Energy Research and Development Division
FINAL PROJECT REPORT

PROTOTYPE SCALE BIOREFINERY INTEGRATION WITH RENWEABLE HEAT AND POWER

Sustainable Integration of Feedstock, Anaerobic Digestion, Gasification and Solar Cogen with Biodiesel Production

Prepared for: California Energy Commission
Prepared by: Biodiesel Industries of Ventura, LLC, a subsidiary of Biodico

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PREFACE

The California Energy Commission Energy Research and Development Division supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

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Sustainable Integration of Feedstock, Anaerobic Digestion, Gasification, and Solar Cogen with Biodiesel Production is the final report for the Prototype Scale Biorefinery Integration project (PIR-11-030) conducted by Biodiesel Industies of Ventura, LLC. The information from this project contributes to Energy Research and Development Division's Industrial/Agricultural/Water End-Use Energy Efficiency Program.

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ABSTRACT

Biodiesel production is one of the most promising pathways toward creating a sustainable transportation infrastructure in California. The fuel can be produced from a wide variety of locally grown resources, and can be produced and used with very low carbon intensity. There are several notable ways to improve the overall economic and environmental lifecycle though, in the growth of the feedstock, the use of feedstock byproducts, the use of biodiesel byproducts, and the use of renewable combined heat and power for production. Under PIR-11-030, Biodico analyzed, implemented, and optimized the use of inedible crops grown for biodiesel production, gasification of inedible seed meal, anaerobic digestion of the crude glycerin byproduct of biodiesel production, and use of solar thermal cogeneration to power the sustainable biofuel production. Dozens of varietals of castor, brassica, and pennycress were analyzed. Gasification was performed on a 20 kW grid-connected gasifier with heat recovery. Anaerobic digestion was performed on three prototype scale anaerobic digesters with varying process technologies. The solar cogeneration equipment was parabolic mirrored thin strip photovoltaic panels with heat recovery. Summaries of results from the report are included as final compiled data and greenhouse gas results are calculated. Economic and environmental analysis was performed on the data gained through testing and operation.

Keywords: California Energy Commission, biofuel, biodiesel, biogas, anaerobic digestion, gasification, syngas, solar, solar thermal, cogen, glycerin, crude glycerin, sustainability, distributed renewable combined heat and power, greenhouse gases, algae, algaculture, Artemia, brine shrimp, camelina, canola, castor, pennycress, MPU©

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EXECUTIVE SUMMARY

Introduction

Biodiesel is one of the most promising pathways to energy independence and societal sustainability in California and globally today. Biodiesel can be produced from a wide variety of fats and oils, can run in any diesel engine with little or no modifications, and can be produced with very low carbon intensity. Many of the byproducts in the production stream have no widely available renewable uses and, in several cases, have no widely available uses at all. This project was undertaken to determine how well these byproducts can be used to create combined heat and power and, combined with other technologies such as combined solar thermal, how well biodiesel can be produced entirely from self-generated heat and power and whether production facilities can be transformed into electricity exporting nodes.

Project Purpose

Biodico sought to create new renewable resources and to generate new sources of energy at several stages along the biodiesel production pathway: feedstock growth, feedstock processing, biodiesel production, and byproduct disposal. In doing so, significant economic and environmental gains can be made to the biodiesel production process.

The carbon intensity of biodiesel can vary substantially though, from 11.76 g CO2e/MJ for biodiesel produced from waste cooking oil to 83.25 g CO2e/MJ for soybean biodiesel. For food grade crops such as soybeans, large penalties are levied on the resulting fuel for indirect land use. To create a sustainable model going into the future, inedible crops will need to be developed for the State of California. Biodico tested various inedible crops for their energy production potential.

Usually seed meal is used for animal or human consumption, but in the case of inedible seed meal there isn't a clear pathway toward beneficial use. Gasification is a technology that allows for solid biomass to be converted into syngas, a combination of carbon monoxide and hydrogen, which can be combusted to create combined heat and power. Biodico sought to determine the suitability of inedible seed meal in gasification.

Crude glycerin is produced through biodiesel production at about a 1:4 ratio of total biodiesel production volume. While glycerin is used in a plethora of household and industrial products, the crude glycerin from biodiesel production contains lots of soaps, emulsified fatty acid compounds, water, and in some cases methanol. The cost for commercial glycerin producers to refine this material for sale exceeds the value of the product and disposal becomes a liability for many producers. Biodico examined the potential for prototype scale combined heat and power production from glycerin through anaerobic digestion.

A 20 kW solar thermal array was also installed at the Biodico production facility in Red Rock Ranch (Five Points, California). The system uses parabolic reflectors to direct the radiation to a thin strip solar panel mounted on heat recapture loops, providing 20 kW of electricity and 20 kW of thermal energy. Biodiesel production actually uses more heat energy than electrical energy so solar thermal technology seems well suited for co-location with biodiesel production

sites. Biodico assessed the suitability of this technology to providing reliable and sufficient heat and power for biodiesel production.

Project Process

Biodico analyzed 76 varietals of brassica, pennycress, and castor crops grown by UC Davis on agricultural test plots throughout California for energy potential. Seeds were tested for moisture content, oil content, volatile solids content, and ash content. A life cycle model was set up to determine likely energy yields from each of the varietals.

Biodico used a 20 kW gasifier to test the inedible seed meal. Tests were run on castor, canola, pennycress, and camelina meal. The seed meal was tested with and against a baseline of another unused resource in the San Joaquin Valley, almond orchard prunings. Densities of each material were obtained and the kWh of power generated by weight of analyte was tested. The gasifier was grid connected and the heat was captured for use in anaerobic digestion. The gasifier was also used heaviliy outside of the seed meal tests to access its overall contribution to the integrated bioenergy production.

In previous work with the CEC (ARV-10-024) Biodico found that glycerin will very successfully produce combustible methane through anaerobic digestion at a laboratory scale and analyzed its use with various co-digestants. Under PIR-11-030, Biodico looked at three anaerobic digester technologies representative of the current state of the art at the prototype scale using glycerin as both a co-digestant and as a standalone energy source. Each digester was operated for at least three months and particular attention was paid to the gas production rates and volumes, the gas composition, and the digestion rates as well as the chemical and physical characteristics of the incoming material (influent) and the outgoing material (effluent).

The solar thermal array was grid connected and the heat was tied in to the overall process. Throughout the project, the output of the array was monitored and recorded.

Project Results

The feedstock tests showed that low carbon intensity feedstocks can be produced in-state in the Central Valley. They also showed that the byproducts can be effectively used to create combined heat and power.

The gasifier tests showed that a variety of agricultural wastes from California's agricultural operations can be used to produce combined heat and power for the Modular Purification Unit. More specifically, they showed that the byproducts from the crops that are used to create biodiesel on marginal farmland can be used for combined heat and power through gasification and anaerobic digestion.

The anaerobic digesters that were used to digest the glycerin were very different. For the Novus, Himark, and SeaHold digesters, the project team found that the optimum percentage of glycerin to run in the digester remained fairly consistent across technologies. The volume of methane produced per volume of glycerin also remained relatively consistent throughout. There were significant performance differences between digesters in the hydraulic retention time, the required labor, and the use of byproducts.

The solar CHP (Combined Heat and Power) work was also successful in that it allowed for enough heat and power to be generated to significantly add to the sustainability of the MPU and to reduce the overall carbon intensity.

Project Benefits

The project demonstrates the downstream lifecycle of energy production from feedstocks that are grown on marginal farmland. This allows for further use of these crops in a commercial capacity. The project also provides a clear pathway for the use of glycerin in commercial or municipal scale anaerobic digesters. Finding that the glycerin has similar effects on digesters regardless of scale has potentially large ramifications on the confidence that large digester operators have in operating with the new feedstock. The same sort of gains are realized from the gasifier work. The use of seed meal in the gasifiers and the characterization of the power output on the prototype scale can help to give larger scale gasifier operators confidence in the use of the feedstock and can help farmers understand the true value of marginal land bioenergy crops. The solar thermal work can also serve as an example for the integration of the technology into liquid biofuel production sites.

The project produced low carbon intensity heat and power to support the production of biodiesel. The work was performed in a region of economic hardship, and expansion of this work can provide jobs and economic growth to the area. If expanded to meet the feedstock needs of the 18 million gallon per year biodiesel production facility currently installed at Red Rock Ranch, this project can significantly reduce greenhouse gases and criteria pollutants in an area of high air pollution.

CHAPTER 1:
Feedstock Cultivation, Harvesting, and Processing

1.1 Cultivate, harvest and process (oil extraction) castor at Red Rock Ranch and UC Davis Ag Field Stations at Davis, Five Points, the Imperial Valley and Salinas

Biodico tested 31 different seed varietals for energy potential. The varietals were grown at five locations: the UC Davis Westside Research and Extension Center located adjacent to Red Rock Ranch, the UC Davis Desert Research and Extension Center in the Imperial Valley, the UC Davis Salinas Research Station, the UC Davis Agricultural Experiment Station on campus, and at the Biodico Jatropha Grove in Santa Barbara. The varietals are of castor, camelina, canola, jatropha, and pennycress plants. The oilseeds are first tested thermogravimetrically to determine the total moisture, ash, and potential energy as volatile solids of the whole seed. A separate sample of the seed is then tested in a Soxhlet apparatus to extract the oil and to separate the dry meal. The dry meal is then tested thermogravimetrically to determine the volatile solids content and the ash content. This helps to determine how much energy the meal will be able to produce in gasification and what percentage will be used for biochar. In total, this divides the seeds into four parts: water content, oil, volatile solids, and ash. The water and moisture is evaporated off in the extrusion process, the oil is used to make biodiesel, the volatile solids are converted to carbon monoxide and hydrogen syngas in the gasifier, and the ash is used as biochar from the gasifier. The Process Flow Diagram (PFD) illustrates the pathway of the seeds after they enter the facility (Figure 1).

Figure 1: Process Flow Diagram for Seed Testing

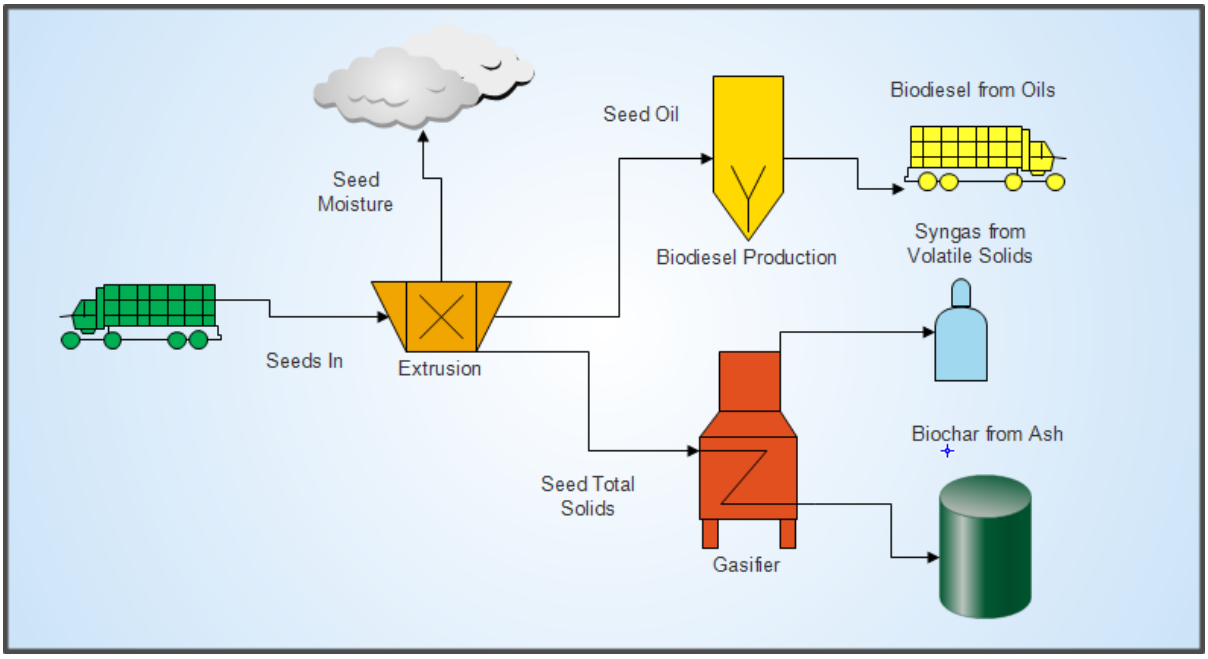

Image Credit: Biodico

Figure 2 provides the results of the first thermogravimetric test in which the seeds are split into moisture, volatile solids (including oil), and ash (fixed solids). The DK samples are various varietals of castor seed.

Figure 2: Full Seed Thermogravimetric Profiles

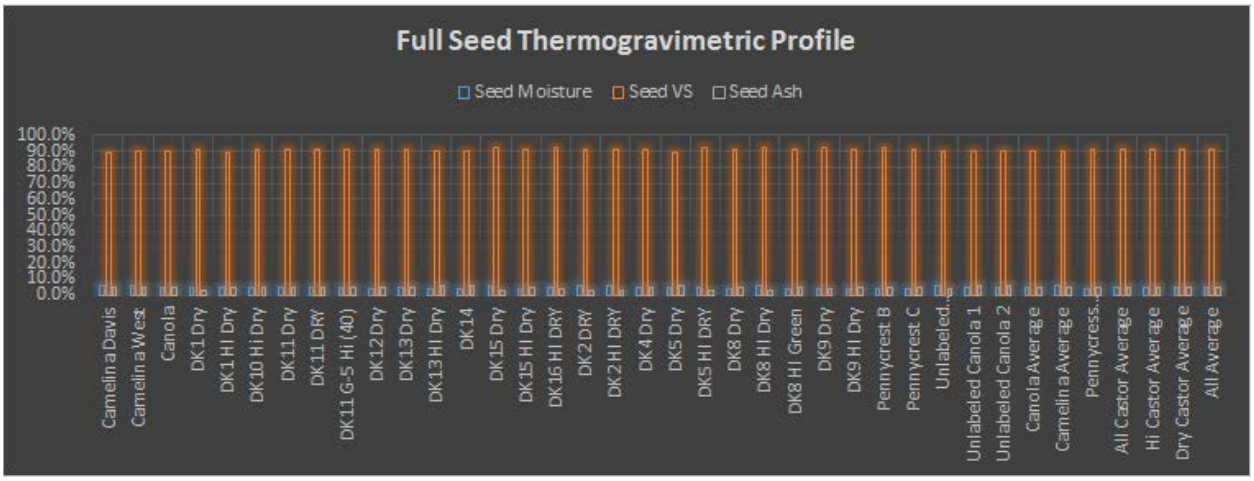

Image Credit: Biodico

Since the volatile solids content makes up the majority of the total seed solids (generally over 90%), the moisture and ash content can be difficult to visualize on the chart above. Figure 3 shows only the moisture and ash content.

Figure 3: Full Seed Moisture and Ash Profiles

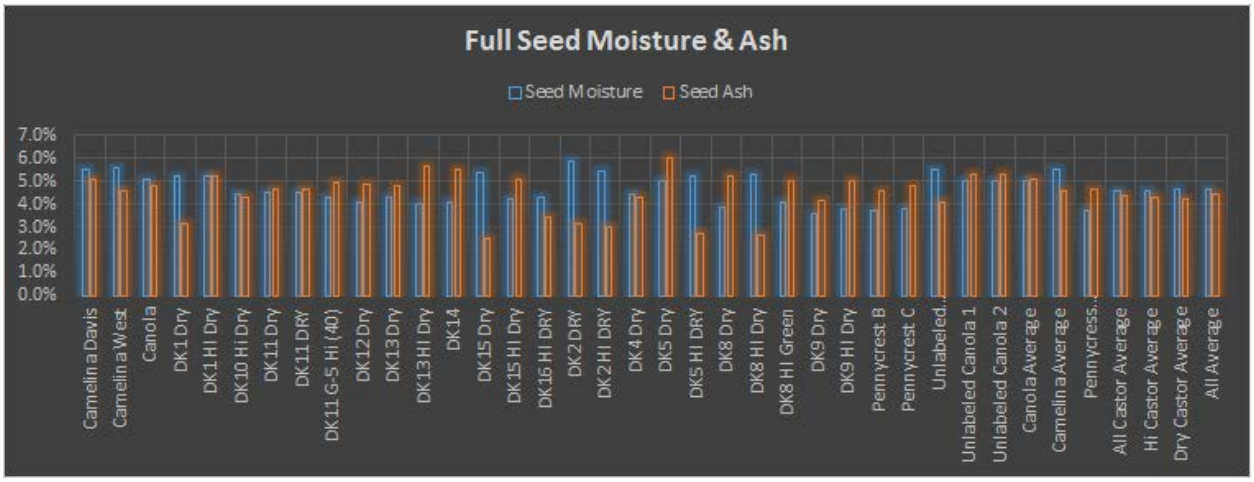

Image Credit: Biodico

The next test performed on each of the seed samples was a Soxhlet oil extraction. This determines the oil concentration of each of the samples (Figure 4).

Figure 4: Seed Varietal Oil Profiles

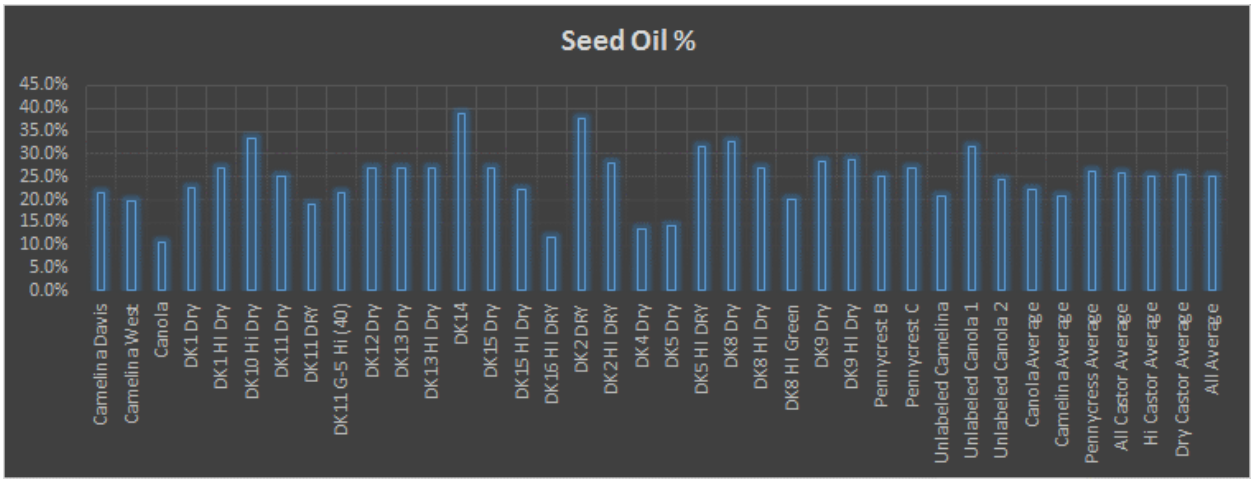

Image Credit: Biodico

Just as each sample of seed mass can be divided into moisture, volatile solids, and ash, each seed sample can also be divided into moisture, oil, and meal. The meal can then be calculated as the portion of the seed weight that is not moisture and that is not oil. The seed meal and the oil concentrations of the seed weight are provided in Figure 5.

Figure 5: Seed Oil and Meal Profiles

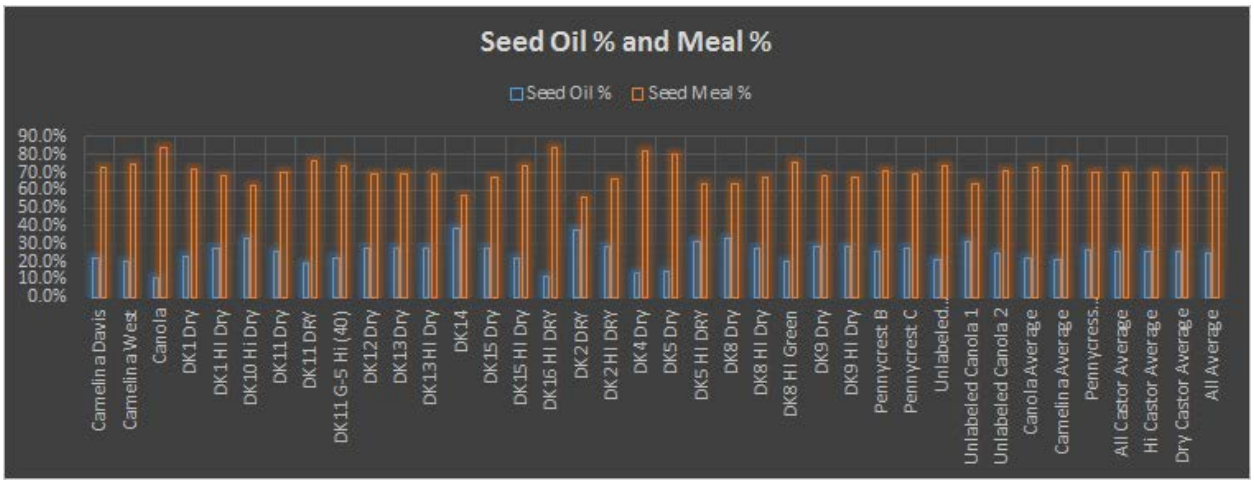

Image Credit: Biodico

The oil is all composed of volatile solids, but not all volatile solids are oil. The meal contains the volatile solids that are not oil and the ash content. The volatile solids in the meal can be called volatile carbohydrates and they will be converted to electricity and recaptured process heat in the gasifier. The ash content will be used as biochar to add carbon to the soil for agriculture. In order to determine the split between volatile carbohydrates and ash in each of the meal samples a thermogravimetric analysis was performed (Figure 6).

Figure 6: Seed Meal Thermogravimetric Profiles

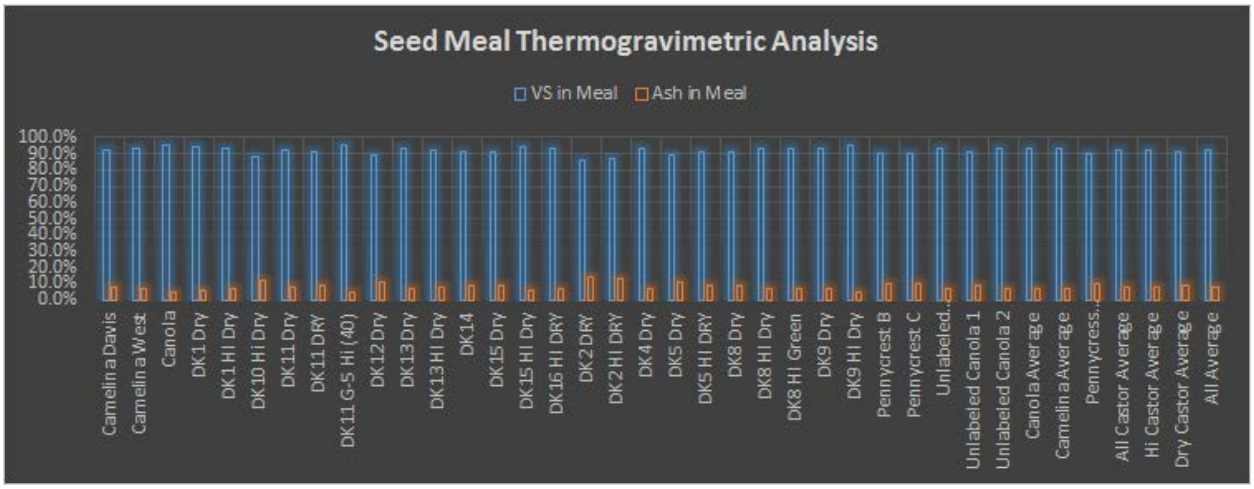

Image Credit: Biodico

This allows an entire analysis of the seed to be given: the moisture that will be lost in the seed press, the oil that will be used to make biodiesel, the volatile carbohydrates that will be used to generate electricity, and the ash that will be used as biochar. The division of the whole seed into these four parts is shown in Figure 7.

Figure 7: Full Seed Combined Profiles

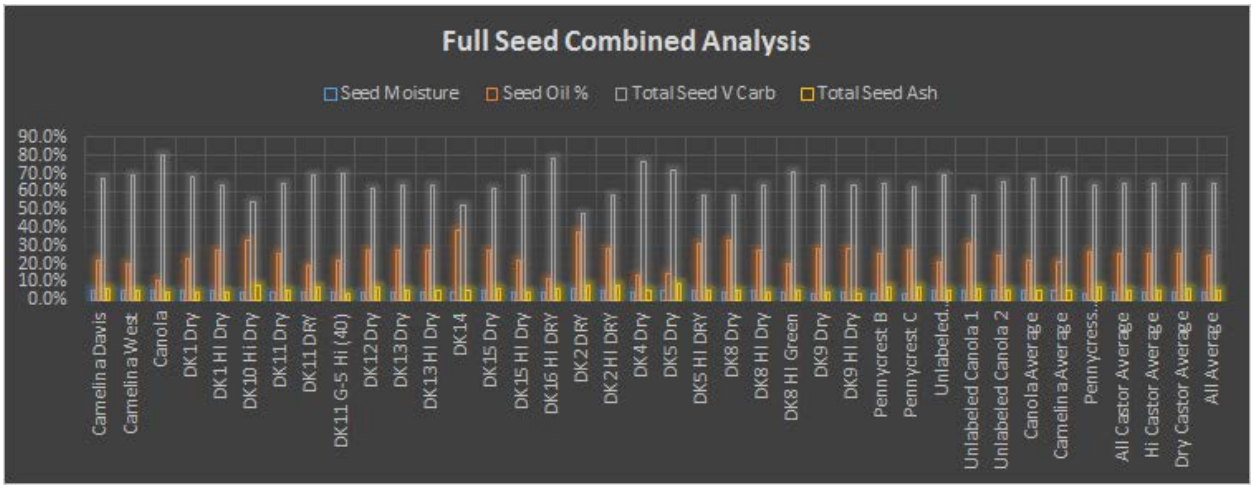

Image Credit: Biodico

This data can be used to calculate the gallons of oil per ton of seed meal for each varietal (Figure 8).

Figure 8: Gallons of Oil per Ton of Seed by Varietal

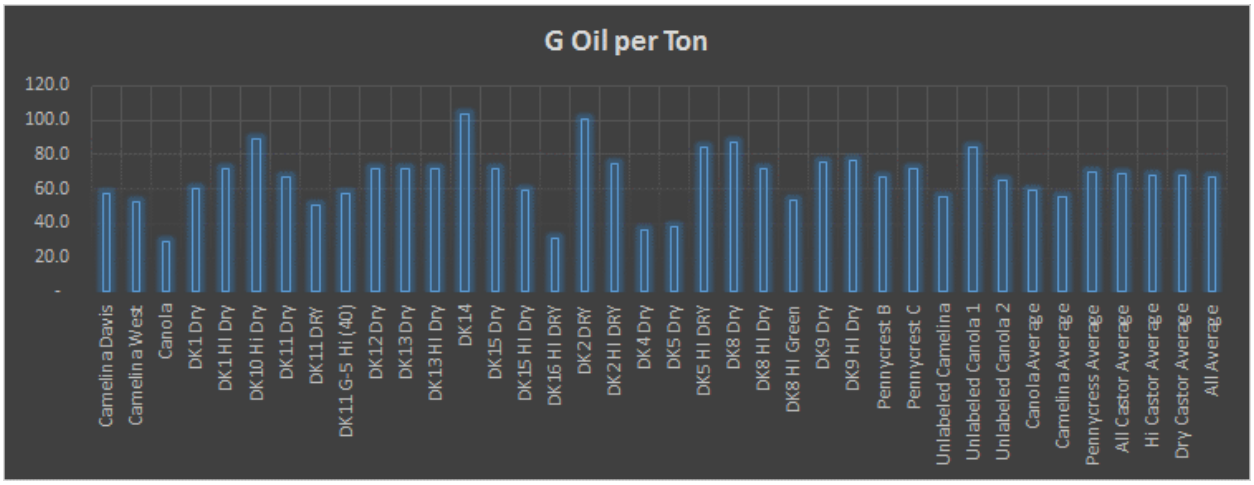

Image Credit: Biodico

The volatile carbohydrate concentration data gained from the Soxhlet and thermogravimetric analyses can be used to project the kWh of electricity per ton of seeds (Figure 9).

Figure 9: Gasifier kWh per Ton by Seed Varietal

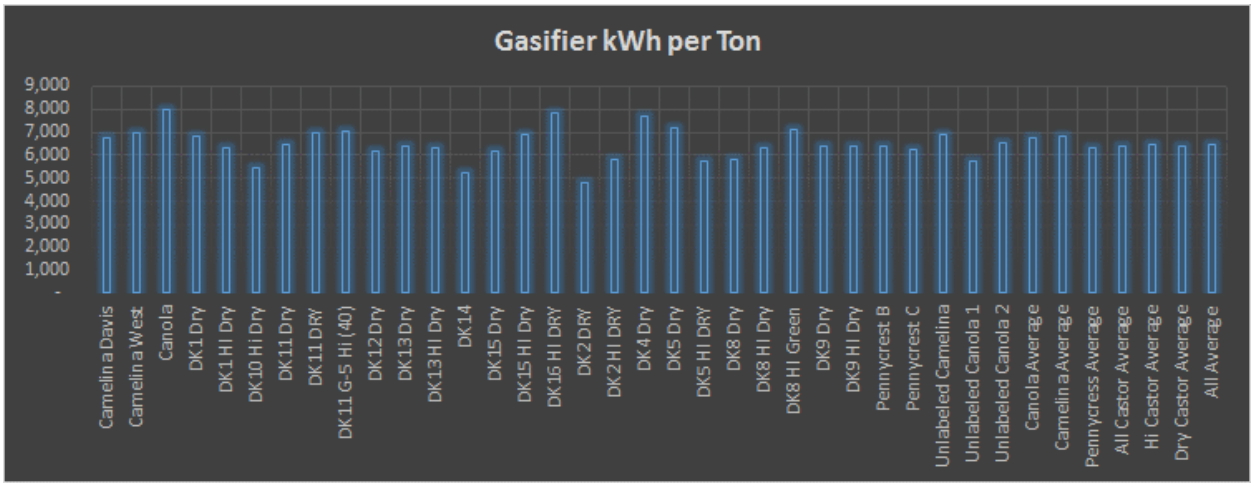

Image Credit: Biodico

The volatile carbohydrate concentration data gained from the Soxhlet and thermogravimetric tests can also be used to project the Mmbtus of heating energy per ton of seeds (Figure 10).

Figure 10: Heat Mmbtus per Ton by Seed Varietal

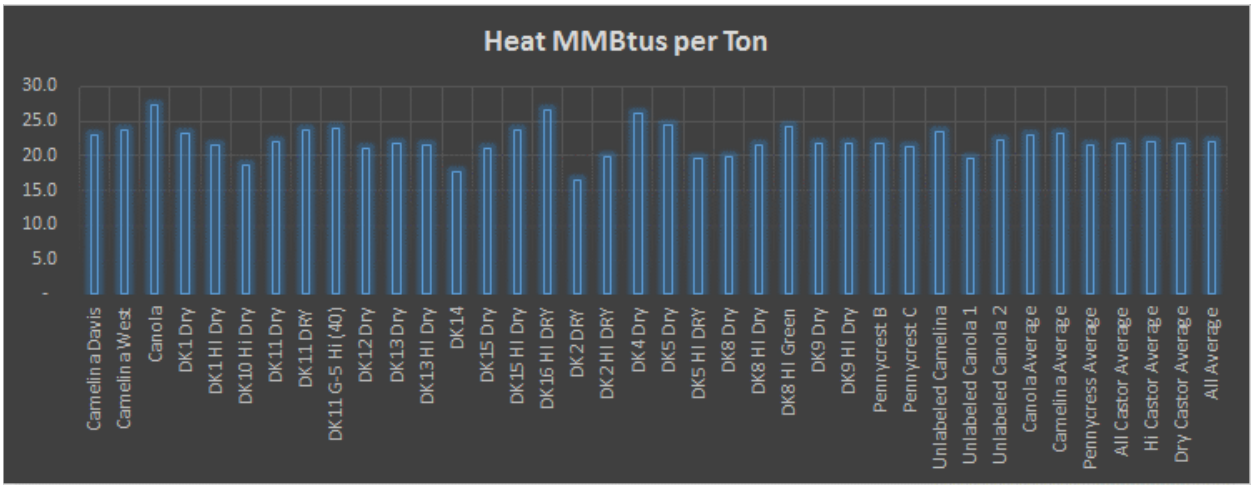

Image Credit: Biodico

These tests are combined together in Figure 11 and show the concentration of energy by type in each seed varietal. To effectively compare the energy types with each other, they are all converted to Mmbtus. Biodiesel has 119,500 Btus per gallon.

Figure 11: Energy Profile for Seed Varietals

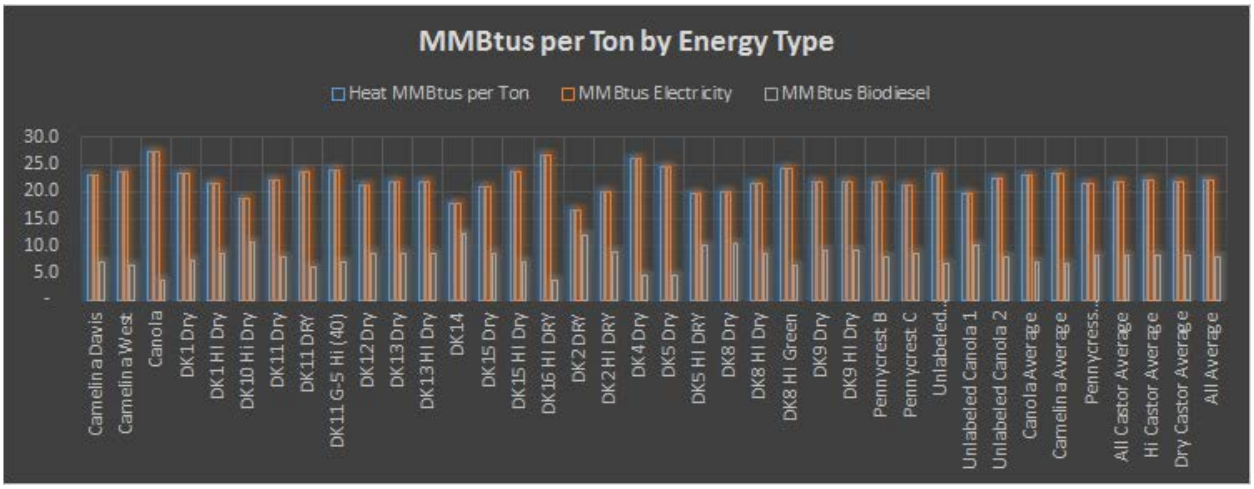

Image Credit: Biodico

Displaying the Mmbtus of energy by energy type as a pie chart can help to visualize the differences between the varietals. The averages for each species are provided in Figure 12.

