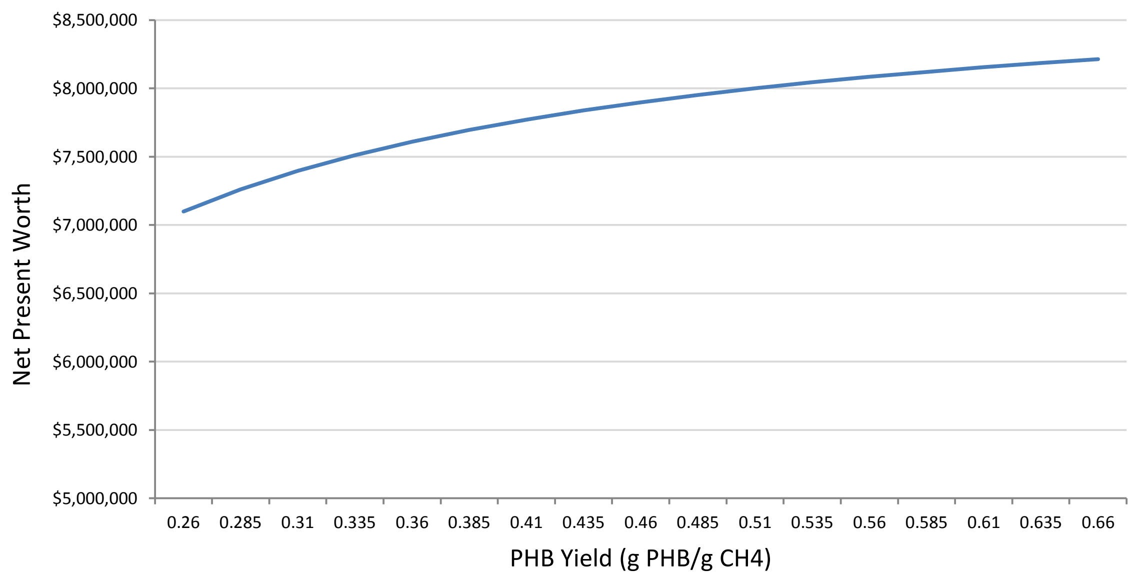


Figure 19 - NPW as a Function of PHB Yield



Energy procurement and LFG collection status

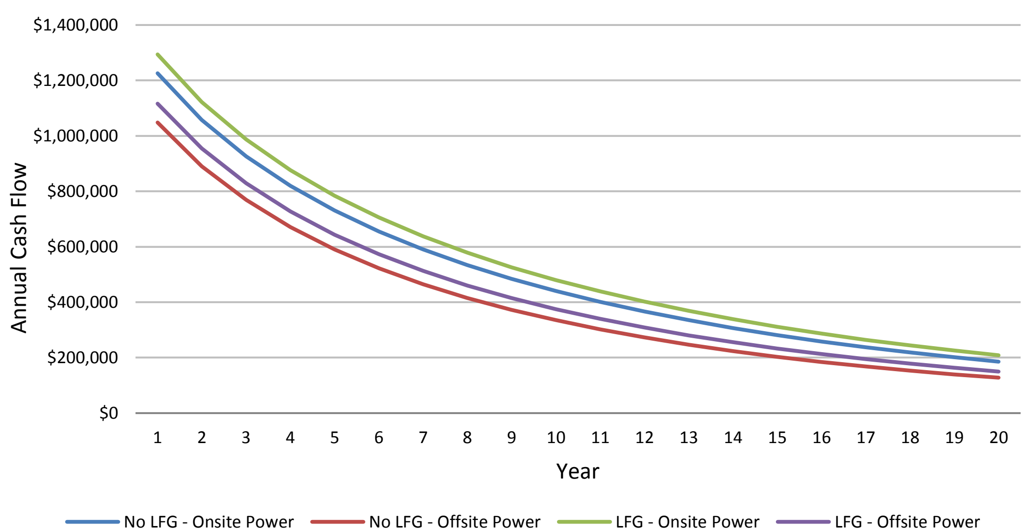
The three model scenarios discussed in the previous section have assumed a facility must implement a CH_4 collection system and that the facility will generate power onsite. Because some facilities may purchase power to meet the energy requirement of the PHB production process or may already have CH_4 collection in place, here we consider such cases. Table 9 below considers four cases: (1) an LFG collection system has not yet been implemented and power will be generated onsite, (2) an LFG collection system has not yet been implemented and power will be purchased, (3) an LFG collection system is already in place and power will be generated onsite, and (4) an LFG collection system is already in place and power will be purchased. All other model assumptions of the *baseline scenario* are held constant in all cases. For cases in which power is purchased, U.S. Energy Information Administration (EIA) California power price forecasts are utilized to calculate energy cost. Here we see that the worst-case scenario is the scenario in which an LFG collection system must be constructed and power is purchased.

Table 9 - Net Present Worth by Energy Procurement Category and LFG Collection Status

	Onsite Power	Offsite Power
LFG Collection System not in Place	$8,084,032	$6,568,668
LFG Collection System in Place	$9,895,164	$8,379,800

Figure 20 below displays a plot of annual cash flow for each case described above.

Figure 20 - Annual Cash Flow by Energy Procurement Category and LFG Collection Status



Equipment costs and annual O&M

Initial capital costs associated with equipment procurement are very uncertain. Likewise, the annual operations and maintenance (O&M) costs are difficult to forecast given the novel nature of this process. Here in Table 10 we can see the effect that these assumptions have on the Net Present Worth (NPW) of the project. The NPW of the project is certainly sensitive to these assumptions; however, the project still retains a positive value as these assumptions are increased to very high levels.

