CALIFORNIA ENERGY COMMISSION

CALIFORNIA NATURAL RESOURCES AGENCY

Clean Transportation Program

FINAL PROJECT REPORT

Development of a Pilot Production Plant for Soladiesel Utilizing California Feedstocks

Prepared for: California Energy Commission

Prepared by: Solazyme, Inc.

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Helen Gibson
Stephen Decker
Gayle McKenzie
Jill Kauffman Johnson
Ana Echaniz
Primary Author(s)

Solazyme, Inc.
225 Gateway Boulevard
South San Francisco, CA 94080
Solazyme, Inc. website (www.solazyme.com)

Agreement Number: ARV-10-047

Hieu Nguyen
Commission Agreement Manager

Elizabeth John
Branch Manager
MEDIUM- AND HEAVY-DUTY ZERO EMISSION TECHNOLOGIES

Hannon Rasool
Director
FUELS AND TRANSPORTATION

Drew Bohan
Executive Director

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PREFACE

Assembly Bill 118 (Núñez, Chapter 750, Statutes of 2007) created the Clean Transportation Program. The statute authorizes the California Energy Commission (CEC) to develop and deploy alternative and renewable fuels and advanced transportation technologies to help attain the state's climate change policies. Assembly Bill 8 (Perea, Chapter 401, Statutes of 2013) reauthorizes the Clean Transportation Program through January 1, 2024, and specifies that the CEC allocate up to $20 million per year (or up to 20 percent of each fiscal year's funds) in funding for hydrogen station development until at least 100 stations are operational.

The Clean Transportation Program has an annual budget of about $100 million and provides financial support for projects that:

- Reduce California's use and dependence on petroleum transportation fuels and increase the use of alternative and renewable fuels and advanced vehicle technologies.
- Produce sustainable alternative and renewable low-carbon fuels in California.
- Expand alternative fueling infrastructure and fueling stations.
- Improve the efficiency, performance, and market viability of alternative light-, medium-, and heavy-duty vehicle technologies.
- Retrofit medium- and heavy-duty on-road and nonroad vehicle fleets to alternative technologies or fuel use.
- Expand the alternative fueling infrastructure available to existing fleets, public transit, and transportation corridors.
- Establish workforce-training programs and conduct public outreach on the benefits of alternative transportation fuels and vehicle technologies.

To be eligible for funding under the Clean Transportation Program, a project must be consistent with the CEC's annual Clean Transportation Program Investment Plan Update. The CEC issued PON-09-604 to provide funding opportunities under the ARFVT Program for the development of new, California-based biofuel production plants and to enhance the operation of existing ethanol production plants to increase statewide biofuel production and reduce greenhouse gas (GHG) emissions. In response to PON-09-604, the recipient submitted an application which was proposed for funding in the CEC's notice of proposed awards June 10, 2011, and the agreement was executed as ARV-10-047 on February 4, 2011.

ABSTRACT

Solazyme, Inc. makes renewable oils and other bioproducts. The company's proprietary technology uses highly optimized microalgae in an industrial fermentation process to transform a growing range of abundant plant-based sugars into high-value triglyceride oils and other bioproducts.

Solazyme's process is compatible with commercial-scale and widely available fermentation equipment. Solazyme's pilot plant in South San Francisco, as a result of work performed under ARV-10-047, has recovery operations capable of handling material from both 600- and 1,000-liter fermenters. These pilot plant modifications have enabled the company to produce samples of its algae oils to test new process conditions at an intermediate scale and more easily scale up to larger fermentation vessels. Solazyme has scaled up its technology platform, operating at the lab (5-15 liter), pilot (600-1,000 liter), demonstration (120,000 liters), and commercial (approximately 500,000 liters and above) fermentation scale.

In this project, we successfully designed and configured a pilot scale oil production facility to demonstrate a process for producing renewable algae oil using a California sugar beet feedstock via an algal fermentation process. The renewable algae oil produced in this pilot plant was converted to renewable diesel that meets American Society for Testing and Materials D975 Grade 2 Ultra Low Sulfur Grade specifications. This algal-derived renewable diesel was tested in diesel engines to evaluate its engine emissions and efficiency. The engine testing data generated positive air emissions and fuel consumption data.

Solazyme conducted a Field-to-Wheels Life Cycle Analysis of the sugar beet to algae oil to renewable diesel pathway, evaluating the carbon intensity of the entire process from cultivation of the sugar beet feedstock through the production and testing of the algal-derived renewable diesel. The Life Cycle Analysis showed this process has a lower carbon footprint than the lifecycle of petroleum-based diesel.

When designing and configuring the pilot scale oil production facility, the company evaluated the potential for designing a production facility, leveraging the conversion of an idled corn ethanol plant. This evaluation determined that conversion of a corn ethanol plant to an algae oil production plant would not be an optimal model; however, the evaluation and the project results did conclude that there is sufficient impetus to evaluate other possible co-located production facilities for generating cleaner burning, lower greenhouse gas footprint, and domestically produced fuel

Keywords: Solazyme, renewable diesel, algae, sugar beet, algae oil, fermentation, pilot plant

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EXECUTIVE SUMMARY

Solazyme, Inc. makes renewable oils and other bioproducts. The company's proprietary technology uses highly optimized microalgae in an industrial fermentation process to transform a growing range of abundant plant-based sugars into high-value triglyceride oils and other bioproducts.

Under CEC Award Number ARV-10-047, Solazyme Inc. proposed to design and configure a pilot scale oil production facility to demonstrate a process for producing renewable algae oil using a California feedstock via an algal fermentation process. The renewable algae oil produced would then be converted to renewable diesel and tested in diesel engines to evaluate engine emissions and efficiency. In addition, when designing and configuring the pilot scale oil production facility, the company proposed to evaluate the potential for designing a production facility, leveraging the conversion of an idled corn ethanol plant.

Solazyme's process is compatible with commercial-scale and widely available fermentation equipment. Solazyme's pilot plant in South San Francisco, California, because of work performed under the CEC Award, has recovery operations capable of handling material from both 600- and 1,000-liter fermenters. These pilot plant modifications have enabled the company to produce samples of its algae oils to test new process conditions at an intermediate scale and more easily scale up to larger fermentation vessels. Solazyme has scaled up its technology platform, operating at lab (5-15 liter), pilot (600-1,000 liter), demonstration (120,000 liter) and commercial (approximately 500,000 liter and above) fermentation scale.

In this CEC project, and in accordance with our proposal, we successfully designed and configured a pilot scale oil production facility to demonstrate a process for producing renewable algae oil using a California sugar beet feedstock via an algal fermentation process. The renewable algae oil produced in this pilot plant was then converted to renewable diesel that met American Society for Testing and Materials D975 Grade 2 Ultra Low Sulfur Grade specifications and subsequently tested in diesel engines to evaluate the fuel's engine emissions and efficiency.

Design and Construction

Solazyme Inc. worked with an architectural design firm to prepare the design documents for installing new equipment and utilities in Solazyme Inc.'s existing South San Francisco pilot plant facility. On a parallel track, we also worked with the architectural design firm to determine the appropriate sizing, design, and procurement of the required algae oil recovery equipment so that long lead time equipment could be order. We then worked with a contractor to build out the pilot plant and install the equipment for operation.

Testing of the new equipment went through successful installation, operation and performance qualification testing and all equipment proved to function as designed. Individual unit operations were tested to shake down the equipment using standard sugar feedstocks and fermentation processes. After demonstrating the successful individual equipment operations, the entire oil production process was demonstrated successfully from fermentation to refined algae oil. Finally, we conducted the production process using California produced sugar beet as the fermentation feedstock to produce approximately 83 gallons of algae oil for conversion into renewable diesel.

Renewable Diesel and Engine Testing

Conversion of algae oil to renewable diesel was performed at Southwest Research Institute in San Antonio, Texas. A third party supplied the two catalysts required for hydrodeoxygenation and isomerization of the algae oil. The process yielded approximately 38 gallons of renewable diesel which passed all the American Society for Testing and Materials D975 Grade 2 Low Sulfur Diesel specifications.

Engine testing of this algal derived renewable diesel was performed at the National Renewable Energy Laboratory to evaluate the fuel's emissions and fuel economy in comparison to a United States Environmental Protection Agency Certified Fuel Ultra Low Sulfur Diesel standard as well as the California Air Resources Board standard. Results of engine out tests (Untreated exhaust) of Solazyme algal derived renewable diesel show significant reduction in particulate matter of 42-60 percent as well as Oxides of Nitrogen reduction in engine out tests by the Federal Test Procedure and the Supplemental Emissions Test. Tailpipe emissions for Oxides of Nitrogen, carbon monoxide, and Total Hydrocarbons were equivalent for all fuels and below the Nitrogen Oxide certification level of the engine, reflecting the effectiveness of the diesel oxidation catalyst, diesel particulate filter, and selective catalytic reduction exhaust after treatment.

Results from the Federal Test Procedure and Supplemental Emissions Test protocols indicated that Algal Derived Renewable Diesel had "4 percent better fuel consumption than the Environmental Protection Agency Certified Fuel Ultra Low Sulfur Diesel standard and 2.6 percent better fuel consumption than the California Air Resources Board Standard Fuel." The dramatic reduction in Particulate Matter in Algal Derived Renewable Diesel could potentially lead to further fuel economies since less fuel is needed to regenerate the diesel particulate filter. Similarly, Algal Derived Renewable Diesel's lower nitrogen oxides emissions would require less diesel exhaust fluid to be used in the after-treatment device.