Figure 12: Energy Type by Plant Species Summary

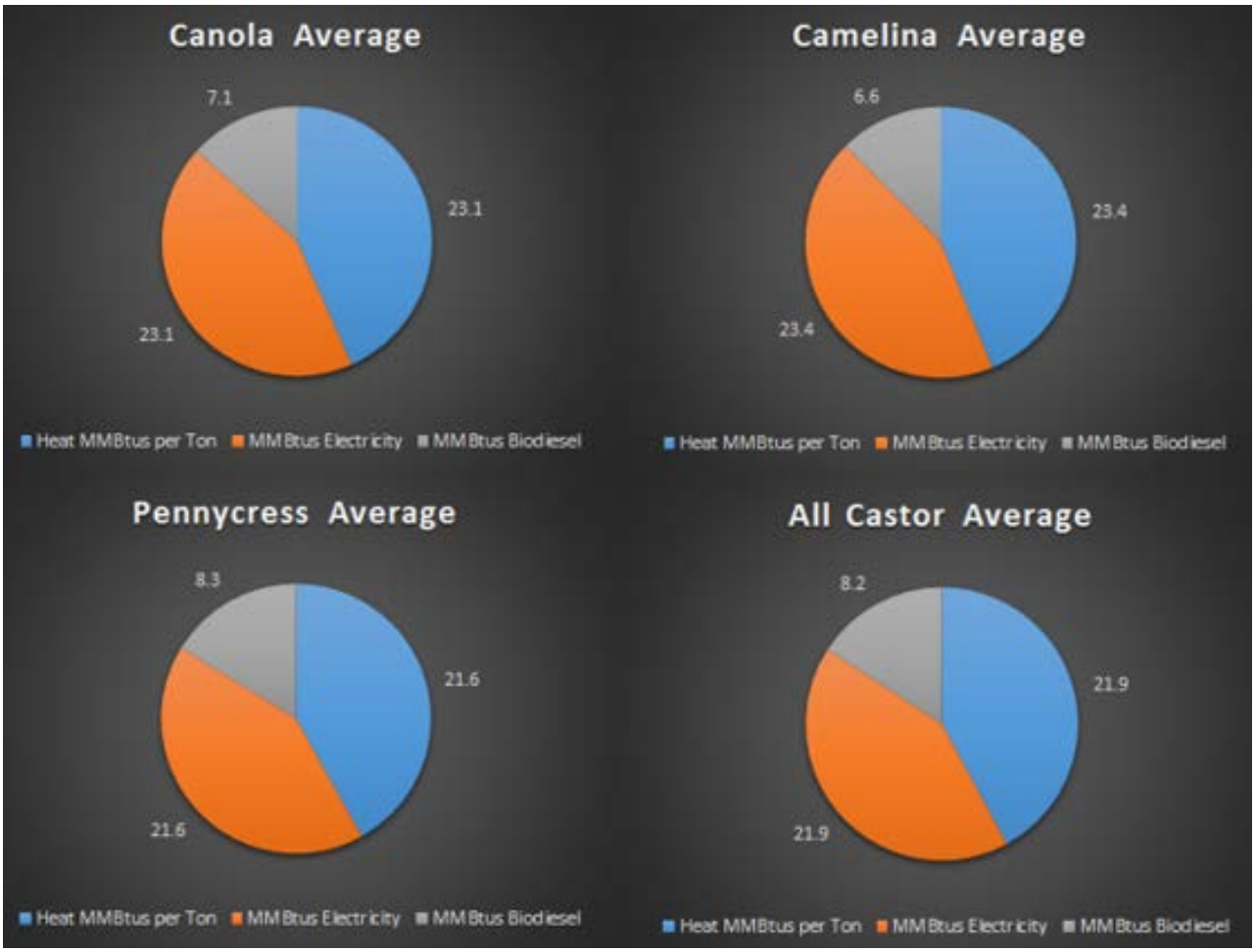

Image Credit: Biodico

1.2 Expand algaculture ponds, cultivate, harvest and process (oil extraction) algae/Artemia at NBVC

Algae harvests have been regularly performed on Biodico's algaculture ponds at the Naval Base Ventura County. In previously performed work, Biodico found optimum levels of the manipulable variables of salinity, pH, harvesting mesh size, and nutrient type and quantity as well as non-manipulable varietals (for this system) of temperature and solar irradiance. The previous study also took into account the effect of uncontrolled (for this setup) environmental factors of sunlight and temperature.

For this project, bulk harvesting data was taken to extract the oil for reference fuel production. Feed was added to the system as found by the best results from previous work. The reference fuel will allow for the *Artemia* oil to be included in Biodico's FTNIR method for real time testing of fuel.

1.3 Transport seeds, oil and oil extraction solids to NBVC

The seeds were transported from the UC Davis agricultural research stations to UC Davis for dehulling and then to NBVC. Figure 13 shows a seed cleaner and dehuller similar to the one that was used at UC Davis for this work. At NBVC the seeds were tested in the laboratory as shown in section 1.1 for accurate assessments of oil content, moisture content, ash content, and volatile solids content.

Figure 13: Seed cleaner and dehuller

Image Credit: Almaco.

The seeds were also processed through the GFE oil extractor to get larger volumes of oil and seed meal for further testing (Figure 14).

Figure 14: GFE Oil Extractor

Image Credit: Biodico

The meal was grouped together by species: castor, canola, jatropha, pennycress, and camelina. The meal was then transported back to RRR for use in the gasifier.

1.4 Report on volumes produced and crush yields

The report on the volumes produced, the yields per acre, and numerous other crop production data points are given in Appendix 1: UC Davis Report.

The sample sizes for most of the varietals that were tested by thermogravimetry and Soxhlet extraction weren't large enough to run through the oil seed press. The castor varietals, for example, were grown on smaller plots and the seed volumes that were available were limited. Seven of the varietals, however, were provided in large enough quantities to run through the press. The yields for each of these species of seeds on the larger prototype extrusion scale are provided in Figure 15.

Figure 15: Seed Crushing Data

Seed Crushing Data						
Seed Type	mL Oil	Seed lbs	Press Time Minutes	Meal lbs	Seed kg	Oil L/Seed kg
Camelina	1730	13	60	8.7	5.9	0.29
Rossien Canola	1500	14	60	10.6	6.4	0.24
Camelina Davis	2113	14	60	9.3	6.4	0.33
Camelina West	2645	15	45	9	6.8	0.39
Canola	2050	17	60	11.9	7.7	0.27
Unlabeled Pennycress	1500	15	60	10.8	6.8	0.22
Canola 2	2170	12	60	7.2	5.5	0.40

Image Credit: Biodico

CHAPTER 2:
Fabrication & Installation

2.1 Ensure that subcontractors fabricate and install solar cogen, gasification and anaerobic digestion equipment at NBVC

The solar cogen was installed by Cogenra and is effectively producing heat and electricity (Figure 16). A full description of the system and its performance can be found in Appendix 1: Cogenra Report.

Figure 16: Solar Cogen produces both heat and power

Image Credit: Biodico

The anaerobic digesters were installed by Novus, Himark, and Seahold sequentially. This allowed for Biodico and the rest of the project team to be able to focus more on each of the technologies during their operation periods.

The Novus system was the first to be installed (Figure 17).

Figure 17: Novus Anaerobic Digester

Image Credit: Novus.

The digester is a fixed film multi-stage mesophilic reactor with a total of 2,000 gallons of digester space and a hydraulic retention time of four days. The feedstock for the digester is loaded in at 500 gallons per day to a 1,000 gallon tank where the hydrolysis, acetogenesis, and acidogenesis take place. On average, the substrate will spend two days in this primary tank, named the hydrolysis tank. From the hydrolysis tank, the material passes through a screw press to remove the remaining solids. The solids are removed so that the fixed film layers in the final reactors don't clog. After the material passes through the screw press, its composition will primarily be a solution of acetic acid and acetate in water, along with dissolved trace nutrients. This material is dubbed leachate in the Novus process and it is stored in the leachate tanks. At this point the process flow changes from a batch feed process of discrete chunks of material to a continuous flow pump that feeds from the leachate tanks into the final digesters, termed the methanogenesis tanks. Figure 18 shows the general process flow for the Novus system.

Figure 18: Novus Overview PFD

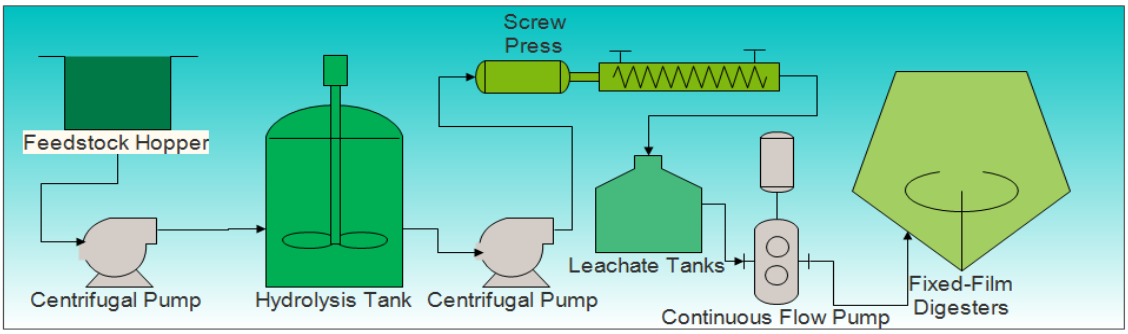

Image Credit: Biodico

The Himark digester was the second system operated under this project (Figure 19).

Figure 19: Himark Anaerobic Digester

Image Credit: Himark.

The Himark digester is a 590 gallon (2,225 liter) thermophilic digester with a 10 day hydraulic retention time. While the retention time is quite a bit longer than Novus' four day retention time, it is still quite a bit shorter than the standard 30 day HRT that is common at municipal wastewater treatment plant anaerobic digesters throughout the world. While thermophilic digester temperatures will generally decrease the stability of digeters, the higher temperature also shortens the HRT. This allows the Himark digester to cut the process time down with a relatively simple design (Figure 20).

Figure 20: Himark Overview PFD

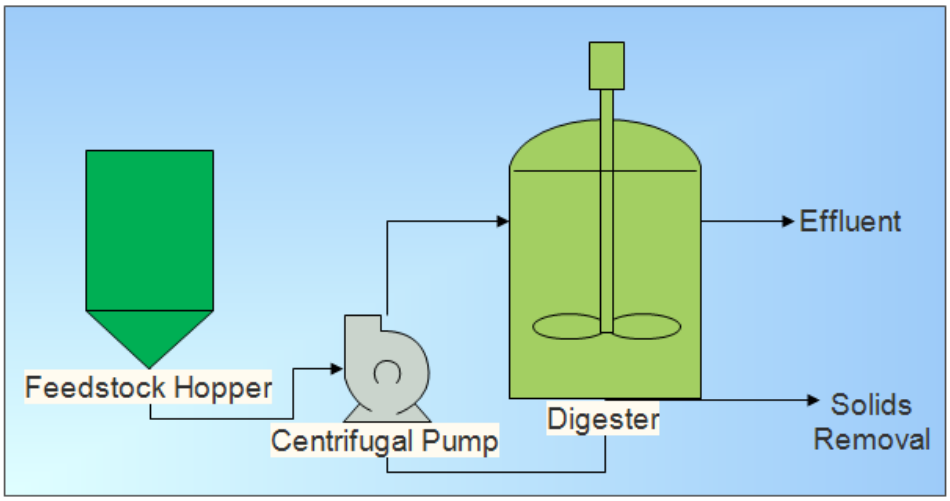

Image Credit: Biodico

The Seahold unit was the third unit to be operated at RRR (Figure 21).

Figure 21: Seahold Anaerobic Digester

Image Credit: Biodico

The Seahold unit was designed to be able to operate with a number of different process flow designs. The unit was started in batch digester mode in order to seed the unit and was then changed to operate as an upflow anaerobic sludge blanket (UASB) digester in order to collect data. Each of the three digesters has a 500 gallon total capacity, but a third of the capacity is kept liquid-free as head space. In the UASB configuration the feedstock hopper feeds into the rightmost digester from the bottom of the tank. From there the digestate leaves the tank at the spillover hose located two thirds of the way up the digester and feeds into the bottom of the next digester. This is repeated through digesters two and three until the effluent leaves from digester three's (the far left digester) spillover line. The UASB system has been tested at sub-mesophilic temperatures and was kept with the ambient atmosphere from the start of operations in September. A PFD for the system is shown in Figure 22 with the codes for each of the digester parts in Figure 23.

Figure 22: Seahold Overview PFD

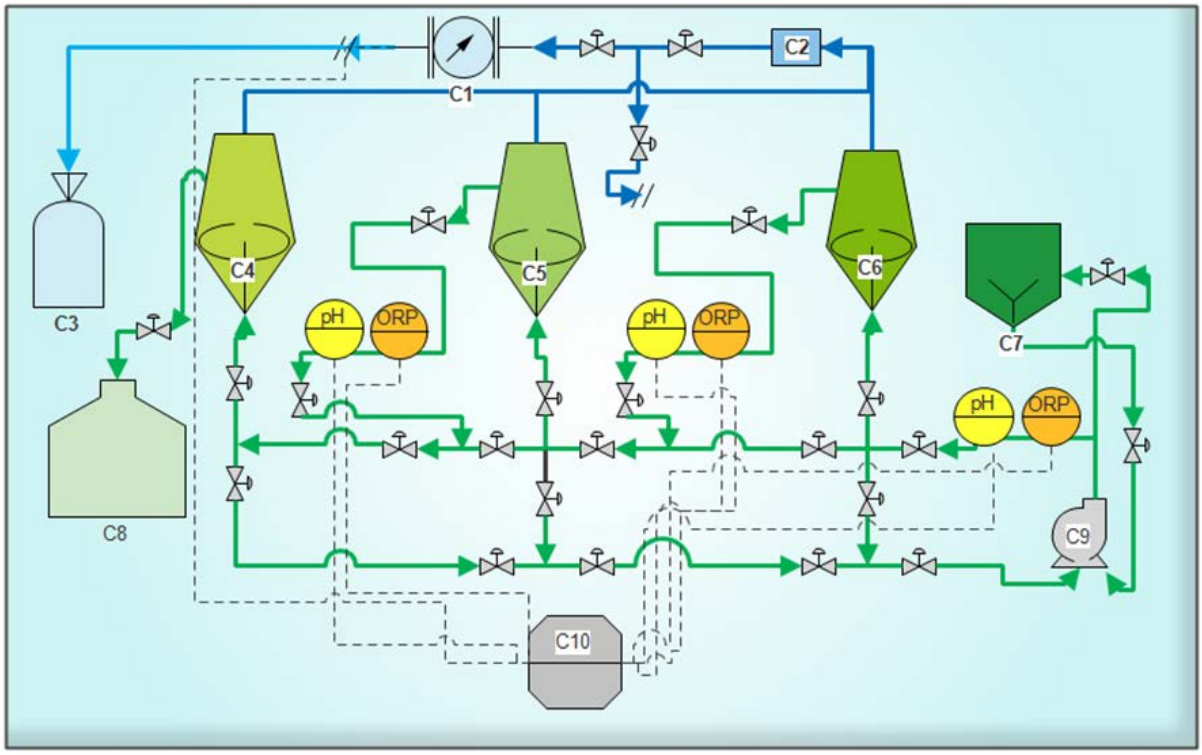

Image Credit: Biodico

Figure 23: Seahold PFD Legend

PFD Legend			
Code	Equipment	Flow/Volume	
C1	Biogas Flow Meter	60	L/min
C2	Water Knockout	NA	
C3	Biogas Surge Tank	6,000	L
C4	Digester 3	500	G
C5	Digester 2	500	G
C6	Digester 1	500	G
C7	Influent Tank	215	G
C8	Effluent Tote	300	G
C9	Centifugal Pump	20	GPM

Image Credit: Biodico

2.2 Provide validation reports from the Navy that the algaculture, solar cogen, gasification and anaerobic digestion equipment has been installed at NBVC

Representatives from NAVFAC EXWC have been to Red Rock Ranch on several occasions to check the installation for the Cogenra solar cogen equipment, the APL gasification equipment, the Novus anaerobic digestion equipment, the Himark anaerobic digestion equipment, and the Seahold anaerobic digestion equipment. Figure 24 is a validation report from the Navy for the installation of the equipment.

Figure 24: NAVFAC EXWC Validation

BIODICO
SUSTAINABLE BIOREFINERIES

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NAVFAC EXWC INSTALLATION VALIDATION FOR BIODIESEL INDUSTRIES OF VENTURA

CEC PROJECT: PIR-11-030

On the visit dates listed below, the following items were found to be installed at the Biodico project site at Red Rock Ranch in Five Points, CA.

COMPONENT	DATE	INITIALS	
Cogenra Solar Cogen	May 29, 2015	BH	KL
APL Gasifier	May 29, 2015	BH	KL
Novus AD System	Aug 22, 2013	BH	KL
Himark AD System	Dec 10, 2013	BH	KL
Seahold AD System	May 29, 2015	BH	KL

Bruce Holden

Bruce Holden, PE
NAVFAC EXWC

Kyle Lawrence
NAVFAC EXWC

Image Credit: Biodico

CHAPTER 3:
Integrate, Interconnect and Start-Up the Equipment

3.1 Integrate Task 4 equipment with the biodiesel production facility at Red Rock Ranch

The location of the anaerobic digesters, the gasifier, and the solar cogen was changed from NBVC to RRR at the start of the grant. Biodico is currently finishing construction of an 18 million gallon per year commercial biodiesel production facility at RRR and the equipment from the grant project has been tied into the infrastructure. The power from both the gasifier and the solar cogen is tied into the power grid onsite and the heat from the gasifier has been tied into the Seahold digester system. Heat exchangers and piping have been set up for this heat energy to feed into the 10 MMGPY biodiesel plant as well. A picture of the gasifier is given in Figure 25. See an overview of the system at https://www.youtube.com/watch?v=rIj0fl76V3E.

Figure 25: APL Gasifier

3.2 Interconnect the Task 4 equipment with the utility provider at Red Rock Ranch

Interconnection to PG&E has been completed and the system is logging electric production (Figure 26).

Figure 26: PG&E Interconnect

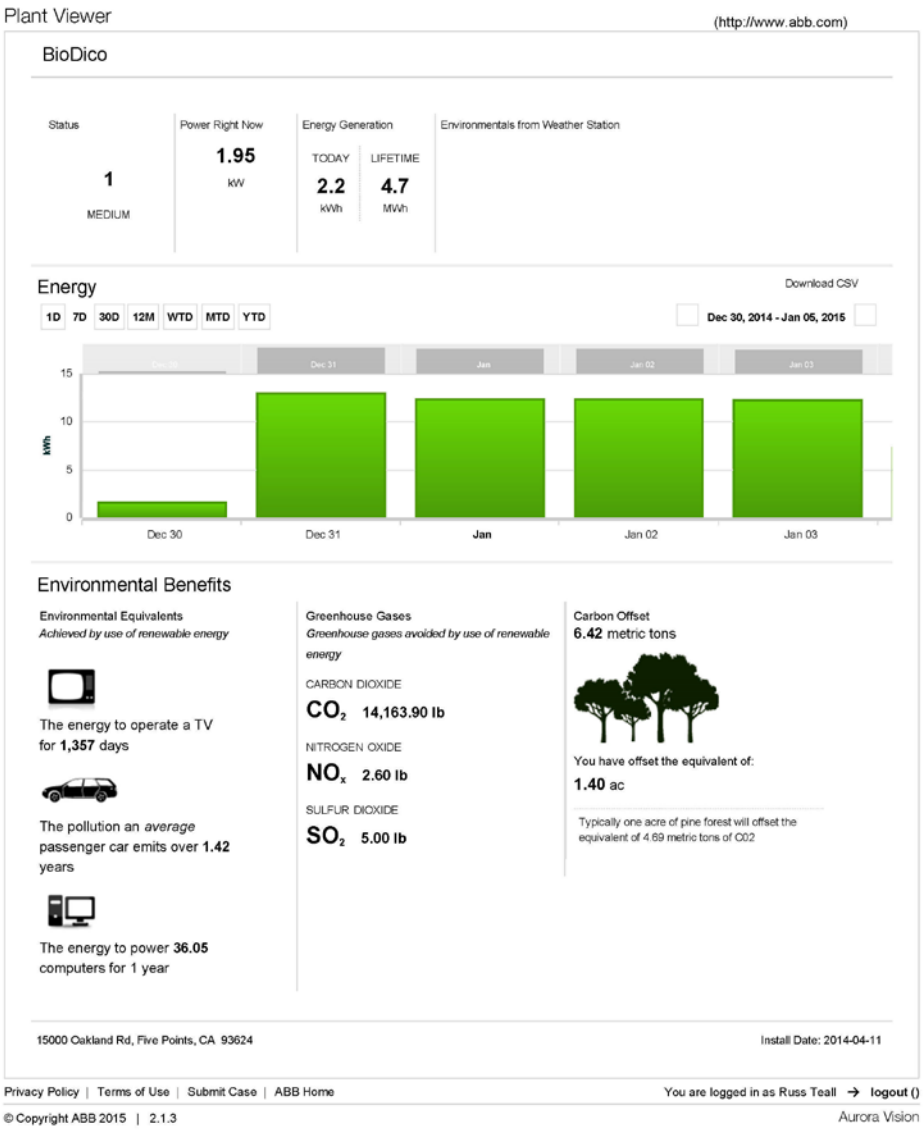

Image Credit: Biodico

3.3 Operate the integrated and interconnected Task 4 equipment at Red Rock Ranch

3.3.1 Novus

The Novus unit began operations on April 1, 2013 and continued operations through October 23, 2013. Throughout the process three streams were tested in Biodico's Naval lab to gauge the performance of the system: the glycerin entering the system, the leachate just before methanogenesis, and the effluent exiting the system (termed digestate in the Novus system). The gas production, the oxidation reduction potential (ORP) of the different digester stages, and the pH of the different digester stages were measured by the facility onsite. The pH is an indicator of the amount of acetic acid built up in the digester at various stages. Generally, if the pH level drops below 6.0 in a digester, the acetic acid is starting to build up too much and the methanogens are in danger of crashing. In the case of the Novus equipment, the acetogenesis and acidogenesis are performed in a separate tank and at the "leachate" stage, the pH should be low. The acetic acid blend is then fed into the methanogenesis tanks where the pH should be above 6.0. The ORP gives a value for the digester solution's affinity to acquire electrons and be reduced. This allows for the digester operator to determine the stage of digestion and whether the microbes in that stage are healthy. The test was started with a combination of manure and glycerin in order to build up the nutrient base for the microbes. The test was then switched over to all glycerin and no manure and used a synthetic nutrient blend to maintain the health of the microbes. The optimum percentage of glycerin to add to the digester, without manure, was found to be 0.7% per day by volume. Multiplying this by the HRT gives a loaded glycerin percentage in the digester of 2.8% by volume. Figure 27 shows the average standard cubic feet per minute by day from the middle of May to the end of October.

Figure 27: Novus SCFM per Day of Biogas

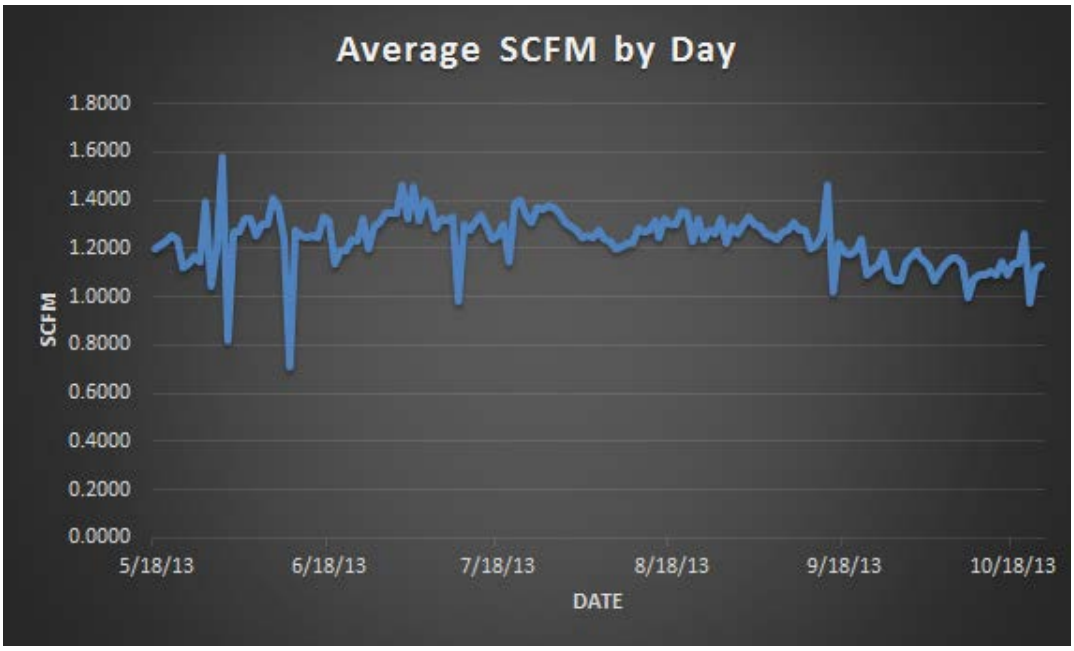

Image Credit: Biodico

The ORP for the Novus digester through production is shown in Figure 28. The 2001 line represents the hydrolysis tank. The 4001 and 4002 lines represent the methanogenesis tanks. The top target range is for the hydrolysis, acetogenesis, and acidogenesis portions of the process. The bottom target range is for the methanogenesis portion of the process. The line showing the new glycerin happened when the composition of the glycerin coming into the equipment changed part of the way through the test. The new glycerin was the byproduct of a biodiesel production reaction that included an acid esterification step. The acid esterification uses sulfuric acid and, as a result, the sulfate concentration in the glycerin was significantly higher. This caused sulfur reducing bacteria to grow along with the methanogens and caused the digester to have worse performance. The shift was reflected in the ORP readings of the digesters.

Figure 28: Novus ORP

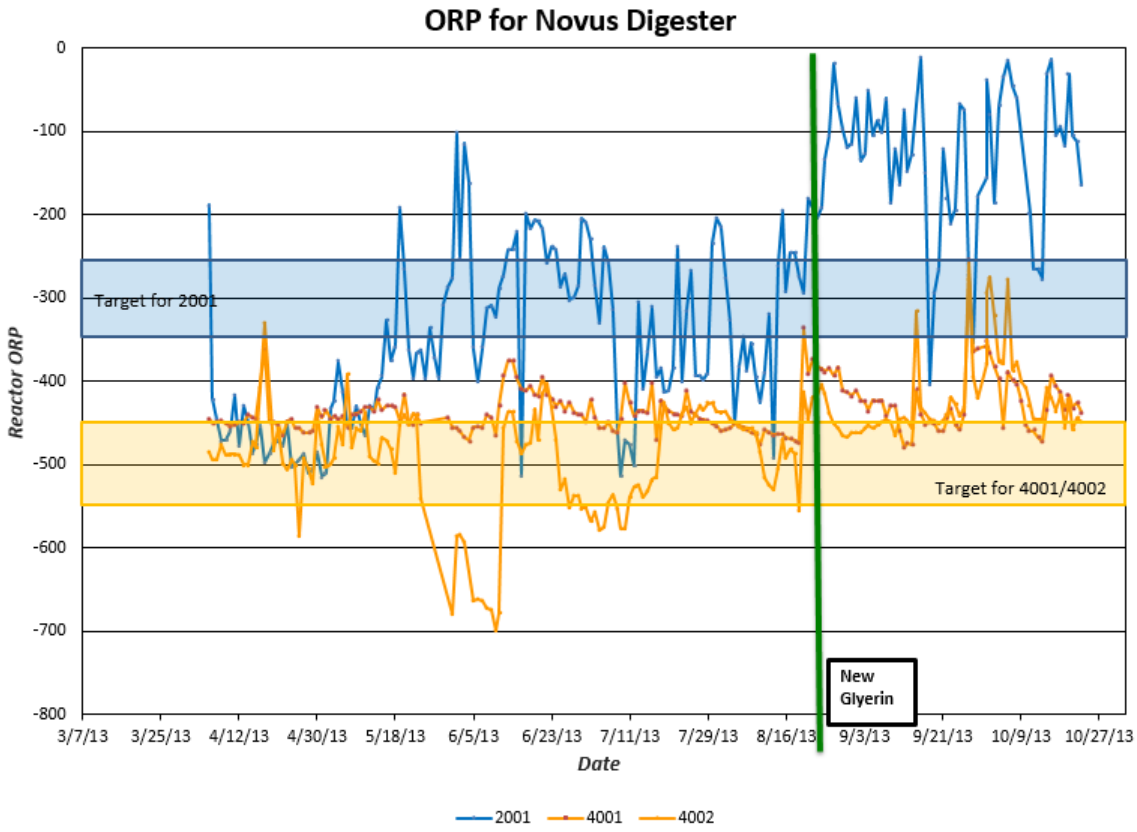

Image Credit: Biodico

The COD for the leachate and digestate in the Novus system is given in Figure 29. The leachate is taken after the the influent passes through the stages of hydrolysis, acetogenesis, and acidogenesis and the digestate is taken after the leachate passes through methanogenesis. As such, it is expected that the COD for the leachate is higher than the COD for the digestate. The rising and falling of the COD for both samples also mirror each other week to week, which is also expected because both samples are from different points in the same process flow.

Figure 29: Novus COD

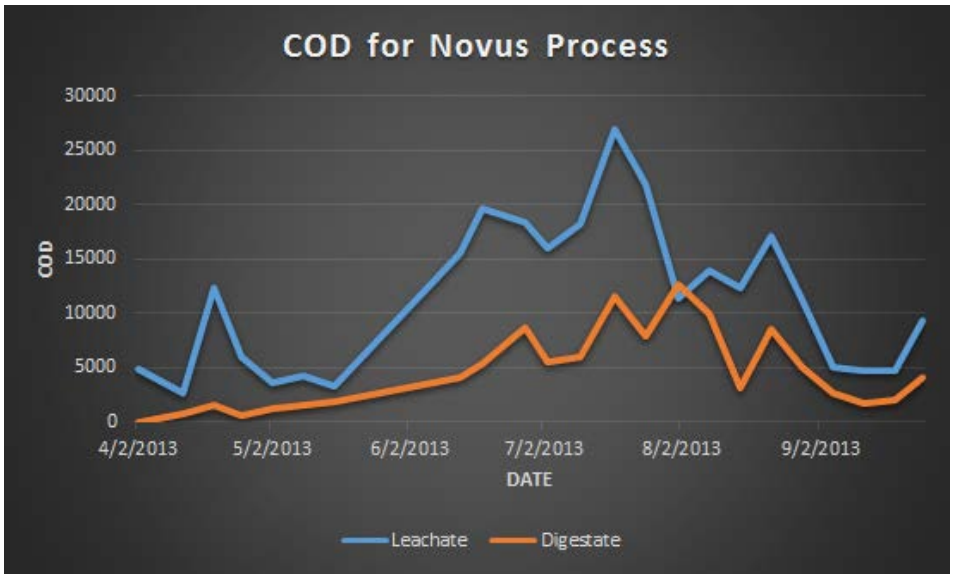

Image Credit: Biodico

The pH for the reactors in the Novus unit in-situ are provided in Figure 30. As with the ORP chart, the 2001 line shows the hydrolysis tank where hydrolysis, acetogenesis, and acidogenesis are performed and the 4001 and 4002 tanks are for the methanogenesis reactors. The methanogenesis tanks stayed within the target region for most of the production time, but the hydrolysis tank did not drop as low as anticipated. When it did drop into the range though, as marked by the new glycerin line, production volumes decreased.

Figure 30: Novus pH

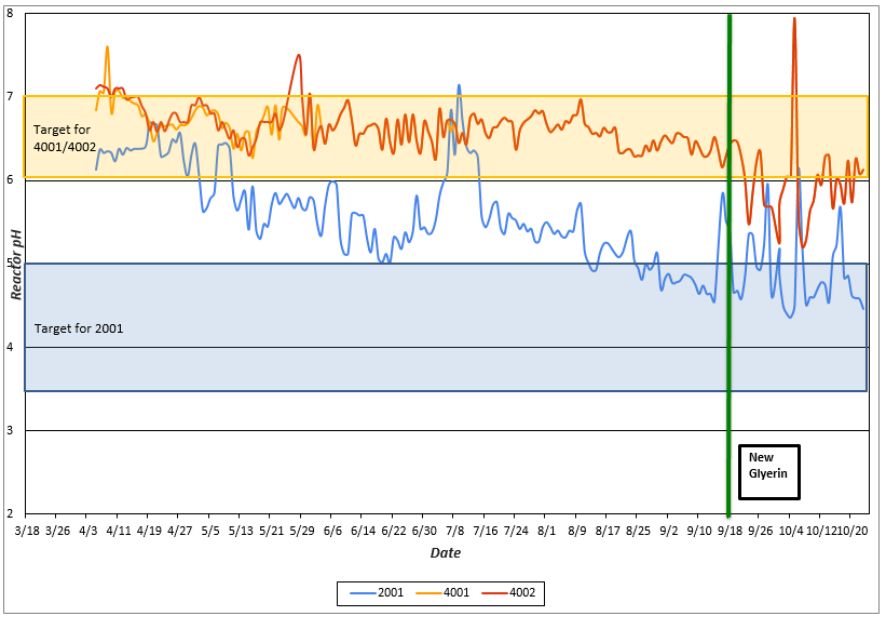

Image Credit: Novus.

The pH for the leachate, digestate, and glycerin streams out of the digester and not in-situ are seen in Figure 31. The pH for the glycerin is always slightly basic and averages around 9. The leachate is slightly acidic. It is taken after the process leaves tank 2001, passes through the screw press, and enters the leachate tanks, but before it enters methonagoenesis tanks 4001 and 4002. The pH of the leachate is generally between the pH of 2001 and the higher pH of 4001 and 4002. The digestate is taken after the acetic acid from tanks 4001 and 4002 is converted into methane and carbon dioxide so it is generally the same as or higher than the pH of those tanks.

Figure 31: Novus pH

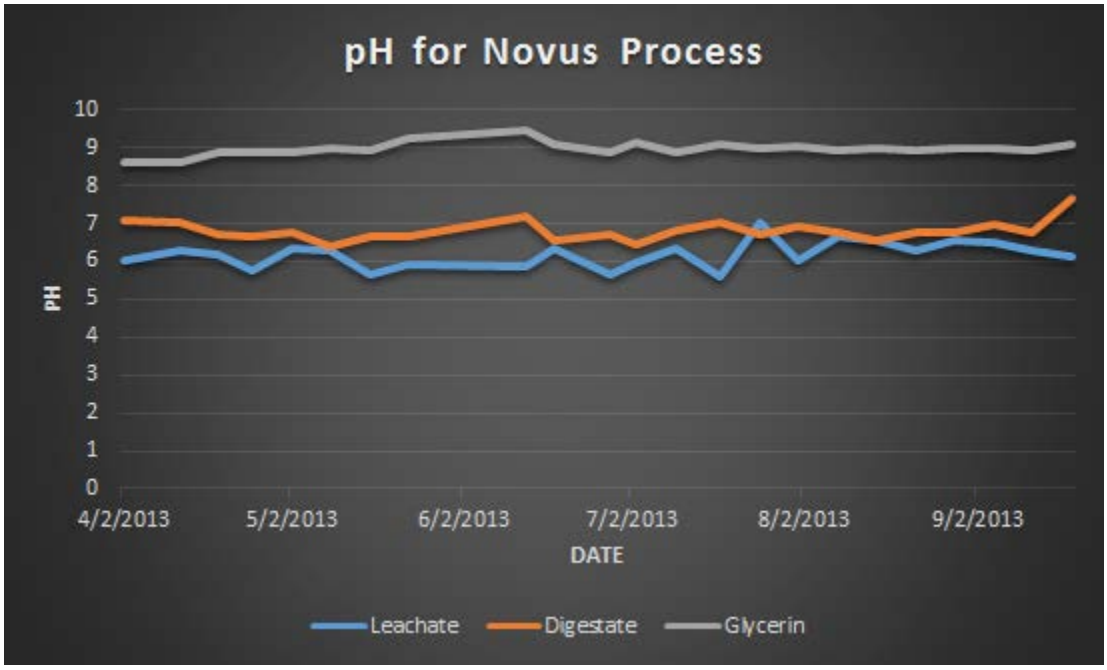

Image Credit: Biodico

The alkalinity for both the leachate and the digestate are given in Figure 32. The leachate has a higher acetic acid content than the digestate and generally has less alkalinity than the digestate. Both samples are healthy.

