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FINAL PROJECT REPORT

Dairy Waste-to-Bioenergy via Integration of Concentrating Solar Power and High Temperature Conversion Process

Gavin Newsom, Governor
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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solutions, foster regional innovation and bring ideas from the lab to the marketplace. The CEC and the state's three largest investor-owned utilities—Pacific Gas and Electric Company, San Diego Gas & Electric Company and Southern California Edison Company—were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

The CEC is committed to ensuring public participation in its research and development programs that promote greater reliability, lower costs, and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean, conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

Dairy Waste-to-Bioenergy via Integration of Concentrating Solar Power and High Temperature Conversion Process is the final report for the Dairy Waste-to-Bioenergy via the Integration of Concentrating Solar Power and High Temperature Conversion Process project (EPC-14-047) conducted by Southern California Gas Company. The information from this project contributes to the Energy Research and Development Division's EPIC Program.

For more information about the Energy Research and Development Division, please visit the [CEC's research website](http://www.energy.ca.gov/research/) (www.energy.ca.gov/research/) or contact the CEC at 916-327-1551.

ABSTRACT

Hyperlight Energy is developing a novel concentrated solar power reflector and receiver system called Hylux™ that can generate electricity or provide process heat. The reflector system consists of a water-borne, extruded plastic tube structure upon which flat glass mirror slats are mounted. Simple links connect arrays of these tubes and control the alignment of the mirrors and track the sun throughout the day. Using low-cost, long-life plastic, and minimizing the use of steel and concrete, significant cost savings can be achieved. This project sought to integrate concentrated solar power and Genifuel Corporation's hydrothermal processing system for the first time to convert wet biomass, such as dairy manure, into renewable crude oil and natural gas, and to move the two technologies through the final stages of development in preparation for commercial deployment. Initial testing of a Hylux™ pilot production line and a reflector array was conducted at Hyperlight's facility in Lakeside, California, followed by limited on-sun testing of an array at the company's Brawley, California test site. Subsequently a half-acre array, consisting of the receiver subsystem designed and built in this project, was manufactured, installed, and tested in Brawley. Thermal efficiency achieved in this project testing has been 60 percent to 85 percent. Issues in manufacturing, logistics, and installation were identified. Design improvements to make the manufacturing and installation processes simpler and more robust have been identified and planned for the future. Importantly, the level of performance so far supports economical installation at customer sites under existing commercial grant programs for both the Hylux™ and Genifuel hydrothermal processing systems. However, it is not clear that a significant market exists at present for integrated concentrated solar power and hydrothermal processing systems.

Keywords: Concentrated solar power, linear fresnel reflector, hydrothermal processing, liquefaction, catalytic, gasification

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EXECUTIVE SUMMARY

Introduction

The electricity sector in California is faced with an unprecedented challenge: to have 100 percent of total retail sales come from renewable energy and zero-carbon resources by December 31, 2045 (Senate Bill 100, Chapter 312, Statutes of 2018). This ambitious goal will boost the state's energy self-reliance, benefit the environment, and generate jobs. To achieve these benefits, with the highest benefit to ratepayers, emerging technologies are needed that can cost-effectively capture and store renewable energy.

Hyperlight Energy and Genifuel Corporation are pursuing technologies to meet this challenge in two important ways. First, Hyperlight Energy is developing Hylux™, a novel, low-cost concentrated solar power (CSP) technology. CSP uses mirrors or lenses to concentrate sunlight onto a receiver and convert light energy into heat; the heat is then used to create steam to drive a turbine or used to provide industrial process heat; systems can include thermal energy storage to allow the system to generate electricity during cloudy periods or between sunset and sunrise. The Hyperlight technology replaces expensive concrete and steel typically used to mount and aim glass mirrors in other CSP technologies with low-cost materials and production techniques. Hylux™ uses linear Fresnel reflector (LFR) geometry, composed of a series of flat mirror facets arrayed side by side, similar to what a parabolic reflector would look like if it were cut into flat slats and arrayed flat on the ground. Each mirror facet can be mounted on an identical, low cost plastic support, which lends itself to low cost, mass manufacturing. In contrast to solar photovoltaic technology, which converts sunlight directly into electricity that must be used immediately or stored in expensive batteries, CSP technology converts sunlight into heat that can be stored in low-cost materials and used in other industrial processes to convert waste products into chemicals that can also store energy. Second, Genifuel is developing hydrothermal liquefaction and catalytic hydrothermal gasification (also called hydrothermal processing, or HTP), which uses heat energy to convert wet biomass—such as dairy manure—into renewable crude oil and natural gas. Renewable natural gas can be stored at low cost and large scale in ways that batteries will never be able to achieve. This project not only advances each of these technologies individually, but linked them together for the first time, using solar process heat to drive hydrothermal processing.