Field-to-Wheels Life Cycle Analysis of the Sugar Beet to Algae Oil to Renewable Diesel Pathway

We conducted a Field-to-Wheels Life Cycle Analysis of sugar beet to algae oil to renewable diesel. The Life Cycle Analysis was conducted subject to and based on the following assumptions and data limitations: data for European sugar beet farming was employed because there was no publicly available data for sugar beet farming in California; heat and power sources for the sugar beet processing and part of the algae oil processing were cogenerated from natural gas; the electricity used to power the algae oil processing was a California average grid electricity mix; and generic US data were used for evaluation of many of the impact categories associated with the baseline standard Ultra Low Sulfur Diesel.

In the Life Cycle Analysis, the criteria and air toxic pollutants of Algal Derived Renewable Diesel were compared to Ultra Low Sulfur Diesel and found to be nearly equivalent. Areas where Algal Derived Renewable Diesel yielded at least 40 percent less emissions than Ultra Low Sulfur Diesel included carbon monoxide and sulfur oxides. The Life Cycle Analysis indicated that Algal Derived Renewable Diesel yielded higher emissions in particulate matter, Formaldehyde and Acetaldehyde primarily due to the diesel emissions from tractor use in sugar beet farming in the sugar beet to algae oil to renewable diesel production process.

The Carbon Intensity for Green House Gas emissions was calculated for renewable diesel and compared to Ultra Low Sulfur Diesel. Based on this analysis, Solazyme's Algal Derived Renewable Diesel had approximately 30 percent lower greenhouse gas emissions than Ultra Low Sulfur Diesel. The greenhouse gas emissions from sugar beet cultivation and processing constituted the largest greenhouse gas component of the Life Cycle Analysis. The greenhouse gas emissions could be reduced through higher utilization of renewable electricity for the sugar beet mill and algae oil production facility.

The Algal Derived Renewable Diesel made from the sugar beet to algae oil to renewable diesel pathway burns cleaner and has a lower carbon intensity than fuel meeting petroleum-based diesel standards. Solazyme's Algal Derived Renewable Diesel might be useful to support older engines found in industrial and farming equipment that do not have after treatment systems such as particulate filters and other catalytic exhaust reduction systems. Future efforts to improve the carbon footprint of this fuel could include use of renewable energy to power the sugar beet mill and algae oil production facility and improved farming methods. Co-locating an algae oil production facility with a California sugar beet sugar production facility would potentially offer an opportunity to effectively utilize local energy resources and generate new jobs and revenues for the State of California.

Conversion of an Idled Corn Ethanol Producing Plant

When designing and configuring the pilot scale oil production facility, the company also evaluated the potential for designing a production facility, leveraging the conversion of a converted idled corn ethanol plant. From this evaluation, we determined that conversion of a corn ethanol plant to an algae oil production plant would not be an optimal model; however, the evaluation and the project results did lead us to conclude that there is sufficient impetus to evaluate other possible co-located production facilities for generating cleaner burning, lower greenhouse gas, and domestically produced fuel.

CHAPTER 1: Introduction

Solazyme, Inc.'s CEC Award: An Overview

Solazyme, Inc. (Solazyme) makes renewable oils and other bioproducts. The company's proprietary technology uses highly optimized microalgae in an industrial fermentation process to transform a growing range of abundant plant-based sugars into high-value triglyceride oils and other bioproducts. Solazyme can tailor the composition of its oils and bioproducts to address specific customer requirements, offering superior performance characteristics and value, compared with conventionally sourced products.

Solazyme's algae oil has a composition ideal as a feedstock for conversion into Fatty Acid Methyl Ester based biodiesel and hydrotreated renewable diesel which can be carried out using standard technologies. Other companies have been trying to exploit algae as a potential source of renewable biofuel, mostly focusing on phototrophic grown algae, which rely directly on photosynthesis to grow and on algal ponds or photo bioreactors in which to accumulate algal biomass. Solazyme's innovative algal process does not rely on photosynthesis or outdoor ponds / photoreactors in which productivities are very low, but rather on heterotrophic algae that can grow and generate biomass in the dark. These heterotrophic algae ingest organic (carbon-containing) molecules present in feedstocks and convert these carbons into oil in standard industrial fermentation vessels. The feedstocks are in the form of readily available sugars obtained from sugarcane or sugar beets, as well as newly emerging cellulosic sugars derived from sustainable, non-food plant matter such as municipal green waste, switchgrass, corn stover, etc. All these feedstocks in turn are derived from plants that grow and fix carbon using photosynthesis. Solazyme's technology thus exploits "indirect photosynthesis" — a term that differentiates the company's process from photosynthetic algal cultivation.

Fuels that Solazyme has produced successfully, include Algal Derived Renewable Diesel (Soladiesel$_{BD}$®) an American Society for Testing and Materials (ASTM) D6751 biodiesel, a Fatty Acid Methyl Ester; Soladiesel$_{RD}$®, an ASTM D975 renewable diesel; Solajet™, an ASTM 7566 Aviation Turbine Fuel; and renewable diesel and renewable jet fuel that meet the Navy's HRD76 and HRJ5 specifications, respectively, for advanced drop in biofuels.

Under California Energy Commission Award Number ARV-10-047, Solazyme proposed to design and configure a pilot scale oil production facility to demonstrate a process for producing renewable algae oil from a California feedstock via an algal fermentation process. The renewable algae oil produced would then be converted to renewable diesel and tested in diesel engines to evaluate engine emissions and efficiency. In addition, when designing and configuring the pilot scale oil production facility, the company proposed to evaluate the potential for designing a production facility, leveraging the conversion of an idled converted corn ethanol plant.

Solazyme's process is compatible with commercial-scale and widely available fermentation equipment. The company operates its lab and pilot fermentation and recovery equipment as scaled-down versions of its large commercial engineering designs. Solazyme's pilot plant in South San Francisco, California, which as a result of work performed under the CEC Award, has recovery operations capable of handling material from both 600- and 1,000-liter fermenters. These pilot plant modifications have enabled the company to produce samples of its algae oils to test new process conditions at an intermediate scale and more easily scale up to larger fermentation vessels. Solazyme has scaled up its technology platform, successfully operating at lab (5-15 liter), pilot (600-1,000 liter), demonstration (120,000 liter) and commercial (approximately 500,000 liter and above) fermentation scale.

Objectives of the CEC Award

Under the CEC Award, beginning in 2010, Solazyme set out to achieve the following objectives:

1. To build a pilot-scale integrated biorefinery quickly by leveraging previously installed fermentation capacity at a pre-existing, pilot-scale bioproduction facility and adding and integrating the necessary algae oil recovery equipment.
2. To operate the pilot plant using algae strains previously developed by Solazyme, while successfully utilizing California produced sugar beet feedstock from the Imperial Valley, and to validate production cost projections at full commercial scale.
3. To refine the purified algae oil to renewable diesel at a scale sufficiently large to analyze and demonstrate the quality of this fuel.
4. To collaborate with an original engine manufacturer and/or other appropriate testing facility to analyze, test and demonstrate the use of renewable diesel in an automobile engine or other appropriate test platform.
5. To maintain a flexible project plan and adhere to best project management practices to meet all objectives on or ahead of schedule and on or below budget.

The Purpose of this Project

As part of its mandate, the CEC supports research and development programs that advance transportation technology that increases sustainability and decreases the carbon footprint. Drivers for increasing the use of alternative, low carbon fuels in California include the petroleum fuel reduction goals established under Assembly Bill 2076 (Shelley, Chapter 936, Statutes of 2000) aimed at reducing the state's petroleum dependency. In addition, the Low Carbon Fuel Standard, developed in response to Executive Order S-1-07, requires fuel suppliers and distributors to reduce the carbon intensity of their fuels by ten percent by 2020.

Achieving these goals will require the dramatic increase in the production of biofuels in California over the next decade. However, to meet the Low Carbon Fuel Standard, the production of advanced biofuels derived from dedicated energy feedstocks will be required as these fuels will have the low Carbon Intensity needed to achieve the ten percent reduction requirement. The traditional biofuel used in California has largely been corn-based ethanol blended into gasoline fuel. Biodiesel blends require a separate fuel delivery infrastructure because their characteristics prevent them from being completely fungible with petroleum diesel throughout the fuel delivery system.

Renewable diesels produced through hydrotreatment processes (if they meet the ASTM specifications for diesel fuel (ASTM D975)) would be completely fungible with the existing petroleum diesel distribution pathway. An opportunity exists for rapidly increasing renewable diesel production via algal fermentation. Ethanol plants have common equipment and utilities with a commercial plant producing renewable algae oil via the algal fermentation platform used in Solazyme's technology platform. These plants have fermenters and utilities that could potentially be employed in Solazyme's algal fermentation renewable diesel production pathway.

Accordingly, in furtherance of the above referenced project goals and pursuant to the CEC Award, Solazyme has designed and successfully operated an enhanced pilot plant that includes new oil recovery equipment to produce a total of 285 kg (83 gallons) of algae oil, using California produced sugar beet as feedstock. This algae oil was successfully hydrotreated into renewable diesel meeting the ASTM specifications for diesel fuel (i.e., ASTM D975 Grade 2 Ultra Low Sulfur Grade). The resulting renewable diesel, when tested, was determined to be a cleaner burning fuel than conventional petroleum diesel. Under the CEC Award, Solazyme also evaluated the components of a corn ethanol plant to determine which components could potentially be adapted for use in Solazyme's technology platform.