Figure 32: Novus Alkalinity

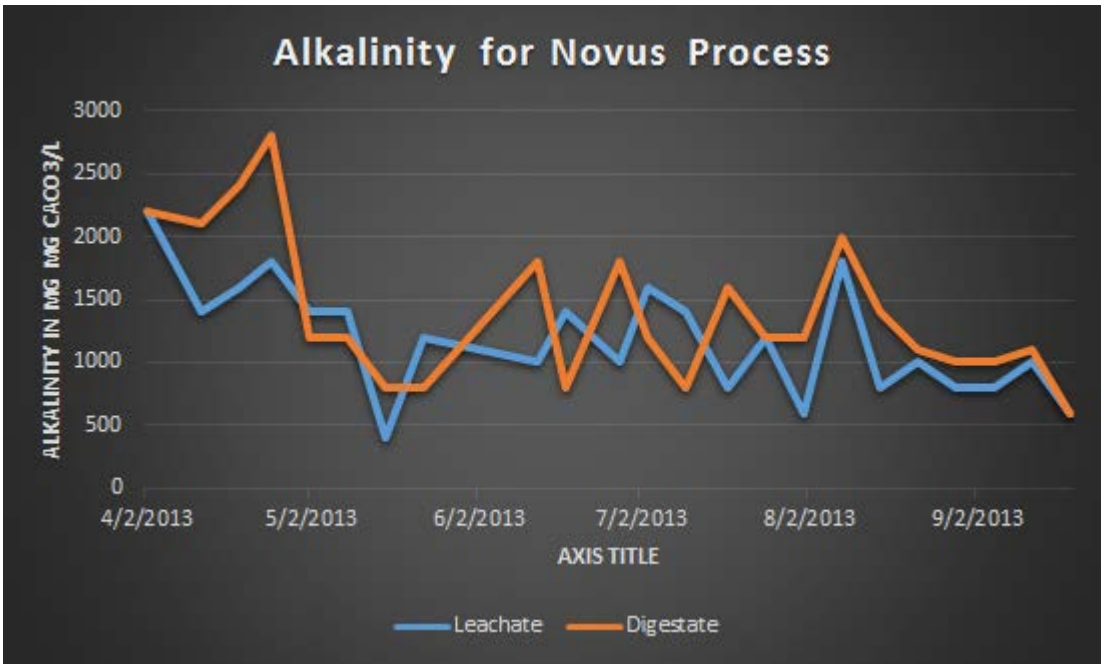

Image Credit: Biodico

For most of the course of the tests the majority of the solids content is volatile suspended solids (Figure 33). VSS make up the majority of the glycerin feedstock. For the earlier, more unpredictable solids values, manure was also being used as a feedstock supplement to the glycerin.

Figure 33: Novus Leachate Solids

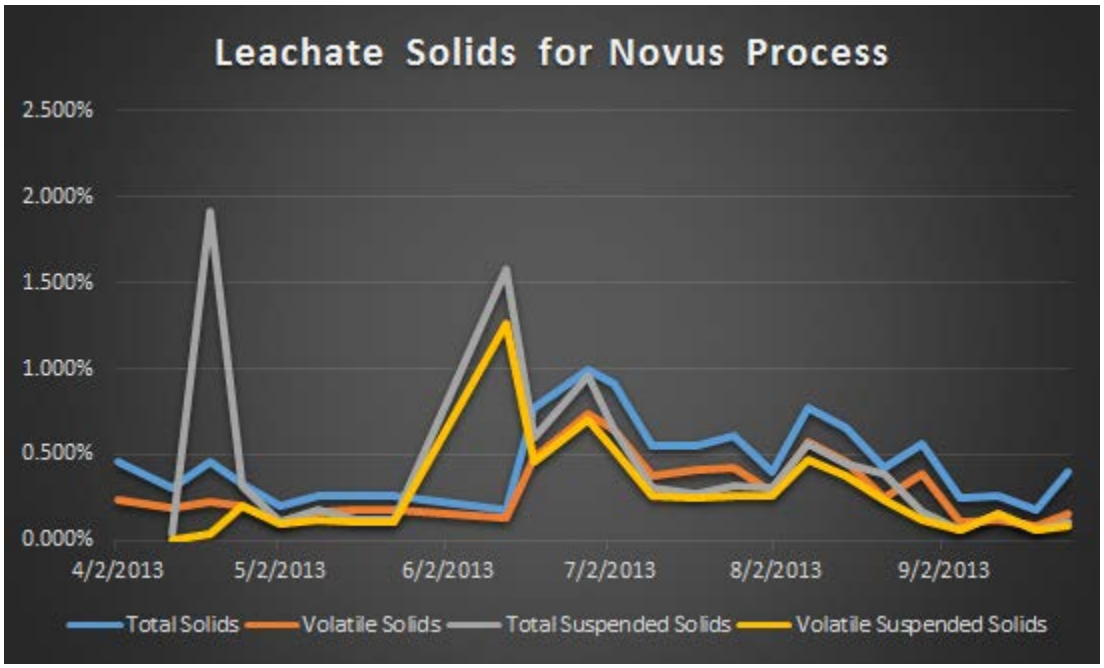

Image Credit: Biodico

The results for the digestate solids are more predictable (Figure 34). Even with spikes in overall values, the ratios between the types of solids are much more consistent. This makes sense, as these samples are taken after the methanogenesis phase when the digestion of the material has been completed.

Figure 34: Novus Digestate Solids

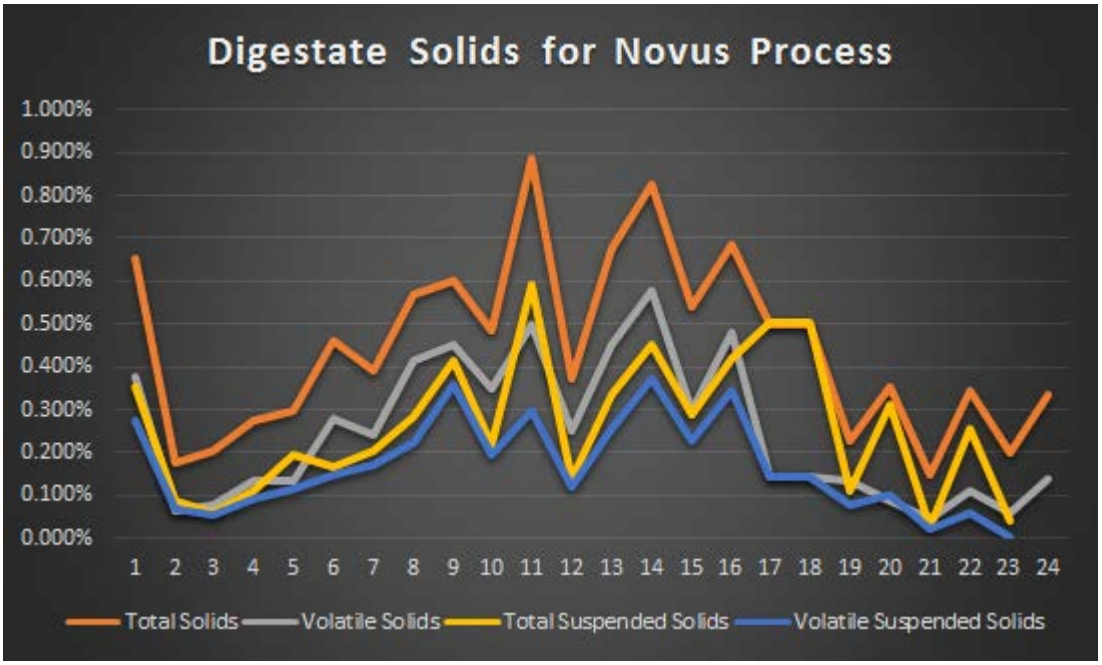

Image Credit: Biodico

Though glycerin is liquid at ambient temperature, it has a higher boiling point than water. Total solids are defined as anything with a higher boiling point than water. The relative solids content of the glycerin and the ratio of volatile solids to fixed solids remained relatively consistent through the course of the Novus tests, but the solids content spiked at the beginning of September (Figure 35). This spike may have been the result of new glycerin with less moisture entering the process, but the continual rise from September onward makes it likely that the shift was also due to the evaporation of moisture from the storage tank in which it was held. The storage tank is in an outdoor shaded area and seasonal changes in the amount of sunlight on the tank at the end of the hot summer would have made the tank significantly hotter.

Figure 35: Novus Glycerin Solids

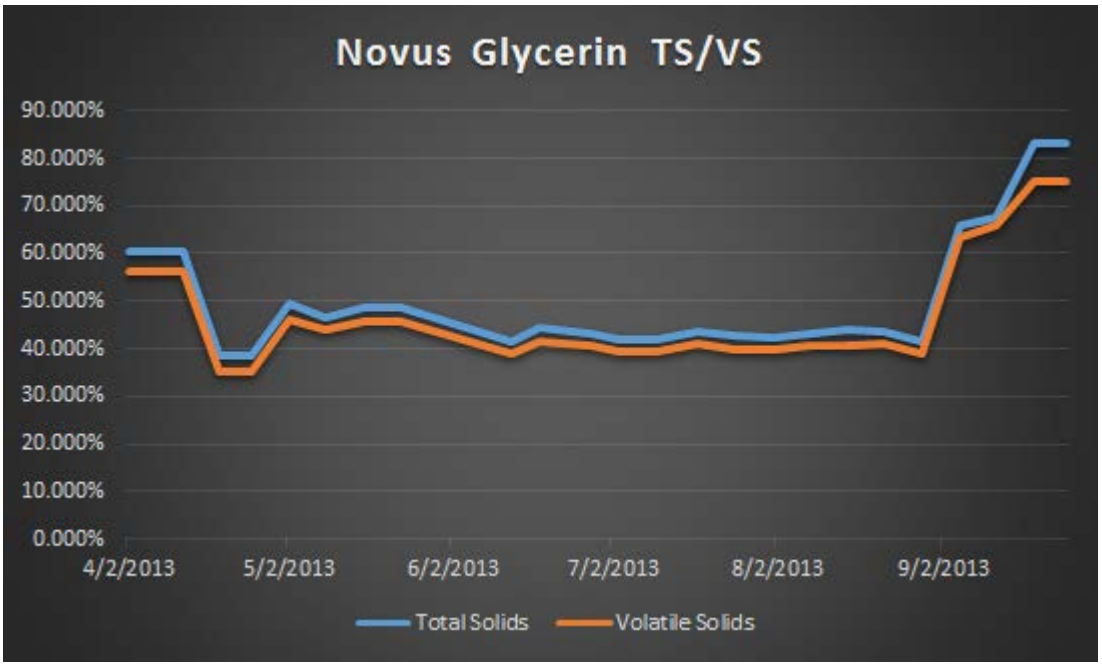

Image Credit: Biodico

3.3.2 Himark

The Himark system, as previously noted in the PFD in Figure 20, performs the anaerobic digestion for the system in one vessel. As opposed to the leachate and digestate samples from the Novus system, only one sample was needed to track the progress of the Himark system, the digestate taken from the digester tank.

The COD for the Himark system was taken to the point of system crash twice, which occurred at the two peaks (Figure 36). The first crash was at the very high value of roughly 95,000 mg/L of digestate, after which the system was stabilized. The second crash occurred at the still high level of 80,000 mg/L of digestate. Finding the ideal glycerin concentration in a thermophilic system was a matter of trial and error though for the project team, and by varying the COD so widely, important information was gained.

Figure 36: Himark COD

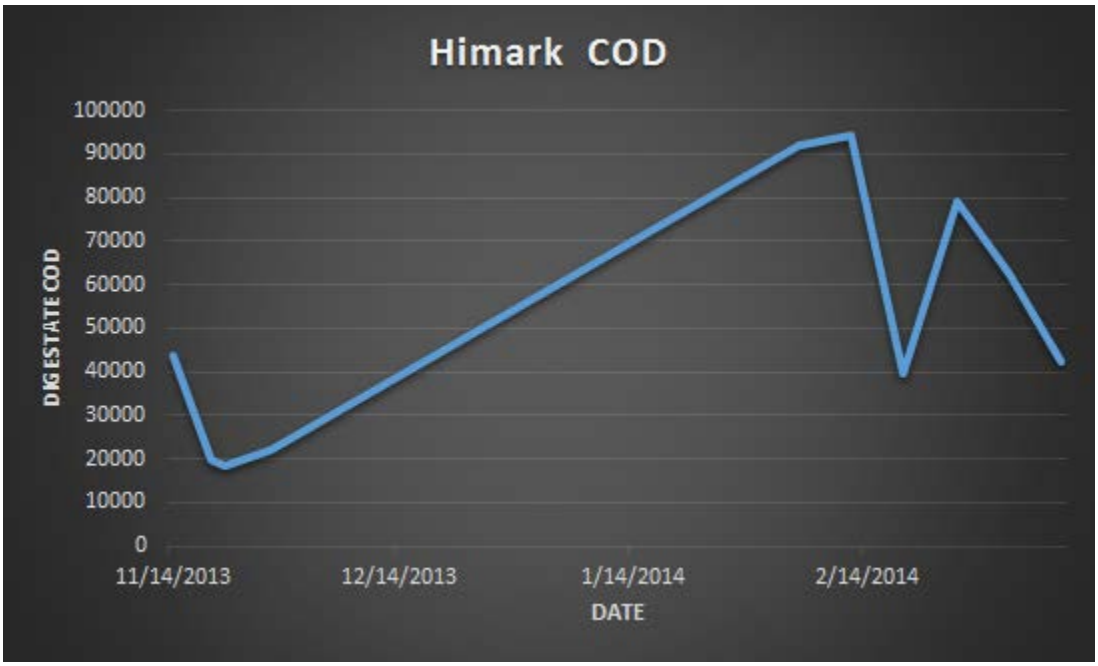

Image Credit: Biodico

The pH levels for the Himark digester remained very healthy throughout the course of the test run, even when the digesters crashed. Since the build up of acetic acid is the cause of methanogen die off and is usually the fairly immediate precursor to a digester crash, a slightly alkaline pH is preferable. Slight, but not major, dips can be seen at the two system crash points. A spike in the pH can be seen at the low point of COD loading (Figure 37).

Figure 37: Himark pH

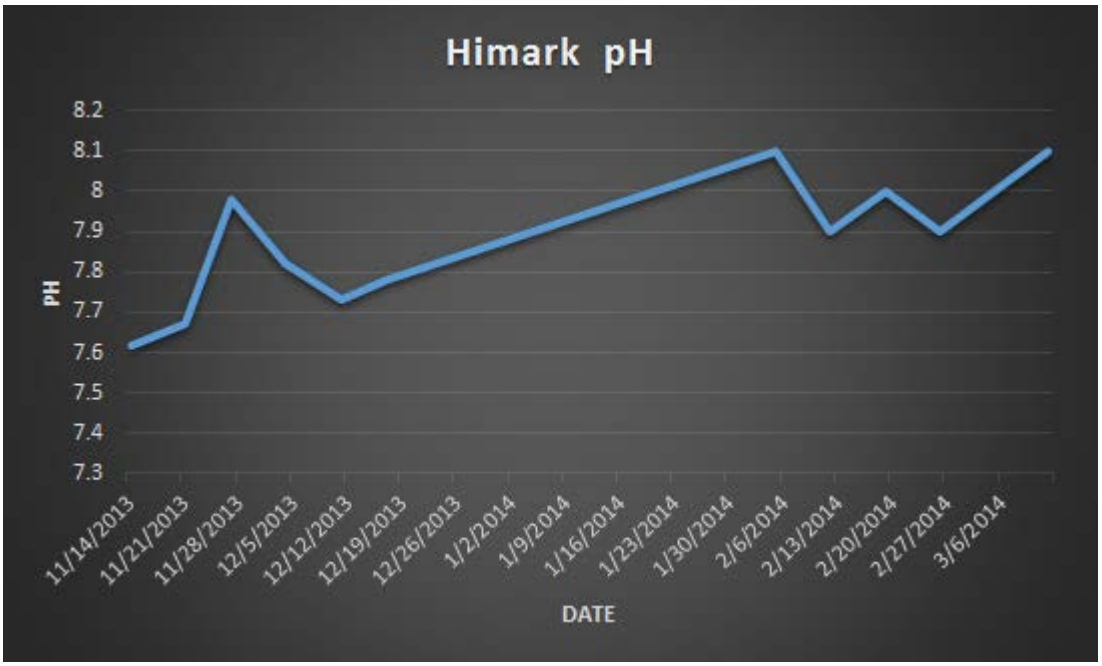

Image Credit: Biodico

The same can be said of the alkalinity, which remained very high throughout the course of the digestion. Even the low point of 8,000 mg/L of calcium carbonate equivalent is a healthy level for alkalinity. As with the pH, very slight dips can be seen at the two system crash points (Figure 38). The alkalinity was significantly lower at the low point of COD loading.

Figure 38: Himark Alkalinity

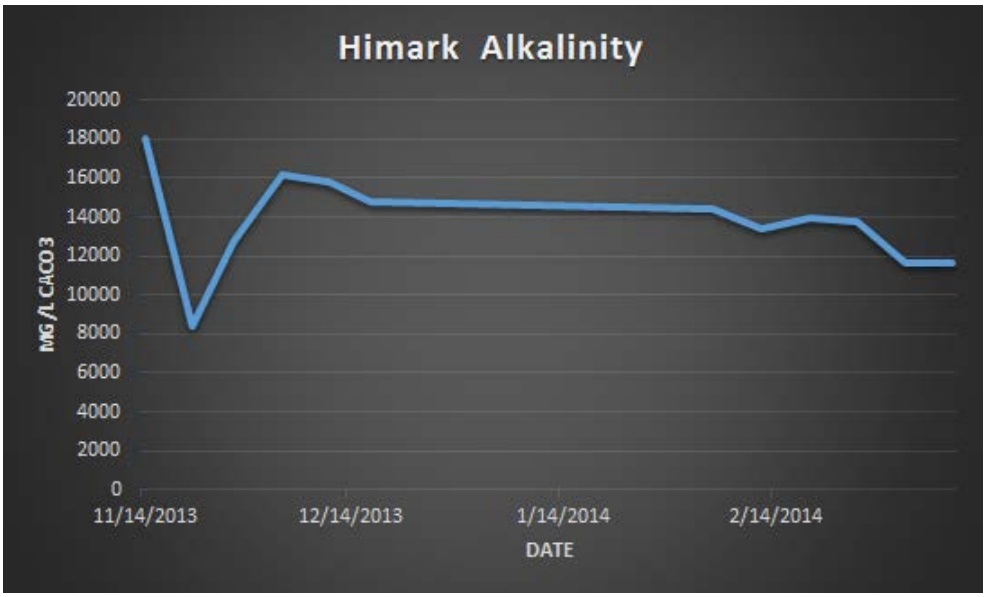

Image Credit: Biodico

The solids content of the Himark digestate show, as did Novus, a consistent ratio between total and volatile solids (Figure 39). The percentage of volatile solids is lower for the Himark digestate than for Novus because all of the processes of anaerobic digestion, hydrolysis, acetogenesis, acidogenesis, and methanogenesis simultaneously occur in one digestion vessel. When the digester crashed toward the end of the chart, there was a significant solids build up. There was also a solids build up at the low alkalinity level point in November 2013 as the digester was brought up to production.

Figure 39: Himark Solids

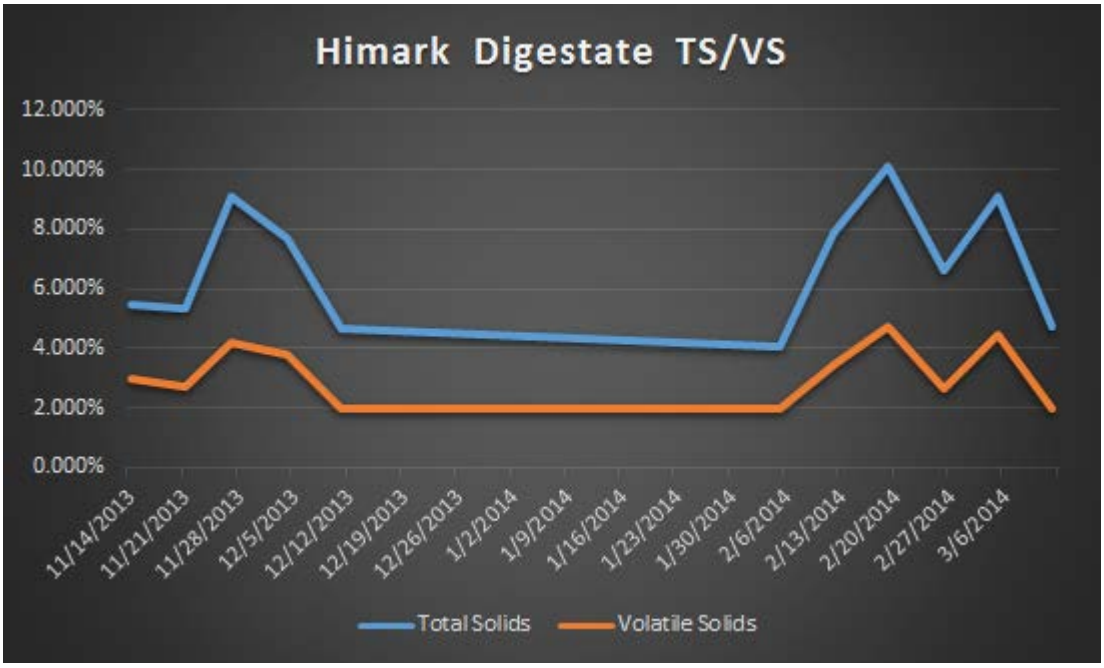

Image Credit: Biodico

3.3.3 Seahold

The Seahold system can be best analyzed by splitting up the digestion time into four stages. Multiple volume measurements were taken per day so the volumes per day on any given day often appear twice.

Stage One

Stage one from October 2014 to March 2015, was run on a ten day HRT at ambient temperature. The system produced less gas than at mesophilic or thermophilic ranges, but served as a data point to round out the demonstration. By the end of the cycle, the system had crashed and stopped producing gas. The gas production for stage one is shown in Figure 40.

Figure 40: Seahold Stage 1 Gas per Day

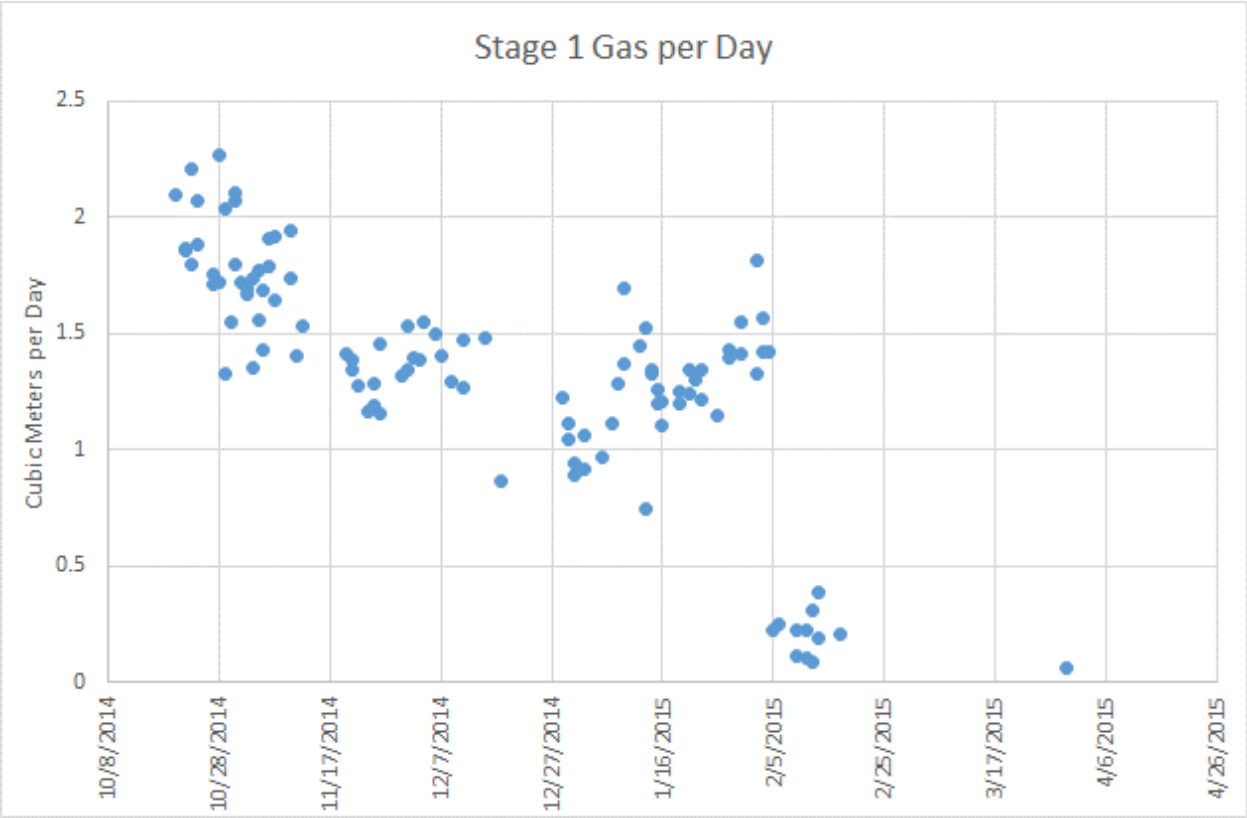

Image Credit: Biodico

Surprisingly, even through the course of the crash, the pH probes showed a relatively consistent, neutral reading. This will likely lead to design changes for future iterations of the system, as the acetic acid was built up in the digesters prior to the crash at the end of the stage, but was not captured in the spillover lines (Figure 41). As described in the PFD for the digester, each of the three tanks has a pH probe inserted into its spill over line that feeds into the next tank.

Figure 41: Seahold Stage 1 pH

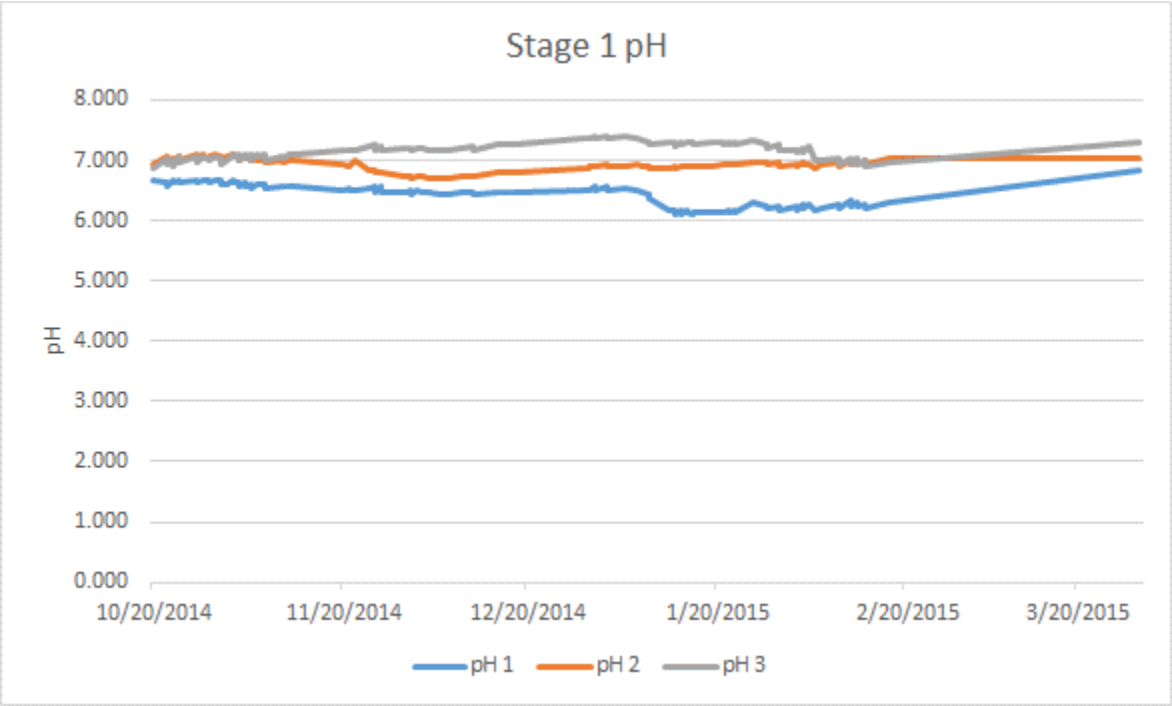

Image Credit: Biodico

The ORP, however, did show large changes through the course of the first stage, with the ORP of the first and second digesters essentially switching values partway through the test run (Figure 42). This shows the majority of the methanogenesis moving from tank 1 to tank 2 as the acetic acid builds up in tank 1. As described in the PFD for the digester, each of the three tanks has a pH probe inserted into its spill over line that feeds into the next tank.

Figure 42: Seahold Stage 1 ORP

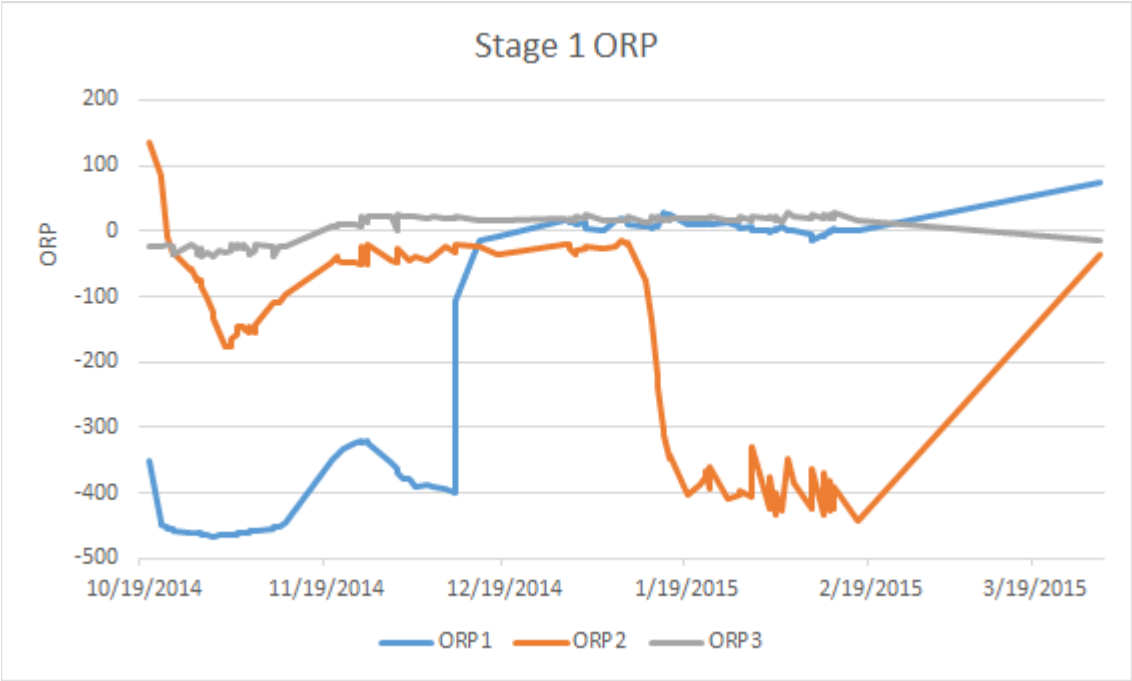

Image Credit: Biodico

Stage Two

Stage two, a brief stage for five days in March 2015, was the time taken for the system to acclimate from the crash at the end of stage one to a fresh load of wastewater effluent and 2.8% glycerin at mesophilic temperatures. Predictably, the gas production spiked with this surge of new material into the digester as shown in the gas production chart (Figure 43). This was a one time only glycerin addition to bring the digester up to its equilibrium loading capacity.

Figure 43: Seahold Stage 2 Biogas Production

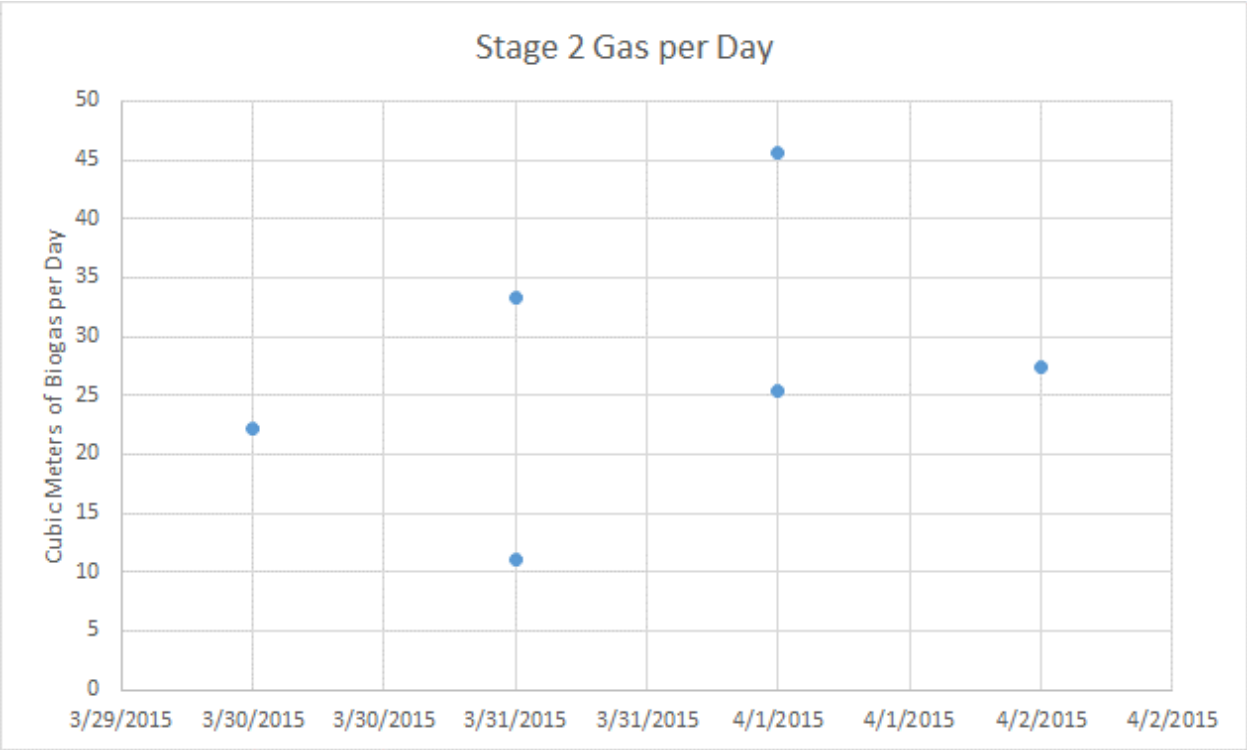

Image Credit: Biodico

The pH meters are set up on spillover lines for the system so the first tank's pH meter gives the same reading as the pH of the glycerin for some time before gradually drifting down (Figure 44). On pH meter 1 the build up of glycerin likely reached the point where the pH probe was submerged entirely in glycerin.