Table 10 - NPW by Initial Capital Investment (Equipment) and O&M

Initial Capital Investment (Equipment) – Baseline value in red[††]

Annual O&M Costs (Labor Included)	$250,000	$550,000	$850,000	$1,150,000	$1,450,000	$1,750,000	$2,050,000	$2,350,000	$2,650,000	$2,950,000
$150,000	$8,826,494	$8,601,920	$8,377,346	$8,152,772	$7,928,198	$7,703,625	$7,479,051	$7,254,477	$7,029,903	$6,805,329
$250,000	$8,182,343	***$7,957,769***	$7,733,195	$7,508,621	$7,284,048	$7,059,474	$6,834,900	$6,610,326	$6,385,753	$6,161,179
$350,000	$7,538,192	$7,313,618	$7,089,045	$6,864,471	$6,639,897	$6,415,323	$6,190,749	$5,966,176	$5,741,602	$5,517,028
$450,000	$6,894,041	$6,669,468	$6,444,894	$6,220,320	$5,995,746	$5,771,172	$5,546,599	$5,322,025	$5,097,451	$4,872,877
$550,000	$6,249,891	$6,025,317	$5,800,743	$5,576,169	$5,351,595	$5,127,022	$4,902,448	$4,677,874	$4,453,300	$4,228,726
$650,000	$5,605,740	$5,381,166	$5,156,592	$4,932,018	$4,707,445	$4,482,871	$4,258,297	$4,033,723	$3,809,149	$3,584,576
$750,000	$4,961,589	$4,737,015	$4,512,441	$4,287,868	$4,063,294	$3,838,720	$3,614,146	$3,389,572	$3,164,999	$2,940,425
$850,000	$4,317,438	$4,092,864	$3,868,291	$3,643,717	$3,419,143	$3,194,569	$2,969,995	$2,745,422	$2,520,848	$2,296,274
$950,000	$3,673,287	$3,448,714	$3,224,140	$2,999,566	$2,774,992	$2,550,699	$2,328,508	$2,103,417	$1,882,126	$1,656,068
$1,050,000	$3,031,455	$2,810,134	$2,584,429	$2,362,427	$2,135,345	$1,912,346	$1,684,178	$1,460,243	$1,230,924	$1,005,695

[††] Baseline value is approximate, capital investment and O&M are rounded to nearest $50,000

Figure 21 and Figure 22 below indicate the effect that each of these parameters will have on the NPW of the project with all other factors held constant. Here we see that if annual O&M (labor included) exceeds $1.5 million, the project will operate at a net loss over this time horizon. The NPW is much less sensitive to assumptions regarding initial capital costs. At a much higher than expected level of $4 million we find that the project can still operate at a profit over this time horizon.

Figure 21 - NPW by Annual O&M

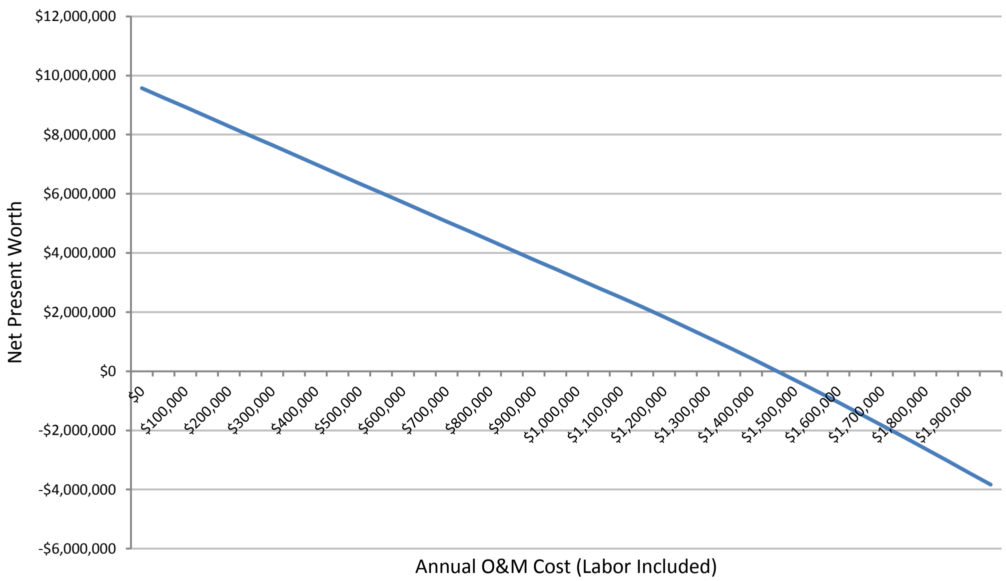
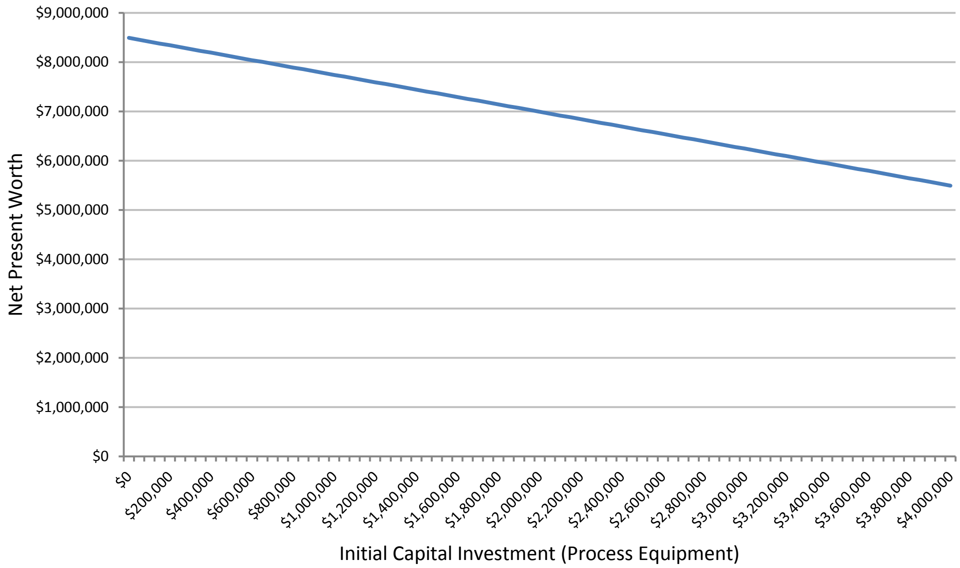