CHAPTER 2: Technical Tasks

To meet the objectives of the CEC Award Number ARV-10-047, the company divided the technical tasks into several discreet phases. These phases were labeled as Tasks 2 through 6 under the CEC Award Scope of Work. In this Chapter 2, we have summarized the work performed under each task.

Task 2 Design, Construct, and Commission Solazyme Pilot Plant

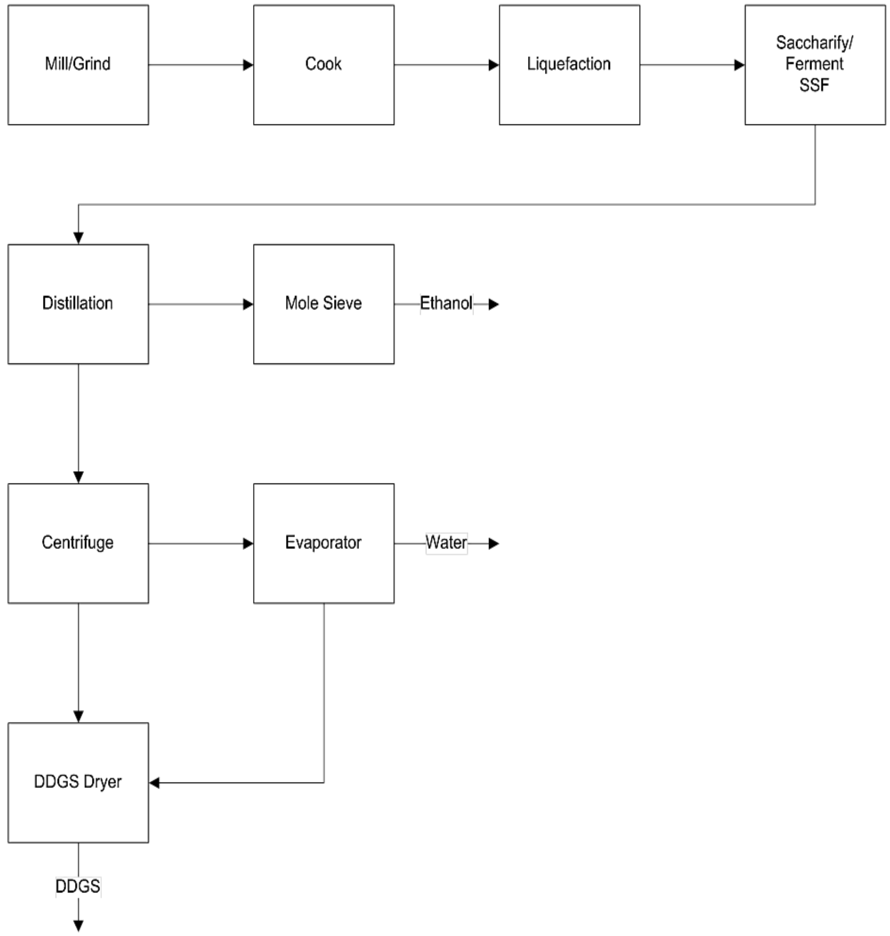
The company's goals in Task 2 were to design, construct and commission a pilot plant at Solazyme's South San Francisco facility to model a modified ethanol plant. We reported in the Task 2 Summary Report submitted in April 2013 as well as at the Critical Progress Review Meeting held in May 2013 that the above Task 2 goals were met. Thereafter, in accordance with the Award Scope of Work, the CEC Commission Manager approved the continuation of the project.

Assessment of Corn Ethanol Unit Operations

To evaluate the repurposing of an idled corn ethanol plant for producing algae oil, we assessed the unit operations associated with corn ethanol processing and the corresponding infrastructure typically used in such plants. From our review, we determined that a majority of the U.S. corn-ethanol plants use the dry mill process (Dale, R, and Tyner, W., Economic and Technical Analysis of Ethanol Dry Milling: Model Description, Purdue University Staff Paper #06-04, 2006). Though wet milling offers several co-product options, it is more capital intensive and generally more energy intensive than dry milling (Wu, M., Analysis of the Efficiency of the U.S. Ethanol Industry 2007, Argonne National Laboratory, 2008). Because the dry mill process is more widely used this was the process that we evaluated. A typical flow sheet for a dry mill ethanol plant is presented in Figure 1.

Figure 1: Typical Dry Mill Process to Produce Ethanol from Corn

- Majority of the US corn-ethanol plants use the dry mill process.
- Prior to fermentation, corn is ground, cooked and treated with enzymes to provide access to the sugars for fermentation.
- During fermentation, enzymes are added to continue to break down starch into sugars which are converted to ethanol.
- After fermentation, ethanol is purified using distillation and mole sieve. The unfermentable portion is dried to produce dried distillers grains and solubles (DDGS) a co-product.



Source: Solazyme

Upon completing the analysis of the corn ethanol wet mill and dry mill processes, we evaluated the suitability of the equipment and utilities in a dry mill corn ethanol plant for use in the Solazyme process to ascertain whether equipment could be re-purposed. While the Solazyme process is proprietary and cannot be fully described here, a white paper was completed to serve as a reference for the pilot plant design. The white paper findings are summarized in Table 1, which describes the suitability of each unit operation of a corn ethanol process for possible use in the Solazyme process.

Table 1: Evaluation of The Corn Ethanol Plant for Algae Oil Process

Unit operation	Corn ethanol design	Suitable for algal oil process?
Fermentation	Yeast is used as the biocatalyst to convert sugar to ethanol in atmospheric, anaerobic vessels requiring some cooling.	No
Evaporation	Thin stillage is concentrated from 5 to 10% solids up to 30 to 60% solids. Several evaporator technologies have been used.	Yes
Drying	Various types of driers are used to drive water from centrifuge solids and evaporated syrup to produce DDGS.	Possible
Centrifugation	Decanter centrifuges are used to separate the whole stillage into insoluble and soluble fractions as part of the DDGS process.	Yes
Milling	Hammer mills are typically used to grind the corn prior to cooking.	Yes
Distillation	Tray distillation columns are used to separate water and solids from ethanol.	Possible

Source: Solazyme

This analysis was memorialized in an in-house white paper that was used to inform the design basis for designing the pilot plant. We concluded from this analysis that, while there is potential to use or repurpose some of the equipment found in a corn ethanol plant for producing algae oil, the overall improvement costs and loss of process effectiveness would not support the conversion of an idled corn ethanol plant into an algae oil production plant.

Pilot Plant Design and Construction

The pilot plant design focused primarily on the downstream processing unit operations, adding, and integrating the necessary algae oil recovery equipment while leveraging previously installed fermentation capacity.

The first step was to engage an architectural design firm to design the facility including process/mechanical, architectural, electrical, and structural design. The corn ethanol white paper as well as our experience at other manufacturing sites helped to inform the design process. An initial conceptual design was used to develop early layout designs to facilitate specification of long lead time equipment. The equipment and utility specifications and procurement continued in parallel with a second phase of design resulting in a construction design package that was issued for permitting and as part of a request for proposal for construction.

The construction phase was bid in a Request for Proposal process, a general contractor selected, and a contract put into place. Construction was divided into two phases. In the initial phase, boiler/dryer upgrades were undertaken, including installation of a new boiler to provide more consistent, higher-pressure steam to serve key equipment. In addition, modifications to the dryer ducts, filters and fan in the existing design were pursued, increasing dryer throughput by approximately 50 percent to 75 percent.

In the second phase of construction, we installed the new oil recovery equipment and modified the pilot plant's utilities infrastructure to support this new equipment. The equipment procurement, factory acceptance testing, shipment, installation, and commissioning occurred throughout 2012. Notable support equipment installed in this second construction phase included a mass spectrometer and load cells for enhanced fermentation control. Utility upgrades included the installation of a new process water chiller as well as the above-described boiler.

Commissioning and Shakedown Testing

The equipment was commissioned pursuant to an established Installation Qualification, Operational Qualification and Performance Qualification model. Startup operations, including staff training, were initiated in January 2013.

Task 3 Pilot Scale Production of Algae Oil

The goal of Task 3 was to complete pilot scale production of algae oil. The algae oil produced in this phase provided the necessary oil feedstock to produce algal derived fuel in Task 4 *Refine and Analyze Renewable Diesel.* We reported in the Task 3 Summary Report in February 2014 and at the Critical Progress Review Meeting held in March 2014, that the Task 3 goal was met. Thereafter, in accordance with the Award Scope of Work, the CEC Agreement Manager approved the continuation of the project

Develop Test Plan

The first step in Task 3 was to develop a plan specifying the process parameters, analysis procedures and protocols for pilot scale production of algae oil. The team developed and finalized the ***CEC Task 3 Test Plan*** which included calculations of the quantity of algae oil that would be required to produce sufficient algal derived renewable diesel fuel for the engine testing planned in Task 4. Based on the unit operation production yield assumptions from fermentation through extraction and refinement of oil, we developed the assumptions set forth in Table 2.

Table 2: Algae Oil Production Estimate

Test	Amount Required
Compositional Analysis (ASTM D975)	5 Liters /1 Gallon
Engine Testing	200 Liters / 50 gallons

Source: Solazyme

Based on the requirements outlined above, Solazyme targeted production of one hundred gallons of algae oil.