Figure 44: Seahold Stage 2 pH

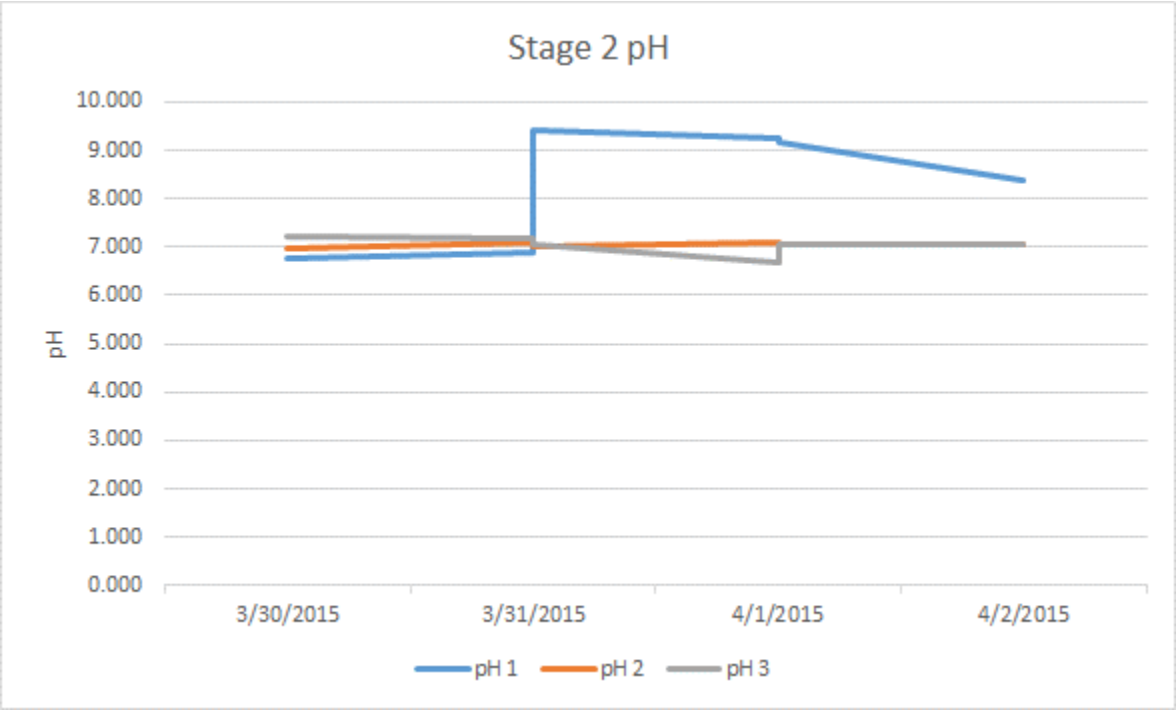

Image Credit: Biodico

The ORP of the tanks is displayed in Figure 45. As the chart shows, the ORP of tank one dropped almost immediately as the glycerin was added, pairing to the gas production increase and the increase in the pH.

Figure 45: Seahold Stage 2 ORP

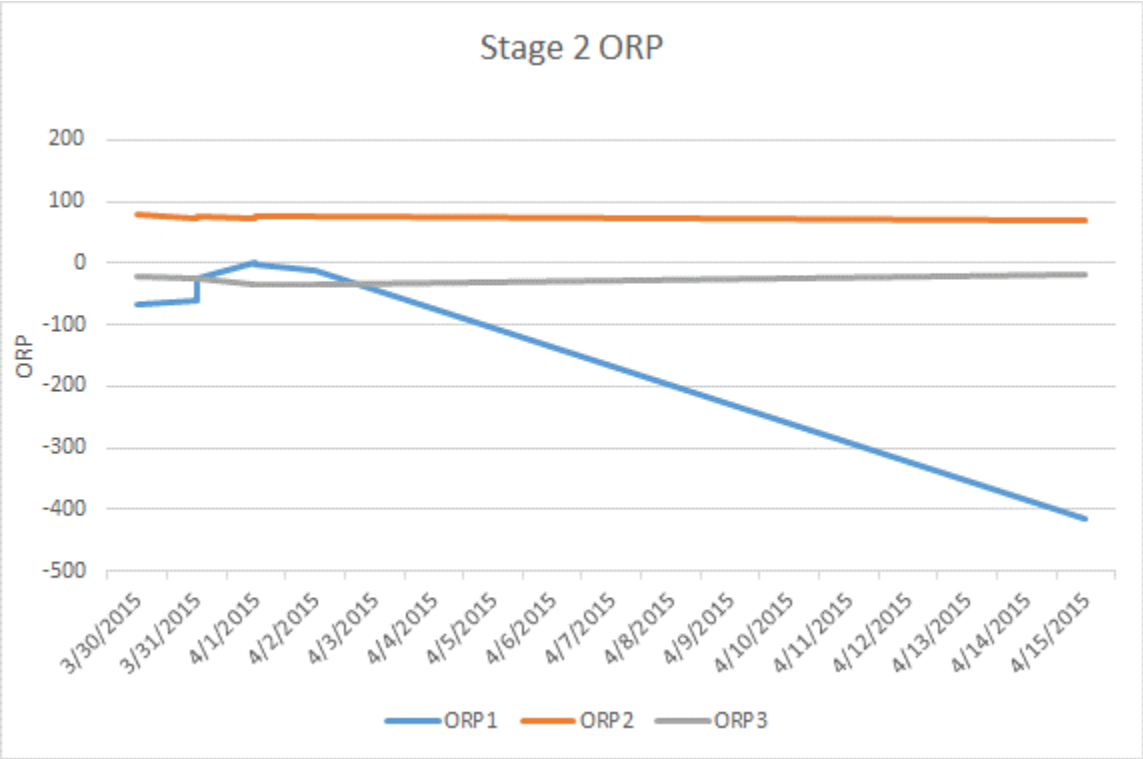

Image Credit: Biodico

Stage Three

Stage three, for the majority of April 2015, was a run load of 2.8% glycerin by digester volume to the system with a HRT of ten days, for a total loading rate of 0.28% digester volume by day. The gas production here is down from the initial surge of glycerin, but is significantly higher than the gas production from even the highest values of stage one (Figure 46).

Figure 46: Seahold Stage 3 Biogas Production

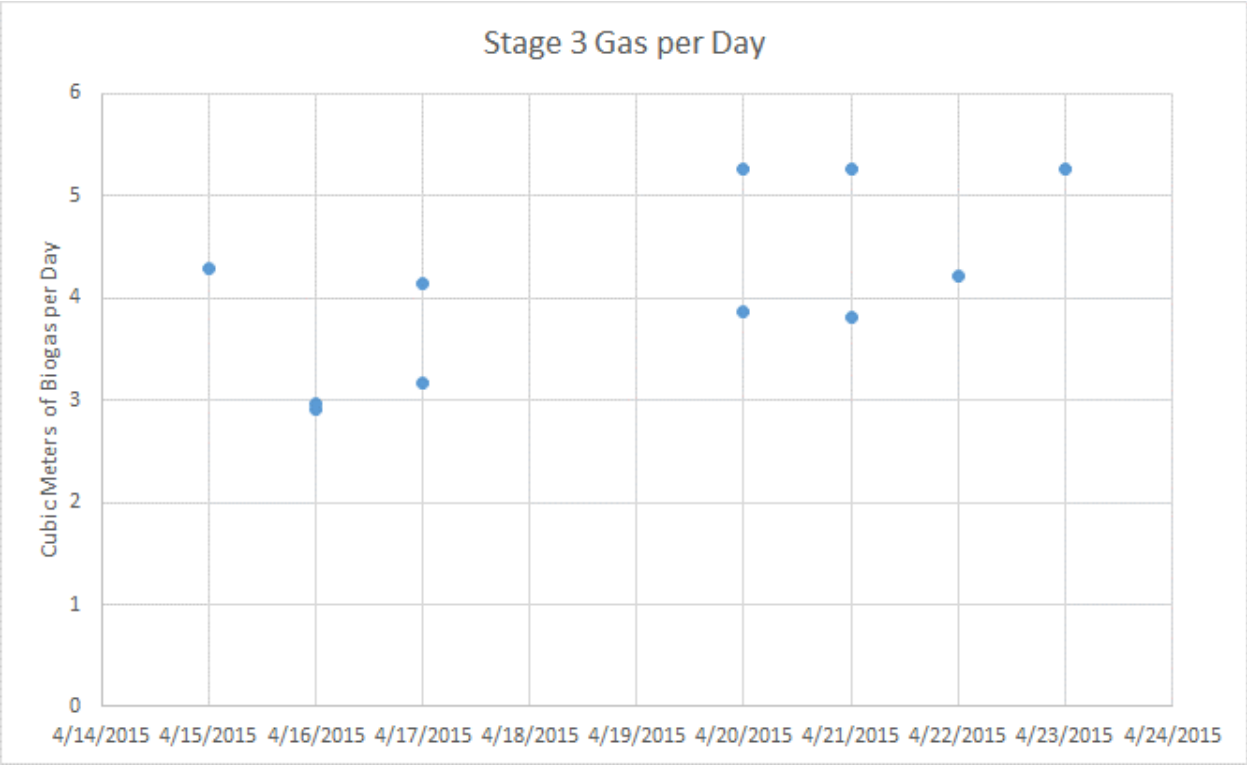

Image Credit: Biodico

The pH for all of the tanks here is very healthy at slightly alkaline values (Figure 47). As noted in stage two, pH probe one is subject to a glycerin phase forming and bringing the value of the pH to alkaline levels. The sharp shift in pH on April 23 can likely be attributed to a slug of the glycerin washing out of the line.

Figure 47: Seahold Stage 3 pH

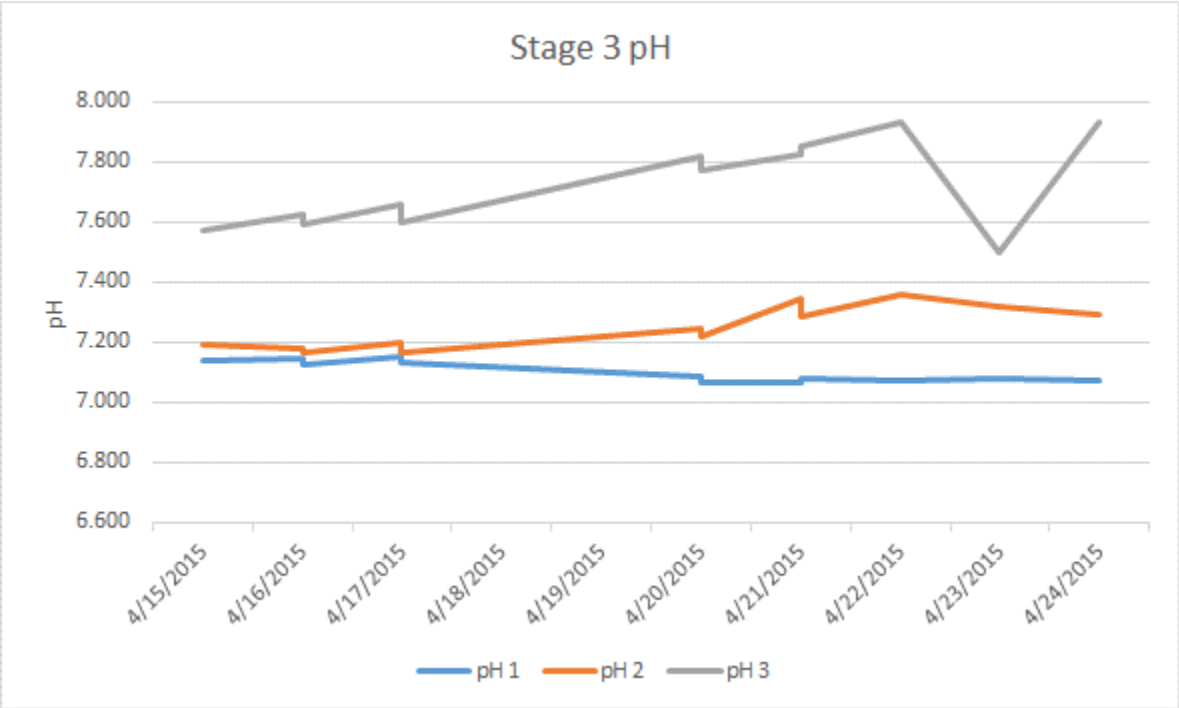

Image Credit: Biodico

The ORP of the system remained at the levels that were reached after the initial spike of glycerin (Figure 48).

Figure 48: Seahold Stage 3 ORP

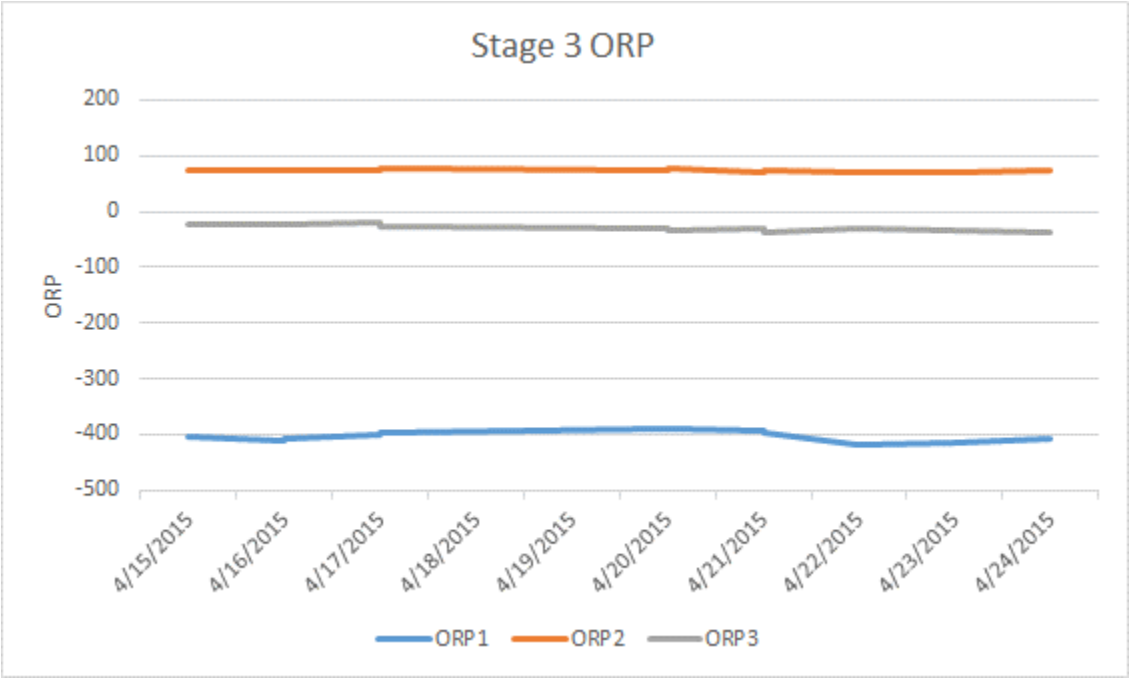

Image Credit: Biodico

Stage Four

Stage four, for May 2015, was a run load of 2.8% glycerin by digester volume to the system with a HRT of six days, for a total loading rate of 0.47% digester volume by day. The gas production is more variable at this loading rate than it was at the 10 day HRT, but the ratio of the increased loading is a very close match to the ratio of increased gas production (Figure 49).

Figure 49: Seahold Stage 4 Biogas Production

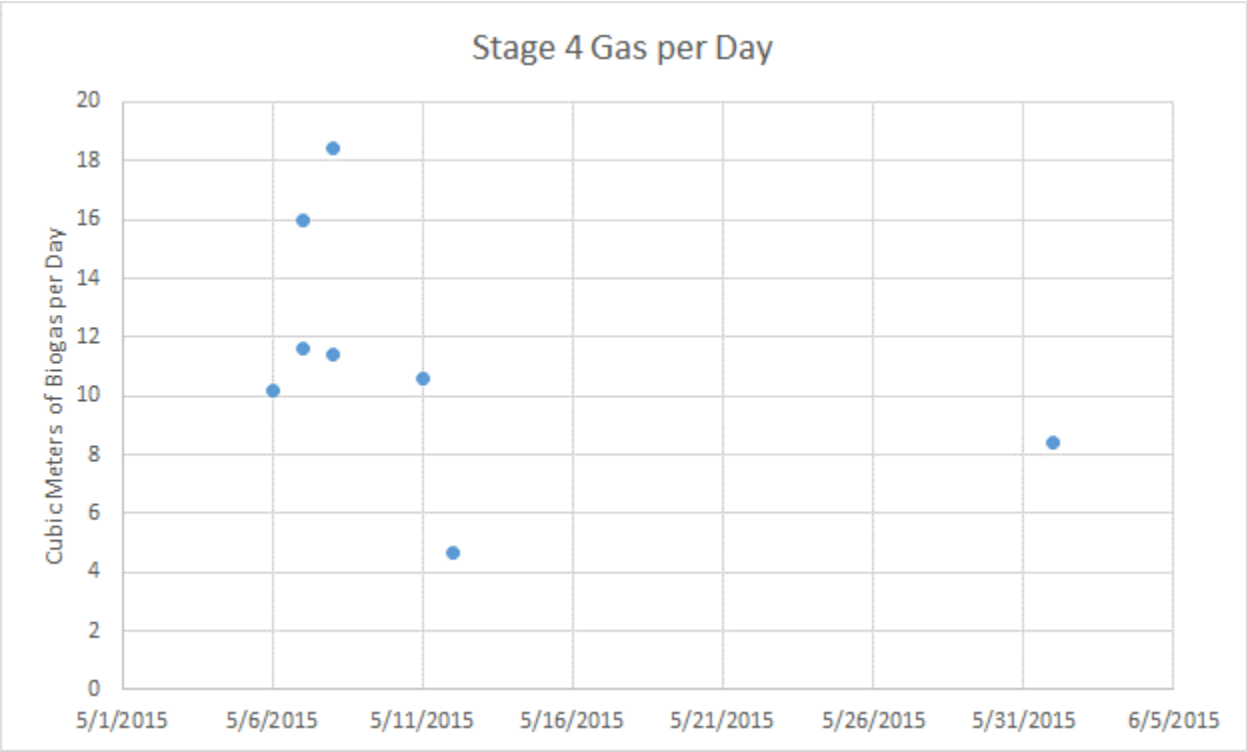

Image Credit: Biodico

The increased glycerin load rate caused the pH to rise (Figure 50).

Figure 50: Seahold Stage 4 pH

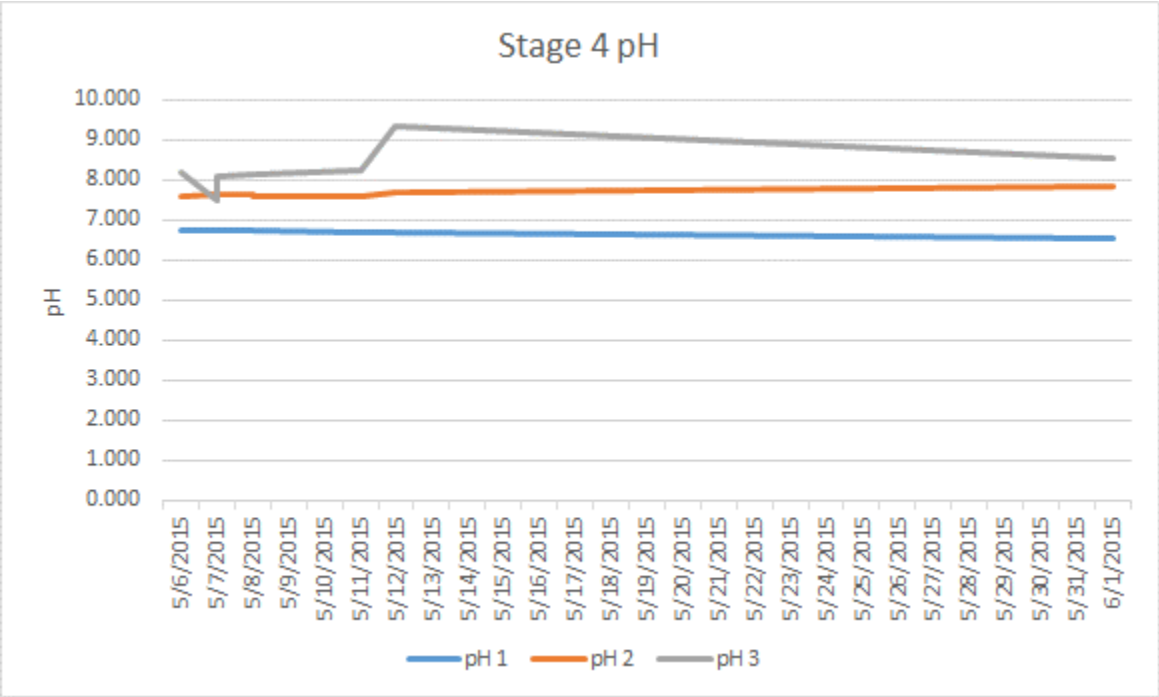

Image Credit: Biodico

Figure 51 shows the ORP for the three digesters. Tanks one and two remained relatively unchanged, though there was a gradual decrease in the ORP of tank three.

Figure 51: Seahold Stage 4 ORP

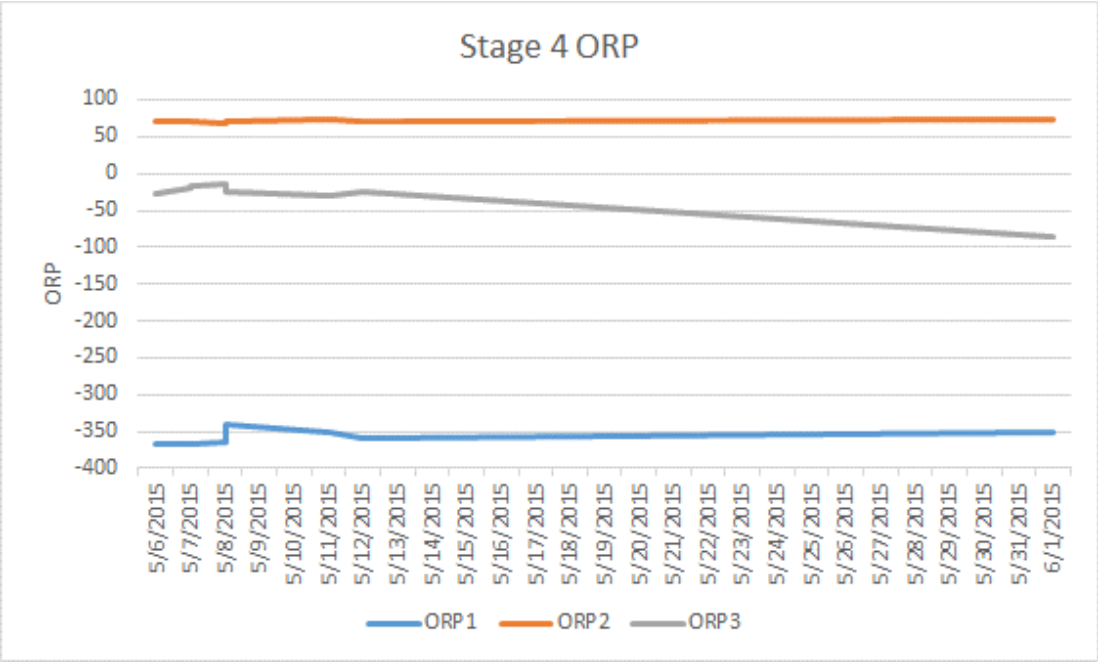

Image Credit: Biodico

Figure 52 shows the composition of the biogas produced by the digester during stage four of the test runs. The methane percentage of 69.4 is comparable with the Novus and Himark digesters.

Figure 52: Seahold Biogas Composition

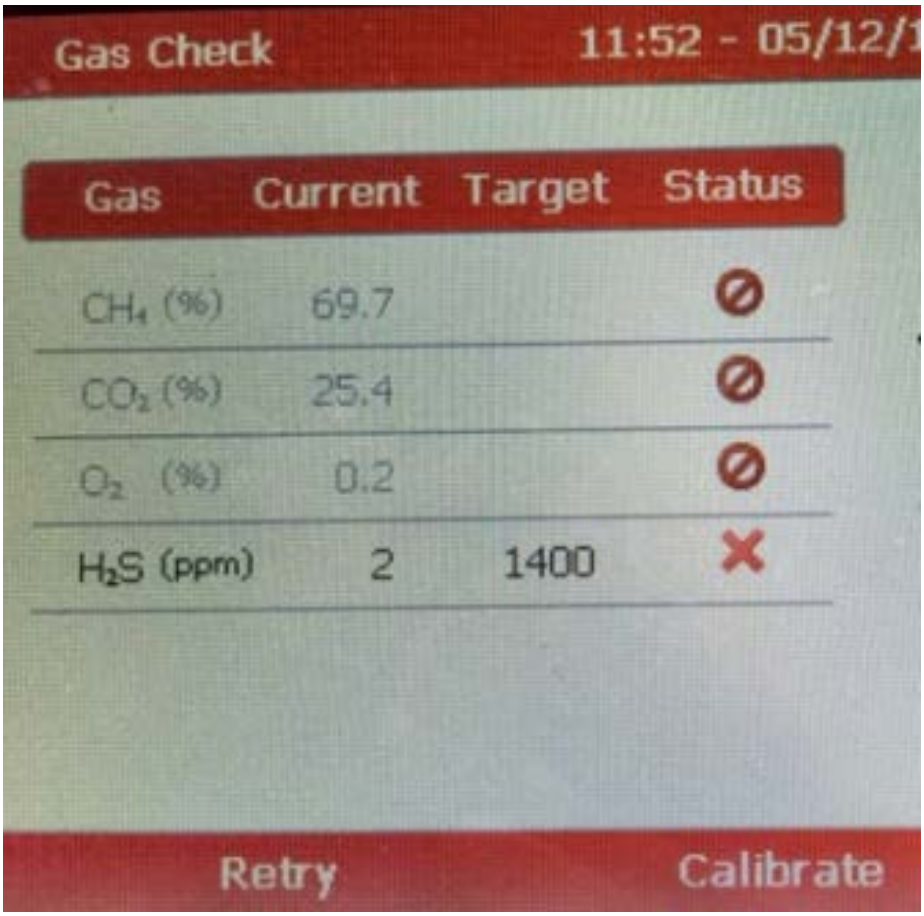

Image Credit: Biodico

3.4 Provide a validation report from the Navy that the integration, interconnection and startup operation of the Task 4 equipment has been completed

The following italicized text is a letter signed by Bruce Holden and Kyle Lawrence with Naval Facilities Expeditionary Warfare Center (NAVFAC EXWC).

Over the course of this project engineers from the Naval Facilities Expeditionary Warfare Center have traveled to Red Rock Ranch to ensure that the equipment for the project has been integrated, interconnected, and was operational. This includes the Cogenra solar CHP array, the APL gasifier, the Novus anaerobic digester, the Himark anaerobic digester, and the Seahold anaerobic digester.

The Cogenra array was successfully installed, the solar tracking mechanism and heat exchanger were found to be in working order, the heat is effectively transferred to the heat exchanger, and the electricity

generated has been connected to the grid. The equipment was validated to be in working order and connected to the grid on May 29, 2015.

The APL gasifier was successfully installed, the electricity generated has been connected to the grid, and the heat generated from the gasifier has been connected to the heat exchanger loop. CHP has been made from the gasification of agricultural waste from the surrounding area and from seed meal byproducts from the crops tested through the course of this project. The gasifier was replaced by APL for a newer model in 2015, and the new model gasifer was validated to be in working order with a heating system connected to the other portions of the facility on May 29, 2015.

The Novus anaerobic digester was the first of three anaerobic digesters to be installed and operated. It was operated on crude glycerin from biodiesel production and was effective at producing biogas that was tested for methane content for well over three months. The Novus digester was validated to be in working order on three consecutive trips on May 25,2013; August 11, 2013; and August 22, 2013.

The Himark anaerobic digester was the second of three anaerobic digesters to be installed and operated. It was operated on crude glycerin from biodiesel production and was effective at producing biogas for a period of over three months. The Himark digester was validated to be in operation on December 10, 2013.

The Seahold anaerobic digester was the third of three anaerobic digesters to be installed and operated. Process changes were made to the system in 2015 and the heat from the solar cogen and the gasifier were connected to the system. The mesophilic upflow anaerobic sludge blanket design was validated to be in good working order and producing gas on May 29, 2015.

Bruce Holden

Bruce Holden, PE
NAVFAC EXWC

Kyle Lawrence

Kyle Lawrence
NAVFAC EXWC

CHAPTER 4:
Operate the Equipment Using Feedstocks

4.1 Operate the Task 4 equipment utilizing feedstocks produced during Task 3 for gasification and anaerobic digestion

Gasification was performed with the meal from the seeds harvested at the UC Davis agricultural research stations. Of dozens of varietals, the meal was split into categories by species: canola, castor, camelina, and pennycress. The yields for each of the varietals are given in Figure 53.

Figure 53: Seed Meal Gasification Runs

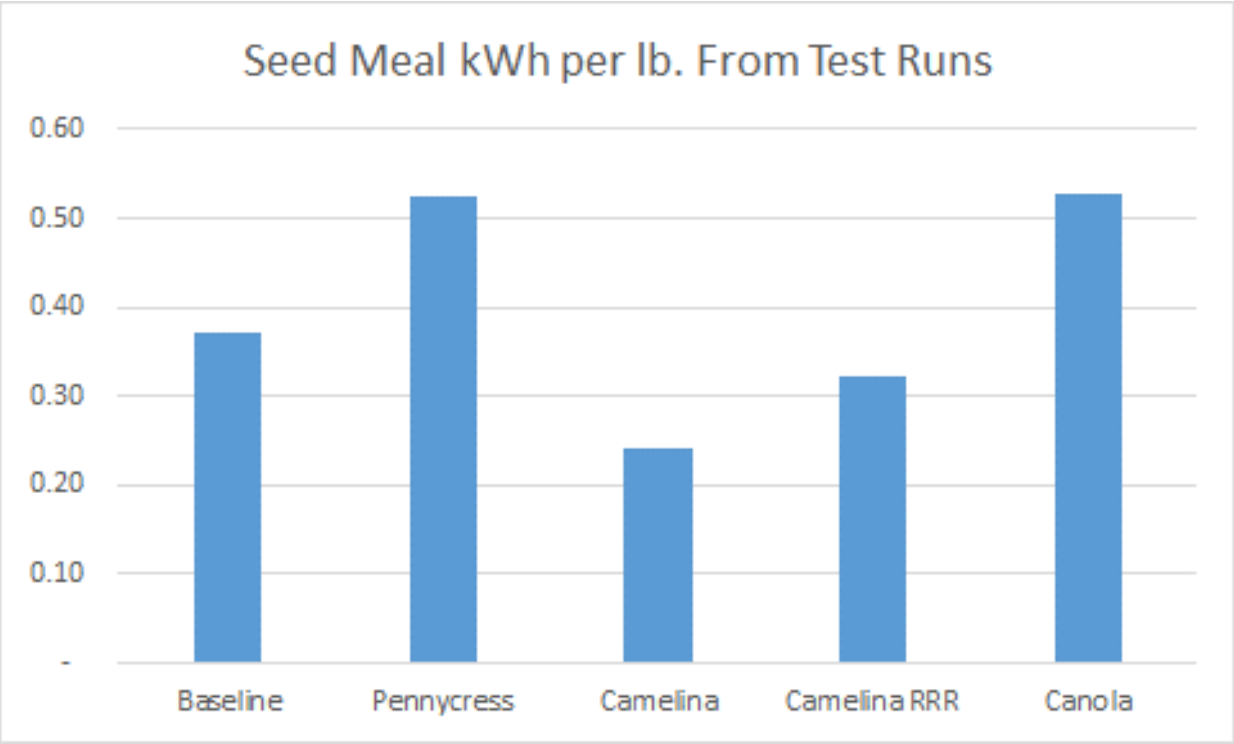

Image Credit: Biodico

For the gasifier runs a baseline test was taken of woodchips for kWh produced by weight and gasifier runtime by weight. Seed meal was then weighed out and added to woodchips for individual runs to determine the power production of each type of meal. The gasifier takes some material to ramp up to starting temperature and to start the generator, so having the same woodchip baseline at the bottom of each gasifier test helps to improve the repeatability of the tests. The additional power and runtime over the baseline amount that is generated from each run of woodchips and meal can be attributed to the seed meal.

Each of the types of seed meal was run as a 10% blend with woodchips. This is done to allow for the granier consistency of the seed meal to run smoothly in the gasifier and allows for the

seed meal to be effectively compared to other gasification feedstocks and for the different meals to be effectively compared with each other. The margin of error for each of the test runs is estimated at 25%. A baseline test was performed with woodchips only. This was done so that the gas production attributed to the woodchips in each of the blended tests could be separated out and the gas production attributed to each of the types of seed meal could be found (Figure 54). The "d kWh" column gives the delta kWh, or the change in kWh generated from the start of the test to the time noted.

Figure 54: Woodchip Gasification Baseline

Woodchip Baseline							
Time	kWh	Minutes	d kWh	Inches	lbs. Fuel	kWh/lb	kW Load
13:20	176	-	0	15	0		
13:50	182.7	30	6.7	17	12.2	0.548	13.4
14:20	188.8	60	12.8	20	30.6	0.419	12.8
14:50	196.4	90	20.4	24	55.0	0.371	13.6

Start Pounds	55
Inches Change	9
lbs/Inch	6.1
kWh/lb	0.37

Image Credit: Biodico

The top part of the graph gives the data recorded at thirty-minute intervals throughout the test. The gasifier keeps an aggregated log of total kWh produced. From this, a delta kWh can be determined for the test run. The inches measurement is for inches below the top of the feedstock hopper. Since the fuel was weighed out before adding it to the hopper and the volume and depth of the feedstock are measured, the volume and height density of the fuel can be determined and the pounds per inch can be used to determine the weight of fuel burned throughout the test. The value at the bottom of the chart shows the kWh generated per pound of feedstock. This value is used for the remaining tests to determine the power generation attributable to the woodchips in a blended mixture. Figure 55 shows the results of the pennycress test.

Figure 55: Pennycress Gasification

Pennycress							
Time	kWh	Minutes	d kWh	Inches	lbs. Fuel	kWh/lb	kW Load
11:30	152.2	-	0	26	61.1		
12:15	161.2	45	9	24.25	50.4	0.179	12.0

Baseline Pounds	30.0	Inches Loaded	2.50	kWh Total	9.00
Test Fuel Pounds	3.3	Inches Burned	1.75	kWh from Wood	7.79
Total Pounds	33.3	Wood lbs. Burned	21.00	kWh from Meal	1.21
Start Inches	23.5	Meal lbs. Burned	2.31	kWh/lb Meal	0.52
lbs/Inch	13.32	Total lbs. Burned	23.31		

Image Credit: Biodico

The charts for the seed meal tests are a little more complex than the baseline chart since the power generated by the baseline must be taken out of the total power generated. The inches that are burned may be different than the inches that are loaded, so that must be taken into account as well. The baseline pounds and the fuel (seed meal) pounds are recorded separately and then added together to give total pounts. The start inches are recorded so that the total inches added can be taken by subtracting the start inches from the initial inches measurement at the start of the test. The pounds per inch is taken as the ratio of pounds to total inches loaded. The inches burned is taken as the difference between the starting inches measurement and the last inches measurement taken after the test. The ratio of inches loaded to inches burned gives the percentage of fuel loaded that was burned for the test. This is multiplied into the wood and meal loaded to give the pounds burned of each component. The kWh from wood is taken by multiplying the value found in the baseline test and the total pounds of wood burned. This is substracted from the total kWh generated to give the kWh from meal for the tests. This value is then divided by the total pounds of meal burned to give the kWh per pound for the meal, the value on the bottom right of the chart.

Figure 56 provides the test results for camelina meal. The methodology for determining the kWh per pound of camelina seed meal is the same as for the pennycress meal.

Figure 56: Camelina Gasification

Camelina Meal							
Time	kWh	Minutes	d kWh	Inches	lbs. Fuel	kWh/lb	kW Load
9:45	132.1	-	0	16	-		
10:20	138	35	5.9	18	11.23	0.525	10.1
10:45	143.9	60	11.8	21	28.08	0.420	11.8
11:30	152.2	105	20.1	26	56.16	0.358	11.5

Baseline Pounds	63	Inches Loaded	12.50	kWh Total	20.10
Test Fuel Pounds	7	Inches Burned	10.00	kWh from Wood	18.72
Total Pounds	70	Wood lbs. Burned	50.48	kWh from Meal	1.38
Start Inches	28.5	Meal lbs. Burned	5.68	kWh/lb Meal	0.24
lbs/Inch	5.62	Total lbs. Burned	56.16		

Image Credit: Biodico

A second sample of the camelina meal provided by UC Davis from the WREC adjacent to RRR was marked as specifically selected for the Westside Fresno County region (Figure 57). The methodology for determining the kWh per pound of camelina seed meal is the same as for the the other meal tests.