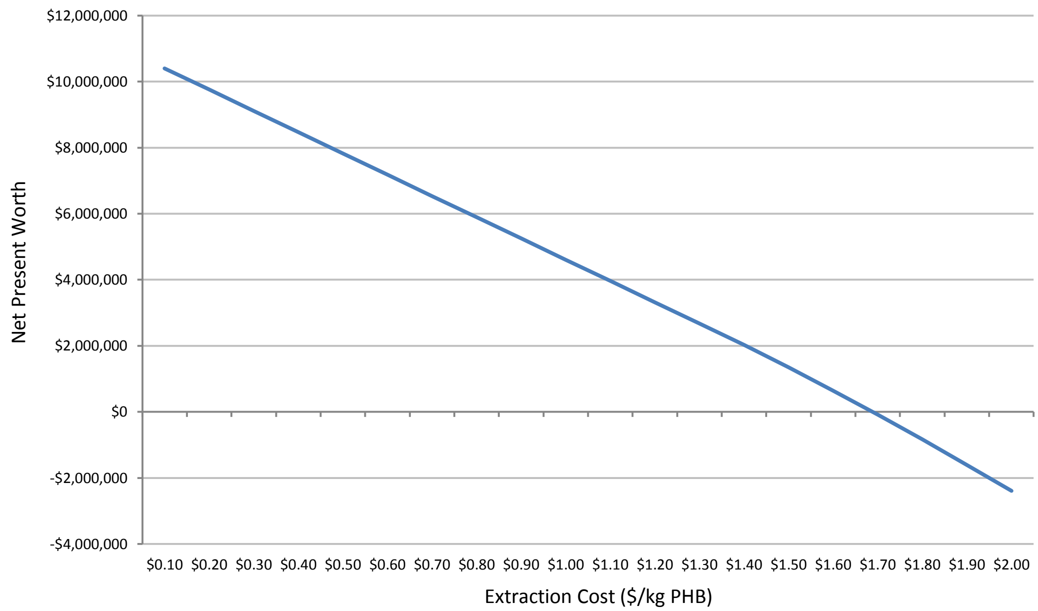
Figure 22 - NPW as a Function of Initial Capital Investment (Process Equipment)



Extraction costs

As seen above, extraction and nutrient costs account for an extremely high proportion of the total costs associated with a PHB production facility. Figure 23 below displays the net present worth (NPW) as a function of total extraction cost per kg PHB. We find that if extraction costs exceed a level of $1.70 per kg PHB the project will suffer a net loss over the 20-year time horizon. Due to the high impact that extraction cost per unit of PHB has on the NPW of this project, it is vital for the economic success of a production facility to confirm volume of extraction chemicals per volume of PHB yield and costs associated with these chemicals.

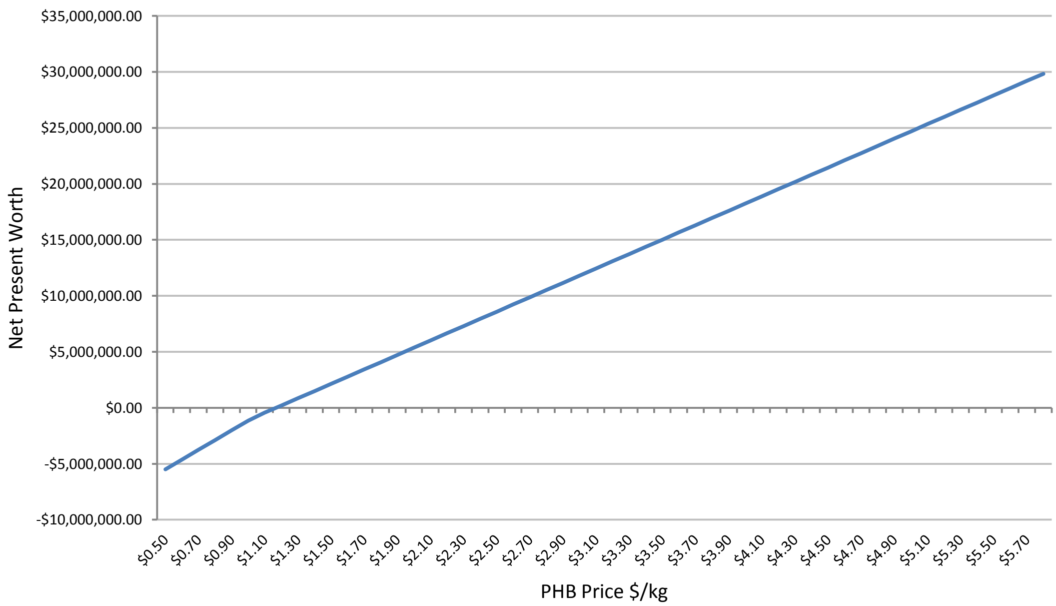
Figure 23 - NPW as a Function of Extraction Cost



PHB price

The price at which a small-scale PHB production facility will be able to sell the resin produced will have an extremely large impact on the economic viability of the facility. Figure 24 below shows the relationship between the sale price of PHB resin in price per kg and net present value (NPW) of the facility. In this sensitivity analysis we assume a constant price over the entire time horizon of the project. Here we vary the price of PHB while keeping all other baseline assumptions constant. According to this model framework the NPW of a facility will be positive as price is above approximately $1.20 per kg.

Figure 24 - NPW as a Function of PHB Price



Conclusion and Summary of Findings

Bioplastic markets and potential replacement of conventional plastics

The production and disposal of conventional plastics is associated with considerable environmental challenges. In 2010, the EPA estimated 31 million tons of plastic waste was generated in the United States, which accounted for approximately 12.4 percent of total municipal solid waste in that year.[144] Substitution for conventional plastics with biobased alternatives may mitigate environmental challenges and may offer economic opportunities.

Although bioplastics still represent a small fraction of overall plastic production, bioplastic demand has increased rapidly in recent years and it appears that they will continue to account for an increasing share of total plastic demand. The largest factor impeding greater adoption of bioplastics is the price premium. Bioplastic resin prices are still significantly higher than conventional alternatives and this has been a barrier to their more widespread adoption. It is predicted that prices will continue to fall in the bioplastic market and this will lead to increased adoption of bioplastics for a variety of applications.