The Solazyme algae oil production processes and procedures were developed and optimized for producing the requisite algae oil. Utilizing pilot plant data and our manufacturing experience, we established a specification for the algae oil as a fuel feedstock. The proprietary ***Solazyme RB Algae Fuel Oil Specification*** was established to achieve a low sulfur content to meet the low sulfur ASTM D975 specification **(*ASTM D975 Grade 2 Ultra Low Sulfur Grade*)** and the general requirements for the catalysts that would be used in the fuel refining.

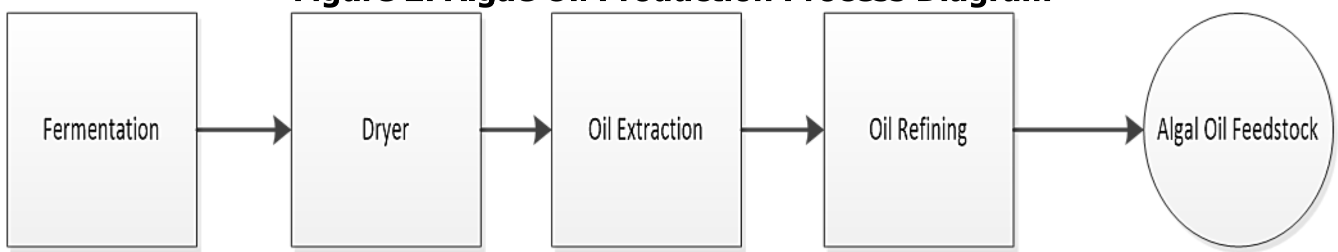
Raw material procurement

Based on the estimate shown in Table 2, the team determined the quantity of sugar needed for the pilot program to produce one hundred gallons of algae oil. Solazyme purchased California grown sugar beet through Spreckles Sugar in Brawley, California. Solazyme procured enough sugar to conduct up to ten pilot scale runs as well as the other materials required to complete these runs.

Engineering and Pilot Plant Runs

Several test runs were performed to line out all the new equipment unit operations prior to producing the algae oil using California grown sugar beet. We conducted fermentations up to 1000-liter scale. Fermented material was harvested and then dried and processed, using our extraction and refining unit operations. Standard feedstocks were employed in these engineering "test" runs to ensure successful shake down of the new equipment. A process for the production of algae oil, shown in Figure 2, was defined from these engineering runs, providing the basis for the production runs using the California sugar beet feedstock.

Figure 2: Algae Oil Production Process Diagram



Source: Solazyme

Three runs were then conducted using the sugar beet feedstock procured for this project. The biomass from these runs was then stored, pending the scheduling of fuel refining dates. Once the fuel refining dates were scheduled, Solazyme extracted the algae oil from the stored biomass and refined it. This work yielded approximately 313 liters (83 gallons) of algae oil suitable for use as a fuel feedstock. The algae oil was tested and met the proprietary ***Solazyme RB Algae Fuel Oil Specification*** with excellent recovery and quality.

Figure 3: Algae Oil Production Phases

Source: Solazyme

Task 4 Refine and Analyze Renewable Diesel

The goal of Task 4 was to refine a sufficient portion of the algae oil produced in Task 3 into renewable diesel at the Chevron refinery in Richmond, California, or an equivalent facility to allow for engine testing. Accordingly, Solazyme required a sufficient quantity of fuel refined from the algae oil feedstock to allow for the engine testing anticipated under Task 5 *Test Renewable Diesel*. The company submitted its Task 4 Report to the CEC in December 2014.

Contractor Selection – Fuel Refining

As part of Task 4, Solazyme prepared a Request for Proposal for the conversion of one hundred gallons of algae oil into renewable diesel that met ASTM D975 specifications. This RFP was sent to two companies capable of pilot scale fuel refining. A third company was identified but it declined to participate. It is noteworthy that there are only a few companies that provide this type of service at small pilot production scale, and thus the bids for this small-scale fuel refining were significantly higher in cost than the anticipated in the original budget. Ultimately, the company elected to work with Southwest Research Institute (SwRI). The parties entered a contract for this work and, thereafter, Solazyme shipped the algae oil to SwRI.

Conversion of Algae Oil to Renewable Diesel

Conversion of algae oil to renewable diesel is a two-step process requiring two different catalysts. The first step, hydroxydeoxygenation, utilizes a catalyst that is readily available commercially and converts the algae oil triglycerides to n-paraffins. The second step, isomerization, requires a catalyst that is difficult to obtain, and is typically proprietary. The HI is used to reduce the cloud point of the renewable diesel to a target of less than 0°C. Working with SwRI, a catalyst agreement was put in place with a third party to provide the required amount of both catalysts to process Solazyme's algae oil.

The HDO catalyst was loaded and prepared in two reactors in series and 72.5 gallons of algae oil were converted to 67.8 gallons of HDO product with a cloud point of 27.3°C. The reactors were then cleaned and reloaded with the second HI catalyst and the HDO product isomerized. A product with target cloud point of less than 0°C was generated with a final yield of 38.2 gallons of algal derived renewable diesel. Lubricity and conductivity additives were added to the renewable diesel to ensure that all the ASTM D975 Grade 2 Ultra Low Sulfur Grade standards were met.

Analysis of Renewable Diesel

The renewable diesel produced from Solazyme's algae oil was tested against **ASTM D975 Grade 2 Ultra Low Sulfur Grade** specifications and met all the ASTM requirements, shown in Table 3.

Table 3: Renewable Diesel Analysis Results

ASTM D975 Grade 2 D S15						
Property	Test	Specification	Units		CEC result	pass/fail
Flash Point	D93	52	°C	min	52	pass
Water and Sediment	D2709	0.05	% vol	max	<0.005	pass
Distillation Temp	D86	282	°C90%, % vol recovered	min	560.5	pass
Ash	D482	0.01	% mass	max	<0.001%	pass
Sulfur	D5453	15	ppm	max	0.8	pass
Copper strip corrosion 3 hours min, control temp 50C	D130	No. 3		max	1A	pass
Cetane number	D613	40		min	72.4	pass
Aromaticity	D1319	35	% vol	max	0.2	pass
Operability Requirements						
Cloud Point	D2500	none SZ target -10C	°C	max	-6	
Ramsbottom carbon residue	D524	0.35	% mass	max	0.03	pass
Lubricity	D6079	520	microns	max	353	pass
Conductivity	D2624	25	pS/m	min	90	pass

Source: Solazyme

Task 5 Engine Test Renewable Diesel

The goal of Task 5 was to engine test the algal derived renewable diesel (Soladiesel_{RD}) produced in Task 4 *Refine and Analyze Renewable Diesel*. The Task 5 Report was submitted to the CEC in December 2014.

Contractor Selection

Two contractor sites were identified for the engine testing, and after consideration, the National Renewable Energy Laboratory (NREL) was selected to perform the work. A contract was put in place in order that NREL could perform the fuel testing based on the test plan described below.

Engine Testing Plan

The intention of the engine testing was to generate engine emissions and efficiency comparison data to the Environmental Protection Agency Certification Diesel Standard as well as the California Air Resources Board Standard. The ***2014 Solazyme Refuel Engine Testing Plan*** provided by NREL outlines the test parameters for Cycles, Engine, Data Acquisition, Emissions and Fuels, and is summarized as follows:

- Engine Dynamometer Test Cycles:
  - Federal Test Procedure (FTP) heavy-duty engine dynamometer transient test cycle http://www.dieselnet.com/standards/cycles/ftp_trans.php
  - Supplemental Emissions Test (SET) steady state engine dynamometer http://www.dieselnet.com/standards/cycles/set.php
- Engine: 2012 Cummins ISL345 – 8.9L – 345 HP with a diesel oxidation catalyst, diesel particulate filter, and selective catalytic reduction exhaust after treatment
- Data Acquisition:
  - Fuel consumption (scale based gravimetric approach)
  - Typical engine operating temperatures and pressures
- Emissions:
  - Dilute tailpipe measurements for oxides of nitrogen (NOx), carbon dioxide (CO_2), carbon monoxide (CO), oxygen and Total Hydrocarbons (THC).
  - Raw engine out measurements for NOx, NO, NO_2 and particulate matter (PM)
- Fuels:
  - Baseline Certification Diesel Ultra Low Sulfur Diesel. (ULSD)
  - California Air Resources Board reference diesel standard. (CARB Fuel)
  - Solazyme algal derived renewable diesel fuel ($Soladiesel_{RD}$)

Engine Testing Methods

$Soladiesel_{RD}$, ULSD, and CARB Fuel were engine tested using two cycles, the FTP transient cycle and the SET ramped modal cycle. Each cycle was completed a minimum of three times with a hot start for each fuel. Each test is described below.

The FTP heavy-duty transient cycle is used for regulatory emission testing of heavy-duty on-road engines in the United States [40 CFR 86.1333]. The transient test was developed to consider a variety of heavy-duty truck and bus driving patterns on roads and expressways in US cities, including traffic in and around the cities.

The cycle is run as both a cold- and a hot-start test. Typically, the engine is soaked overnight, and a cold-start test is performed in the morning. The cold-start test is followed by a 20-minute soak period and a minimum of three consecutive hot-start tests, with a 20-minute soak period between each hot-start test. The composite, brake-specific FTP results are obtained by dividing the weighed emissions and fuel consumption (in grams) by the weighed mechanical work in brake horsepower per hour.