Figure 57: Camelina RRR Gasification

Camelina RRR Meal							
Time	kWh	Minutes	d kWh	Inches	lbs. Fuel	kWh/lb	kW Load
7:45	107.3	-	0	16	-		
8:15	114.2	35	6.9	18	12.2	0.565	11.8
8:45	121	60	13.7	21.5	33.6	0.408	13.7
9:15	127.8	105	20.5	26	61.1	0.335	11.7
9:45	132	105	24.7	28.5	76.4	0.323	14.1

Baseline Pounds	63	Inches Loaded	13.00	kWh Total	24.70
Test Fuel Pounds	7	Inches Burned	12.50	kWh from Wood	22.50
Total Pounds	70	Wood lbs. Burned	60.67	kWh from Meal	2.20
Start Inches	29.0	Meal lbs. Burned	6.83	kWh/lb Meal	0.32
lbs/Inch	5.40	Total lbs. Burned	67.50		

Image Credit: Biodico

Figure 58 gives the test results for canola meal. The methodology for determining the kWh per pound of camelina seed meal is the same as for the other meal tests.

Figure 58: Canola Gasification

Canola Meal							
Time	kWh	Minutes	d kWh	Inches	lbs. Fuel	kWh/lb	kW Load
12:20	162.2	-	0	17	6.1		
12:50	168.5	30	6.3	19	18.3	0.344	12.6
1:20	176	60	13.8	24	48.9	0.282	13.8

Baseline Pounds	41	Inches Loaded	9.00	kWh Total	13.80
Test Fuel Pounds	5	Inches Burned	7.00	kWh from Wood	11.91
Total Pounds	46	Wood lbs. Burned	32.12	kWh from Meal	1.89
Start Inches	26.0	Meal lbs. Burned	3.58	kWh/lb Meal	0.53
lbs/Inch	5.10	Total lbs. Burned	35.70		

Image Credit: Biodico

4.2 Collect data for economic, social and environmental sustainability analysis

Data was collected through the course of the project for economic, social, and environmental analysis. Much of the economic data analysis comes from the energy yield data gained from operation of the various operational parts of the project as well as capital costs and labor costs provided by the various vendors. Much of the social data analysis comes from meetings with stakeholders in the project and in the region, as well as from analysis of the project inline with current legislation and incentives. Much of the environmental analysis comes from the data gained from the operation of the various components of the project and from the analysis of the data toward commercialization projections.

A survey to collect economic, social, and environmental sustainability was also given to all of the anaerobic digestion technology providers. The questions from the survey and the responses are given below.

> **Question: What would it cost for an interested party to buy your equipment at the prototype scale that was demonstrated under this project?**

Himark Response: As a single unit, the prototype would cost on the order of USD$200,000. It should be noted that the unit was designed to be manufactured in a fabrication shop and manufacture of multiple units either simultaneously or serially would result in very significant unit cost savings.

Novus Response: The prototype as built cost Novus $375,000 for a throughput capacity of 2000 liters/d and an organic mass load of 80 kg COD/d. The prototype can be redesigned to gain some efficiencies in manufacture and equipment. A redesigned and optimized prototype is estimated to cost about $300,000 including these efficiencies.

Seahold Response: The prototype used repurposed tanks which allowed it to be built for roughly $50,000. A similar prototype with new tanks would cost roughly $70,000.

Question: What is the commercial installed cost for your technology based on (AD) feedstock capacity or (solar cogen) kWh output (gasification could fall under either)?

Himark Response: The capital cost of an AD facility can have a very high variability depending on a number of factors:

- Feedtock quality (moisture content, organic content, freshness, and contaminants)
- Selected use of bioGas (whether for thermal energy; cogeneration of thermal energy and electricity; electrical generation (via internal combustion engine, turbine, or solid oxide fuel cell); pipeline-grade gas (for pipeline injection, CNG, LNG), or; chemical feedstock (notably for refineries or for gas-to-liquids).
- Selected use of digestate (solids and/or liquids, required post-treatment)
- Location
- Selected degree of redundancy (for maximum operational flexibility, for maximum uptime)

Himark-designed facilities that have been constructed had lower CAPEX that the industry-wide average, usually approaching the lower end of the established range of $2,500-5,000/kWe (complete project capex including ALL hard and soft costs except for financing costs); Significant returns to scale exist, such that a 10MWe facility can have a capex much closer to the lower end of the spectrum than a 0.5MWe facility.

Novus Response: The installed cost of a full scale facility is a function of several considerations:

- Type of feedstock, feed rates, processing needed for the feedstock, and ancillary chemical and nutrient feed systems needed to make the feedstock amenable to AD and preserve longevity of the plant.
- The proposed use of biogas will determine the degree of purification required and thus dictate the biogas cleaning and compression requirements. Biogas can be used for heat, power generation, pipeline injection or manufacture of higher value products such as liquid hydrocarbons. Each of the uses has a different degree of upgrading required.
- Site conditions.
- Use and disposal of digestate – upgraded to organic fertilizer or disposed of as is.
- Degree of sophistication required and redundancy.

We have designed and constructed facilities of all sizes. We are currently building a 1300 tpd plant that will produce 3.0 MMSCFD of pipeline quality natural gas and 1500 gpd of 6-2-6 fertilizer for about $20 million.

Seahold Response: The biggest cost of the Seahold system is the steel tanks used as digesters. Costs for steel tanks can be estimated by the rule of six tenths, given below.

$$Tank\ Cost\ A = Tank\ Cost\ B * \left(\frac{Size\ of\ Tank\ A}{Size\ of\ Tank\ B}\right)^{0.6}$$

If a baseline cost is generated from current tank prices that generates the representative cost of a one gallon tank, then the equation can be simplified to:

$$Tank\ Cost = Baseline\ Cost * Tank\ Volume^{0.6}$$

This methodology is used in the chart below to calculate a digester cost for four 6,000 gallon tanks capable of generating 24 kW of electricity (Figure 59).

Figure 59: Seahold Rough Estimate

Seahold Rough Cost Estimate	
kW	24
HRT Day	6
HRT Hour	144
kWh Needed	3456
kWh/Gallon Glycerin	5
Gallons of Glycerin	691.2
% Glycerine	2.8%
Digester Volume	24,686
Tanks	4
Volume per Tank	6,000
Baseline Factor	$ 51.42
Cost per Tank	$ 9,507
Total Cost	$ 38,026
Additional Costs	$ 10,000
Total Cost	$ 48,026
Cost per kW	$ 2,001.09

Image Credit: Biodico

Since the UASB design doesn't require any stirrers or circulation pumps, the costs on top of the steel tanks are relatively low compared to other digester technologies.

Question: Are there any equipment items with short lifespans that will add appreciably to the cost after installation?

Himark Response: Not especially. Most equipment in a Himark-designed AD facility is "off-the-shelf". Himark has made considerable efforts to allow for client flexibility in the selection of equipment (i.e. we will specify a pump with a certain duty, and provide exemplar types, but a client is free to select the most cost-effective pump available in their area). Himark finds that this not only minimizes the capital cost, but also enhances the maintainability of equipment and minimizes downtime due to delays in shipping spare parts for specialized equipment around the globe.

Novus Response: All equipment used in a Novus facility is standard wastewater and digestion equipment with decades of operating history. The equipment is available from multiple vendors and is designed to operate for the life of the facility. Like any operational facility, the equipment does have sacrificial wear items such as bearings, seals, and membranes that need to be replaced at the end of their useful life to maintain uptime. The cost of these items is factored into the Operation and Maintenance budget and will not add appreciably to the cost after installation.

Seahold Response: The most likely equipment to fail will be the the probes and the hose for the peristaltic pump. None of these items is expensive to replace. The System does not use very many moving parts.

Question: What is the labor requirement for operation in terms of manpower and expertise (as it differs from the prototype equipment)?

Himark Response: The labour [sic] requirement of an AD facility can have variability depending on a number of factors:

- Operations schedule (12/24, 24/7, etc., which ties in to the degree of automation). In most cases commercial facilities are staffed 24/7.
- Maintenance philosophy
- Labour productivity
- Integrated operations that generate synergies

In general, a ~10-15MWe facility would have a staff complement between 12 and 16, and a ~1-3MW facility would have a staff complement between 4 and 6. The additional staff requirement with scale are largely driven by logistical complexity with feedstock delivery and digestate handling, as well as maintenance requirements, core operations are usually handled by 1-2 people per shift.

Novus Response: Labor requirement for the plant is limited to one operator and one maintenance person per shift. Specific site and project requirements may dictate adjustments to this need.

Seahold Requirement: No labor is required at all for the day to day operations for the Seahold plant. If it is run on glycerin only, then the loading rate will be set ahead of time and the influent will be fed by a peristaltic pump. Periodic work will need to be performed for testing samples from the various ports on the plant to make sure that the probes are working. A daily check should also be made to ensure that the pump is working properly and that there are no leaks for a full size plant.

Question: What is the anticipated operational cost of the equipment?

Himark Response: The operational cost of an AD facility can have variability depending on a number of factors:

- Labour requirements (in part driven by automation and factors noted above, but generally stable)
- Energy efficiency (both electrical and thermal and in some cases also including process fuels like Natural Gas, Diesel etc. - Himark systems are designed for high thermal efficiency, making use of waste heat for process wherever possible)
- Chemical requirements (for process, for gas quality requirements, and for post-treatment)
- Post-treatment option selected for digestate

In general, the operational cost of an AD facility is limited to basic O&M costs expected for an operational facility with the type of equipment employed (pumps, motors, etc), as there are limited additional inputs aside from the feedstock the operational cost can be considered relatively low.

Novus Response: The operating cost of the equipment is variable and is dependent of the size of facility, type of feedstock, end use of the biogas fertilizer and regulatory requirements. The operating cost of the facility could range from about $2.00-$ 4.00 per ton capacity.

Seahold Reponse: The operational cost of the equipment is minimal since the labor requirements are minimal. Process heat may be generated by the CHP generator if the methane is used for power generation onsite. Because the glycerin will be lacking in nutrients, there will be some cost associated with supplemental nutrient addition to the feed.

Question: What is the anticipated ROI/payback for a commercial project?

Himark Response: The ROI for AD facilities can have high variability depending on a number of factors:

- Cost of alternative energy source (in some situations, especially in far-flung deployment) the real cost of electricity or gas can be very high)
- Cost of alternative disposal for material used as AD feedstock (tipping fees)
- Revenue available from Digestate
- Revenue available from credits for avoidance of emissions (Landfill diversion credits, LCFS credits, RINs, Carbon Offset Credits)
- Integrated operations that generate synergies

In general, a large-scale AD facility able to take waste with a significant tipping fee and sell energy at a value that recognizes the environmental attributes (such as CNG + LCFS + RINs) will experience an ROI in the 25-50% range.

Novus Response: Novus builds the facilities with a mix of commercial debt and equity. The annual IRR for a typical facility is about 25-50% and results in a payback period of 2-4 years.

Seahold Response: The ROI is highly dependent on the value of the electricity that the plant generates. If the electricity is all used onsite, then it is replacing electricity that would otherwise

need to be purchased and is given a much higher value than the value that it receives if it is being sold back to the grid. If the electricity is used onsite and the price per kWh is $0.20, then the ROI is roughly 75% and the payback period is 16 months. If the electricity is only sold back to the grid, then the ROI is roughly 25% and the payback period is four years. The relationship between these two is roughly linear for the percentage of the electricity used onsite.

Question: How long does facility fabrication/installation take?

Himark Response: Himark can carry our process design within 60-90 days for most facilities, and a competent EPC can then effect detailed engineering, procurement and construction in about 9-12 months. In most cases the gas utilization equipment will have the longest lead time and may take as much as 8 months for delivery.

Novus Response: A commercial facility can be built in about 8-10 months including design, equipment procurement, construction and start-up.

Seahold Response: After permitting is taken care of, a commercial facility can be built in three months.

Question: What is the commercial scale footprint?

Himark Response: The footprint of an AD system can vary depending on a number of factors:

- As the system production levels are dependent on the working volume of the digesters, the amount and quality of feedstock will determine the amount of working volume needed.
- Options selected on the use of bioGas will have an impact on the space requirements
- Options selected on pre-treatment and post-treatment will have a significant impact on the space requirements

In general, a ~1-10MW AD facility will have a footprint in the 3-14 acre range. Facility footprint can be minimized by employing vertical space, which of course comes with higher capex.

Question: What would be shipped and what would be fabricated onsite/locally for the example of a Red Rock Ranch installation?

Himark Response: A Himark facility will have a large proportion of onsite construction. As much of the facility is a civil work (digesters are the main feature), this can certainly be done onsite. Process equipment will likely be shipped to the site from vendors and placed and installed by the EPC.

Novus Response: The NBC™ system does not need large digesters. Our 1300 tpd facility uses a mere 2 acre site for the entire plant including the digesters, feedstock and digestate processing, gas upgrading facilities and staff areas.

Seahold Response: The core digestion equipment takes a 20′ by 20′ footprint for every 6 kW of power capacity and the digesters are designed to be stacked directly next to each other. Additional space is needed for the CHP generation equipment and the gas storage, which will depend on the project and on the application.

Question: What are the major permitting issues?

Himark Response: In certain jurisdictions the main permitting issues will be around air emissions. This is certainly the case in California, and almost entirely rules out internal combustion engines as an option for cogeneration of heat and electricity (other options do exist). Other key considerations for permitting will be around the logistical flow of feedstock and digestate, civil construction, site water management, etc.

Novus Response: The NBC™3333 system removes materials that would otherwise pollute the environment. Jurisdictions in other states have been very supportive of the technology and have determined it to be beneficial with minimal effect to the environment. The only permitting issues that need to be commonly addressed are the management of storm runoff around feedstock areas, air quality permitting for the waste gas flare, and permits for the receipt and processing of residues in the facility. There are no other requirements due to the benefits to the environment.

Seahold Response: Air emission requirements will have to be addressed. In addition, gas storage requirements will also need to be examined. If the electricity generated is to be sold back to the grid, there may be some hurdles associated with grid interconnection.

4.3 Analyze data for economic, social and environmental sustainability

The charts below show the economic, environmental, and social sustainability of the project in terms of feedstocks, energy, labor incentives, and biofuel. The project was shown to have significant economic benefits in all of the above categories. The feedstocks grown are economically advantageous to most crops grown for standard biodiesel production. They are grown on lower cost marginal land and use less water. With the MPU, the byproducts are also used to create economically valuable energy through gasification and anaerobic digestion (Figure 60). Furthermore, the energy generated by solar CHP and from the crude glycerin through anaerobic digestion adds additional economic benefit. The labor requirements for energy production are fully assessed in 7.1.2 Project the "installed cost" and "payback period" for the integrated and interconnected system. Incentives from the production from the MPU are increased over those of standard biodiesel production by the use of the byproducts and lower carbon intensity feedstocks.

Figure 60: MPU Economic Sustainability

Economic Sustainability	
Topic	**Description**
Feedstocks	Marginal Land, Byproducts Usable for CHP
Energy	Biodiesel, Glycerin, Gasification, Solar Cogen
Labor	Different Technologies Assessed for Different Availabilities
Incentives	Incentives from Production of Biodiesel and CHP
Biofuel	Saleable Biodiesel and CHP

Image Credit: Biodico

Using entire output of the feedstocks, rather than just the oil, in addition to using low CI feedstocks improves the environmental sustainability of the project (Figure 61). This also allows the project to operate on internally produced heat and power rather than relying on the grid. The green jobs provided by the MPU are outlined in more detail in 7.1.2 Project the "installed cost" and "payback period" for the integrated and interconnected system. The project also directly displaces 18 millions gallons of petroleum diesel and over 100,000 kWh of electricity per year.

Figure 61: Environmental Sustainability

Environmental Sustainability	
Topic	**Description**
Feedstocks	Greater GHG Reductions from Reuse of Feedstocks
Energy	Does Not Rely on External Energy
Labor	Green Jobs
Incentives	Greater Incentives from Lower GHG
Biofuel	Providing Renewable Alternative to Fossil Fuel

Image Credit: Biodico

By using marginal land with less water, the impact of agriculture for biodiesel production on surrounding community resources in minimized (Figure 62). There is an excess of CHP produced by the project that allows an increase in local distributed generation. The project also brings jobs, investment, and tax revenues to the region. West Fresno County is one of the most impoverished regions in California, and incentives are available for providing development and employment opportunities. Locally available biodiesel production will also increase the energy security and stability for the region.

Figure 62: Social Sustainability

Social Sustainability	
Topic	**Description**
Feedstocks	Low Impact on Community Resources
Energy	Provides Local Distributed Generation
Labor	Local Jobs, Investment & Taxes
Incentives	Incentives for Development in Hardest Hit Areas
Biofuel	Locally Available Biodiesel Production

Image Credit: Biodico

4.3.1 AD Ranking Matrix

Based on the data gained from the operation of each of the anaerobic digester units, a ranking system was set up to determine their economic sustainability, employment and operation requirements, and the logistics needed for installation in new locations. Metrics were also included at the request of Naval EXWC that will have cross-applicability between the State of

California and the DOD. The rankings table is given in Figure 63, and each of the ranking metrics is further explained in subsections.

Figure 63: AD Ranking Matrix

	Novus	Himark	Seahold
Performance			
Gas Production	8	8	8
Gas Production Speed (HRT)	8	5	6
Gas Quality	8	8	7
Reliability	7	6	7
Required Maintenance	7	8	8
Operability			
Labor Requirements	6	8	9
Training Requirements	7	6	8
Ease of Operations	7	6	9
Required Tech Support	6	8	9
Ease of Tech Support	9	5	5
Feedstock			
Material Requirements	7	5	7
Versatility	6	8	4
Survivability	5	7	4
Effluent Use/Quality	9	5	6
Logistics			
Footprint (Size)	7	9	9
Weight	7	8	8
Self-Sufficiency	8	8	8
Average Ranking	7.2	6.9	7.2

Image Credit: Biodico

4.3.1.1 Gas Production

How well did the digester produce gas in terms of volumes produced per unit of digester capacity/footprint? How well did the gas production compare to other digesters of the same size?

Novus: All three of the digesters produced gas in comparable volumes per liter of glycerin influent. The gas production volume was roughly 800 times the volume of glycerin added.

Himark: All three of the digesters produced gas in comparable volumes per liter of glycerin influent. The gas production volume was roughly 800 times the volume of glycerin added.

Seahold: All three of the digesters produced gas in comparable volumes per liter of glycerin influent. The gas production volume was roughly 800 times the volume of glycerin added.

4.3.1.2 Gas Production Speed

How quickly did the digester produce gas? What was the hydraulic retention time compared to standard wastewater treatment facilities?

Novus: The Novus unit has the fastest gas production speed of the three digestion units and produced gas from the glycerin feedstock within four days. Standard wastewater treatment facilities require thirty days hydraulic retention time. The increase in gas production rate is primarily due to the process flow characteristics of the system.

Himark: The Himark unit has a significantly faster gas production time of ten days as compared to thirty days. The increase in gas production rate is primarily due to the increase in temperature, from mesophilic to thermophilic, of the system.

Seahold: The Seahold unit has a very fast gas production speed of six days. The increase in gas production speed is primarily due to the UASB process flow type.

4.3.1.3 Gas Quality

What was the methane content of the gas coming out? How suitable is the gas for power production?

Novus: The gas quality from the Novus equipment was better than average for wastewater treatment facilities. Most advanced wastewater treatment technologies produce gas with a methane content of 50% to 75%. Novus produced biogas with roughly 74% methane as shown in the lab report below. The analysis was done by Pace Analytical according to ASTM method D1945 (Figure 64).

Figure 64: Analytic Results

ANALYTICAL RESULTS

Project: Biodico-Seahold-NovusStudy Rev
Pace Project No.: 10234907

Sample: G-061813 **Lab ID: 10234907001** Collected: 06/18/13 14:00 Received: 07/11/13 09:12 Matrix: Air

Parameters	Results	Units	Report Limit	DF	Prepared	Analyzed	CAS No.	Qual
Method 3C AIR - Fixed Gases	Analytical Method: Method 3C Gases							
Carbon dioxide	**21.1**	%	9.5	4.77		07/12/13 12:43	124-38-9	
Carbon monoxide	ND	%	1.9	4.77		07/12/13 12:43	630-08-0	
Methane	**74.3**	%	19.1	4.77		07/12/13 12:43	74-82-8	
Nitrogen	ND	%	38.2	4.77		07/12/13 12:43	7727-37-9	
Oxygen	ND	%	9.5	4.77		07/12/13 12:43	7782-44-7	

Image Credit: Biodico

Himark: The gas quality from the Himark equipment was also better than average for wastewater treatment facilities. The methane was measured in real-time with inline equipment installed in the prototype facility. The daily average methane content in the biogas produced reached 71%.

Seahold: The gas quality of the Seahold unit was marginally lower than the quality of the Novus or Himark units at 69.4% methane content. This is still markedly higher than the methane content from most anaerobic digestion operations.

4.3.1.4 Reliability

How reliable was the system in terms of consistent gas production? Is this system capable of reliable power production?

Novus: The system produced a reliable stream of gas volume with a reliable content. Given a consistent feedstock stream, the power output should be consistent, and, even with feedstock changes, if the feedstock stream is from a well characterized source, then the output should be predictable.

Himark: The Himark system produced a similarly consistent volume of gas with a similarly reliable methane content. The reliability and predictability of the power production are fairly close to the Novus unit.

Seahold: The Seahold unit also produced a very consistent volume of gas as measured against the volume of incoming glycerin.

4.3.1.5 Labor Requirements

How do the labor requirements of this system compare to other digesters? Were more or less hours needed to run the system? Would more or less employees be required for an estimated scale-up of the system?

Novus: The labor for this system was not arduous, but it did require more time daily than the other digesters. Both the Novus and the Himark system required daily manual feedstock loading into the hopper that was to enter the system. The Novus system, however, had more components, including a screw press between the hydrolysis/acetogenesis and the methanogenesis stages used to remove the solids from the leachate. The screw press required monitoring, which was not strenuous or difficult, but took employee time. Approximate time per day was three to four man hours.

Himark: The labor for this system was not very time consuming, but did require someone onsite for two loading periods each day and testing time for solids content and FOS/TAC testing (acidity and alkalinity). The approximate time per day for feedstock loading and digestate testing was two hours per day.

Seahold: This system was designed to require minimal labor. The feedstock pump is continuous, and no dilution of glycerin is needed for the technology. This means that a tote full of glycerin will last for weeks on the prototype scale unit without needing replacement. Much information about the health of the system can be determined by the pH and ORP meters and by the gas production, which are all monitored remotely. Periodic testing should be done with new feedstocks, but generally no more than weekly testing should be needed. The approximate time per week is three hours, averaging just under half an hour per day.

4.3.1.6 Training Requirements

How do the training requirements of the system compare to other digesters? Is more or less time needed for training? Is the training more or less difficult for employees?

Novus: The training for this system is not difficult. The pumps and valves are controlled by PLC which can be accessed remotely for technical support or for remote operation of a future full scale system without loading requirements or screw press monitoring requirements. The system was operated for this project by a man with mechanical experience in agricultural work and operational sense, but no real technical experience and zero computer experience.

Himark: The training for this system is only slightly difficult. The system is controlled by two three way switches with a total of nine options for system settings. The switch settings are not very intuitive for non-technically minded operators. Aside from that though, the system design is simple and easy to operate.

Seahold: The training for this system is almost non-existent. There is just a single switch controlling the pump speed and areas for the influent and effluent. If periodic testing of the digester contents for health is to be performed onsite though, some laboratory training will be needed.

4.3.1.7 Ease of Operations

How physically and/or mentally demanding is the job of keeping the digester operating?

Novus: The digester operation is only slightly physically demanding. Loading the feedstock requires the operator to lift five gallon buckets of glycerin weighing about 60 pounds each into a

hopper just above waist height. The day to day digester operation is not very mentally demanding.

Himark: The digester operation carries the same physical demands. Loading the feedstock requires the operator to lift five gallon buckets of glycerin weighing about 60 pounds each into a hopper just above waist height. The day to day digester operation is not very mentally demanding.

Seahold: There are almost no digester operations to speak of, only ensuring that the influent and effluent tanks are not run empty or full respectively. Some knowledge of the system is needed to perform checks.

4.3.1.8 Material Requirements

What is needed in terms of external nutrients and/or co-feedstocks to effectively run the facility with crude glycerin? Are the materials easily sourced and/or shipped? Are they expensive?

Novus: The digester required either nutrients or a nutrient rich codigestant such as manure. The nutrients in the blend were sourced from Fisher Scientific and are also available from a wide variety of other sources.

Himark: This digester also required either a nutrient rich codigestant or a nutrient blend provided by Himark. The blend was a proprietary mixture provided by Himark rather than a mix of widely available nutrients.

Seahold: The digester does not require much nutrient addition at all. Because the material flows upward through the sludge slowly, the sludge retention time is very high. The nutrients are not washed out of the system and even though the glycerin lacks nutrients, they do not require continual replenishing. When they do need to be replenished, supplemental nutrients can be added to the glycerin.

4.3.1.9 Versatility

How well does the system respond to different types of feedstock? Are many changes needed to change between feedstocks?

Novus: The system can respond reasonably well to different types of feedstock, but the fixed films in the methanogenesis tank are high performance and new feedstocks should be gradually introduced to ensure adaptability.

Himark: The Himark system performs the best of the three in being able to take in any kind of feedstock. It is one CSTR tank and not very susceptible to shocks from different feedstock types.

Seahold: The Seahold system is the least versatile of the three. The UASB is dependent on a consistent stream of feedstock entering the system and for any changes the pump and the flow rate would need to be recalibrated. Too high of solids content may lead to some physical barriers. Glycerin has very low solids content, though, so that issue is not addressed for this application.

4.3.1.10 Survivability

How well does the system survive changing conditions? Can it handle changes in feedstock, unexpected site problems (power, water, etc. shortage), operational mistakes in the field, etc.?

Novus: The system needs to be adjusted to new feedstocks gradually for good performance. This is kind of a double edged sword resulting from the digestion technique. The high sludge retention time allows for quick digestion, but leaves the system slower to respond to changes. The system crashed with the introduction of glycerin from a different source that had a higher sulfur content. Power or water losses can threaten the survivability of the sludge in the reactor.

Himark: The system responded fairly poorly to changes in COD. It crashed twice and came very close to crashing a third time over the course of the demonstration. It ships well though and since the sludge retention time is not important to the system, loss of power and/or water onsite may be detrimental for the period of the outage, but bringing it back up to full production rates afterward is almost immediate.

Seahold: The system can handle changes in COD and temperature to some extent and is not worse than the other two systems in those respects. Where it ranked lower, though, was in the restart procedure in the event of a crash or in the event of system reshipping. The sludge blanket must be built up over time, and if the system crashes it must be reseeded with sludge granules from a wastewater treatment plant before operating. Though it can begin producing gas again right away, it can take up to 30 days to bring it back up to optimum operability.

4.3.1.11 Effluent Use/Quality

How suitable is the effluent leaving the system for use in agriculture, algaculture, and/or other uses? What is the overall quality of the effluent?

Novus: The effluent is cleaned up after digestion almost to the quality of potable water and can be used for irrigation. This can add significant value to the process in agricultural areas as the effluent becomes a value added byproduct. The impurities in the effluent can be used as fertilizer in some applications.

Himark: The effluent is not cleaned up or treated and so is standard as compared to other wastewater treatment systems.

Seahold: The effluent is not cleaned up or treated as it is with the Novus system. The upflow system, however, leads it to be relatively free of sediment and it is significantly cleaner than the blended average of the digester.

4.3.1.12 Footprint

How much space does the unit take up? How much preparation is needed for the site the equipment will be installed on?

Novus: The Novus unit is stored inside of a standard shipping container with length, width, and height dimensions of 40′, 8′, and 8′. The ratio of processed influent volume to footprint and volume is very high and everything is generally well arranged to maximize use of the space. Even the gas storage is inside. The gas measurement is performed by two monometers

consisting of two 500 gallon poly tanks each. Two of those poly tanks could be removed if another system of gas measurement was used.

Himark: The Himark unit is stored inside of a half standard shipping container with length, width, and height dimensions of 20′, 8′, and 8′. The ratio of processed influent volume to footprint and volume is reasonable, but unlike Novus, the gas is not stored inside. Inside storage is not necessarily an advantage, but the need for external gas storage will add more to the footprint.

Seahold: The Seahold unit is shippable within a half standard shipping container, but again, unlike Novus, the gas is not stored inside the container.

4.3.1.13 Transportability

How easy is the equipment to move to a location for operations? Once onsite how easy is it to prepare the system for use? How easy is it to change sites for the equipment?

Novus: The entire system fits within a standard shipping container and is physically easy to ship. The tanks need to be secured, but the system can be shipped in its running configuration. The microbial colonies in the sludge, though, are susceptible to dying off if the shipping process takes too long, resulting in a relatively time consuming ramp up to full capacity.

Himark: The entire system fits within a half standard shipping container and is physically easy to transport. Just like with the Novus system, the tanks need to be secured and the system can be shipped in its running configuration. A gas storage system needs to be set up onsite, but setting up a gas bladder or other low cost storage system onsite is fairly straight-forward.

Seahold: The transportability is almost identical to the transportability of the Himark system.

4.3.1.14 Self-Sufficiency

How reliant is the material on external infrastructure? How easy is it to replace parts that commonly wear out or that may break? What other external requirements exist for the system?

Novus: The Novus system is dependent on a consistent power and water supply. Parts are generally easy to replace with standard hardware, though some specialty items like heaters and screw press parts need to be replaced by manufacturer provided parts. Nutrients are supplied by chemical companies, but must be shipped in.

Himark: The Himark system is also dependent on a consistent power and water supply. Parts are generally easy to replace with standard hardware. Nutrients supplied by Himark will need to be shipped in.

Seahold: The Seahold system is also dependent on a consistent power and water supply. For this project, the solar cogen and the gasifier were used to provide the heating and power for the system, as they could have for any of the previous two systems had the timing been different. The Seahold system does not require as much in the way of shipped-in nutrients.

4.3.1.15 Conclusion

In colnclusion, each of the digesters has strong and weak points and the choice of which type of digester to use and from what manufacturer would be largely project dependent. The Novus system would be ideal for a single type of feedstock where power generation will be very valuable and where a dedicated operator will be on site to ensure that everything will run correctly. It has the potential to be the highest performing of the three sytems. The Himark system would be ideal in a situation where feedstock types may vary and where the system may be shut down for periods of time. The Seahold system would be ideal for deployment in areas where the feedstock type will be

4.4 Perform life cycle analysis and pursue a LCFS pathway for the integrated system using Task 3 feedstocks and Task 4 equipment

The PFD shows all of the pieces of capital equipment and the lines for electrical, biomass, heat, and water (Figure 65).

Figure 65: MPU PFD

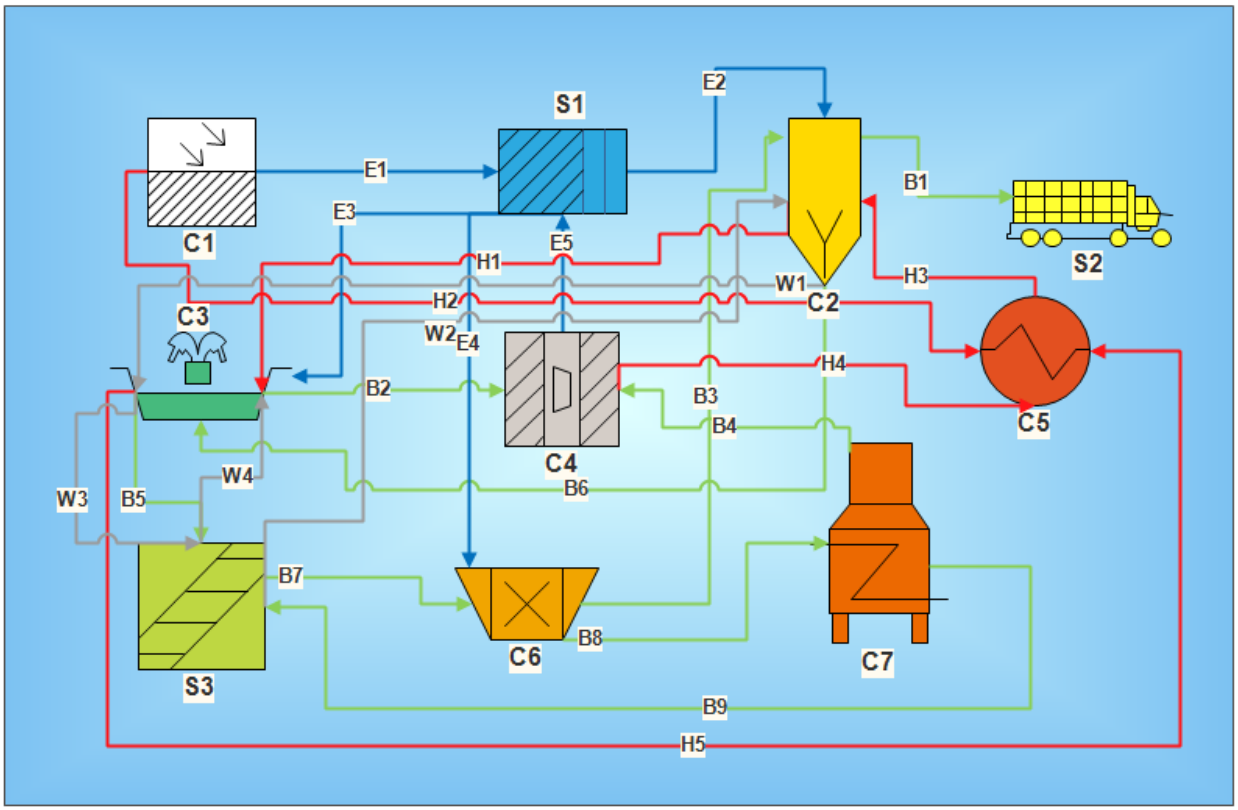

Image Credit: Biodico

The lines given in the PFD are given in more detail (Figure 66).

Figure 66: MPU PFD Table

Core Equipment	
C1	Solar Cogen
C2	Biodiesel Production
C3	Anaerobic Digestion
C4	CHP Generator
C5	Heat Exchanger
C6	Oil Extruder
C7	Gasifier

Site Equipment/Infrastructure	
S1	Power Hub
S2	Biodiesel Sales
S3	Agriculture
S4	Biochar Storage

Biomass Lines			
	Material	From	To
B1	Biodiesel	Biodiesel Plant	Sales
B2	Biogas	AD	Generator
B3	Oil	Oil Extruder	Biodiesel Plant
B4	Syngas	Gasifier	Generator
B5	Effluent	AD	Ponds
B6	Crude Glycerin	Biodiesel Plant	AD
B7	Seeds	Agriculture	Oil Extruder
B8	Seed Meal	Oil Extruder	Gasifier
B9	Biochar	Gasifier	Agriculture

Electrical Lines		
	From	To
E1	Solar Cogen	Power Hub
E2	Power Hub	Biodiesel Plant
E3	Power Hub	AD
E4	Power Hub	Extruder
E5	Gasifier	Power Hub

Heat Lines		
	From	To
H1	CHP Generator	Heat Exchanger
H2	Heat Exchanger	Biodiesel Plant
H3	Biodiesel Plant	AD
H4	AD	Ponds
H5	Ponds	Atmosphere

Water Lines		
	From	To
W1	Biodiesel Plant	AD
W2	Agriculture	Biodiesel Plant
W3	AD	Agriculture
W4	Agriculture	AD

Image Credit: Biodico

The scales chosen for commercial development based on the work performed are to bring the gasification capacity up to 100 kW and to bring the AD unit up to a large enough scale to provide the remaining heat and power needed for the entire facility. Figure 67 provides the biomass line process flow for the commercial facility at this scale.

Figure 67: Biomass Lines

Biomass Lines				
	Material	Qty	From	To
B1	Biodiesel	10 MMGPY	Biodiesel Plant	Sales
B2	Biogas	7.56 MMm3	AD	Generator
B3	Oil	10 MMGPY	Oil Extruder	Biodiesel Plant
B4	Syngas	154 MMm3	Gasifier	Generator
B5	Effluent	87.8 MMGPY	AD	Ponds/Ag
B6	Crude Glycerin	125,000 GPY	Biodiesel Plant	AD
B7	Seeds	138,000 MTPY	Agriculture	Oil Extruder
B8	Seed Meal	237,000 lbPY	Oil Extruder	Gasifier
B9	Biochar	7,880 MTPY	Gasifier	Agriculture

Image Credit: Biodico

Most of the process flow lines ultimately scale from the biodiesel production capacity of the system, 10 million gallons per year (Figure 68).