Despite their high cost, steel and concrete construction are currently the dominant paradigm in CSP. Using alternative construction materials to mount and aim glass mirrors could affect accuracy and durability of the technology; for example, one cannot simply replace metal components with plastic because plastic would not be strong enough, long enough, to be cost effective. Hyperlight Energy has reinvented CSP by replacing the typical CSP truss support structures with extruded tube components that are well suited for plastics. Hyperlight Energy proved the optical accuracy and durability of its extruded plastic components in a previous project funded by the Energy Commission. Nevertheless, multiple technology development gaps remain, one of which was addressed in this project.

The main gap is the quality of the receiver. Previous work on CSP technology focused on the optical accuracy of the reflector system, with less effort dedicated to the receiver. However, thermal efficiency in CSP depends in large part on the receiver system, requiring development of an optimized receiver for the Hylux™ platform. Genifuel HTP operates at 360° C. Solar

process heat delivered at lower than that temperature necessitates a trim heater in the HTP system to raise the feedstock to the required temperature. For this reason the fraction of solar energy input into the process is maximized by increasing temperature. Moreover, when considering a receiver, the primary way to increase temperature is to reduce thermal loss. This strategy also improves energy capture, which improves overall system economics. For this reason, irrespective of integration with HTP, it makes sense for Hyperlight Energy to upgrade its receiver.

This project focused on the receiver performance gap to facilitate integration with the Genifuel HTP system. The project is closely related to another EPIC project, EPC-16-016, which has a heavier emphasis on addressing the primary reflector system, because a CSP receiver cannot function without a reflector and vice versa.

CSP as a category is not well suited to small-scale deployments and requires considerable capital to test and deploy new technologies. When investing large amounts of capital in energy projects, market players prefer the lowest technology risk possible. Established CSP technologies based on steel and concrete are therefore preferred and new technologies are difficult to fund. Similarly, high-temperature and pressure-processing technologies, such as HTP, require higher-cost components to handle process flows safely. This means projects must be larger in scale to be cost effective, triggering the need for higher capital investment, which again makes funding difficult given market preference for lower-risk existing technologies.

Project Purpose

The purpose of this project was to dramatically improve the thermal efficiency of Hyperlight Energy's CSP technology and integrate HTP with CSP for the first time. Prior to this project, Hyperlight Energy had not deployed a system capable of delivering heat transfer fluid (HTF) at temperatures above 200° C. An increase in HTF temperature closer to the operating temperature of HTP (360° C) means an increase in the fraction of heat energy input into the process from CSP (as contrasted with heat input from the system trim heater). This is a benefit because it increases the renewable component of energy in the end products. The project was also intended to encourage use of this technology combination throughout California to convert cattle manure into renewable natural gas using solar energy, and to store it in low-cost, large-scale storage in ways that batteries cannot. This project also helps advance the individual CSP and HTP technologies in their own right, bringing down the costs for a wide range of individual applications.

The goals and objectives of this project from the original statement of work were to:

- Integrate CSP and HTP into a single system.
- Process dairy manure into renewable natural gas and bio-crude.
- Determine the operating conditions that produce the best yields of renewable natural gas and biocrude.
- Determine the best strategy for storing diurnal CSP heat for the HTP continuous system.
- Better understand the economics of integrated CSP/HTP systems located at dairy farms and determine the best mix of renewable natural gas to biocrude for maximum economic viability.