Although PLA resin—in particular Ingeo brand polymer from NatureWorks—accounts for the largest share of the bioplastic resin market, the family of PHA resins, including PHB, offers desirable physical characteristics that may be suitable for a broad range of product categories. Such polymers may be suitable for both rigid and flexible plastic applications and they may be processed using existing injection molding equipment.

PHAs also have good degradability characteristics. According to one study, they may degrade in 45 days to eight weeks depending on conditions.[145] Therefore, they have the potential to create a closed-loop methane cycle whereby waste methane may be captured, used in the form of biopolymer, and then recaptured after consumer use.[‡‡]

As discussed in this report, there is very substantial growth expected to occur in world bioplastic production. It is expected that the bioplastic packaging market alone will grow from an estimated 125,000 metric tons in 2010 to approximately 884,000 metric tons by 2020.[146] In addition, it has been estimated that PHA resin in particular is likely to achieve 41 percent growth in demand over this 10-year period.[147]

There are certain characteristics of PHA polymers that will impede their adoption in certain end use categories. The opaque coloration and incompatibility with carbonated beverages will be a barrier to adoption particularly in the beverage container sector.

[‡‡] Estimating the costs of infrastructure development and other factors associated with recapturing PHA products—or any bioplastics—at the end of their life is beyond the scope of this report.

Assessment of site locations for PHB production from waste methane

Analysis of data provided by California solid waste landfill and wastewater treatment facilities indicates that many such facilities have (or could potentially implement) gas collection systems capturing sufficient methane to provide the feedstock for a small-scale PHB production facility. At a production level of 1,000 metric tons annually, research from Stanford University suggests that annual methane capture required would be approximately 1,785 metric tons including estimated requirements for on-site power generation. At this level in California, we estimate there are 49 landfills and 10 wastewater treatment facilities (for which data is available) that would likely attain sufficient capture to produce at this level.

Certain characteristics of these locations will be critical when assessing locations for the construction of a PHB production facility. The five most critical characteristics are:

(1) Facility size (measured in total waste in place or average dry weather flow for landfills and wastewater treatment facilities respectively)

(2) Current generation status (if CH_4 is currently used for power production and if so, what percentage of total CH_4 available is used)

(3) Location and installed power transmission infrastructure

(4) Current CH_4 and power generation contract status

(5) Volume of excess CH_4 currently captured and flared.

We find that optimal sites are likely to be mid-sized landfills or WWTFs that may or may not currently capture CH_4 but do not generate electricity and thus are not subject to contractual agreements with local utilities for power generation. Facilities that exhibit these characteristics and have little or no access to installed power transmission infrastructure may have particular interest in the implementation of PHB production. This may offer such facilities a means by which to turn the CH_4 waste byproduct into a value-added product that can easily be transported where power generation requires expensive power transmission capacity.

Some studies have found (Choi et al) that agricultural byproducts could be an attractive feedstock for PHB production due to their low cost. This may have implications for the Stanford process, which could utilize low-cost waste methane feedstock to produce PHB resin.

Economic feasibility of PHB plastics from waste methane

The authors recognize that certain conditions are not addressed in the reference scenarios. For instance, these scenarios do not examine the impact that lower than anticipated CH_4 capture may have on the project value. If a facility were constructed at a site that is expected to achieve sufficient CH_4 capture to produce 1 kt annually while generating power onsite but is unable to achieve this level of production, this will negatively impact cash flow. Another scenario that is not modeled here is a scenario under which there is not enough market capacity to purchase the PHB resin. Rather, here we assume that PHB resin prices exogenously set in the model represent market-clearing prices where supply equals demand in the PHB resin market. We model low price scenarios but do not take into account the possibility that there are insufficient buyers willing to purchase PHB resin at any price, leaving the production facility with unsellable resin and reduced profit.

However, we find that given reasonable assumptions, utilizing this process to produce PHB resin at California landfills and WWTFs would likely be economically viable. As discussed above, even under adverse cost conditions the net present worth (NPW) of this type of waste-to-methane facility may be profitable. The model constructed for this report indicates that given baseline assumptions such a facility could have a positive NPW for any PHB price above $1.17/kg ($0.53/lb.). The authors recognize that this value is highly sensitive to modeling assumptions; however, it does illustrate that given reasonable input parameters and conditions it is likely that such a facility would be profitable.

Due to the high degree of uncertainty, we have conducted various sensitivity analyses to determine the degree to which the NPW of a PHB production facility is sensitive to certain modeling assumptions. Sensitivity analyses were conducted with respect to the following parameters:

(1) the Stanford estimated PHB yield and energy requirements

(2) energy procurement method and LFG collection status

(3) equipment capital costs and annual O&M costs (including labor)

(4) extraction and nutrient costs

(5) PHB price.

We find that the greatest sensitivity lies in the costs associated with PHB price and the extraction process. At publication time the precise method of extraction for the Stanford Process was still not concretely determined, but has a significant impact on the NPW of the facility. However, within the context of this modeling methodology we can see the effect of extraction costs on a dollars-per-unit PHB basis independent of the method chosen for extraction.

We find that given baseline parameters, if extraction costs are below $1.68/kg PHB, the production facility may be economically viable. If costs associated with this process can be more concretely determined and proven to be viable on a commercial scale there would be significantly less financial risk in the implementation of such a facility. This may seem to contradict intuition regarding economies of scale, but in this scenario variable costs are the dominant consideration, rendering these facilities more scalable.

As mentioned in the introduction, estimates in this report indicate the authors' best estimates given current data available. Prior to undertaking the construction of such a facility it would be necessary to consult a gas capture engineering specialist in order to perform a more detailed assessment of the particular site conditions, cost considerations, and methane capture potential along with an accurate assessment of actual site-specific equipment and process related costs.