Figure 68: Biodiesel Plant to Sales

B1 Calculations	
MMGPY Biodiesel	18
MMLPY Biodiesel	68.0
Specific Gravity	0.88
Metric Tons	5.99E+04

Image Credit: Biodico

The biogas lines are scaled from the amount of power generation that will be required by the system. The solar panels provide 20 kW and the expanded gasifier will provide another 100 kW. The total electrical use of the facility is 350 kW. The electrical values are provided in detail later in this section, but 100,000 gallons per year of glycerin digestion will be required to make up the additional necessary power (Figure 69). Crude glycerin is created as 25% of the total biodiesel production of a facility by volume, so only a small percentage of the total glycerin created will be used. The volume of biogas produced per volume of glycerin is taken from the volumes observed in both the Himark and the Novus units. The methane percentage in the biogas is taken from testing done on the biogas produced from the digesters.

Figure 69: Crude Glycerin to AD

B2 Calculations	
GPY Crude Glycerin to AD	100,000
LPY C Gly to AD	378,100
m3 C Gly to AD	3.78E+02
Biogas/C Gly (vol/vol)	800
m3 Biogas	3.02E+05
Methane/Biogas (vol/vol)	70%
m3 Methane	2.12E+05
m3 CO2	9.07E+04

Image Credit: Biodico

The transesterification reaction actually produces 106 gallons of methylesters per 100 gallons of incoming triglycerides. In reality though, even with first-use vegetable oil, as is used in this projection, the yields are closer to 100 gallons of methylesters out. Transesterification is a double displacement that temporarily forms free fatty acids that bond to the methyl groups. A small portion of these fatty acid chains will react with the sodium catalyst to form soaps, and the reaction yields in a commercial setting are not perfect. Incidentally, this is what causes the impurity in the glycerin byproduct. The yield of 100% by volume is given in Figure 70.

Figure 70: Oil to Biodiesel Plant

B3 Calculations	
MMGPY Biodiesel	10
Biodiesel/Oil (vol/vol)	100%
MMGPY Oil to Biodiesel	10

Image Credit: Biodico

The transesterification reaction is shown in Figure 71.

Figure 71: Transesterification Reaction

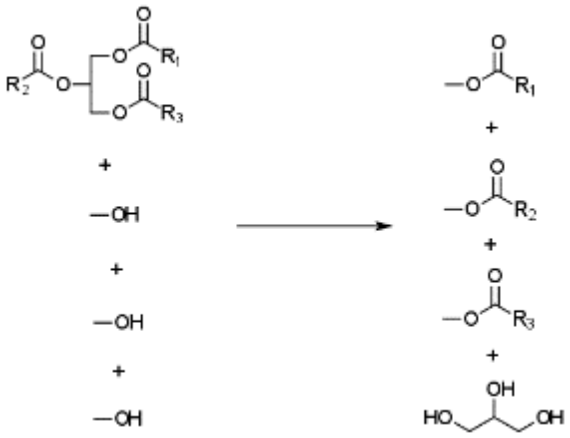

Image Credit: Biodico

The calculations show the volume of syngas produced from the incoming metric tons per year of seed meal (Figure 72). The yield tests were actually performed to determine the hours of generator engine runtime and the kWh produced by weight from the seed meal, so the values for syngas volume were calculated from kWh produced. The efficiency of the generator engine is 25%, so the MJ of total syngas per pound of seed meal and then for all of the seed meal can be calculated. The MJ per cubic meter of syngas are known, so the cubic meters of syngas produced can then be calculated.

Figure 72: Syngas from Gasifier

B4 Calculations	
TPY Seed Meal	1.18E+03
lbs per Year Seed Meal	2.37E+06
kWh generated per lb	0.4
MMBtu generated per lb.	1.26E-03
MJ generated per lb.	1.33E+00
Engine Efficiency	25%
MJ in Biogas/lb Seed Meal	5.33E+00
MJ Total Biogas	1.26E+07
MJ per m3	10
Total m3 Syngas	1,261,144

Image Credit: Biodico

The gallons of effluent are calculated in Figure 73. The ideal glycerin percentages by volume are taken from the results of the Novus, Himark, and AMPTS systems. The amount of influent that will come into the system per year is just a matter of taking the incoming glycerin and dividing it by the percentage of volume that it will make up. The rate of glycerin destruction in the anaerobic digestion is roughly 60%, meaning that 60% of the mass of glycerin will be converted into biogas. This takes 600,000 gallons out of the incoming effluent per year and leaves 3.5 million gallons per year in effluent discharge. This value was determined by analyzing the solids concentration of the influent vs the effluent for the digesters in operation. In the chart, GPY stands for gallons per year and glycerin destruction is the percentage of glycerin that is converted to biogas and does not leave with the effluent.

Figure 73: AD Effluent to Ag

B5 Calculations	
GPY Glycerin	100,000
% Glycerin	2.8%
Total G Influent	3.57E+06
% Glycerin Destruction	60.0%
GPY Destrucion	60,000
GPY to Ag	3.51E+06

Image Credit: Biodico

The quick calculation in Figure 74 shows the amount of crude glycerin that will be produced by the biodiesel plant per year. The MPU produces 25% crude glycerin by biodiesel volume per year for first use oils.

Figure 74: Glycerin from Biodiesel Plant

B6 Calculations	
MMGPY Biodiesel	18
% of Crude Glycerin (vol)	25%
MMGPY Crude Glycerin	4.5

Image Credit: Biodico

The calculation in Figure 75 shows how many metric tons per year of incoming seeds will be needed to produce 10 million gallons of oil. The average percentage of oil found in the seeds was used to find the value.

Figure 75: Seeds to Extruders

B7 Calculations	
MMGPY Oil Out	18
MMLPY Oil Out	68.0
Specific Gravity of Oil	0.91
Metric Tons Oil Out	6.19E+04
% Oil Average in Seeds	25%
Metric Tons Seeds In	2.49E+05

Image Credit: Biodico

The amount of seed meal that is needed for a 100 kW gasifier is provided in Figure 76.

Figure 76: Seed Meal to Gasifiers

B8 Calculations	
kW Gasifier Capacity	100
Short Tons per Year Seed Meal	118
lbs per Year Seed Meal	2.37E+05

Image Credit: Biodico

The weight of biochar out of the seed meal is given in Figure 77. This is based on the average amount of fixed (non-volatile) solids found across the testing of all of the seed varietals.

Figure 77: Biochar from Gasifier

B9 Calculations	
lbs Seed Meal In	2.37E+05
% Carbon Ash	8%
lbs Biochar Out	1.92E+04

Image Credit: Biodico

The legend for the electrical lines for the MPU is provided in Figure 78. All of the values are scaled to the quantities given in the previous biomass calculations.

Figure 78: Electrical Lines

Electrical Lines		
	From	To
E1	Solar Cogen	Power Hub
E2	Power Hub	Biodiesel Plant
E3	Power Hub	AD
E4	Power Hub	Extruder
E5	Gasifier	Power Hub

Image Credit: Biodico

The calculations in Figure 79 are for the kWh per year from the solar panels at RRR at full operation. The total panel setup is rated for 20 kW of electricity generation, but the actual amount generated depends on the insolation to the area, the area of solar panels, and the efficiency of the panels. The values are then converted to total kWh per year.

Figure 79: Electricity from Solar Panels

E1	
Total kWh per m2 per Day	5.75
% Efficiency	12%
Solar kWh per m2 per Day	0.69
Total m2 Panels	100
Solar kWh per Day	69
Solar kWh per Year	2.52E+04

Image Credit: Biodico

The calculations in Figure 80 are for the total kWh used per year by the biodiesel production portion of the MPU. The electricity use is significantly lower than conventional production models, which are included as a comparison. The MPU model does not require distillation or vapor recovery, which are the two most energy intensive portions of production.

Figure 80: Electricity to Biodiesel Plant

E2		
Production Model	Conventional	ARIES
Distillation kWh	100,740	0
Liquid Transfer kWh	12,433	12,433
Vapor Recovery kWh	722,700	0
Computers & Incidental kWh	96,360	96,360
Total kWh Biodiesel Production	932,233	108,793
As % of Conventional	100.0%	11.7%

Image Credit: Biodico

Figure 81 shows the energy use per cubic meter of capacity for the proposed anaerobic digestion portion of the system. The electricity use statistics were provided by the equipment vendors who contracted on the project.

Figure 81: Electricity to AD

E3	
kW per m3 Capacity	0.01
m3 Capacity	259
Annual kWh Electricity	22,680

Image Credit: Biodico

Figure 82 shows the energy use required by the seed press for this project. The model outlined was chosen by trade study and one unit is currently installed at Red Rock Ranch.

Figure 82: Electricty to Extruders

E4	
Make	Insta-Pro
Model	5005
HP	66.5
kW	48.9
Press lb/Hr	4,200
lbs/kWh	85.9
lb Feed	2.53E+08
Year Hrs Req	60,238
Year kWh Req	2.95E+06

Image Credit: Biodico

Figure 83 shows the electricity generation from both the syngas and the biogas. The efficiency of generation from the biogas is roughly 30% and the efficiency from the syngas is roughly 25%. Using seed meal is 10% with 90% coming from woodchips, as in the gasifier test runs. Woodchips are currently a disposal liability from surrounding orchards in the Central Valley and are abundantly available for free.

Figure 83: Electricity from Generator

E5	
MJ Electricity per m^3 Methane	37.3
kWh Electricity per m^3 Methane	10.4
Annual m^3 Methane	2.12E+05
Annual kWh Electricity from CH4	2.19E+06
kW of Commercial Generator	100
kWh per Ton Seed Meal/Woodchips	740
Tons per Year of Meal/Woodchips	1,184
Tons per Year of Seed Meal	118
Tons per Year of Woodchips	1,065
Annual kWh Electricity from Syngas	8.76E+05

Image Credit: Biodico

The total exportable kWh is provided in Figure 84. Energy is sold back to the grid for much less than it was purchased for, so this system was scaled to only produce as much electricity as needed for the project onsite. The kWh generated is from the anaerobic digester, the gasifier, and the solar cogen. The total kWh used is the electricity used by all components of the project.

Figure 84: Sum Electricity Use

Sum Electricity	
Total kWh Generated	3.10E+06
Total kWh Used	3.06E+06
Total Exportable kWh	3.99E+04

Image Credit: Biodico

The legend for the heat lines is in Figure 85. The heat lines are set up as a cascade from the biodiesel production to the anaerobic digestion since the required temperature for biodiesel production is higher.

Figure 85: Heat Lines

Heat Lines		
	From	To
H1	Solar Cogen	Heat Exchanger
H2	Generator	Heat Exchanger
H3	Heat Exchanger	Biodiesel Plant
H4	Biodiesel Plant	AD
H5	AD	Heat Exchanger

Image Credit: Biodico

The heat generated by the solar CHP is provided in Figure 86. As with the electricity from the solar cogen, the heat is linearly scalable to the area of panels, so the extrapolation is straightforward.

Figure 86: Heat from Solar Cogen

H1	
Solar kWh per m2 per Day	0.69
Total m2 Panels	100
Solar kWh per Day	69
MMBtu Heat per kWh Elec	1
MMBtu Heat per Day	69
MMBtu Heat per Year	2.52E+04

Image Credit: Biodico

The Mmbtus of heat energy that are captured as the electricity is generated from both biogas and syngas are shown in Figure 87. This heating energy then flows into the heat exchanger loop for use in the biodiesel plant and the anaerobic digestion.

Figure 87: Heat from Generator

H2	
MMBtu per kWh	3.41E-03
kWh from Biogas	2.19E+06
kWh from Syngas	8.76E+05
Total kWh	3.07E+06
Total MMBtu	1.05E+04

Image Credit: Biodico

The Btus required for biodiesel production are shown in Figure 88. The biodiesel reaction rate increases with temperature, but the methanol boils off at 154°F so the reaction is run at a safe

temperature of 140°F. The two major factors for the heat energy are ramping the heat of 10 million gallons of oil per year up to 140°F from average ambient temperature and countering heat loss while the heated feedstock waits to enter the reaction phase and heat loss between reactions.

Figure 88: Heating for Biodiesel

H3	
Btus per lb per °F	0.4
Btus per G per °F	3
Starting Temperature	65
Reaction Temperature	140
Btus per G	236
MMGPY	18
Heat Ramp MMBtus per Year	4,250
Heat Loss MMBtus per Year	4,785
Total Heating MMBtus per Year	9,035

Image Credit: Biodico

The calculations in Figure 89 show the total heat requirements of the anaerobic digestion. Mesophilic temperatures of 95°F and thermophilic temperatures of 131°F were both tested during the course of this project. To estimate conservatively, thermophilic temperatures are used for the AD projection and the average mesophilic temperature of 65°F is used for the incoming material.

Figure 89: Heating for Anaerobic Digestion

H4	
Starting Temperature	65
Process Temeprature	131
GPY Glycerin	100,000
lbs per Year Glycerin	1,006,236
Glycerin Btus per lb per °F	0.576
MMBtus per Year for Glycerin	17
MMGPY Reclaimed Water	3.47
MM lbs per Year Water	28.9
Water Btus per lb per °F	1.000
MMBtus per Year for Water	1,909
MMBtus per Year Total	1,926

Image Credit: Biodico

Figure 90 shows the total exportable or otherwise useable Mmbtus of heat energy. The efficiency of the heat exchanger is given as 90%. The system was scaled to provide the electric

needs of the system, and the heat is well in excess of what is needed. In the case of RRR it would likely be used for process heating on a co-located ethanol facility.

Figure 90: Total Heat Use

H5	
MMBtu Heat In	1.38E+06
MMBtu Heat Used	3.27E+04
Heat Loop Efficiency	50%
Excess MMBtu Heat	6.75E+05

Image Credit: Biodico

The legend for the water lines is provided in Figure 91. The project at Red Rock Ranch, by virtue of colocation with agriculture, has been able to direcly test the use of water to and from agricultural plots for these process flows.

Figure 91: Water Lines

Water Lines		
	From	To
W1	Biodiesel Plant	AD
W2	Agriculture	Biodiesel Plant
W3	AD	Agriculture
W4	Agriculture	AD

Image Credit: Biodico

The volumes of water required for biodiesel production are approximately 30% of the total volume of biodiesel produced (Figure 92). The water wash stages of biodiesel production are to pick up trace polar contaminants that are solubilized in the non-polar biodiesel layer after the transesterifications such as methanol and free glycerin. The volumes aren't large and don't contribute substantially to the volume of water leaving the reactor, but the specification for methanol is low at 0.2% and the specification for free glycerin is especially low at 0.02% by weight. Even so, the trace methanol in the biodiesel would make the wash water directly leaving the facility unsuitable for agriculture. Though small, it does act as added energy for AD.

Figure 92: Water to and from Biodiesel

W1 & W2	
MMGPY Biodiesel	10
Water/Biodiesel (vol/vol)	30%
MMGPY Water	3

Image Credit: Biodico

The water leaving the anaerobic digester has been double counted in this process flow as both water and biomass. The sludge in the effluent has organic material in it, but the Novus process is designed to remove that material and capture it as fertilizer to be used separately while sending out clean water (Figure 93). Blended together, the mix of water and organic effluent from glycerin (not municipal wastewater) has been and can be used directly in the agriculture process to grow crops for energy as a kind of blended mixture of fertilizer and water. Biodico has thus opted to include this material under both categories.

Figure 93: Effluent to Ag

W3	
GPY Glycerin	100,000
% Glycerin	2.8%
Total Influent	3.57E+06
% Glycerin Destruction	60.0%
GPY Destrucion	60,000.0
GPY to Ag	3.51E+06

Image Credit: Biodico

Just as the water from the digester can be used in the irrigation of energy crops, the waste irrigation from energy and/or food crops can be used to dilute the glycerin for the anaerobic digester (Figure 94). The wash water from the biodiesel production process makes up most of the total water needed for the AD and the rest can come from reclaimed agriculture water.

Figure 94: Ag Water to AD

W4	
GPY Needed	3.47E+06
GPY from Bio	3.00E+06
MMGPY from Ag	4.71E+05

Image Credit: Biodico

The work required on the biomass crops for LCFS pathway determination is currently being performed by Dr. Kaffka and his group (Appendix 2: UC Davis Report).

CHAPTER 5:
Independent Measurement and Verification

5.1 Provide an independent measurement and verification report from the Navy regarding Task 6 activities

Measurement and verification was performed on the equipment as outlined in sections 2.2 and 3.4 of this report.

NAVFAC EXWC and Cardno undertook an extensive environmental analysis of the project under National Environmental Protection Act requirements for an Environmental Assessement (EA). A complete EA was prepared and made available for public review as well as the Navy's chain of command. The final assessment was a Finding of No Significant Impact (FONSI).

The proposed action described in the EA was the integration of renewable combined heat and power with a 10 mgy biodiesel plant and algaculture. The facility would be made of modular, portable infrastructure to produce and distribute reliable and clean energy (i.e., biodiesel, electricity, and heat). Excess electricity would be provided to the Navy and/or fed back into the grid via an existing electrical connection. Renewable heat generated onsite would be used during the biodiesel production process, and the need for a boiler unit would be eliminated.

Major new components of the proposed action included expanded use of solar cogeneration technology as well as the installation of algae tanks that would be used to research the production of brine shrimp for use as feedstock. The preferred alternative (Alternative 2) also includes the use of anaerobic digesters and a gasifier. If implemented, the current facility's total footprint of 0.46 acre would be expanded to a total of approximately 1.02 acres. The expanded facility would increase capacity for R&D purposes, reduce waste streams, create some feedstocks onsite, provide excess electricity to the Navy and/or the grid, and virtually eliminate waste from the production process.

Public involvement included a 15-day public comment period for the Draft EA that ended on 29 October 2014. Letters were mailed to interested parties in the community, local government agencies, and other stakeholders announcing the availability of the Draft EA for review and comment. A Notice of Availability (NOA) was published in the Ventura County Star Newspaper for three consecutive days for the Draft EA (11, 12, 13 Oct. 2014) and for the Final EA and FONSI, and both were made available electronically via the Navy Region Southwest website. The Draft EA was also made available in hard copy at Oxnard Public Library, Santa Barbara Public Library, E.P. Foster Library, and Ray D. Preuter Library.

Finding of No Significant Impact: Based on the analysis in the EA and coordination with Naval Base Ventura County, State Historic Preservation Office, Ventura County Air Pollution Control District, Ventura County Environmental Health Division, and the City of Oxnard, the Navy found that implementation of a biodiesel production and algaculture facility supported by solar cogeneration, anaerobic digestion and biomass gasification would not significuantly impact the quality of the environment.

5.2 Provide an independent measurement and verification report from UC Davis regarding cultivation, harvesting and processing of castor

The report from UC Davis is attached in Appendix 2.

CHAPTER 6:
Technology Transfer Activities

6.1 Provide a Technology Transfer Plan

RE: Biodico - Data, research tools and resources sharing plan and procedures

This section describes how Biodico will oversee the intellectual property produced by Biodico, which includes external co-investigators, collaborators, and consultants at Seahold, Novus, Himark, Cogenra, APL, UC Davis, and Red Rock Ranch in their research conducted under CEC contract PIR-11-030 . Intellectual Property issues were addressed in the subcontracts with each collaborator and are included as a part of this final report in Appendix X.

All participating institutions are experienced and knowledgeable in capturing and protecting bioenergy related intellectual property and have already shown the ability to advance intellectual property to commercial scales.

Technology transfer for this project was and will be conducted through passive information sharing; active information sharing; tacit information sharing; cooperative involvement and demonstration activities; and possible future patents, licensing, and standards.

Passive information sharing is achieved through the publication of research and demonstration findings. This final report comprises a summary of the work performed under this project and the findings will be published by the California Energy Commission, and will be accessible by the public. The monthly reports, which have been provided to the California Energy Commission, are also public information.

Active information sharing is knowledge transfer through personal interactions. There were many opportunities for active information sharing through the course of this project. Biodico and subcontractors operating under Biodico were trained by the technology providers to operate all of the relevant equipment. The NAVFAC EXWC made periodic site visits to RRR to learn about the operations of the equipment and to gauge its potential for military operations. Many other meetings between stakeholders were held to exchange information through the course of the project at NBVC, RRR, and contractor locations.

Tacit information sharing is the informal sharing that occurs through the course of relationship building and more formal sharing that occurs through the course of education and training. The more informal type of information sharing occurred actively between organizations as a part of the common goals of the project. More formal education and training occurred between organizations in order to perform the grant work and through the internship program that Biodico held with UCSB under which student interns were able to learn by assisting in the grant work.

Cooperative involvement is the sharing of information as a means to make joint decisions. Throughout the process this occurred between the manufacturers of the equipment and the

operators of the equipment (Biodico and subcontractors). The Navy also helped to make contributing decisions as to the direction of the work.

Sharing Data: The participating institutions will follow Energy Commission policies concerning the sharing of research data. As outlined by the Energy Commission, the participating institutions will make available to the public the results of this collaboration and any accompanying data that were supported by the Energy Commission.

Sharing Research Materials: The participating institutions will also comply with the Energy Commission requirements governing technology transfer and adhere to the policies and guidelines of Energy Commission addressing technology transfer and the distribution of Energy Commission funded research materials. Participating institutions in possession of materials generated during the course of the Energy Commission contract PIR-11-030 will strive to make the unique research resources readily available for research purposes to members of Energy Commission contract PIR-11-030, non-profit organizations, and commercial collaborators in accordance with Energy Commission guidelines. Participating institutions will not be expected to share internally held intellectual property.

Licensing of Intellectual Property: Participating institutions will license intellectual property developed by their institution as they see fit within their organization. Shared information will be treated as confidential by participating institutions and commercial collaborators as is necessary. If and when ownership of Energy Commission contract PIR-11-030 technology involves multiple institutions, the participating institutions will form agreements involving the consolidation and central management of intellectual property rights. Similarly, participating institutions will collaborate to package technologies under contract PIR-11-030 for licensing as necessary to commercially develop such technologies in a timely fashion.

Participating institutions will make adaptations of their own technologies available for licensing at their discretion. Commercial collaborators interested in licensing technologies used under Energy Commission contract PIR-11-030 shall notify the participating institution having ownership of the particular intellectual property in which they are interested. Licenses will be executed when appropriate and milestones will be used to insure that the licensing leads to timely commercial development. In such licenses, the participating institution will strive to limit the exclusive license to the commercial field of use, retaining rights regarding use and distribution of any technology that is a research tool.

CHAPTER 7:
Commercialization Readiness Plan

7.1 Prepare a Commercialization Readiness Plan

7.1.1 Identify critical supply and support systems that will be needed to introduce a commercially viable product

The supply and support systems for the commercially scaled facility are found in Setion 4.4. Perform life cycle analysis and pursue a LCFS pathway for the integrated system using Task 3 feedstocks and Task 4 equipment

7.1.2 Project the "installed cost" and "payback period" for the integrated and interconnected system

The total capital cost for the commercialization of the project is given in Figure 95. Each of the major listed costs is further detailed in subsequent subcharts. For most of the costs, the projected commercial cost is extrapolated from some combination of the costs incurred for the prototyping of the project, the projected commercial costs from the individual vendors, and costs from past commercial scale projects where available.

Figure 95: Capital Equipment

Capital Equipment		Capacity	Units	Cost
C1	Solar Cogen	20	kW	Installed
C2	Biodiesel Production	10	MMGPY	$5,800,000
C3	Anaerobic Digestion	89.3	MMGPY	$871,590
C4	CHP Generator	400	kW	$392,000
C5	Heat Exchanger	35,659	MMBtu	$86,088
C6	Oil Extruder	115,000	MTPY	$5,250,000
C7	Gasifier	100	kW	$150,000
Sum	Project Capital Cost			$12,549,679

Image Credit: Biodico

The biodiesel plant capex is given in more detail below. The line items are the manufacturing and installation costs of the major components of a commercial biodiesel plant. Biodico is currently in the process of finishing construction on an 18 million gallon per year biodiesel production facility in Fresno County and is in the process of construction on a 10 million gallon per year production facility in Ventura County. Biodico has also built and operated facilities in Texas, Colorado, Las Vegas, and Australia. The costs are accurate values from recent development (Figure 96).

Figure 96: Biodiesel Plant Capex

C2: Biodiesel Plant Capex	
Component	**Cost**
Feedstock	$ 1,000,000
Reactors	$ 2,500,000
Dryers	$ 200,000
Filters	$ 100,000
Storage	$ 1,200,000
ARIES Automation, FTIR, GWR	$ 800,000
Biodiesel Plant Total	**$ 5,800,000**

Image Credit: Biodico

Figure 97 gives the Capex of the anaerobic digestion system. The Himark costs were given in terms of kW capacity, the Novus in terms of tons per day, and the Seahold in terms of gallons per year. A blended average of the three costs was given as a total projected cost.

Figure 97: AD Capex

AD Capex	
Glycerin Gallons	100,000
Dilution Rate	2.8%
Total Gallons	3,571,429
Avg Daily Gallons	9,785
Avg Tons per Day	49
HRT	4 to 10
Himark $/kW Comm	$ 3,750.00
Total kW	250
Himark Est. Cost	$ 939,135
Novus $/Ton per Day	$ 16,000
Novus Est. Cost	$ 782,779
Seahold $/GPY	$ 0.25
Seahold Est Cost	$ 892,857
Average Equipment Cost	$ 871,590

Image Credit: Biodico

The Capex for the CHP generator is provided in Figure 98. A Capstone 200 kW microturbine was used as a price reference. The Capstone microturbines are California made and are setup to run specifically off of biogas (http://www.capstoneturbine.com/_docs/datasheets/C200%20High%20NatGas_331042E_lowres.pdf). Two units will be able to process all of the biogas and syngas produced by the project.

Figure 98: Generator Capex

C4: CHP Generator	
Total kWh	3.10E+06
kW Capacity	353
kW per Generator Unit	200
Cost per Generator Unit	$ 196,000
Units Needed	2
Total CHP Generator Capex	**$ 392,000**

Image Credit: Biodico

The majority of the cost is in the heat sink tank, but the costs for the pump and heat exchanger are also included (Figure 99).

Figure 99: Heat Exchanger Capex

C5: Heat Exchanger	
Annual MMBtu from Gasifier	2.99E+03
Annual MMBtu from AD	7.49E+03
Annual MMBtu from Solar Cogen	2.52E+04
Total Annual MMBtu	3.57E+04
Average Btu per Hour	4.07E+06
Exchanger Capacity	3.80E+06
Exchanger Unit Cost	$5,900
Exchangers Needed	1
Total Exchanger Cost	$5,900
Inlet Temperature °F	65
Outlet Temperature °F	140
GPM	1,290
Pump Cost	$2,000
Hours of Btu Storage	2.40E+01
Btus per Storage Period	9.77E+07
Temperature Difference °F	75
Gallons Water Needed	1.56E+05
Steel Tank Cost per Gallon	$0.50
Tank Cost for Heat Sink	$78,188
Total Heat Exchanger Cost	**$86,088**

Image Credit: Biodico

The oil extruder costs are in Figure 100. Seven units will be needed to produce 18 mmgpy of fuel.

Figure 100: Oil Extruder Capex

C6: Oil Extruder	
Extruder/Expeller	$ 450,000
Electrical	$ 250,000
Pellitizer	$ 50,000
Unit Oil Extraction Capex	$ 750,000
Unit Oil Extraction Capex	$1,050,000
Units Needed	7
Total Oil Extrusion Capex	**$ 5,250,000**

Image Credit: Biodico

The Capex for the gasifier has been estimated by APL to be $1.50 per kW capacity for a commercial scale unit. This gives a total cost of $150,000 as shown in Figure 101.

Figure 101: Gasifier Capex

C7: Gasifier	
kW Capacity	100
W Capacity	100,000
Cost per W	$ 1.50
Total Gasifier Capex	**$ 150,000**

Image Credit: Biodico

The total labor requirements for the operation are given in Figure 102. The average wages for each of the portions of the facility are given as well as the total wages. The jobs for each individual component are broken out in more detail below. For each of the detailed charts, a Bureau of Labor Statistics (BLS) employment number is given as reference. The solar cogen does not need a full time operator. The labor is set up for 24 hour a day operation and the wages include benefits.

Figure 102: Employment

Employees by Operation		Employees	Average Wage	Total Wages
C1	Solar Cogen	0	$ -	$ -
C2	Biodiesel Production	9	$ 56,178	$ 505,600
C3	Anaerobic Digestion	6	$ 42,000	$ 252,000
C6	Oil Extruder	16	$ 37,625	$ 602,000
C7	Gasifier	6	$ 42,000	$ 252,000
Admin	Administrative	4	$ 59,500	$ 238,000
Sum	Total Project	**41**	**$ 45,112.20**	**$ 1,849,600**

Image Credit: Biodico

The biodiesel production jobs are detailed in Figure 103. Each shift takes two operators to run and a plant manager is needed to oversee the facility. The plant manager will oversee the AD and the gasifier in addition to the biodiesel processing.

Figure 103: Biodiesel Labor Costs

C2: Biodiesel Labor Costs				
Job Description	BLS	Number	Wages	Total
Plant Manager	71-2112	1	$ 96,000	$ 96,000
Lead Operator	15-8091	4	$ 57,600	$ 230,400
Production Assistant	51-9099	4	$ 44,800	$ 179,200
Total Labor		9		$ 505,600

Image Credit: Biodico

The AD labor costs are detailed in Figure 104. Unlike the biodiesel production facility, the AD plant should not require 24-hour operation or supervision. The operator requirements were taken as a blended average of the three systems.

Figure 104: AD Labor Costs

C3: AD Labor Costs				
Job Description	BLS	Number	Wages	Total
Lead Operator	51-8031	3	$ 54,000	$ 162,000
Production Assistant	51-9098	3	$ 30,000	$ 90,000
Total Labor		6		$ 252,000

Image Credit: Biodico

The oil extrusion labor requirements are provided in Figure 105. Since there are seven separate extruders operating, two industrial mechanics will be needed for the units. They will also be on hand to work on other parts of the project as needed.

Figure 105: Oil Extrusion Labor Costs

C6: Oil Extrusion Labor Costs				
Job Description	BLS	Number	Wages	Total
Crusher Operators	15-9020	12	$ 34,000	$ 408,000
Crusher Supervisors	51-1011	2	$ 47,000	$ 94,000
Industrial Mechanics*	49-9041	2	$ 50,000	$ 100,000
Total Labor		16		$ 602,000

Image Credit: Biodico

The labor required for the gasifier is shown in Figure 106. The gasifer, like the biodiesel plant, will require full-time operation. The operation can be handled by one production assistant though and only one full-time lead operator who becomes an expert in the system is needed.

Figure 106: Gasifier Labor Costs

C7: Gasifier Labor Costs				
Job Description	BLS	Number	Wages	Total
Lead Operator	51-8031	1	$ 54,000	$ 54,000
Production Assistant	51-9098	4	$ 30,000	$ 120,000
Total Labor		5		$ 174,000

Image Credit: Biodico

The administrative labor costs are given in Figure 107. The project will need a payroll clerk, a bookkeeping clerk and a receptionist.

Figure 107: Administrator Labor Costs

Administrative Labor Costs				
Job Description	BLS	Number	Wages	Total
Payroll Clerks	43-3051	1	$ 44,000	$ 44,000
Bookkeeping Clerks	43-3031	1	$ 44,000	$ 44,000
Receptionist	43-4171	1	$ 30,000	$ 30,000
Total Labor		4		$ 118,000

Image Credit: Biodico

The annual costs and profits are given in Figure 108. The total net annual profit is $7,417,000. The 10% maintenance cost is based on past experience operating commercial biodiesel production facilities.

Figure 108: Project Costs and Profits

Annual Costs/Gains		Units	Used	Made	Net	Unit Price	Net Total
S1	Power Hub	kWh	3.06E+06	3.10E+06	3.99E+04	$0.07	$2,795
S2	Fresh Water	MM G	3	0	-3	$258	-$774
S3	Biodiesel Sales	G	0	1.80E+07	1.80E+07	$4.24	$76,320,000
S4	Feedstock Purchases	lbs	4.97E+08		-4.97E+08	$0.12	-$59,678,458
S5	Chemical Purchases	G	Misc	0	Misc	Misc	-$7,443,360
Office	Modular Office Rental	Bldgs	2	0	-2	$60,000	-$120,000
Maintenance		10% of Project Cost					-$1,254,968
Labor	Labor Costs						-$1,651,600
Net	Total Project Goods/Energy Net Profit						$6,173,635

Image Credit: Biodico

The biodiesel sales figures are given in Figure 109. As the LCFS pathway work continues, the profitability of the fuel should increase.

Figure 109: Biodiesel Costs

S3: Biodiesel	
Biodiesel Sales Revenue/gal[1]	$3.59
RFS2 RINs Sales/gal[1]	$0.65
Blenders/ Small Producers "Credit"/gal	$0.00
LCFS CI (gCO_2^e/MJ)[2]	TBD
Total Net Sales/gal	$4.24
Total Net Sales	$76,320,000.00

Image Credit: Biodico

The chemicals required for production are outlined in Figure 110. The majority of the chemical costs are from methanol. Biodico is collocating its production facility with an ethanol production facility and may be able to synergize and cut costs in the future.

Figure 110: Chemical Costs

S5: Major Chemicals	
Chemical	Annual Cost
Methanol	$5,220,000
Alkali Methoxide	$1,665,000
Acid	$288,360
Additives & Other	$270,000
Total Chemicals	$7,443,360

Image Credit: Biodico

The anticipated return on investment for the project is 49.2% annually (Figure 111).

Figure 111: ROI

Return on Investment	
Capital Cost	$12,549,679
Annual Net Gain	$6,173,635
Return on Investment	49.2%

Image Credit: Biodico

7.1.3 Calculate the expected investment threshold to launch the commercial product

Biodico has almost finished installing the biodiesel production portion of the facility at RRR and would need roughly an additional $7,500,000 to complete the capital infrastructure upgrades to convert the facility into a completely renewable facility with the ability to bring in inedible crops grown on surrounding farms. This may be achieved through private funding, grant funding, or internally generated funding.

7.1.4 Provide an implementation plan to ramp up to full commercialization

Biodico plans to enter production on its 18 mmgpy facility in July 2015. The profit margins per gallon are not as high from oil as they are from extruded seeds, electricity needs to be purchased from the grid, and the project is not as sustainable, but Biodico plans to reinvest some of the profits of production into building out capabilities for anaerobic digestion, gasification, and extrusion. Implementation may be ramped up significantly by outside investment into the facility upgrades.

GLOSSARY

ACRONYMS	
AD	Anaerobic Digestion
AMPTS	Automated Methane Potential Test System
APL	All Power Laboratories
BLS	Bureau of Labor Statistics
CHP	Combined Heat and Power
CNG	Compressed Natural Gas
CSTR	Continuously Stirred Tank Reactor
DK	Label for a Group of Castor Plant Varietals
EPC	Engineer Procure and Construct
EA	Environmental Assessment
FAME	Fatty Acid Methyl Esters
FONSI	Finding of No Significant Impact
FTNIR	Fourier Transform Near Infrared Spectroscopy
GFE	GFE Global, Inc.
GHG	Greenhouse Gas
GHI	Clobal Horizon Irradiance
HRT	Hydraulic Retention Time
iBOS	Integrated Balance of System
IRR	Internal Rate of Return
LSD	Latin Square Design
LCFS	Low Carbon Fuel Standard
MPU	Modular Production Unit
NEPA	National Environmental Policy Act
NREL	National Renewable Energy Laboratory
NBVC	Naval Base Ventura County
NAVFAC EXWC	Naval Facilities Engineering and Expeditionary Warfare Center
NOA	Notice of Availability
NBC	Novus Biocatalytic Conversion
ORP	Oxidation Reduction Potential
PV	Photovoltaic
PFD	Process Flow Diagram
RIN	Renewable Identification Number
RRR	Red Rock Ranch
RD&D	Research and Development Division
ROI	Return on Investment
SCFM	Standard Cubic Feet per Minute
UCDREC	University of California Desert Research and Extension Center
WREC	Westside Research and Extension Center

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APPENDIX A:
Cogenra Report

Cogenra CPVT T14 System Architecture & Cost Performance Analysis

Cogenra Solar is California-based solar technology manufacturer that designs, manufactures and delivers PV&Thermal solar systems for large commercial and utility-scale by combining high-efficiency photovoltaic cells and a single-axis horizontal tracker with proprietary low-concentration optics and efficient, active cooling of the photovoltaic cells. The proprietary technology utilized in Cogenra's T14 system is field proven in over forty installations worldwide, including leading hotels, corporate campuses, US Army and Navy bases, wineries, dairies, universities and medical centers. The T14 installation at BioDico was the first CPVT T14 installation. Most recently, a 1MW T14 PV installation by Cogenra at Tucson, AZ was successfully commissioned. .