Project Approach

The project team was composed of a prime contractor, Southern California Gas Company (SoCalGas), and four subcontractors: Hyperlight Energy, Genifuel Corporation, the National Renewable Energy Laboratory, and Energy Solutions. Hyperlight Energy is an emerging technology company that is developing the Hylux™ technology. Genifuel Corporation is an emerging technology company that is developing its HTP technology. The National Renewable Energy Laboratory, a globally recognized leader in renewable energy research and development, provided design support and analysis. Energy Solutions is a consultancy that specializes in energy research and analysis as well as energy efficiency program design and implementation.

The project team designed and fabricated an improved CSP receiver subsystem, a half-acre CSP array in Brawley, California, and a mobile containerized HTP system. Testing of intermediate scale systems and subsystems was conducted in Lakeside and Carson, with full scale testing at San Diego State University's satellite campus in Brawley.

As described above, a technology development gap was the performance of the CSP receiver. Fortunately, one of the major components of a linear Fresnel reflector receiver, the heat collection element, is a commercially available, off-the-shelf component. What remained was for the project team to select the right heat collection element and implement a new secondary reflector design to closely match the configuration of the primary reflector. The National Renewable Energy Laboratory was instrumental in achieving this task. An additional non-technical barrier was simply sourcing the heat collection elements from the manufacturer, who required an order larger than Hyperlight Energy, as an emerging technology provider, was able to place. The solution was to "piggy-back" on other, larger orders from other global players.

One of the main challenges in this project was the design, procurement, and construction of the heat transfer fluid handling subsystem. While not an area of technical innovation, this element was necessary to be able to test other aspects of the system. To address the challenges around the heat transfer fluid system, the team needed to modify the schedule and scope of the project to achieve project goals and objectives.

From the CSP perspective, this project was mainly concerned with the performance of the receiver subsystem. The primary means of addressing this issue involved two main efforts, the switch to commercially available off-the-shelf heat collection elements and a custom designed secondary reflector component.

The project also benefited from the formation of a technical advisory committee to provide technical and market feedback for the idea of producing biocrude from cow manure.

Project Results

This project met two key goals and objectives. First, the project integrated CSP and HTP technologies for the first time. Second, the analysis of the economics of CSP integrated with HTP at dairies allows better understanding of this integration. A major conclusion is that from a techno-economic standpoint, the cost effectiveness of an integrated CSP/HTP project will positively correlate with project size; that is, larger projects will be more cost effective because

of fixed costs associated with the heat transfer fluid handling subsystem and economies of scale in the HTP hardware.

In terms of operation of the integrated system, issues that affected the schedule limited the set of operating conditions and feedstocks that could be tested. Despite that limitation, the experience gained and knowledge gained in this project will be valuable going forward.

Although the integrated system still needs to be operated in the future in more configurations and with additional feedstocks, the individual parts of the system, specifically Hylux™ CSP and the Genifuel HTP, were operated independently. Specific, limited operating configurations were used that demonstrate the successful completion of project goals and objectives. In particular, project results for Hylux™ were promising enough that a commercial customer proposed to install the CSP technology at one of its facilities as part of the Food Production Investment Program administered by the CEC that provides grants to help food processors save energy and money while reducing greenhouse gas emissions. The technology would be installed as a stand-alone CSP system, not an integrated CSP/HTP system.

While Hyperlight Energy plans to fully implement the technical fixes developed during this project on limited configurations of the Brawley system and continue data collection at the site, there is no additional research needed prior to commercial deployment of the technology.

Technology/Knowledge Transfer

Hyperlight Energy's main focus in technology transfer is commercialization. The beachhead market for Hyperlight Energy's Hylux™ is the food processing industry through the Food Production Investment Program. This program is a critical component to overcome obstacles to commercialization of emerging technologies, including access to capital and risk aversion. Hyperlight developed multiple customer leads during this project, including food processors in the San Joaquin Valley, one of whom has submitted a grant application to deploy Hylux™ at one of their facilities.