Appendix A

DTSC Cost Estimates

Cost Estimates for PHB Manufacturing Equipment as Estimated by the California Department of Toxic Substances Control

PHB process with 125 million pound per year production rate

Approach: Ex Situ Discount rate (real): 2.30%	Capital Cost	Annual Average O&M	Total O&M	O&M Present Worth	Project Present Worth
Phase element name	$Y2011	$Y2011	$Y2011	$Y2011	$Y2011
PHB METHANE FEED PROCESS					
12 Primary Reactors	1,240,000	18,000	540,000	390,000	1,630,000
12 Secondary Reactors	971,000	1,000	20,000	10,000	981,000
PHB Hydraulic Belt	60,000	30,000	890,000	640,000	700,000
PHB Rotary Drum Heater	1,600,000	30,000	890,000	640,000	2,240,000
PHB Underwater pelletizer	300,000	16,000	470,000	340,000	640,000
Recycled PHB Hammer Mill	162,000	376,000	11,270,000	8,080,000	8,242,000
Allocated PHB bulk Material storage	17,000				17,000
Allocated PHB overhead Electrical distribution	13,000				13,000
Allocated PHB Boiler costs (17,863 lb steam/hour)	1,734,000	940,000	28,200,000	20,210,000	21,944,000
Subtotal for PHB Process Line	6,097,000				36,407,000
20% Contingency	1,219,000				1,219,000
Total Project Cost	7,316,000	1,411,000	42,280,000	30,310,000	37,626,000

Appendix B

Federal and State Corporate Tax Table

State and Federal Corporate Tax Rates[148]

Federal Corporate Tax Rate

Net Income	Rate (%)
First $50,000	15
$50,000 to $75,000	25
$75,000 to $100,000	34
$100,000 to $335,000 (a)	39
$335,000 to $10,000,000	34
$10,000,000 to $15,000,000	35
$15,000,000 to $18,333,333 (b)	38
Over $18,333,333	35

California State Corporate Tax Rate: 8.84%

(a) An additional 5 percent tax, not exceeding $11,750, is imposed on taxable income between $100,000 and $335,000 in order to phase out the benefits of the lower graduated rates.

(b) An additional 3 percent tax, not exceeding $100,000, is imposed on taxable income between $15,000,000 and $18,333,333 in order to phase out the benefits of the lower graduated rates.

Source: Treasury Department; Commerce Clearing House (CCH); Tax Foundation

Appendix C

Landfill and Wastewater Treatment Facility CH4 Collection Data

2010 Landfill Data From SWIS Database

** Shaded fields represent data estimated by linear regression and CH_4 content average.

Facility Name	State Ref ID	City	2010 WIP (tons)	Total LFG (scfm)**	CH4 Content (%)**	Total CH4 (cfm)**	CH4 metric tons p.a.
Puente Hills LF	19-AA-0053	South Industry	120,000,000	28,220.0	33.50%	9,453.7	95,964.8
Olinda Alpha SLF	30-AB-0035	Brea	52,000,000	8,066.0	52.00%	4,194.3	42,576.7
Altamont LF	01-AA-0009	Alameda-Unincorporated County	44,000,000	8,104.0	49.87%	4,041.5	41,025.2
Frank R. Bowerman	30-AB-0360	Irvine	43,000,000	6,331.0	49.00%	3,102.2	31,490.4
Miramar SWLF	37-AA-0020	San Diego	32,000,000	4,585.0	47.00%	2,155.0	21,875.0
Scholl Canyon LF	19-AA-0012	Glendale	29,000,000	6,242.0	34.20%	2,134.8	21,670.0
El Sobrante SWLF	33-AA-0217	Corona	28,000,000	2,616.6	45.00%	1,177.5	11,952.7
Chiquita Canyon	19-AA-0052	Castaic	27,000,000	4,116.0	46.00%	1,893.4	19,219.6
Otay SWLF	37-AA-0010	Chula Vista	26,000,000	6,054.0	44.00%	2,663.8	27,039.9
Sunshine Canyon City/County Landfill	19-AA-2000	Sylmar	24,000,000	7,679.0	40.89%	3,139.9	31,873.7
Prima Descha SLF	30-AB-0019	San Juan Capistrano	24,000,000	2,056.0	46.00%	945.8	9,600.4
Calabasas LF	19-AA-0056	Los Angeles-Unincorporated County	23,000,000	5,693.0	29.60%	1,685.1	17,105.8
Kiefer LF	34-AA-0001	Sloughhouse	20,000,000	6,032.0	49.40%	2,979.8	30,248.1
Forward LF (+ Austin Rd LF -0001)	39-AA-0015	Manteca	19,000,000	1,533.0	41.50%	636.2	6,458.0
Corinda Los Trancos LF (Ox Mtn)	41-AA-0002	Half Moon Bay	19,000,000	3,623.3	55.00%	1,992.8	20,229.1
Newby Island	43-AN-0003	Milpitas	19,000,000	2,857.1	46.00%	1,314.3	13,341.2
Sycamore SW LF	37-AA-0023	San Diego	18,000,000	2,564.0	43.00%	1,102.5	11,191.7
Simi Valley LF	56-AA-0007	Simi Valley	17,000,000	2,860.1	46.50%	1,329.9	13,500.2
Vasco Road LF	01-AA-0010	Alameda-Unincorporated County	13,000,000	1,875.0	44.40%	832.5	8,450.7
Fontana RDS (Mid-Valley)	36-AA-0055	Rialto	12,000,000	2,221.0	44.40%	986.1	10,010.2
Potrero Hills	48-AA-0075	Suisun City	11,800,000	1,846.0	51.00%	941.5	9,556.8
Keller Canyon LF	07-AA-0032	Pittsburg	11,000,000	1,849.0	56.60%	1,046.5	10,623.4
	10-AA-0009	Fresno	11,000,000	1,100.0	48.00%	528.0	5,359.7