The T14 product also includes optional waste heat recovery for solar cogeneration applications such as BioFuel, district heating and cooling plants, water treatment and desalination plants, or energy storage for on-demand solar power at night. Cogenra's current generation concentrating CPV/T modules can deliver heat efficiently up to 120C while simultaneously producing PV-based electricity.

The site integration of the CPV/T T14 systems in PV-Thermal operation consists of the solar system in closed-loop, exchanging heat through heat exchangers with a solar tank. The solar tank provides heat to the customer-side loop by another set of heat exchangers. The on-board control system enables the T14 system to track the sun as well as regulate and control the flow of heat transfer fluid through the system. A layout of the system installation is given in Figure 113.

Figure 112: System Diagram and Site Installation

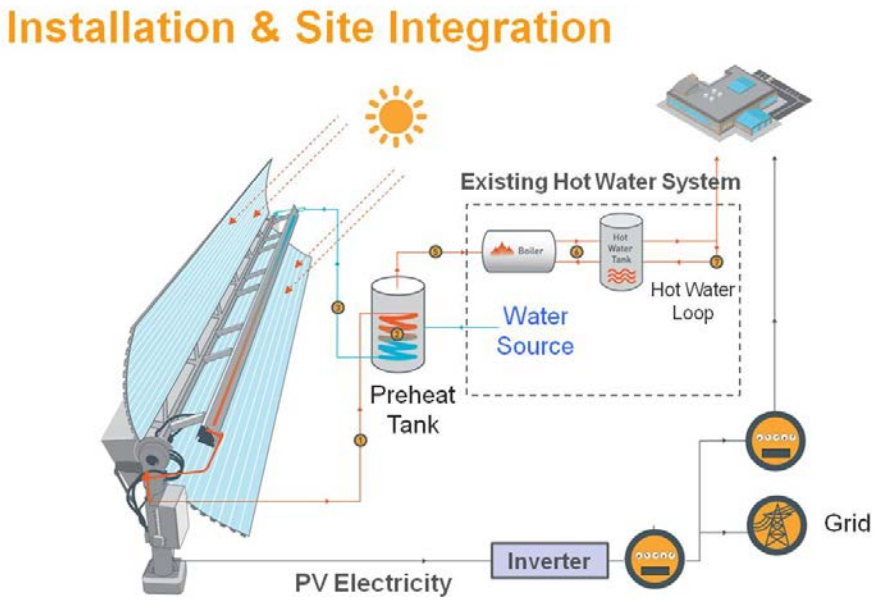


Image Credit: Cogenra

Figure 114 shows the high level system diagram for the onboard controls. A cooling loop is included only in situations where the T14 systems are operating in a PV-only mode. For PV-Thermal applications, the integrated Balance of System (iBOS) unit, which comprises of the pumps, pressure and temperatures sensors, and controllers, is utilized to enable optimal performance of the system. The iBOS unit is also the primary control module that enable safe operation of the system, to ensure the receivers operate within the prescribed temperature and to avoid over-heating of the receivers, detect if there are any leaks or pressure drops in the solar loop. The iBOS controller places the system into a de-track mode if such situation arise.

Figure 113: High Level Control System Diagram

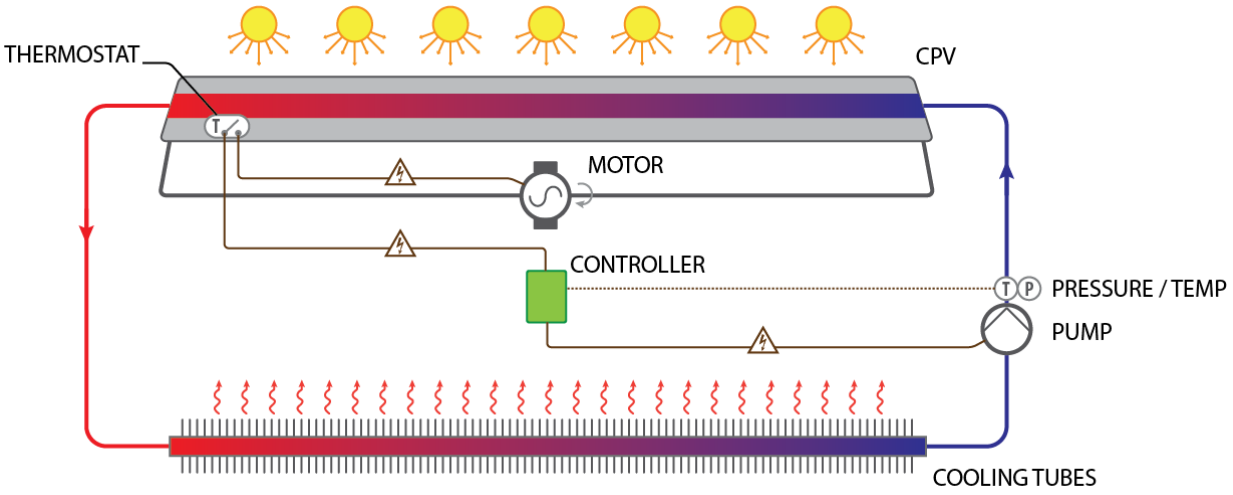


Image Credit: Cogenra

The physical location of the pumps and controller was found to be optimal at the center of the structure adjacent to the tracking slew gear. Figure 113 was created in the design phase to demonstrate the location and the photograph shows a prototype connected in the Cogenra R&D facilities. Figure 115 shows a T14 system in operation.

Figure 114: Biodico T14 System Installation

Image Credit: Cogenra

The electrical output of the T14 system is integrated into a standard inverter which outputs standard AC to the customer facility. Figure 116 shows the inverter utilized at this installation.

In this installation a string inverter was selected as the increased number of maximum powerpoint trackers offers potential for increased output from a Cogenra array. In the Cogenra design, each system is able to track independently and ensure that maximum power is captured from each pair of systems connected.

Figure 115: Selected Inverter

Image Credit: Aurora

Figure 116: Typical IV Curve Tracing of T14 System Performance

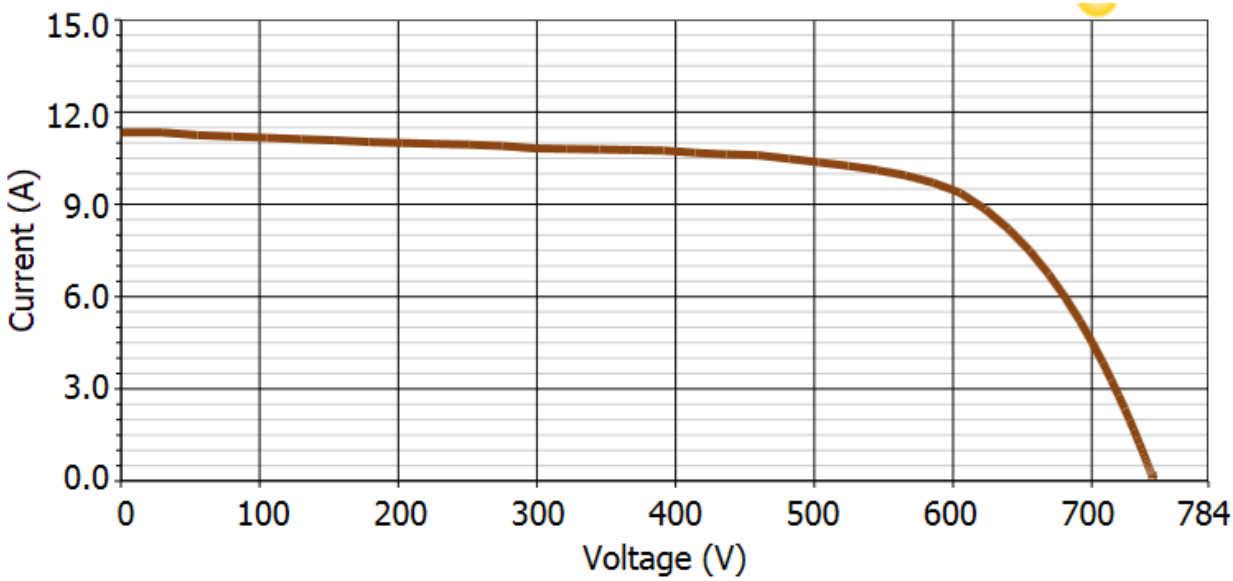


Image Credit: Cogenra

T14 System Performance

The following outlines the performance analysis of the T14 arrays installed at BIODICO. Figure 117 shows a typical IV curve for performance checking. A weather station was installed on 2/1/2015 that measures wind speed, wind direction, ambient temperature, relative humidity, global horizontal irradiance (GHI) and diffuse irradiance. This analysis covers the period from 2/1/15 to 3/7/15 during periods when the systems were fully operational and tracking. Due to internet connection issues, the monitoring of the system was intermitted and prevented Cogenra from getting continues data from the site. Nevertheless, the sample of data available, lead us to some of the conclusions and recommendations that we'll discuss later.

Cogenra solar has developed a performance model based on years of experience comparing field data to theoretical output power. The general model can be configured to accurately predict the power output based on a particular product configuration and site specific weather data (real time data from an onsite weather station or Typical Meteorological Year data from third party sites such as NREL).

Product Configuration:

- Cell type (efficiency vs concentration and temperature)
- Thermal conductivity of encapsulant
- Thermal conductivity of substrate
- Flow rate, pressure, and convection coefficient of heat transfer fluid
- Mirror reflectivity and shape quality
- Concentration factor
- Optical properties of protective top layer

Site Specific Configuration:

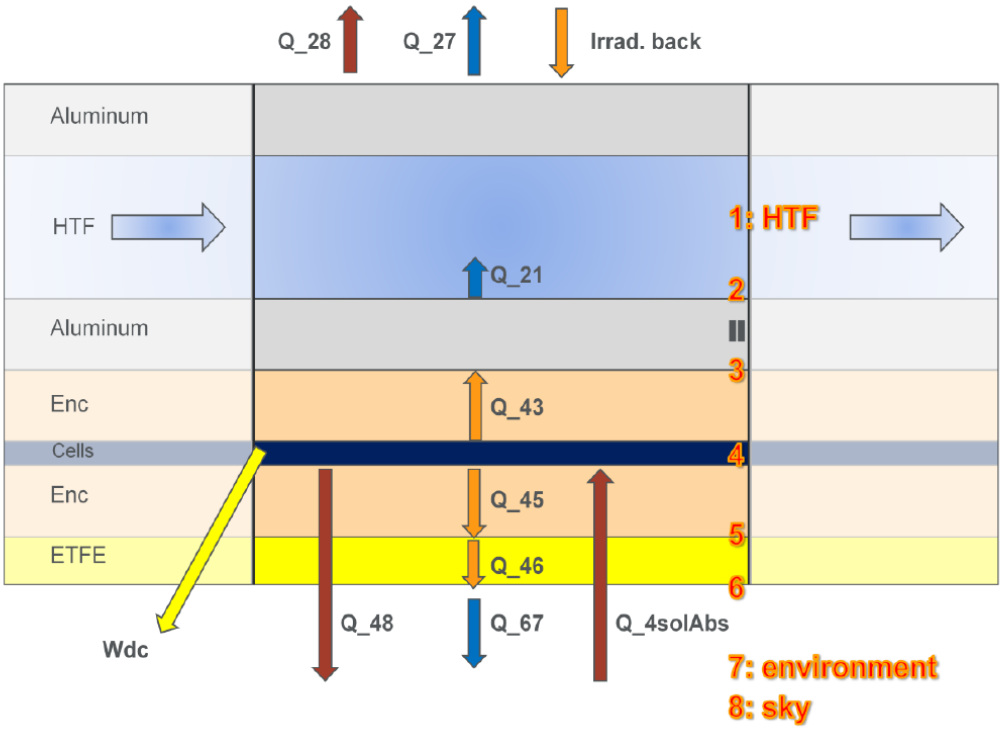
- Wiring length
- Inverter type
- Row spacing

Site specific weather data:

- Direct normal irradiance
- Global horizontal irradiance
- Solar position (based on latitude and longitude and system roll angle)
- Wind speed
- Ambient temperature

Based on these inputs the model performs an energy balance at each time step as shown in Figure 118.

Figure 117: Performance Model Energy Balance Diagram



The numbers 2, 3, 5 and 6 represent interfaces. Number 4 represents the cells.

Image Credit: Cogenra

Figure 119 represents the comparison between predicted DC output energy (kWh,dc) of the PV production vs. the actual measured energy output. The power ratio varies between a low of 77% and a high of 86%. It is typical for installations in agricultural setting to have significant performance impact due to steady soiling of the mirror beds. This performance impact is estimate to account for as much as 15-25% power loss at this installation and is highly variable during the year. Cogenra's performance model assumes a yearly average soiling of only 5%, which is based on other locations. Also we can see how the performance 'track' the weather, as weeks 9 and 10 the irradiation was low and the expected output was low as well.

Figure 118: kWh Measured vs Predicted

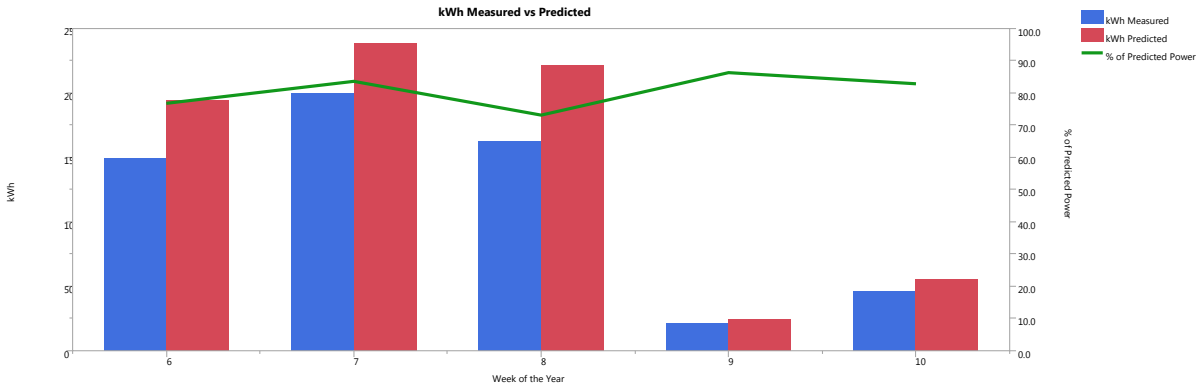


Image Credit: Cogenra

The thermal production of the system is plotted in Figure 120.

Figure 119: System Thermal Production

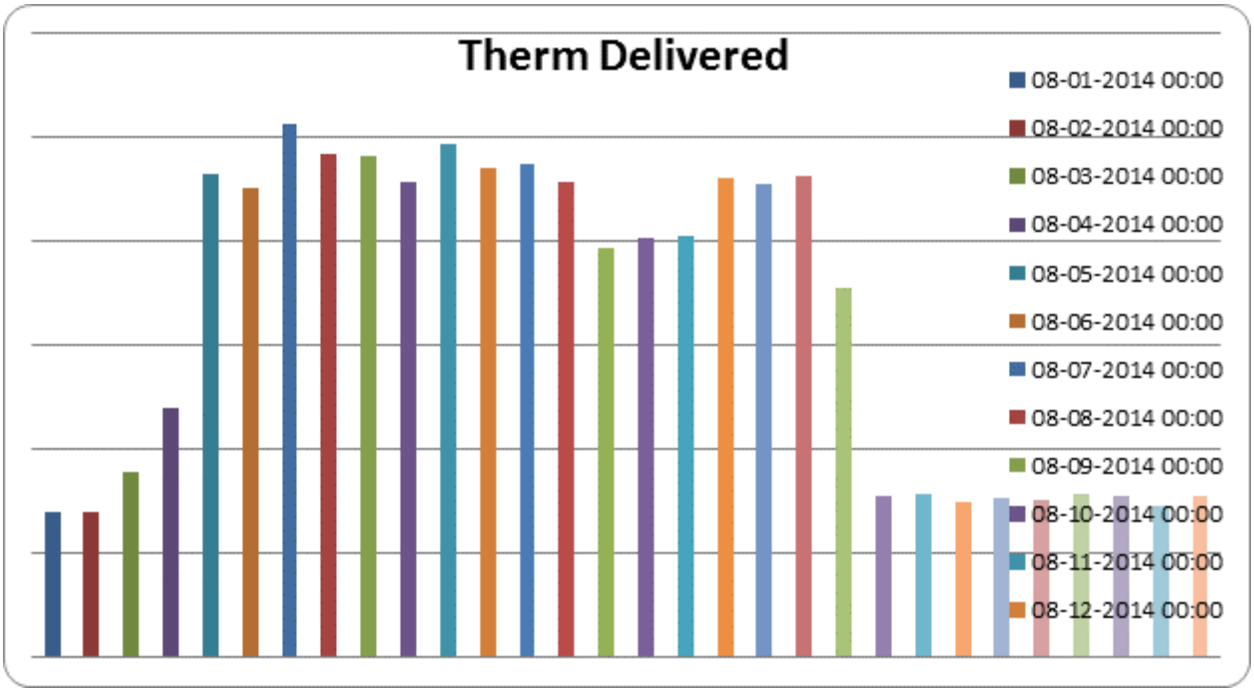


Image Credit: Cogenra

System Downtime & Maintenance:

The solar systems at the BIODICO installation suffered some production loss during the early stage of the project due to various installation and start-up issues, about 10% of the time was lost in the first few months of operation. One of the main issues was related to the specific site integration and interface to a heat exchanger, Later we found out that there is a large pressure

drop in the pipes connecting the system to the heat exchanger and in the heat exchanger. Cogenra will add a booster pump to resolve that issue.

While most of the issues were basic routine faults that were resolved during the course of the installation, the primary ones that affected significant production performance were due to 1). Communication failure and 2). Solar loop pressure drops.

1. COMMUNICATION ISSUES: Early on in the commission of the site, communication dropped between the inverter and the com box. We re-established the connection by reconfiguring the com port, isolating the com box as the issue, and replacing the unit.
2. PRESSURE DROPS - The majority of system downtime and maintenance can be traced to what we suspect is a slow leak in the hydronics connecting the system to the end user. This is peripheral to the T14 systems but ranged from the hydronic connections of the T14 systems to the flexible piping that conveys the heat transfer fluid to the heat exchangers in the tank. When pressure drop occurs, the affected systems de-track, taking it off-sun to prevent overheating. The systems then remain in a stowed position until the pressure drop can be repaired and the system re-pressurized. Later we found out that the main issue was not leaks but high pressure drop in the lines and heat exchanger. Cogenra will add a booster pump to resolve that issue.

Having diagnosed the issue and isolated the weak point in the hydronics of this installation, Cogenra have recently acquired the necessary equipment to troubleshoot specific components and develop detailed resolution plans. These system maintenance and operations are an ongoing effort and Cogenra is committed to resolving these and bringing up the systems performance. Cogenra will continue to monitor, diagnose and perform systematic and timely O&M of these arrays.

System and Installation Cost:

Each site is different and installation cost should be done for the PVT system and for the Site. The CPVT T14 system cost in MW scale cost about $1/W, that cost includes all the system parts needed for installation including the piles. The specific system at BioDico site used concrete blocks instead of driven piles as it was a small installation, which increased the cost.

The site cost depends on the specific site design, length of pipes and heat exchangers needed. The installation at BioDico required many sites visits to do the specific site's design, also the remote location increased the installation cost.

Learning and Recommendations:

There are two main learning points and recommendations:

1. Site Design and pressure drop: Pressure drop in pipes and heat exchanger need to be validated as actual implementation of site might add some pressure drop. The right size pump should be used based on the actual pressure drop in the field. Cogenra will add a booster pump to resolve that issue.

2. The specific process for bio-fuel requires a lot of heat at high temperature, using the T14 as thermal only can benefit the total heat delivery to the process. Cogenra will upgrade one of the systems with Thermal Receivers which can generate more heat at higher temp.

APPENDIX B:
UC Davis Report

Castor (Ricinus *communis* L.) Production in California: Results of variety and agronomic trials-2012 to 2014

J. Hollingsworth[1], O. Bachie[2], R. Hutmacher[1], and S. Kaffka[1*]

Abstract

Castor (Ricinus *communis* L.) variety trials were carried out in the Imperial Valley, western San Joaquin Valley and the southern Sacramento Valley over the 2012-14 period. Nine different cultivars were compared in 2012 and four in the other years. Yields varied from 0.75 to 1.6 t/ac. A saline irrigation trial was carried out in the western San Joaquin Valley in 2013-14 using moderately saline water (4.0 dS/m ECw) for a part of each growing season, simulating late season application of low quality water. Castor was tolerant of the salinity conditions imposed in this trial. In the Imperial Valley, castor was produced both annually and additional plots treated as a perennial. Yields were approximately equivalent in all locations, but changed between years. Perennial plot yields were quite high over a two year period and approximately equal to the best one year results, suggesting that in that location, multiple harvests might be possible from the same field. Potential biodiesel yields from the best performing varieties ranged from 160 to 220 gallons of biodiesel equivalent per acre, depending on the actual oil content of castor seeds.

Introduction

There is significant interest in new crops that might be used for biofuels and which may become part of arable cropping systems in California. Castor (*Ricinus communis* L.)[3] is a promising new, but also an old crop for farmers in California. It was grown in California (primarily in the San Joaquin Valley) commercially until the early 1950s as a source of oil for high quality lubricants, hydraulic fluids, paints and a number of other industrial products (Zimmerman et al., 1958). Elsewhere in the United States, castor has a longer history of production and use, produced off and on since the 1850s. In the mid-1930s, Baker Castor Oil Company began a program to develop domestic production to supply their processing plant in California. Contracts were offered to growers, and limited production developed in the Imperial and San Joaquin Valleys

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[3] R. communis is in the Ricininae subtribe, Acalypheae tribe, and non–latex-containing subfamily Acalyphoideae of family Euphorbiaceae. The family is in order Malpighiales, in the Eurosid I subclade of the Rosidae. Judd et al.1999. Ethiopia is considered to be the most likely center of origin (Severino et al., 2012). Jatrpopa curcas, another new oils seed crop, is also in the same plant family.

(Zimmerman et al., 1958). During the Korean War, castor production was stimulated by a government sponsored procurement program. The production area reached over 20,000 ha in 1951, mainly in Texas, Oklahoma, California, and Arizona. Castor production and processing was discontinued due to declining prices (Brigham, 1993), but has increased again in recent years due to demand as an industrial oil. Castor has shown economic potential as alternative oilseed crop for the mid-south region in the United States, especially Texas, where modest levels of production occur. Prices for refined oil in 2011 have varied between $2000 and $3000 per metric ton (Severino et al., 2012). India is the largest supplier of castor bean oil, but Brazilian production has also increased over the last decade. There are active programs in China and India to expand use, especially in marginal or saline locations. There are reports from Israel, China (Zhou et al., 2010) and India (Rahgavaiha et al., 2006) that Castor has moderate salt tolerance and is reported to be deep rooted.

Severino et al., (2012), in the most recent review of castor production world-wide, report yields in diverse locations varying from 700 to 2,500 lb/ac, but also a few exceptional yields of 4000 lb/ac or more when crops were well-supplied with water and nutrients, and pests and diseases were absent or controlled. California often has high yield levels for many crops, and castor may perform better here than elsewhere.

Castor (Figure 121) is a warm season annual planted when soil temperatures exceed 14 C (55 F). In colder soils, emergence can be slow or irregular. In the San Joaquin Valley, soils temperatures for castor are similar to those needed for cotton and the growing seasons would overlap. It is spring-planted and fall-harvested and may require 180 to 210 days to reach maturity, depending on planting date and growing season temperatures. Castor may grow well when water supplies are limited and under moderately saline conditions. If so, it could play a role in providing an oil supply for in-state production of biodiesel or replace other uses of petroleum for high quality feedstock chemicals and lubricants. The by-product meals would be the source of additional energy or chemical products or can be used as soil amendment. Meals have been used in organic systems as a pesticide since it may have natural nematicidal and other insecticidal properties (Severino et al, 2012).

Figure 120 - Castor Growth and Development

Demand for castor oil has increased rapidly in recent years because it produces a large amount of an hydroxlated fatty acid (ricenoleic acid) (Figure 122). This fatty acid has characteristics which make it useful in industrial feedstock chemical production (Severino et al., 2012).

Figure 121: Ricinoleic Acid

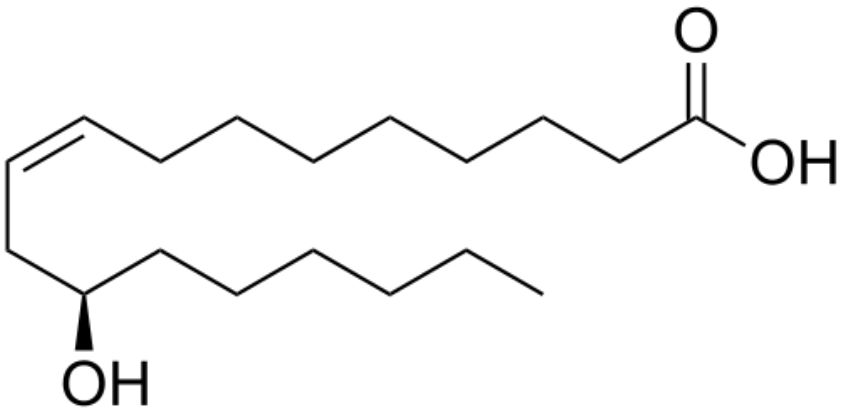

Image Credit: Stephen Kaffka

The molecule pictured is (9*Z*,12*R*)-12-Hydroxyoctadec-9-enoic acid. Reaction points in the molecule include a carboxyl group, a saturated (double) bond and an hydroxyl group. These properties allow for easy modification of the fatty acid for conversion into other feedstock chemical products.

Castor is also reported to be salinity tolerant, but published reports are limited Silva et al (2008; in Portuguese- cited by Severino et al., 2012) reported that seedling emergence was uninhibited up to 7.1 dS/m ECe in soils and reduced by 50% at 13.6 dS/m. Zhou et al, reported similar behavior (2011). Researchers in Texas in the Pecos area report tolerance of Castor to soil salinity greater than 5 dS/m under commercial conditions (Auld, personal communication). Agronomists from Kaiima Seed Company in Israel, report tolerance up to 8.0 dS/m soil ECe without effect on seed yield (Nir, personal communication). If castor is salt-tolerant, it may provide significant advantages for growers in the western San Joaquin Valley, where large areas of drainage impaired land occurs and associated salinity problems, by providing them an additional annual, warm season crop that can be used in crop rotations on the more saline soils in the region. Similarly, growers in the Imperial Valley may benefit from a crop that grows well during the hottest portions of the year, and can be produced on the more saline soils in the region.

Previous work

Castor oil production in the U.S. began as early as the 1850's, with interest in it peaking periodically during the major wars of the 20th World War I, World War II, and the Korean War, due to its industrial uses and lack of import supply (Cline 2012). Commercial production of castor was concentrated in Texas, Oklahoma, Arizona, and California. In an early issue of *California Agriculture*, published in 1949, castor was promoted castor as a potential new oil crop

(Knowles, 1949). The U.S. in 2011 imported $100 million worth of castor oil at a cost of $3,000-$5,000 per short ton (Cline 2012).

Research conducted in Davis, CA, in the 1940's found that yields of castor seed averaged 1.0 to 1.5 tons per acre. Higher yields were expected in the San Joaquin Valley where conditions were considered more favorable, but no trials were conducted. Trials were also planted in Imperial Valley. In the first year yields were lower than in Davis, but an improvement was observed when they planted earlier to avoid high temperatures during establishment (Knowles 1949).

One of the early difficulties with castor was a propensity to shattering or premature seed loss, making it difficult to harvest mechanically. Varieties more suitable to mechanical harvest have been developed since. The development of appropriate irrigation management methods was also important for improving yields, since castor plants are subject to damage from overly saturated soil conditions (Severino et al., 2012). Castor was not economically viable as an industrial crop suitable for mechanization until these improvements were made in the mid-1950's (USDA 1960).

Another difficulty with castor production is that the plant is indeterminate and continues to form new racemes and seeds until harvest. So at harvest, seed consists of mature dry seed and green seed. Castor branches and produces a primary raceme, then several secondary racemes, and if the season is long enough, tertiary racemes. Seeds on tertiary racemes (flower bracts) likely will be green at the effective end of the growing season. Vallejos et al., (2011) determined that the ideal time from harvest was when the majority of seed from all three types of racemes were physiologically mature. They correlated this with an average seed water content of 22%, in turn correlated with 90% of seed being ready for harvest if harvest could be delayed to that point. This emphasizes the need for a longer crop maturation period for maximum yields. A potential solution to the problem of delayed and uneven maturation is to use chemical desiccants, similar to cotton defoliants. Field trials conducted in Florida compared two desiccants which are commonly used on cotton - tribufos and paraquat (Campbell et al. 2014). They found that paraquat was more effective at desiccating and defoliating the leaves, improving harvest efficiency. The study produced relatively low yields (0.3-0.6 tons per acre for the Brigham variety and 0.4-0.5 tons per acre for the Hale variety), but the trial was greatly affected by a pathogenic mold. This suggests that climate may strongly dictate where castor can be successfully grown. The drier weather found in California is more likely to result in pathogen free growing conditions. California's San Joaquin Valley historically has been seen as a good environment for castor growth due to its favorable weather (in particular the low humidity, which reduces disease), quality soils, and availability of irrigation water (Zimmerman et al. 1958).

Industrial uses and biodiesel

The fatty acids in castor oil consist of approximately 80–90% ricinoleic acid, 3–6% linoleic acid, 2–4% oleic acid and 1–5% other saturated fatty acids. The high content of ricinoleic acid is the reason for the versatile value of castor oil in technology (Figure 123: from Scholz and Nogoera da Silva, 2008) (Figure 124). Ricinoleic acid is sometimes confused with ricin, a toxic protein also found in castor seeds (see below), but is not poisonous and even used for medicinal purposes in humans. Castor oil is unique among plant oils because of the high concentration of a single fatty acid, resulting in predictable oil quality. Castor oil has high viscosity over a large range of temperatures, and resistance to degradation from aliphatic petroleum derivatives, making it a valuable lubricant. It also has several reaction points in the ricinoleic fatty acid chain making it susceptible to modification for diverse industrial uses (Severino et al., 2012).

Figure 122: Castor oil and rape seed oil fatty acid compositions

Fatty Acid[1]		Proportion		
		Castor oil		Rape oil
		According to DIN 55939 (%)	According to Bockisch (%)	According to Schuster (%)
Ricinoleic acid	C 18:1-OH	86-92	82-90	0
Linoleic acid	C 18:2	2.8-6	3-6	15-30
Oleic acid	C 18:1	2.5-4	2-4	50-65
Palmitic acid	C 16:0	1-1.5	1-1.5	1-5
Stearic acid	C 18:0	0.5-1.5	-	0.5-2
Linolenic acid	C 18:3	0.2-0.8	0.2-0.6	5-13

1. Scholz, V., & da Silva, J. N. (2008). Prospects and risks of the use of castor oil as a fuel." *Biomass and Bioenergy* 32.2 (2008): 95-100

Image Credit: Stephen Kaffka

Figure 123: Fuel-specific properties of castor oil and rape seed oil

Properties contents[1]	Unit	Rape oil according to DIN 51605	Castor oil according to various sources
Density (15˚C)	kgm^{-3}	900-930	950-974
Flash point according to P.-M	˚C	>220	229-260
Kinematic viscosity (40˚C)	$mm^2 s^{-1}$	<36	240-300
Net calorific value	$MJ kg^{-1}$	>36	37.2-39.5
Flammability (cetane number)	-	>39	42
Coke residues	%	<0.40	0.22

Iodine number	g 100 g^{-1}	95-125	82-90
Sulphur content	mg kg^{-1}	<10	10
Total impurities	mg kg^{-1}	<24	ca. 10
Neutralisation value	mg KOH g^{-1}	<2.0	1.0-4.0
Oxidation resistance (110˚C)	H	>6.0	95
Phosphorous content	mg kg^{-1}	<12	<4
Total content of Mg and Ca	mg kg^{-1}	<20	-
Ash content	%	<0.01	<0.01
Water content	%	<0.07	0.15-0.30
1. Scholz, V., & da Silva, J. N. (2008). Prospects and risks of the use of castor oil as a fuel." Biomass and Bioenergy 32.2 (2008): 95-100			

Image Credit: Stephen Kaffka

For the most part, higher prices for castor oil for industrial uses compared to its value as a **biodiesel feedstock** has limited its use for fuel. Castor can be transformed to biodiesel using FAME (Fatty Acid Methylester) technology, adjusted for its special properties. Castor biodiesel is reported to have especially high lubricity and energy density values (Knothe, 2005). Smaller amounts of biodiesel made from castor are needed to achieve the same energetic and lubricity effects than other vegetable oil feedstocks.

Ricin

A significant hazard associated with the production of castor is ricin in seeds. Ricin is a protein toxin found only in the endosperm of castor seed. It can reach up to 5% of the meal weight remaining after oil extraction (Auld et al. in preparation; Khvostova, 1986). Ingestion of three to five seeds may be fatal to humans (Weber, cited in Romano et al., 1995). This toxin constrains the use of residual castor meal for animal feed and has recently been a concern as a potential bioterrorism agent. Auld et al., recommend extreme care in planting and harvesting castor, and seed handling. Dedicated equipment for harvesting is recommended, with no use of harvesting and handling equipment for food crops, to avoid accidental contamination.

Methods

Castor once was grown and might again be produced as a warm season annual crop in the San Joaquin Valley, and a spring to summer crop in the Imperial Valley. To evaluate the yield potential of current castor cultivars, variety trials were carried out from 2012-2014 in three locations: the University of California, Davis research station in Davis, CA; the University of California West Side Research and Extension Center (UC WSREC) in Five Points, CA; and the University of California Desert Research and Extension Center (UC DREC) in El Centro, CA.

Variety trials were conducted with seed from two sources: Kaiima[4] , an Israeli seed company, and Texas Tech University.

In 2012, Kaiima varieties K75, K93, C855, and C854 and Texas Tech varieties Brigham, Energia, Hale, Memphis, and Ultra Dwarf were assessed in two separate trials. All variety trials used a Latin Square Design (LSD) and were irrigated using furrows. Rows were generally 30 feet long and four row plots were used. The middle two rows were harvested for yield and harvest index determination. Manual weed control was used when necessary. Sixty pounds of N per acre was applied early in the season to each of the Five Points trials. 100 pounds of N were applied to all variety trials based on current industry recommendations and the technical literature.

Nitrogen trials were conducted in Davis using Kaiima's variety K93 in 2013 and 2014. They were planted on 6 June 2013 and 22 May 2014. Four levels of N were applied: 0, 50, 100 and 150 lbs N per acre. Ammonium sulfate was applied by hand at the designated rates on 17 July 2013 and 1 July 2014.

The Davis variety trials were planted on 18 May 2012, 6 June 2013, and 22 May 2014. The Five Points variety trials were planted on 22 May 2012 and 15 April 2013. The El Centro variety trials were planted on 15 May 2012, 11 March 2013, and 29 May 2014.

Although castor is often grown as an annual, it can be a perennial in climates without cold winters. In order to compare the yields between annual and perennial castor, the 2013 El Centro castor was trimmed down after the last harvest in 2013and allowed to regrow the next spring. Its yields were compared to the yields of the castor newly planted in May 2014.