The Supplemental Emissions Test. The SET is a 13-mode steady-state engine dynamometer test, first introduced by the U.S. Environmental Protection Agency as part of the 1998 consent decrees with US heavy-duty engine manufacturers and then included in the 2007 emission standards for heavy-duty engines. In addition to FTP testing, consent decree engines subject to U.S. Environmental Protection Agency 2004 emission standards and model year 2007 and later engines must also demonstrate compliance when tested over the steady-state SET test. For 2010 and later model year heavy-duty engines, manufacturers must use the 2010 ramped mode SET. The SET provides useful fuel consumption data as it is run under load for a longer duration than the FTP.

Engine Testing Results

The $Soladiesel_{RD}$ was shipped from Southwest Research Institute (SwRI) directly to NREL which performed the tests described in Sub-Chapter 2 *Engine Testing Methods*. Fuel performance results are summarized in this Sub-Chapter 2 *Engine Testing Results* and in **Appendix A** (*2014 $Soladiesel_{RD}$ Fuel Comparison Engine Testing*). For the FTP cycles, engine out results for $Soladiesel_{RD}$ had statistically relevant lower criteria pollutants, PM, and NOx, over both ULSD and CARB Fuel. Most notably, there was a 50 percent reduction in PM over ULSD and 42 percent reduction over CARB Fuel. Fuel economy was improved by 3 percent for both ULSD and CARB Fuel, as measured by the Brake Specific Fuel Consumption test. In tests conducted with after treatment systems (tailpipe out), there was no statistically significant difference in emissions of PM or NOx. For the SET cycles, engine out results for $Soladiesel_{RD}$ again had statistically relevant PM reductions over ULSD (60 percent) and CARB Fuel (51 percent) as well as improved fuel economy Brake Specific Fuel Consumption results of 4 percent and 3 percent, respectively, over ULSD and CARB Fuel. $Soladiesel_{RD}$ had lower NO_X emissions than the ULSD but was not significantly different than the CARB Fuel results. Again, there was no significant difference in tailpipe out emissions and all fuels were below the engine certification of 0.33 g/bhp-hr.

Results from the FTP and SET test protocols indicated that $Soladiesel_{RD}$ has better fuel economy then either the ULSD or the CARB Fuel; specifically, NREL reported "4 percent better fuel consumption than the ULSD and 2.6 percent better fuel consumption than the CARB Fuel." In addition, NREL reported that for $Soladiesel_{RD,}$ "Engine out PM was drastically lower at nearly one-half that of the ULSD and approximately 40 percent lower than the CARB Fuel PM results."

The dramatic reduction in PM in $Soladiesel_{RD}$ could potentially lead to further fuel economies since less fuel is needed to regenerate the diesel particulate filter. Similarly, $Soladiesel_{RD}$'s lower NOx emissions would require less diesel exhaust fluid to be used in the after-treatment device (selective catalytic reduction).

Task 6 Data Collection and Analysis

The goal of Task 6 has involved the preparation of a final report that synthesizes and analyzes the project tasks and data for submission to the California Energy Commission. This final report, which has been prepared to fulfill these Task 6 requirements, attempts to consider possible benefits and local impacts of this project, and includes relevant information and project data to support this analysis.

Estimate of Gasoline and/or Petroleum-based Diesel Fuel Annual Displacement

Because there is no blend wall with $Soladiesel_{RD}$ and the fuel delivery infrastructure is compatible with the current petroleum diesel infrastructure, the full capacity of a commercial facility would be capable of displacing petroleum-based diesel per year. As an example, California-based Ethanol (EtOH) production facilities range from 3-60 million gallons/year, as shown in Table 4.

Table 4: Fuel Ethanol Facilities Capacity by State and by Plant (Million Gallons Per Year as of April 2014)

Company	Location	Nameplate Capacity	Operating Production	Under Construction/ Expansion Capacity	Idled From	Idled To
California						
Aemetis	Keyes, CA	55	55	NA	2013-01	2013-04
Calgren Renewable Fuels, LLC	Pixley, CA	60	60	NA	NA	NA
Golden Cheese Company of California	Corona, CA	5	0	NA	NA	NA
Pacific Ethanol	Madera, CA	40	0	NA	early 2009	NA
Pacific Ethanol	Stockton, CA	60	60	NA	NA	NA
Parallel Products	Rancho Cucamonga, CA	*3.0	*3.0	NA	NA	NA
California Total		**223**	**178**	**NA**		
(*) indicates the company's total capacity is divided among its plants						

Source: Solazyme

Life Cycle Analysis of Sugar Beet Produced Renewable Diesel ($Soladiesel_{RD}$)

Solazyme conducted a Field-to-Wheels Life Cycle Analysis of renewable diesel ($Soladiesel_{RD}$) made from algae oil produced using sugar beet feedstock. The Life Cycle Analysis was conducted subject to and based on the following assumptions and data limitations: data for European sugar beet farming was employed because there was no publicly available data for sugar beet farming in California; heat and power sources for the sugar beet processing and part of the algae oil processing were cogenerated from natural gas; the electricity used to power the algae oil processing was a California average grid electricity mix; and generic US data were used for evaluation of many of the impact categories associated with the baseline standard ULSD.

The criteria and air toxic pollutants, shown in Tables 5 and 6, respectively, for $Soladiesel_{RD}$ made with sugar beet feedstock were compared to ULSD and found to be nearly equivalent.

Areas where Soladiesel$_{RD}$ yielded at least 40 percent less emissions than ULSD included CO and SOx. Soladiesel$_{RD}$ yielded 40 percent or higher emissions in PM2.5, Formaldehyde and Acetaldehyde primarily due to the diesel emissions from tractor use in sugar beet farming.

Table 5: Criteria Air Pollutants for Sugar Beet Produced Soladiesel$_{RD}$ Versus Ultra Low Sulfur Diesel

	Criteria Pollutants g/MJ					
	VOC	CO	NOx	PM10	PM2.5	SOx
Sugar Beet RD Field-to-Wheels	0.027	0.055	0.107	0.019	0.011	0.009
Baseline ULSD Well-to-Wheels	0.029	0.148	0.105	0.015	0.008	0.015

Source: Solazyme

Table 6: Air Toxics for Sugar Beet Produced Soladiesel$_{RD}$ Versus Ultra Low Sulfur Diesel

	Air Toxic Pollutant mg/MJ			
	Formaldehyde	Acetaldehyde	Benzene	1-3, Butadiene
Sugar Beet RD Field-to-Wheels	1.03	0.30	0.92	0.18
Baseline ULSD Well-to-Wheels	0.38	0.13	1.07	0.13

Source: Solazyme

Carbon Intensity for GHG emissions was calculated for Soladiesel$_{RD}$ and compared to ULSD. Based on this analysis, Soladiesel$_{RD}$ (i.e., renewable diesel derived from algae oil produced with sugar beet feedstock) has approximately 30 percent lower GHG emissions than ULSD. The GHG emissions attributable to the sugar beet cultivation and processing constitute the largest GHG component of the Life Cycle Analysis. Thus, the GHG emissions could likely be reduced through higher utilization of renewable electricity for the sugar beet mill and algae oil production facility.

Economic Evaluation

Job Creation

An estimate of job creation, economic development, and increased state revenue was based on the current Solazyme model. Solazyme currently has approximately 250 employees worldwide and approximately 75 percent of the company's employees are based in California. The company expects to grow over the next three to five years and it also expects that the employee base in California will increase in this period. If this growth occurs at the anticipated pace, the increase in jobs may contribute to increases in state revenue and community economic development.

Commercialization of Technology

The feasibility of the proposed technology for reducing GHG emissions was achieved at pilot scale. This provides the basis for scaling up and proof of concept of the potential cost-effectiveness of the technology at a larger scale.

Project Performance

In Solazyme's initial proposal, the team estimated that algal derived renewable diesel made with sugar beet feedstock would deliver a GHG reduction of approximately 71 percent when compared to ULSD. After conducting the project, we found that the GHG reductions were approximately 30 percent. This GHG reduction was less than we expected and primarily due to the energy sources used in the sugar beet processing and the operation of the algae oil pilot plant. For the purposes of modeling, we assumed natural gas cogenerated steam and electricity for sugar beet processing, and natural gas derived steam and the California average grid electricity mix for the algae oil pilot plant. If renewable sources of energy could be used to power these operations, the GHG emissions would drop significantly.

There is no technology advancement required for vehicles, vessels, and equipment to use Solazyme's algal derived renewable diesel as it is a "drop in" fuel that is fully compatible with existing petroleum-based infrastructure — including pipelines and other forms of distribution, storage, retailing, and end-use vehicles. Advanced biofuels refined from Solazyme's algae oil can directly replace existing petroleum-based fuels. Solazyme's renewable diesel directly replaces D975 diesel, and has high Cetane number, which allows for more complete combustion. However, this project helped support the proof of concept that Solazyme's algal derived renewable diesel can be produced using sugar beet as a feedstock – a feedstock that is grown in California. This is important in establishing robustness in the diversity of feedstock available in California and subsequent diversity of biofuels that can displace petroleum-based fuels in the State.

CHAPTER 3: Design of Ethanol Plant for Algae Oil Production

Ethanol Plant Conversion Potential

This Sub-Chapter reviews the findings of our internal white paper and provides some guidance on how to design a modified corn ethanol plant for algae oil production.