American Ave.		Unincorporated County					
Tri-Cities LF	01-AA-0008	Fremont	10,000,000	1,854.7	47.00%	871.7	8,848.6
Redwood SLF	21-AA-0001	Novato	9,600,000	2,774.0	50.00%	1,387.0	14,079.5
Tajiguas LF	42-AA-0015	Santa Barbara-Unincorporated County	9,400,000	1,188.0	53.00%	629.6	6,391.5
Badlands DS	33-AA-0006	Moreno Valley	8,800,000	1,027.0	43.40%	445.7	4,524.5
Monterey Peninsula LF	27-AA-0010	Marina	8,400,000	1,244.0	52.10%	648.1	6,579.1
Lamb Canyon DS	33-AA-0007	Beaumont	7,400,000	841.5	42.20%	355.1	3,604.8
Kirby Canyon LF	43-AN-0008	San Jose	7,300,000	1,588.9	48.40%	769.0	7,806.4
Acme Sanitary LF	07-AA-0002	Martinez	7,100,000	1,178.3	43.28%	510.0	5,176.8
Colton LF	36-AA-0051	Colton	6,700,000	952.0	41.40%	394.1	4,000.8
Bakersfield SLF (Bena)	15-AA-0273	Kern-Unincorporated County	6,600,000	696.0	42.80%	297.9	3,023.9
Whittier- Savage Canyon	19-AH-0001	Whittier	6,500,000	1,075.6	43.28%	465.5	4,725.3
Yolo Co. Central LF	57-AA-0001	Davis	6,500,000	1,085.0	49.20%	533.8	5,418.8
Lancaster Waste Mgt.	19-AA-0050	Lancaster	6,200,000	443.5	43.70%	193.8	1,967.5
Toland Rd. LF	56-AA-0005	Santa Paula	6,100,000	1,500.0	51.70%	775.5	7,872.1
Western Regional LF	31-AA-0210	Lincoln	5,800,000	1,382.0	50.00%	691.0	7,014.4
Victorville RDS	36-AA-0045	Victorville	5,400,000	297.0	31.70%	94.1	955.7
Guadalupe SLF	43-AN-0015	San Jose	5,300,000	1,815.8	48.70%	884.3	8,976.3
Foothill LF	39-AA-0004	Linden	5,100,000	835.7	43.28%	361.7	3,671.7
Hwy 59 DS	24-AA-0001	Merced-Unincorporated County	4,700,000	767.2	43.28%	332.1	3,370.6
Hay Road Landfill	48-AA-0002	Vacaville	4,600,000	236.0	48.42%	114.3	1,160.0
Cold Canyon	40-AA-0004	San Luis Obispo	4,400,000	509.6	39.00%	198.7	2,017.5
L & D LF	34-AA-0020	Sacramento	4,200,000	681.6	43.28%	295.0	2,994.4
San Timoteo SWDS	36-AA-0087	Redlands	3,800,000	227.0	39.50%	89.7	910.2
Neal RD LF	04-AA-0002	Butte-Unincorporated County	3,700,000	595.9	43.28%	257.9	2,618.1
City of Santa Maria LF	42-AA-0016	Santa Maria	3,700,000	595.9	43.28%	257.9	2,618.1
Shafter-Wasco SLF	15-AA-0057	Shafter	3,600,000	197.0	37.40%	73.7	747.9
Buena Vista DS	44-AA-0004	Watsonville	3,500,000	561.7	43.28%	243.1	2,467.5
Fink Rd LF	50-AA-0001	Landing	3,300,000	527.4	43.28%	228.3	2,317.0
Visalia DS	54-AA-0009	Visalia	3,200,000	510.3	43.28%	220.8	2,241.8
Fairmead LF	20-AA-0002	Chowchilla	2,900,000	344.0	23.00%	79.1	803.1
Woodville DS	54-AA-0008	Tulare-Unincorporated County	2,900,000	458.9	43.28%	198.6	2,016.0

North County LF	39-AA-0022	Victor	2,800,000	320.0	55.00%	176.0	1,786.6
Anderson LF	45-AA-0020	Anderson	2,700,000	538.7	50.50%	272.0	2,761.6
West Central (Phase 2)	45-AA-0043	Igo	2,600,000	407.5	43.28%	176.4	1,790.2
Ostrom Road SLF	58-AA-0011	Wheatland	2,600,000	509.0	49.74%	253.2	2,570.0
Republic-Imperial	13-AA-0019	Imperial Unincorporated County	2,500,000	151.4	34.85%	52.8	535.6
Avenal LF	16-AA-0004	Avenal	2,200,000	339.0	43.28%	146.7	1,489.2
Kettleman Hills SLF	16-AA-0027	n/a	2,100,000	467.6	49.00%	229.1	2,326.0
City of Santa Cruz LF	44-AA-0001	Santa Cruz	2,100,000	578.2	46.00%	266.0	2,700.1
Ridgecrest SLF	15-AA-0059	Ridgecrest	1,900,000	287.6	43.28%	124.5	1,263.4
California St. LF	36-AA-0017	Redlands	1,900,000	287.6	43.28%	124.5	1,263.4
Barstow RDS	36-AA-0046	San Bernardino-Unincorporated County	1,900,000	141.0	6.60%	9.3	94.5
Teapot Dome DS	54-AA-0004	Porterville	1,900,000	112.0	40.50%	45.4	460.5
Paso Robles LF	40-AA-0001	San Luis Obispo-Unincorporated County	1,700,000	200.0	46.50%	93.0	944.0
Red Bluff LF	52-AA-0001	Red Bluff	1,700,000	250.0	35.00%	87.5	888.2
John Smith Road SWDS	35-AA-0001	Hollister	1,600,000	189.0	38.00%	71.8	729.0
Palo Alto RDS	43-AM-0001	Palo Alto	1,600,000	236.2	43.28%	102.2	1,037.6
Union Mine DS	09-AA-0003	El Dorado Unincorporated County	1,500,000	219.1	43.28%	94.8	962.4
Burbank LF #3	19-AA-0040	Burbank	1,500,000	335.0	47.10%	157.8	1,601.7
Johnson Cnyn LF	27-AA-0005	Gonzales	1,500,000	219.1	43.28%	94.8	962.4
Tehachapi SLF	15-AA-0062	Tehachapi	1,400,000	201.9	43.28%	87.4	887.1
Clovis LF	10-AA-0004	Fresno Unincorporated County	1,300,000	184.8	43.28%	80.0	811.9
Eastlake SLF	17-AA-0001	Clearlake	1,300,000	184.8	43.28%	80.0	811.9
Billy Wright LF	24-AA-0002	Los Banos	1,300,000	184.8	43.28%	80.0	811.9
Taft SLF	15-AA-0061	Taft	1,200,000	167.7	43.28%	72.6	736.6
Landers DS	36-AA-0057	Landers	1,200,000	167.7	43.28%	72.6	736.6
Chicago Grade	40-AA-0008	Templeton	1,200,000	230.0	30.00%	69.0	700.4
Lompoc LF	42-AA-0017	Lompoc	1,200,000	167.7	43.28%	72.6	736.6
City of Watsonville	44-AA-0002	Watsonville	1,200,000	167.7	43.28%	72.6	736.6
Zanker Rd. LF	43-AN-0007	San Jose	1,000,000	133.4	43.28%	57.7	586.1
Clover Flat LF	28-AA-0002	Calistoga	970,000	128.3	43.28%	55.5	563.5
Las Pulgas LF	37-AA-0903	Camp Pendleton	960,000	126.6	43.28%	54.8	556.0
Glenn County LF	11-AA-0001	Glenn Unincorporated County	880,000	112.8	43.28%	48.8	495.8