At Davis in 2014, harvests for both the variety trial and N trial were delayed due to slow seed maturity until early December. However, heavy rainstorms in late November and early December delayed the harvest until January. The storms included heavy winds which caused excessive shattering, making harvest data unreliable. So the trials were abandoned.

Salinity tolerance

Two trials were planted at the WSREC site in an area established for salinity trials, one in 2012 and the second in 2013. Plots were planted at the same time as the variety trials at that location. The same site was used for both trials. Two castor varieties from Kaiima with reported differences in salinity tolerance were evaluated in field plots at the WSREC using high quality water from the Central Valley Project (0.7 dS/m ECw), and shallow well water (4.0 dS/m ECw). Plots were 35 feet long and 6 rows at 30 inch spacing were used. There were buffer areas between plots to isolate irrigation effects. Standard and saline irrigation water was applied

[44] http://kaiima.com/

through a surface drip irrigation system. Crops were established using only higher quality water and surface irrigation. The main plots were separated by variety (there were two Kaiima varieties planted: K93 and C854). The subplots were separated by water salinity level. Originally it was planned to have three irrigation salinity levels (low, medium, and high), but a high level wasn't possible. Plots that had been assigned to receive the high saline water instead received the medium level. There were 24 total subplots, 12 of each variety. Eight subplots received low saline water (approximately 1 dS/m) and 16 subplots received medium saline water (approximately 4 dS/m). Rows were 35 feet long with 10 foot buffers. There were six rows per plot, with two row buffers between the rows. 60 lbs N were applied to all plots early in the season. In the second year, to simplify water delivery, 18 mm Netafim drip tubing (Netafim USA, Fresno, CA) with 18 inch emitter spacing was installed on the surface of the plots on 31 July 2013, after crops were well-established. There were separate lines for the two levels of saline irrigation. Until that point, all the irrigation was fresh water, applied by furrow. Also in the second year, on 8 July 2013 Decagon 5TE soil moisture, temperature, and electrical conductivity sensors (Decagon, Pullman, WA) were installed at depths of nine feet, six feet, three feet, 18 inches, and 10 inches. One set of sensors was installed in each of six subplots, representing the different varieties and salinity levels. Plots in both years were hand harvested in mid-November.

Harvest Procedure

The harvest procedure was the same in all trials. All plots were harvested by hand. A six-foot area from one of the two middle rows in each plot was chosen for a representative subsample. All the green seed was taken from that area. The rest of that row, and the other middle row were then bulk harvested for mature seed only. Fresh weight was recorded, samples were dried, and then the dry weight was recorded. Threshing was done with an ALMACO BT-14 Portable Belt Thresher (ALMACO, Nevada, IA).

Analytical methods

All data analyses were conducted using the program R (R Core Team. 2013. R: A Language and Environment for Statistical Computing). Data were examined for variance heterogeneity and normality. Analysis of variance was used to test for significance of main effects and their interaction.

Results

Castor seed yields

Kaiima varieties. Analysis of the evaluation of Kaiima varieties found that variety, year and location all had a significant effect on seed yield (Figure 123). There was also a significant interaction between year and location irrespective of variety.

Figure 124 - Castor Yields, Source Kaiima

Variety	Year	Location	Yield Tons per acre	SE	SD
C854	2012	Davis	1.27	0.12	0.25
		El Centro	0.83	0.14	0.28
		Five Points	1.14	0.11	0.21
	2013	Davis	0.95	0.18	0.35
		El Centro	1.32	0.11	0.23
		Five Points	0.92	0.10	0.20
C855	2012	Davis	1.29	0.10	0.19
		El Centro	1.63	0.06	0.12
		Five Points	0.99	0.11	0.22
	2013	Davis	0.79	0.18	0.36
		El Centro	1.09	0.16	0.33
		Five Points	0.93	0.16	0.32
K75	2012	Davis	1.25	0.16	0.32
		El Centro	1.15	0.11	0.22
		Five Points	0.86	0.05	0.11
	2013	Davis	1.01	0.15	0.30
		El Centro	1.22	0.08	0.16
		Five Points	0.92	0.04	0.09
K93	2012	Davis	1.37	0.13	0.26
		El Centro	1.53	0.17	0.34
		Five Points	1.25	0.08	0.17
	2013	Davis	1.04	0.09	0.18
		El Centro	1.40	0.09	0.18
		Five Points	1.11	0.08	0.16

	Df	Sum. Suq.	Mean sq.	F-value	Pr(>F)	
Rep	1	0.25	0.24	3.80	0.06	NS
Row	1	0.08	0.08	1.20	0.28	NS
Year	1	0.56	0.56	8.72	<0.01	**
Location	2	1.05	0.52	8.12	<0.01	**
Variety	3	0.73	0.24	3.78	<0.01	**
Year:Location	2	0.46	0.23	3.56	<0.05	*
Year:Variety	3	0.48	0.16	2.51	0.07	NS
Location:Variety	6	0.47	0.08	1.21	0.31	NS
Year:Location:Variety	6	0.78	0.13	2.01	0.08	NS
Residuals	70	4.51	0.06			

Image Credit: Stephen Kaffka

Texas Tech varieties. There was only enough Texas Tech seed to do one year of research at two sites. When analyzed, there was a highly significant location effect, so the locations had to be analyzed separately. There were no significant differences in varieties at Davis. In Five Points, however, variety Energia had significantly greater yields than the variety Ultra Dwarf. Yields were generally higher in Davis. (Figure 124)

Figure 125: Texas Tech Trial, 2012

Variety	Location	Yield Tons per acre	SE	SD
Brigham	Davis	1.41	0.15	0.33
	Five Points	0.91	0.07	0.16
Energia	Davis	1.53	0.13	0.28
	Five Points	1.20	0.08	0.18
Hale	Davis	1.54	0.11	0.25
	Five Points	0.99	0.08	0.18
Memphis	Davis	1.17	0.09	0.19
	Five Points	0.96	0.10	0.17
Ultra Dwarf	Davis	1.17	0.04	0.09
	Five Points	0.75	0.10	0.22

	Df	Sum. Suq.	Mean sq.	F-value	Pr(>F)	
Rep	1	0.0225	0.0225	0.473	0.49572	NS
Location	1	2.012	2.012	42.289	1.04E-07	***
Variety	4	1.0507	0.2627	5.521	0.00128	**
Location:Variety	4	0.1806	0.0451	0.949	0.44621	NS
Residuals	39	1.8555	0.0476			

Image Credit: Stephen Kaffka

Nitrogen study. The nitrogen trial was inadvertently located on a site at the UC Davis research farm that varied due to a sand lens that crossed the plot. This was observed in differential crop height after establishment, and from effects on plot yields that confounded the effect of N treatments. Supplemental irrigation to plots in sandy soils in this lens could not overcome the confounding effects of soil differences, nor could plot randomization. Consequently, there were no significant fertilization effects observed in this trial (Figure 125). The 2014 trial was damaged by intense rain before harvest and so was lost.

Figure 126: Nitrogen Trial Davis 2013

N rate Lbs per acre	Yield Tons per acre	SE	SD
0	0.93	0.18	0.36
50	0.85	0.18	0.36
100	0.72	0.14	0.28
150	0.82	0.18	0.37

	Df	Sum. Sq.	Mean Sq.	F-value	Pr(>F)	
Rep	1	0.006	0.006	0.183	0.68	NS
Row	1	1.069	1.069	31.114	<0.0002	***
N_rate	1	0.042	0.042	1.218	0.29	NS
Row:N_rate	1	0.003	0.003	0.084	0.78	NS
Residuals	11	0.378	0.034			

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Image Credit: Stephen Kaffka

Salinity In this study, the saline water available for irrigation from the site's shallow groundwater well averaged 4 dS/m, which is not very saline. Soil salinity in the surface horizons never increased above 2.5 dS/m ECe using this water. While small differences were observed in most of the comparisons between saline irrigated and non-saline irrigated plots, in neither year were these differences significant. Nor were there significant differences between varieties (Figure 126). So the actual tolerance of castor to more than moderate levels of saline water used for irrigation could not be determined here. There are no reports in English on salt tolerance estimates and crop performance under more severely saline conditions to our knowledge. The experimental setup at WSREC was limited by the low salinity of available groundwater, which has declined unexpectedly from previous years.[5]

[5] In previous trials with sugarbeets and safflower at the same site, shallow well water averaged 6.7 dS/m.

Figure 127: Salinity Trial

Variety	Year	Salinity ECw (dS/m)	Yield T/ac	SE
C854	2012	1	1.23	0.03
		4	1.10	0.07
	2013	1	1.93	0.25
		4	2.02	0.11
K93	2012	1	1.31	0.13
		4	1.28	0.03
	2013	1	1.88	0.20
		4	1.81	0.09

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Rep	1	0.403	0.4026	2.03	0.162
Row	1	0.347	0.3465	1.747	0.193
Salinity	1	0	0	0	0.988
Variety	1	0.001	0.0006	0.003	0.957
Salinity:Variety	1	0.001	0.0007	0.003	0.954

Image Credit: Stephen Kaffka

Water recovery in this trial occurred predominantly from the upper three feet (36 inches) the plot with little change observed in volumetric soil moisture at deeper depths in the soil profile.

Figure 128: Volumetric Soil Moisture

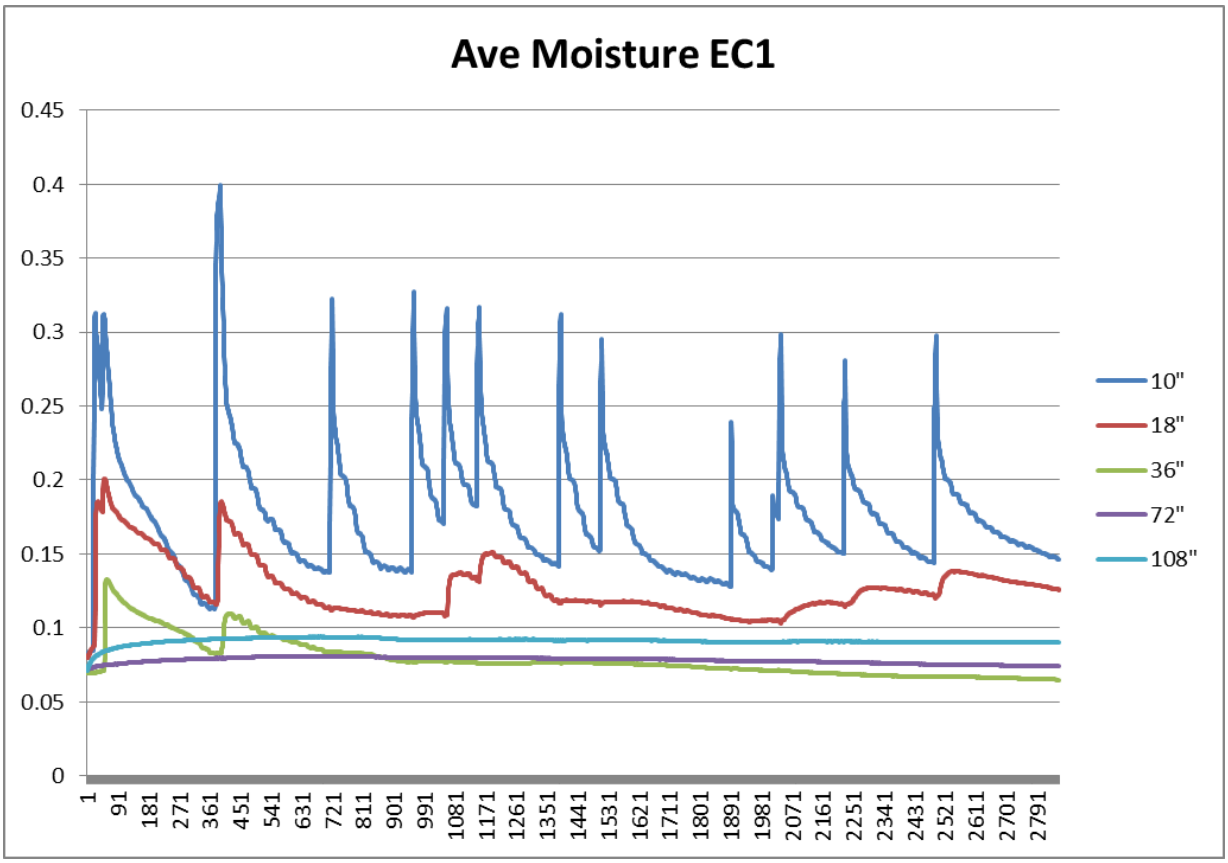

Image Credit: Stephen Kaffka

Figure 127 shows volumetric soil moisture (cm/cm3) by depth at WSREC salinity trial with high quality water.

Figure 129: ECe Values

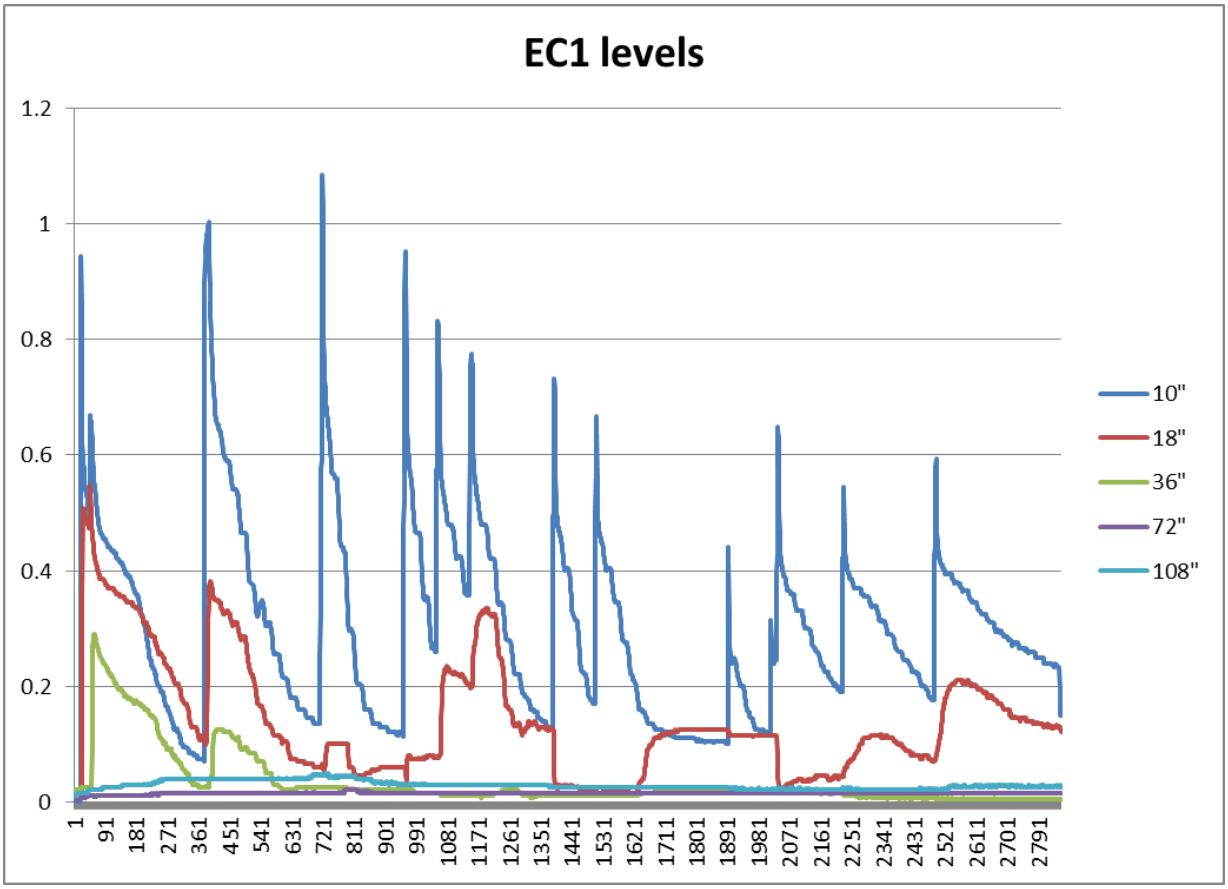

Image Credit: Stephen Kaffka

ECe values (dS/m) in 2014 at WSREC salinity trial with high quality water (0.6 dS/m ECw) are displayed in Figure 128.

Figure 130: Volumetric Soil Moisture 2

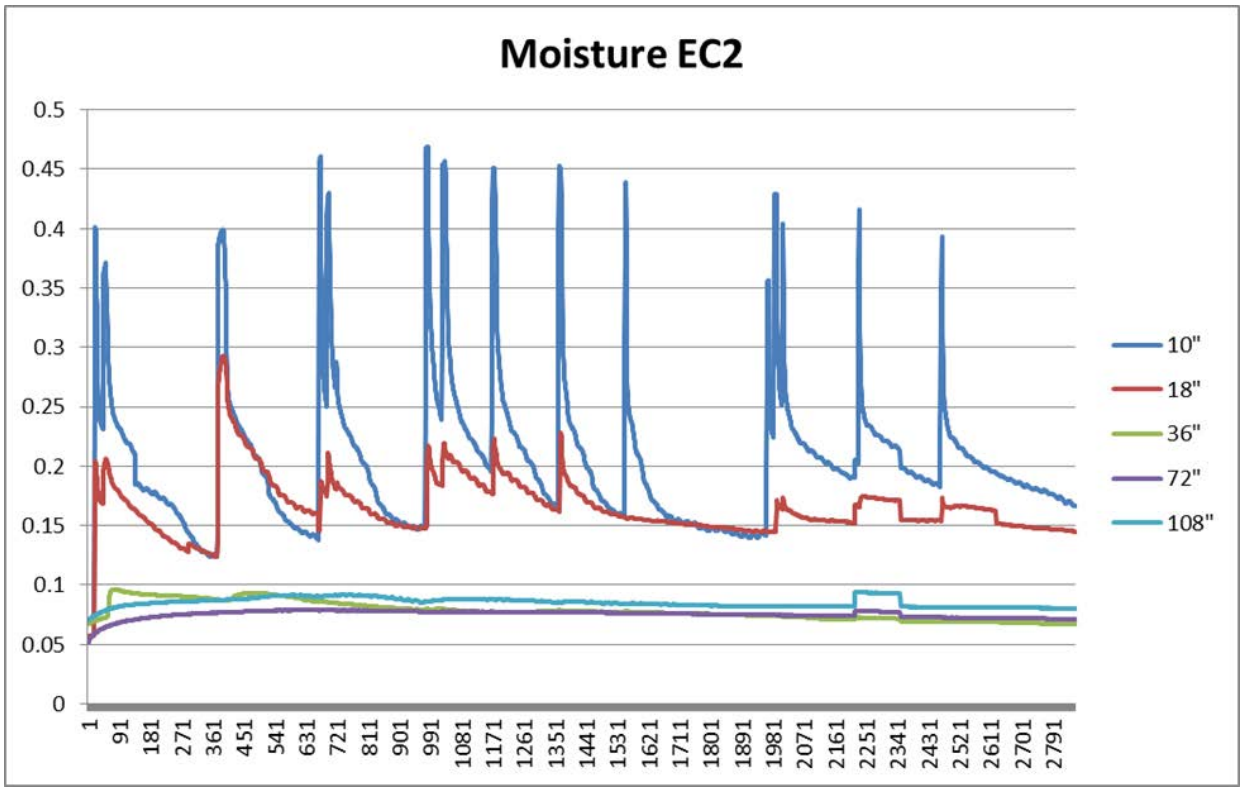

Image Credit: Stephen Kaffka

Figure 129 shows volumetric soil moisture by depth at WSREC salinity trial with moderately saline water .

Figure 131: ECe Values 2

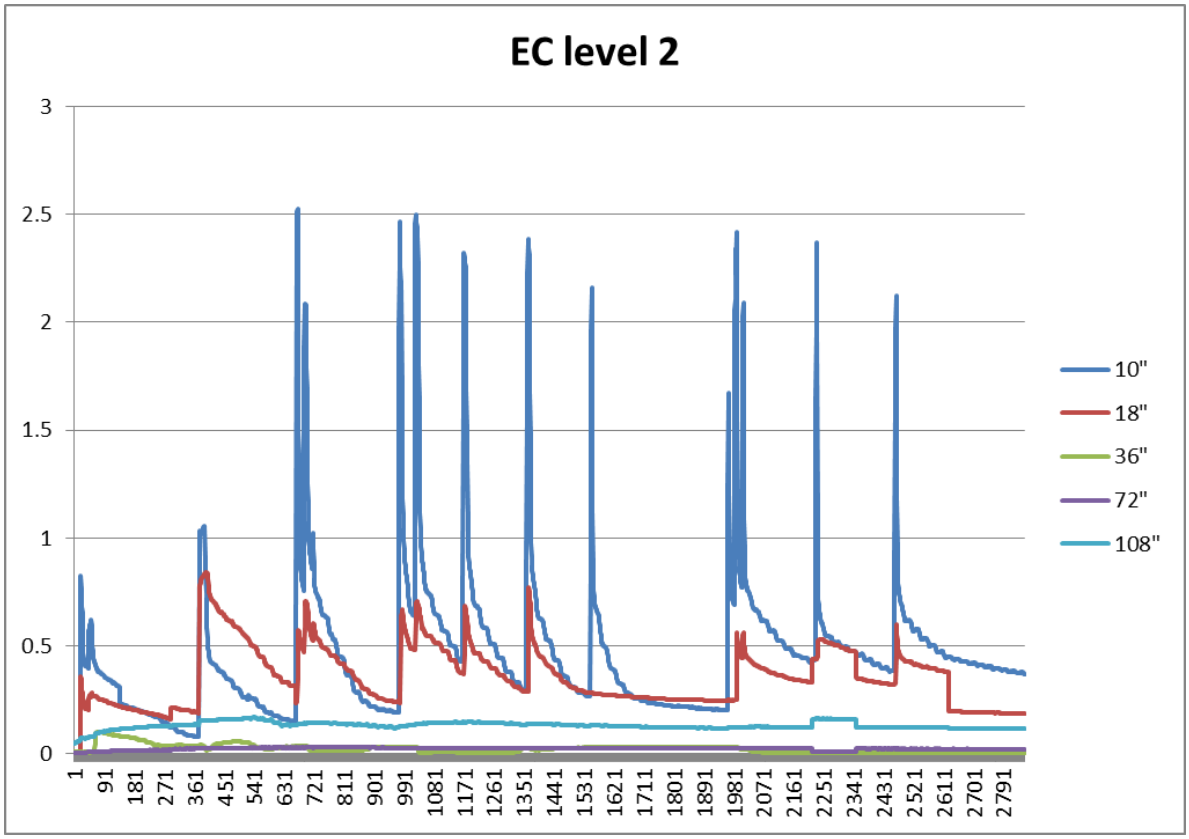

Image Credit: Stephen Kaffka

ECe values in 2014 at WSREC salinity trial with moderately saline water (4.0 dS/m ECw) are displayed in Figure 130.

El Centro 2014

Yields in El Centro were approximately similar on a year to basis as those observed elsewhere in the state. Castor survived through the winter suggesting that with agronomic research to develop best management practices, multiple harvests might be possible in that location. Varieties varied significantly.

Figure 132: Variety Trials El Centro 2014

Harvest Date	Variety	T/ac	SD	SE
Harvest 1	C854	1.32	0.23	0.11
	C855	1.09	0.33	0.16
	K75	1.22	0.16	0.08

	K93	1.40	0.18	0.09
Harvest 2	C854	0.39	0.05	0.10
	C855	0.51	0.09	0.18
	K75	0.59	0.11	0.23
	K93	0.87	0.13	0.25
Harvest 3	C854	0.76	0.01	0.03
	C855	0.91	0.13	0.25
	K75	1.05	0.08	0.17
	K93	1.11	0.06	0.12
Harvest 4	C854	0.34	0.09	0.18
	C855	0.64	0.04	0.09
	K75	0.51	0.06	0.12
	K93	0.65	0.05	0.11

	Df	Sum Sq	Mean Sq	F value	Pr(>F)	
Rep	1	0.017	0.0173	0.501	0.4827	
Month	3	5.516	1.8386	53.338	3.63E-15	***
Variety	3	0.787	0.2624	7.613	0.0003	***
Month:Variety	9	0.472	0.0524	1.521	0.1683	
Residuals	47	1.62	0.0345			

Image Credit: Stephen Kaffka

The crops in Figure 131 were planted in March 2013 and harvested in July 2013, March 2014, July 2014, and November 2014. See figures 7 and 8.

Figure 133: Variety Trial El Centro 2014 #2

Variety	T/ac	SD	SE
C854	0.36	0.03	0.06
C855	0.37	0.12	0.23
K75	0.50	0.06	0.11
K93	0.37	0.04	0.09

	Df	Sum Sq	Mean Sq	F value	Pr(>F)	
Rep	1	0.04851	0.04851	4.287	0.0722	.
Variety	3	0.05557	0.01852	1.637	0.2564	
Rep:Variety	3	0.09573	0.03191	2.82	0.1071	
Residuals	8	0.09053	0.01132			

Image Credit: Stephen Kaffka

The crops shown in Figure 132 were planted in May of 2014 and harvested November 2014.

Discussion

Trials conducted on the UC Davis campus in 2012 and 2013 resulted in yields ranging from 0.75 to 1.5 tons per acre. The yields from the four Kaiima harvests are shown in Figure 133. The Brigham and Hale varieties achieved considerably higher yields in Davis and Five Points than they did in the study conducted in Florida (Campbell et al. 2014). Brigham averaged 1.4 tons per acre in Davis and 0.9 in Five Points. Hale averaged 1.54 tons per acre in Davis and 0.99 tons per acre in Five Points. In comparison, these two varieties when grown in Florida achieved approximately 0.5 tons per acre (Campbell 2014). The total range for all the studies conducted in this work was between 0.72 and 1.63 tons per acre. Though over 60 years has passed from the first castor trials in Davis until now, yields have remained consistent. Historic yields in California reported by Knowles from 1949 based on careful hand harvest methods averaged approximately 1.3 t/ac, but no oil yields were reported. Imperial Valley yields were 0.5 t/ac. The similarity to yields reported from current trials here from the three locations suggests that not much progress has been made in increasing castor yield. Rather, suitability for commercial harvest may have improved.

Figure 134: Perennial Growth Evaluation by Variety

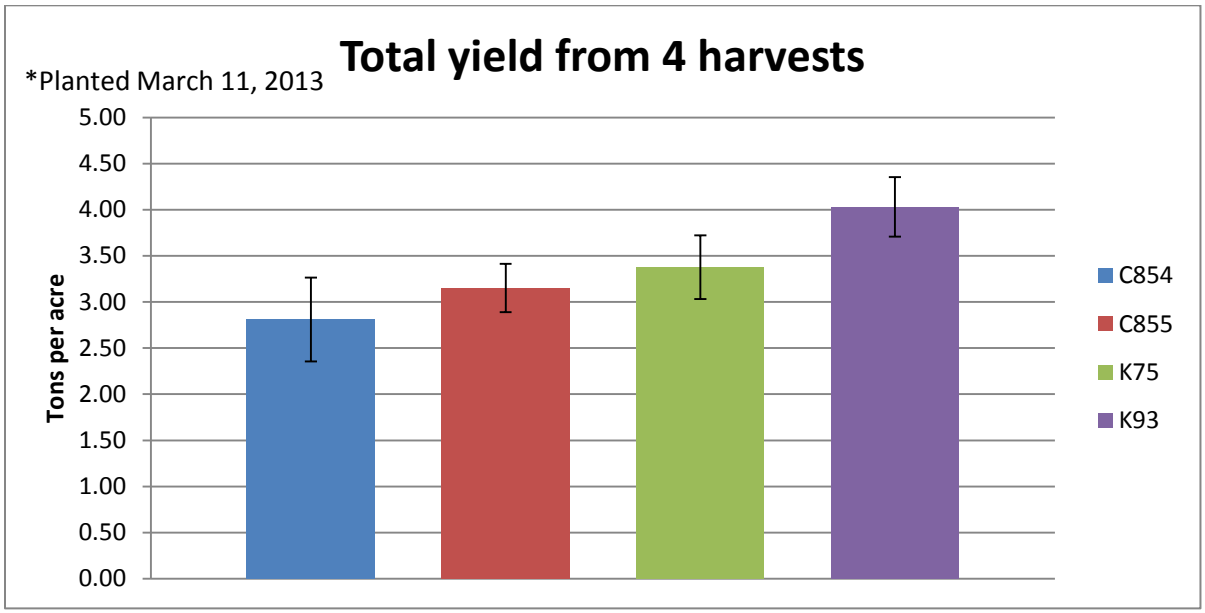

Image Credit: Stephen Kaffka

The four Kaiima varieties were planted March 11, 2013 and harvested four times. Figure 133 shows the yields for each harvest averaged across varieties.

Figure 135: Perennial Growth Evaluation, Yield by Harvest

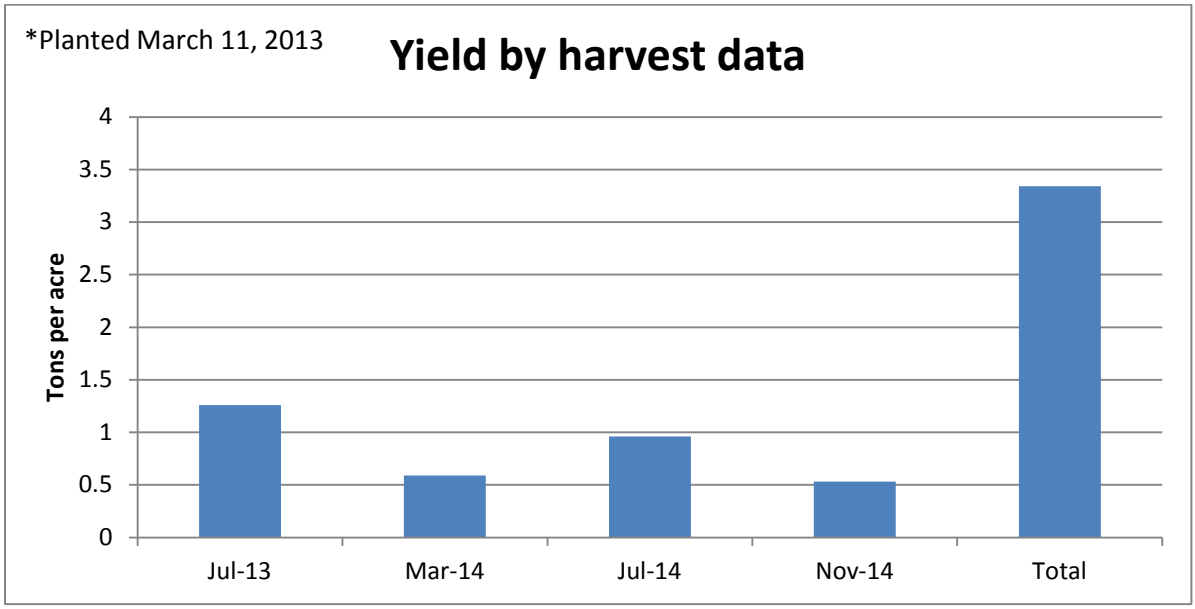

Image Credit: Stephen Kaffka

Koutroubus et al., (1999) reported average castor seed, oil percent and oil yields of 3,300 lb /ac, 50.1 % oil and 1670 lb per acre in northern Greece from irrigated castor. These are among the highest reported in the technical literature on castor. Other yields reported are closer to those observed in these trials. Kittock (1967) in irrigated studies in Texas reported yields ranging from 0.2 to 1.5 t/ac. Baldwin and Cossar reported yields in the mid-south US from different locations and planting dates ranging from approximately 0.1 to 0.9 t/ac. Laureti, in southern Italy reported yields with irrigation of 0.8 t/ac. Yields from Brazil and India, where much commercial castor production occurs are reported in the ranges of 0.25 to 1.0 t/ac. Occasional or record yields equal 2 t/ac (Severino et al., 2012).

Salinity. There were no significant effects from modestly increased saline irrigation treatments in a trial at the WSREC, in which salts were applied with irrigation water, post establishment. Results suggest that in non-saline soils, lower quality water could be used for irrigation without yield effects. There are a few reports that castor is moderately tolerant to salinity in the literature. Zhou et al., (2010) reported adequate emergence for commercial stands at soil salinity levels up to 7.1 dS/m, but no yields were reported. Plant growth up to 45 days was affected modestly at half that level but without significant effect on plant disease mortality.

Pathogens and insect pests

No leaf or stem diseases were observed at any of the trials carried out and reported here, nor were any reported from earlier work in California (Knowles, 1949; Zimmerman et al. 1958). Nonetheless, diseases are reported elsewhere, especially in more humid environments. Severino et al., (2012) provide a review of disease issues reported for castor. As with diseases, numerous insect, mite and nematode species are reported to affect castor growth and yield. Among species common in California, stink bugs, leafhoppers, armyworms and mites are considered significant. In 2013 in the Imperial Valley, plots were treated for several species, including mites and leafhoppers, but no treatments were considered necessary on any of the locations in the central valley. Severino et al., 2012, provide a comprehensive review of reports of insect damage to castor worldwide. If castor were to develop as a commercial crop in California, research on integrated pest management methods would become necessary, but was beyond the scope of the current project.

Biodiesel potential

Oil analyses were not fully available at the time of this report so values for castor oil content were derived from the literature (Figure 133). Based on these values, potential oil yields could be estimated (Figure 134). Converting oil yields to biodiesel values using the best observed yields and the range of seed oil contents in Figure 133, indicated that between 160 and 220 gallons of biodiesel equivalent could be produced per acre in California with modest resource inputs. The potential commercial value of castor oil in California for this purpose would be determined by a complex set of factors associated with the life cycle greenhouse gas emissions associated with its production and manufacture and policy issues about biofuels that are in flux at the state and federal level. Such an analysis was not attempted here. To produce it commercially in California, health and safety issues associated with its production, storage and

manufacture and the fate of oilseed residual meals would have to be carefully developed, so its re-adoption use remains uncertain.

Figure 136: Reported values for castor oil content

Source	Year	Location	% Oil Content
Scholz and Nogueria da Silva	2008		40-55
Ogunniyi	2006		46-55
Akpan, Jimoh, Mohammed	2006	Nigeria	33.2
Weiss	1983		40-60
Conceição′ Candeia, Silva, Fernandes Jr., Souza	2007		47-49
Oilseedcrops.org/castor-bean			50
Auld, Zanotto, McKeon, and Morris	2009		48-60
Wettasinghe	2012		50-60
Luaretti et al	1998	Italy	46.8
			47.6
Koutroubas et al	1999	Greece	51.8
			49.1
			51.7
			49.2
			50
			48.8
Zimmerman, Miller, Knowles	1958	California	40-57
USDA	1960		50-55

Image Credit: Stephen Kaffka

Figure 137: Estimated Oil Yields

Year	Location	Trial	Variety	Ton/ac seed	Ton/ac Oil - low (43%)	Ton/ac oil- high (56%)
2012	Davis	Kaiima	K93	1.39	0.6	0.78
2012	Davis	TT	Hale	1.54	0.66	0.86
2012	WS	Kaiima	K93	1.25	0.54	0.7
2012	WS	TT	Energia	1.2	0.52	0.67
2013	Davis	Kaiima	K93	1.04	0.45	0.58
2013	Imperial	Kaiima	K93	1.4	0.6	0.78
2013	WS	Kaiima	K93	1.11	0.48	0.62
12-Sep	Imperial	Kaiima	K75	0.69	0.3	0.39
12-Dec	Imperial	Kaiima	K75	0.65	0.28	0.36
14-Mar	Imperial	Regrowth Kaiima	K93	0.87	0.37	0.49
14-Jul	Imperial	Regrowth Kaiima	K93	1.11	0.48	0.62
14-Nov	Imperial	Regrowth Kaiima	K93	0.65	0.28	0.36
14-Nov	Imperial	Kaiima	K75	0.5	0.22	0.28

Image Credit: Stephen Kaffka