The fermentation capacity of a dry mill corn ethanol plant is not compatible with the demands of algal fermentation. As shown in Table 1 in Sub-Chapter *2 Assessment of Corn Ethanol Unit Operations*, this unit operation is not suitable for an algae oil production process. Significant modifications to the corn ethanol plant fermenters would be required to make them viable for the algal fermentation process. That is, except in a severely capital constrained environment, and only after successful technical work around and subsequent yield losses could these fermentations be adapted.

Notwithstanding our conclusion that an idled dry mill corn ethanol plant would not be optimally suited for conversion into an algae oil production plant particularly due to the differences in the fermentation processes, we note that some equipment used in the corn ethanol plant could potentially be adapted and repurposed for a larger algae oil production facility. The evaporators used in corn ethanol production could likely be transferable to algae oil production because several types of evaporators could be used to concentrate the algal broth. Both the centrifuge and a hammer mill used in corn ethanol production could potentially be repurposed in a redesign for algae oil production in the oil extraction and refining steps. A corn ethanol distillation column and vacuum system would require modifications to suit the algae oil production process requirements but could be used as part of the oil refining process. Various types of driers used in corn ethanol plants are not necessarily transferable for use in algae oil production and a "case-by case" evaluation would be required.

While there is potential to use or repurpose some of the equipment found in a corn ethanol plant for producing algae oil, the overall improvement costs and loss of process effectiveness do not appear to make this type of plant conversion an economically viable model.

Commercialization of Technology

The feasibility of the proposed technology evaluated in this project for reducing GHG emissions was achieved at pilot scale. This provides the basis for scaling up and proof of concept of the potential cost-effectiveness of the technology at a larger scale. This project also helped support the proof of concept that Solazyme's algal derived renewable diesel can be produced using sugar beet as a feedstock – a feedstock that is grown in California. These project results are important data points in establishing robustness in the diversity of feedstock available in California and subsequent diversity of biofuels that can displace petroleum-based fuels in the State.

Successful Completion of the Project Objectives

This project demonstrates that co-location of an algae oil production facility with feedstocks is a viable idea. Future planners can adapt and take advantage of local synergies to create a local fuel supply that is independent of imports and creates a local economy. The proposed outcome of this grant has been successfully modeled; we have successfully built a pilot plant and made viable renewable feedstock capable of conversion to fuel, thus showing that commercialization of cleaner burning fuels is technologically possible today.

CHAPTER 4: Conclusions

The results of this grant proposal and award demonstrate the potential for algae oil based renewable diesel production. California produced feedstocks are fungible with our technology. Future projects to build on this work might include infrastructure build out at sites of feedstock production, co-locating the entire production process. This could increase the diversity of end markets for local farmers and result in a cleaner, local option for producing crude oil. We have demonstrated that funding the application of technologies that can be adapted to local environments while advancing clean energy policies can foster a viable alternative to fossil fuels.

To reiterate our earlier comments in this Report, the petroleum fuel reduction goals established under Assembly Bill 2076 (Shelley, Chapter 936, Statutes of 2000) aimed at reducing the State's petroleum dependency and the Low-Carbon Fuel Standard, developed in response to Executive Order S-1-07, that requires fuel suppliers and distributors to reduce the carbon intensity of their fuels by ten percent by 2020, will require the dramatic increase in the production of biofuels in California over the next decade. However, to meet the Low Carbon Fuel Standard, the production of advanced biofuels derived from dedicated energy feedstocks will be required as these fuels will have the low Carbon Intensity needed to achieve the ten percent reduction requirement. The traditional biofuel used in California has largely been corn-based ethanol blended into gasoline fuel. Biodiesel blends require a separate fuel delivery infrastructure because their characteristics prevent them from being completely fungible with petroleum diesel throughout the fuel delivery system.

Renewable diesels produced through hydrotreatment processes ASTM specifications for diesel fuel (ASTM D975)) would be completely fungible with the existing petroleum diesel distribution pathway. An opportunity exists for rapidly increasing renewable diesel production via algal fermentation.

GLOSSARY

AMERICAN SOCIETY FOR TESTING AND MATERIALS (ASTM)—An international standards organization that develops and publishes voluntary consensus technical standards for a wide range of materials, products, systems, and services.

CALIFORNIA AIR RESOURCES BOARD DIESEL STANDARD (CARB Fuel)–California regulated diesel fuel that limits sulfur content to fifteen parts per million.

CALIFORNIA ENERGY COMMISSION (CEC)—The state agency established by the Warren-Alquist State Energy Resources Conservation and Development Act in 1974 (Public Resources Code, Sections 25000 et seq.) responsible for energy policy. The CEC's five major areas of responsibilities are:

1. Forecasting future statewide energy needs.
2. Licensing power plants sufficient to meet those needs.
3. Promoting energy conservation and efficiency measures.
4. Developing renewable and alternative energy resources, including providing assistance to develop clean transportation fuels.
5. Planning for and directing state response to energy emergencies.

Funding for the CEC's activities comes from the Energy Resources Program Account, Federal Petroleum Violation Escrow Account, and other sources.

CARBON DIOXIDE (CO2)—A colorless, odorless, nonpoisonous gas that is a normal part of the air. Carbon dioxide is exhaled by humans and animals and is absorbed by green growing things and by the sea. CO2 is the greenhouse gas whose concentration is being most affected directly by human activities. CO2 also serves as the reference to compare all other greenhouse gases (see carbon dioxide equivalent).

FEDERAL TEST PROCEDURE (FTP)—A series of tests defined by the United States Environmental Protection Agency (U.S. EPA) to measure tailpipe emissions and fuel economy of passenger cars (excluding light trucks and heavy-duty vehicles).

GREENHOUSE GAS (GHG)—Any gas that absorbs infrared radiation in the atmosphere. Greenhouse gases include water vapor, carbon dioxide (CO2), methane (CH4), nitrous oxide (NOx), halogenated fluorocarbons (HCFCs), ozone (O3), perfluorinated carbons (PFCs), and hydrofluorocarbons (HFCs).

NATIONAL RENEWABLE ENERGY LABORATORY (NREL)—The United States' primary laboratory for renewable energy and energy efficiency research and development. NREL is the only Federal laboratory dedicated to the research, development, commercialization, and deployment of renewable energy and energy efficiency technologies. Located in Golden, Colorado.

NITROGEN (N, N2)—An essential element of life and a part of all plant and animal proteins. Nitrogen is commercially recovered from the air as ammonia, which is produced by combining nitrogen in the atmosphere with hydrogen from natural gas.

NITROGEN OXIDES (OXIDES OF NITROGEN, NOx)—A general term pertaining to compounds of nitric oxide (NO), nitrogen dioxide (NO_2), and other oxides of nitrogen. Nitrogen oxides are typically created during combustion processes and are major contributors to smog formation and acid deposition. NO_2 is a criteria air pollutant and may result in numerous adverse health effects.

PARTICULATE MATTER (PM)—Unburned fuel particles that form smoke or soot and stick to lung tissue when inhaled. A chief component of exhaust emissions from heavy-duty diesel engines.

SOUTHWEST RESEARCH INSTITUTE (SWRI)–An independent research and development institution that provide services to government and industrial clients in the field of transportation, biomedical, chemistry, defense, electronics, energy, and construction.[1]

SUPPLEMENTAL EMISSIONS TEST (SET)–A 13-mode steady-state engine dynamometer test, first introduced by the US EPA as part of the 1998 consent decrees with US heavy-duty engine manufacturers and then included in the 2007 emission standards for heavy-duty engines.[2]

ULTRA-LOW SULFUR DIESEL (ULSD)–EPA regulated diesel fuel for all on-road and off-road vehicles with sulfur content of only 15 parts per million.[3]

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[1] Southwest Research Institute webpage https://www.swri.org/who-we-are

[2] DieselNet Heavy-Duty Supplemental Emissions Test (SET) https://dieselnet.com/standards/cycles/set.php

[3] United States Environmental Protection Agency webpage https://www.epa.gov/

Appendix A:
National Renewable Energy Laboratory Report

Figure 4 shows the results of the National Renewable Energy Laboratory's fuel performance test on $Soladiesel_{RD}$.