Blythe DS	33-AA-0017	Blythe	870,000	54.5	12.90%	7.0	71.4
Rock Creek LF	05-AA-0023	Calaveras-Unincorporated County	740,000	88.9	43.28%	38.5	390.4
Mojave-Rosamond SLF	15-AA-0058	Mojave	560,000	58.0	43.28%	25.1	255.0
Calexico DS	13-AA-0004	Imperial-Unincorporated County	510,000	49.5	43.28%	21.4	217.3
Benton Crossing	26-AA-0004	Whitmore Hot Springs	490,000	46.0	43.28%	19.9	202.3
Bass Hill LF	18-AA-0009	Johnstonville	430,000	35.8	43.28%	15.5	157.1
Mariposa Co. SLF	22-AA-0001	Mariposa-Unincorporated County	380,000	27.2	43.28%	11.8	119.5
UC Davis LF	57-AA-0004	Davis	370,000	25.5	43.28%	11.0	112.0
Bishop Sunland	14-AA-0005	Inyo-Unincorporated County	350,000	22.1	43.28%	9.5	96.9
Edwards AFB Main LF	15-AA-0150	Edwards AFB	350,000	22.1	43.28%	9.5	96.9
Vandenburg AFB	42-AA-0012	Vandenberg AFB	330,000	18.6	43.28%	8.1	81.9
Fort Irwin	36-AA-0068	Fort Irwin	300,000	13.5	43.28%	5.8	59.3
Borrego Springs LF	37-AA-0006	Borrego Springs	290,000	11.8	43.28%	5.1	51.8

2010 Wastewater Treatment Facility Data From U.S. EPA Database

** Shaded fields represent data estimated by linear regression and CH_4 content average.

Facility Name	Permit Number	City	Average Dry Weather Flow (mgpd)	Total gas collected (scfm)**	CH_4 Content (%)**	Total CH_4 (cfm)**	CH_4 potential (metric tons p.a.)
Hyperion	CA0109991	Playa Del Rey	379	5,208.3	65.00%	3,385.4	34,365.5
San Diego Metro Biosolids Center	CA0107409	San Diego	240	3,349.7	59.50%	1,993.1	20,231.8
Sacramento Regional County Sanitation District (SRCSD)	CA0077682	Elk Grove	181	2,511.9	59.50%	1,494.6	15,171.4
Orange County S.D. #2	CA1110604	Huntington Beach	127	1,597.2	61.50%	982.3	9,971.3
San Jose/Santa Clara WPCP	CA0037842	San Jose	107	1,461.1	59.50%	869.3	8,824.6
OCSD WRP No. 1	CA0110604	Fountain Valley	90	1,319.4	61.50%	811.5	8,237.1
Fresno-Clovis Regional WRF	CAUP00049	Fresno	66	878.8	59.50%	522.9	5,308.1
San Francisco South East	CA0037664	San Francisco South East	66	878.8	59.50%	522.9	5,308.1
EBMUD	CA0037702	Oakland	66	878.8	59.50%	522.9	5,308.1
Stockton Regional WCF	CA0079138	Stockton	32	396.0	59.50%	235.6	2,392.0
Inland Empire Utilities PLT 1	CA0105279	Ontario	31	380.4	59.50%	226.3	2,297.6
Riverside RWQCP	CA0105350	Riverside	31	377.4	59.50%	224.6	2,279.6
Union SD Raymond A. Boege Alvarado WWTP	CA3037869	Union City	25	371.5	59.00%	219.2	2,225.1
Modesto	CA0079103	Modesto	25	296.2	59.50%	176.2	1,789.0
Oxnard	CA0054097	Oxnard	24	275.3	59.50%	163.8	1,663.0
Encina WPCF	CA0107395	Carlsbad	23	271.5	59.50%	161.5	1,639.8
Santa Cruz	CA0048194	Santa Cruz	21	239.8	59.50%	142.7	1,448.5
Monterey Reg. WPCA	CA0048551	Marina	21	239.8	59.50%	142.7	1,448.5
South Bayside System Authority	CA0038369	Redwood City	20	225.6	59.50%	134.3	1,362.8
Oceanside	CA0037681	San Francisco	18	190.1	59.50%	113.1	1,148.4
Laguna Wastewater Treatment Plant	CA0022764	Santa Rosa	17	183.3	59.50%	109.1	1,107.2
Bakersfield WWTP #3	CAUP00041	Bakersfield	17	181.6	59.50%	108.1	1,096.9
Terminal Island	CA0053856	San Pedro	16	164.6	59.50%	97.9	994.0
Hale Avenue RRF	CA0107981	Escondido	15	160.3	59.50%	95.4	968.2
Valencia WRP/LACSD	CA0054216	Valencia	15	200.0	60.00%	120.0	1,218.1
Fairfield-Suisun WWTP	CA0038024	Fairfield	15	152.9	59.50%	91.0	923.6
Lancaster-LACSD	CAUP00033	Lancaster	15	148.9	59.50%	88.6	899.6
Bakersfield WWTP #2	CAUP00035	Bakersfield	14	139.0	59.50%	82.7	839.6
EMWD - Temecula Valley RWRF	CAUP00047	Temecula	14	97.2	69.00%	67.1	681.0
San Mateo	CA0037541	San Mateo	13	127.6	59.50%	76.0	771.0
Delta Diablo S.D.	CA0038547	Antioch	13	123.4	59.50%	73.4	745.2
Victor Valley W.R.A.	CA0102822	Victorville	12	119.0	59.50%	70.8	718.7