Figure 4: NREL $Soladiesel_{RD}$. Fuel Performance Results

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Date: Friday, November 21, 2014

To: Helen Gibson, Solazyme

From: Robert McCormick, NREL

Jonathan Burton, NREL - ReFUEL Testing

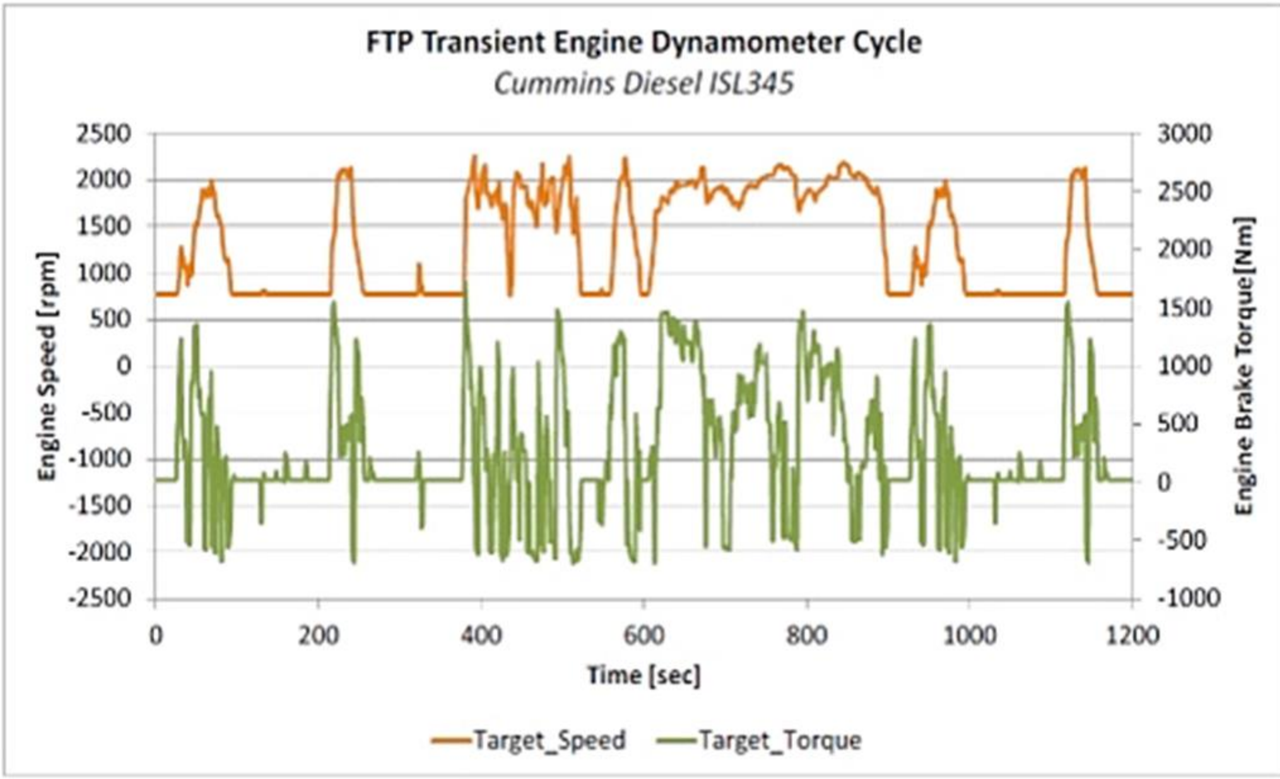
Subject 2014 $Soladiesel_{RD}$ Fuel Comparison Engine

The Renewable Fuels and Lubricants testing laboratory at NREL in Denver Colorado completed fuels performance testing for Solazyme on the $Soladiesel_{RD}$ fuel product against two other standard diesel fuels, Certification ULSD and CARB Reference diesel fuel.

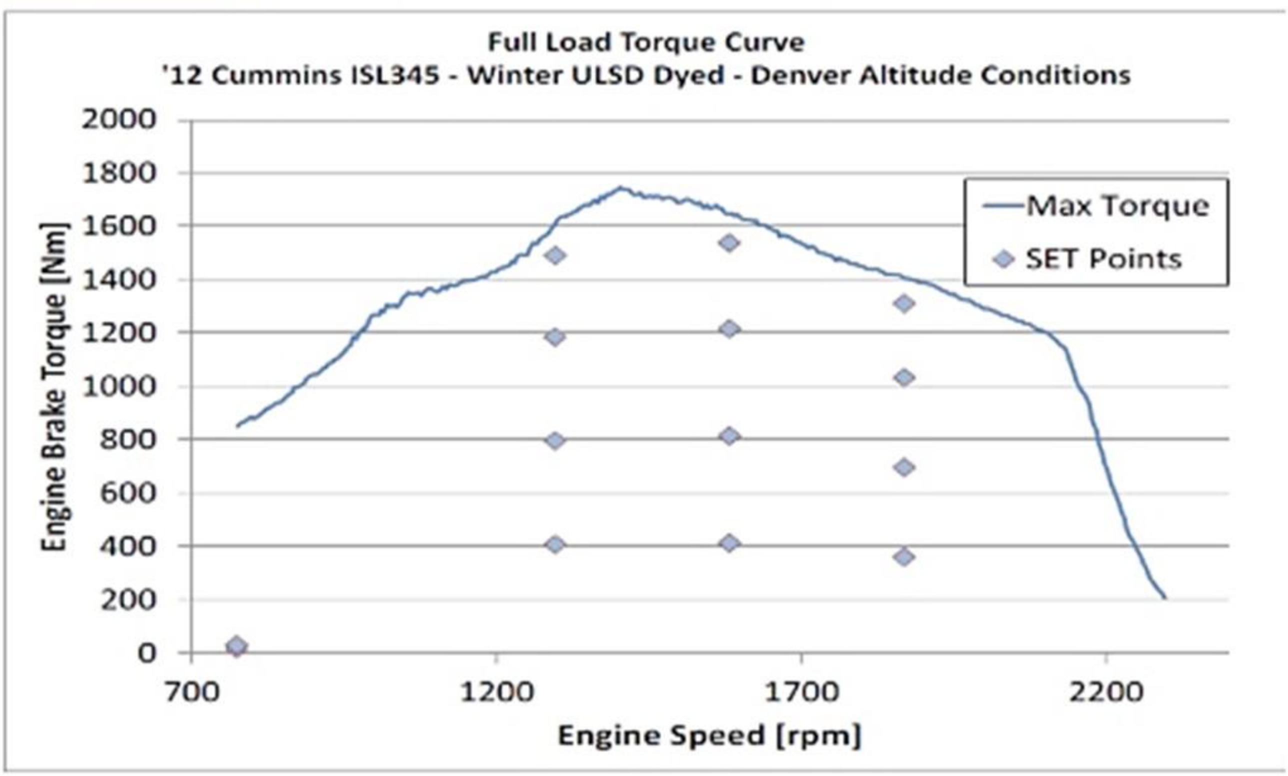
Testing Equipment

Testing was performed on a 2012 Cummins ISL 8.9L diesel engine. This engine uses common rail direct fuel injection, cooled EGR, an exhaust aftertreatment system consisting of a diesel oxidation catalyst, diesel particulate filter, and selective catalytic reduction, in that order of exhaust flow direction. The engine is rated at 345 horsepower at 1900 rpm and is certified to 0.33 g/bHP-hr for nitrogen oxide emissions. The engine is connected to a low inertia electric AC dynamometer with a rated loading capability of 600 HP. Engine intake air and exhaust dilution air were conditioned to

20°C, 855 mbar (approximate Denver ambient pressure), a dewpoint of 12°C, and was High Efficiency Filter Air filtered for all tests. The exhaust was conditioned in a full-flow dilution tunnel and flowrate was measured with a constant volume sampling system.



The second engine drive cycle was the SET ramped modal cycle. This cycle consists of 13 steady state points as shown in the included chart with 20-second-long ramps in between each mode change. The SET is a total of 2400 seconds long. More information on the Supplemental Emissions Test cycle at http://www.dieselnet.com/standards/cycles/set.php.



Results

Fuel performance test results are shown on the next three pages with charts and tables. The data shown in the charts are the average points for each fuel-test cycle and the error bars are one standard deviation. The student's T-test was performed on the data in the table to determine statistical significance between the fuel's performance based on a threshold p-value of 0.05.

For the FTP cycles it can be seen that Soladiesel$_{RD}$ had lower Brake Specific Fuel Consumption, engine out PM, and engine out NO_x, all with statistical confidence. Engine out PM was drastically lower at nearly one-half that of the Cert fuel and approximately 40 percent lower than the CARB fuel PM results. There was no statistical difference in tailpipe out NO_x between the fuels, though all of the values are lower than the certified standard for this engine. The low tailpipe NO_x results are a result of the exhaust selective catalytic reduction system.

For the SET cycles it can be seen that Soladiesel$_{RD}$ had lower Brake Specific Fuel Consumption, and engine out PM, both with strong statistical confidence. PM was approximately half of that for the CARB fuel and was 60 percent lower than the Cert fuel. Soladiesel$_{RD}$ had 4 percent better fuel consumption than the Cert fuel and 2.6 percent better than the CARB fuel. Soladiesel$_{RD}$ also had lower engine out NO_x than the Cert fuel but was not significantly different than the CARB fuel results. Tailpipe out NO_x was nearly the same for all fuels and was below the certification level of the engine for the SET test cycle.

The tables show the NO_2 to NOx ratio for engine out emissions. This number is significant for DPF PM oxidation and selective catalytic reduction processes. This ratio was nearly the same for all fuels. Though tailpipe out CO and THC were measured, the diesel oxidation catalyst efficiency is high enough during the selected test cycles that these emissions were effectively zero for all test runs.