Visalia	CA0079189	Visalia	12	116.4	59.50%	69.3	703.2
Redlands	CAUP00062	Redlands	12	112.0	59.50%	66.7	676.6
Turlock	CA0078948	Turlock	12	110.6	59.50%	65.8	668.1
Oro Loma	CA1037869	San Lorenzo	12	107.8	59.50%	64.1	650.9
Moreno Valley	CAUP00053	Moreno Valley	12	106.3	59.50%	63.3	642.3
Sunnyvale	CA0037621	Sunnyvale	11	103.5	59.50%	61.6	625.2
Tulare	CAUP00022	Tulare	11	101.0	59.50%	60.1	609.7
Dublin-San Ramon	CA0037613	Pleasanton	10	86.5	59.50%	51.4	522.2
Dry Creek	CA0079502	Roseville	10	83.6	59.50%	49.8	505.1
Palmdale-LACSD	CAUP00040	Palmdale	10	75.0	60.00%	45.0	456.8
SOCWA J. B. Latham TP	CA0107417	Dana Point	9	75.5	59.50%	44.9	456.2
SOCWA Regional Treatment Plant	CA0107611	Laguna Niguel	9	75.1	59.50%	44.7	453.6
Hill Canyon WWTP	CA0056294	Camarillo	9	73.3	59.50%	43.6	442.5
San Luis Rey	CA0107433	Oceanside	9	70.8	59.50%	42.2	427.9
Corona	CAUP00043	Corona	9	69.4	59.50%	41.3	419.3
S. San Francisco/San Bruno	CA0038130	S. San Francisco	9	131.9	61.00%	80.5	817.0
Simi Valley	CA0055221	Simi Valley	9	65.2	59.50%	38.8	393.6
Santa Maria	CAUP00032	Santa Maria	8	61.2	59.50%	36.4	369.6
EMWD - San Jacinto RWRF	CAUP00055	Hemet	8	76.4	61.00%	46.6	473.0
Easterly WWTP	CA0077691	Elmira	8	59.5	59.50%	35.4	359.3
Rancho Las Virgenes Compost Facility	CA0056014	Calabasas	8	58.1	59.50%	34.5	350.7
Hayward	CA0037869	Hayward	8	53.8	59.50%	32.0	325.0
Santa Barbara El Estero WWTP	CA0048143	Santa Barbara	8	53.8	59.50%	32.0	325.0
West County Wastewater District WPCP	CA0038539	Richmond	8	49.8	59.50%	29.6	301.0
Central Marin Sanitation Agency	CA0038628	San Rafael	8	49.5	59.50%	29.5	299.3
Clear Creek	CA0079731	Redding	7	47.1	59.50%	28.0	284.7
Rialto WRF	CA0105295	Bloomington	7	46.4	59.50%	27.6	280.4
San Bernardino	CAUP00028	San Bernardino	7	46.4	59.50%	27.6	280.4
Napa	CA0037575	Napa	7	38.2	59.50%	22.7	230.6
Chico	CA0079081	Chico	7	35.3	59.50%	21.0	213.5
Santa Margarita WD Chiquita-WRP	CA1107417	San Juan Capistrano	7	33.9	59.50%	20.2	204.9
White Slough WPCF	CA0079243	Lodi	6	32.5	59.50%	19.3	196.3
Manteca	CA0081558	Manteca	6	29.9	59.50%	17.8	180.9
North San Mateo County Sanitation District	CA0037737	Daly City	6	27.8	59.50%	16.6	168.0
Watsonville	CA0048216	Watsonville	6	26.8	59.50%	16.0	162.0
Yuba City	CA0079260	Yuba City	6	26.8	59.50%	16.0	162.0
Atwater	CA0079197	Atwater	6	26.8	59.50%	16.0	162.0
Palm Springs	CAUP00061	Palm Springs	6	24.4	59.50%	14.5	147.4

Livermore Water Reclamation Plant	CA0038008	Livermore	6	24.3	59.50%	14.4	146.6
North Of River S. D. I WWTF	CAUP00037	Shafter	6	24.0	59.50%	14.3	144.9
Tracy	CA0079154	Tracy	6	19.7	59.50%	11.7	119.1
Colton	CA0105236	Colton	5	14.2	59.50%	8.4	85.7
Davis	CA0079049	Davis	5	12.6	59.50%	7.5	76.3
Hanford	CAUP00006	Hanford	5	12.6	59.50%	7.5	76.3
Goleta	CA0048160	Goleta	5	12.6	59.50%	7.5	76.3
San Leandro	CA2037869	San Leandro	5	11.5	59.50%	6.8	69.4
Petaluma Ellis Creek WRF	CA0037810	Petaluma	5	11.3	59.50%	6.8	68.5
Joint WPCP (Treats sewage from Long Beach, Los Coyotes WRP, La Canada, Pomona, San Jose Creek and Whittier Narrows)	CA0053813	Carson	5	9.4	59.50%	5.6	56.5
Porterville	CAUP00029	Porterville	5	7.4	59.50%	4.4	44.5
Novato S.D. Novato WWTP	CA0037958	Novato	5	5.8	59.50%	3.5	35.1
San Luis Obispo WRF	CA0049224	San Luis Obispo	5	5.5	59.50%	3.3	33.4
Delano	CAUP00005	Delano	4	4.1	59.50%	2.4	24.8
Elk River WWTP	CA0024449	Eureka	4	2.7	59.50%	1.6	16.2
Inland Empire Utilities PLT 2	CA0105287	Chino	4	2.7	59.50%	1.6	16.2
Los Alisos WRP	CA0105031	Lake Forest	4	1.4	59.50%	0.8	8.5

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