Figure: FTP Cycle Test Results

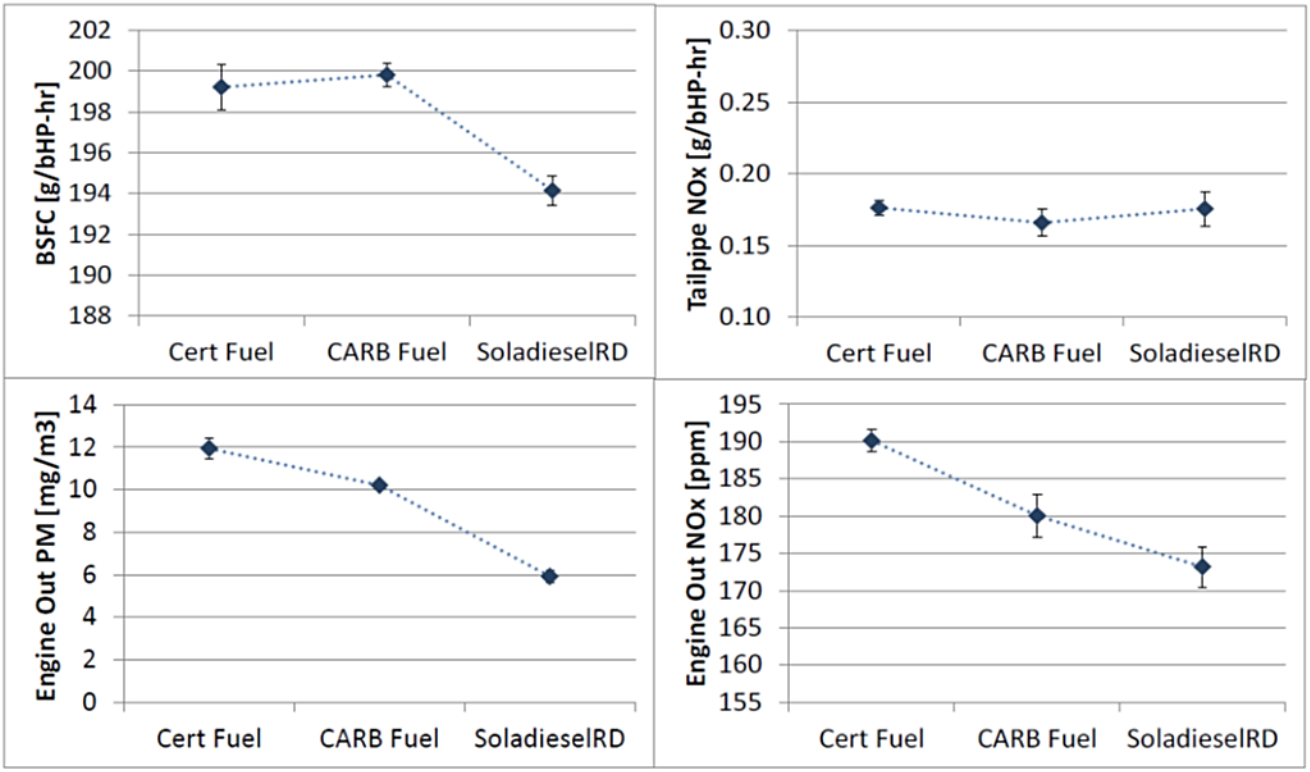


Figure: SET Cycle Test Results

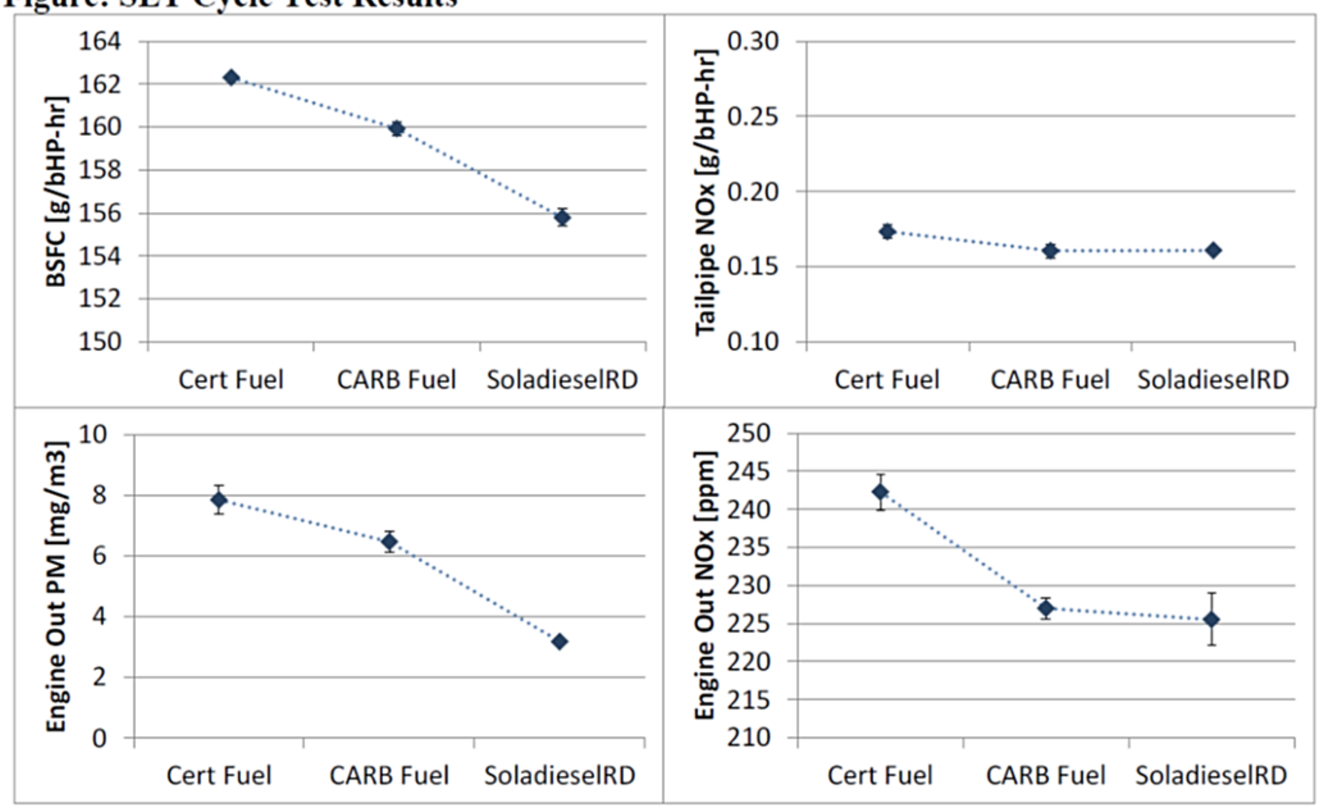


Table: FTP Test Cycle Data

	BSFC	Tailpipe NO_x	Tailpipe CO_2	Engine Out NO_x	Engine Out NO_2/NO_x	Engine Out PM
	(g/bHP-hr)	(g/bHP-hr)	(g/bHP-hr)	(ppm)	(ratio of ppm/ppm)	(mg/m^3)
Cert Fuel Run 1	198.819	0.177	673.112	N/A	N/A	12.574
Cert Fuel Run 2	200.726	0.182	674.174	188.529	0.235	11.432
Cert Fuel Run 3	199.171	0.178	675.560	191.222	0.235	11.807
Cert Fuel Run 4	198.108	0.169	672.127	190.629	0.234	11.920
Avg	199.206	0.176	673.743	190.127	0.235	11.933
Std Dev	1.106	0.005	1.472	1.415	0.001	0.475
CARB Fuel Run 1	200.575	0.182	668.647	176.354	0.233	9.923
CARB Fuel Run 2	200.131	0.162	667.980	178.045	0.231	10.187
CARB Fuel Run 3	198.997	0.162	666.232	182.806	0.223	10.426
CARB Fuel Run 4	199.748	0.158	668.059	182.725	0.221	10.164
CARB Fuel Run 5	199.606	0.165	666.645	180.344	0.221	10.304
Avg	199.811	0.166	667.512	180.055	0.226	10.201
Std Dev	0.591	0.009	1.024	2.851	0.006	0.187
$Soladiesel_{RD}$ Run 1	193.761	0.189	637.827	174.176	0.229	5.792
$Soladiesel_{RD}$ Run 2	193.728	0.168	640.901	170.095	0.227	6.245
$Soladiesel_{RD}$ Run 3	194.952	0.169	642.291	175.269	0.215	5.708
Avg	194.147	0.176	640.340	173.180	0.223	5.915
Std Dev	0.697	0.012	2.284	2.727	0.008	0.289

Table: SET Test Cycle Data

	BSFC	Tailpipe NO_x	Tailpipe CO_2	Engine Out NO_x	Engine Out NO_2/NO_x	Engine Out PM
	(g/bHP-hr)	(g/bHP-hr)	(g/bHP-hr)	(ppm)	(ratio of ppm/ppm)	(mg/m^3)
Cert Fuel Run 1	162.235	0.172	543.487	239.852	0.115	8.389
Cert Fuel Run 2	162.221	0.169	543.991	244.472	0.116	7.510
Cert Fuel Run 3	162.441	0.179	544.620	242.531	0.124	7.631
Avg	162.299	0.173	544.033	242.285	0.119	7.844
Std Dev	0.124	0.005	0.567	2.320	0.005	0.477
CARB Fuel Run 1	160.257	0.165	532.618	227.692	0.108	6.833
CARB Fuel Run 2	159.896	0.156	530.499	225.397	0.126	6.436
CARB Fuel Run 3	159.626	0.161	530.223	227.930	0.131	6.123
Avg	159.926	0.161	531.113	227.006	0.122	6.464
Std Dev	0.317	0.005	1.311	1.399	0.012	0.356
$Soladiesel_{RD}$ Run 1	155.763	0.161	511.077	221.658	0.114	3.204
$Soladiesel_{RD}$ Run 2	155.392	0.161	510.365	226.870	0.119	3.141
$Soladiesel_{RD}$ Run 3	156.181	0.161	511.001	228.058	0.121	3.185
Avg	155.779	0.161	510.814	225.529	0.118	3.177
Std Dev	0.395	0.000	0.391	3.405	0.003	0.033

Source: Solazyme