Looking beyond the beachhead market, mid-term targets for the technology include enhanced oil recovery operations, and long-term targets include hybridization with geothermal power plants and stand-alone power plants. Enhanced oil recovery and power production are both very large markets. Hyperlight Energy has several customer prospects, mostly in the San Joaquin Valley, and is actively pursuing these opportunities through direct outreach. The hope is to establish first customer deployment in Hyperlight's beachhead market effort then follow a path of increasing scale and decreasing cost as commercialization continues.

For Genifuel, commercialization is also proceeding with a recent grant win from the United States Department of Energy to deploy a large HTP system in the San Francisco Bay Area to process municipal waste. Municipal sewage waste is the beachhead market for Genifuel, with other wet biomass feedstocks as mid- and long-term targets.

A technical advisory committee provided reactions and input for the technical development path to the technical team. In addition, technology transfer has advanced through public reports, university sponsored conferences, operator training, technical training, customer development, and safety training.

Benefits to California

Lowering the cost of CSP and increasing the options for storing renewable energy in something other than batteries will help enable the success of SB 100, and aid the state's move to 100 percent renewable and zero-carbon electricity by 2045.

Benefits of meeting the 2045 clean electricity goals include: reducing emissions of greenhouse gases associated with electricity generation, helping the state meet its climate change goals, reducing air pollution in the state and improving air quality, and decreasing reliance on fossil fuels for energy production.

Importantly, Hylux™ is also on track to reach cost parity with natural gas as it scales up in deployments. Lowering the cost of renewable, zero-carbon energy is a huge benefit to California as it will increase the speed of reduction of California's greenhouse gas emissions and fossil natural gas consumption.

Further, CSP will be an important contributor to reaching the state's goal to have 100 percent of total retail sales of electricity come from zero-carbon resources because of inherent cost advantages of low cost thermal energy storage available to CSP but unavailable to other types of renewables.

In addition to the long-term environmental benefits to California, this project also generated short- and long-term economic benefits in the form of jobs. The project generated 9 jobs during execution, and has led to projects that will lead to 10 full time jobs in California, with far greater potential with continued development. In conjunction with the other EPIC project related to this technology, Hyperlight Energy developed methods to produce many of the primary components of the CSP system locally, which will lead to local manufacturing jobs as project components are fabricated. Furthermore, at present all planned Hylux™ installations are in California, leading to substantial additional employment for the installation of the various projects.

Although the project at San Diego State University's satellite campus in Brawley is not a commercial project and will not lead to energy savings, it did lead directly to a commercial project win that will result in 18,000 million British thermal units of thermal energy generated per year, offsetting approximately 1,800 tons of carbon dioxide emissions per year.

Genifuel's technology has a similar suite of benefits to offer. HTP helps reduce a significant waste stream manure into an asset: renewable natural gas and biocrude. This displaces petroleum fuels, and thus reduces emissions from the transportation sector, which is directly responsible for 40% of the state's GHG emissions.

By advancing CSP and HTP, this project should lead to greater awareness of additional energy storage options beyond electric batteries, further supporting the achievement of 100 percent clean electricity in California. The next step for these technologies is commercialization in their beachhead markets.

CHAPTER 1: Introduction

Concentrating Solar Power System

Background

Hyperlight Energy was funded under California Energy Commission's (CEC) Electric Program Investment Charge (EPIC) program to develop a low-cost concentrated solar power (CSP) technology. To achieve this objective, Hyperlight Energy developed an advanced linear Fresnel reflector (LFR) collector design (Figure 1) based on the use of plastic and water as structural materials.

Imitating the strengths of recent low-cost photovoltaic deployments, Hyperlight focused its plant design on a scale that can be installed rapidly and deployed cost-effectively with minimal resources.

The purpose of this project was to improve the performance of the Hyperlight receiver, both optically and thermally, and to integrate and demonstrate Hylux™ with Genifuel's hydrothermal processing (HTP) technology, discussed later in this chapter. The hardware developed in this project is interrelated; for example, the receiver cannot function without the reflector, and vice versa. As a result, this report also discusses a companion Hyperlight project funded under the EPIC Program that is focused on the primary Hylux™ reflector array.¹

Figure 1: Hyperlight Prototype 2014-2016



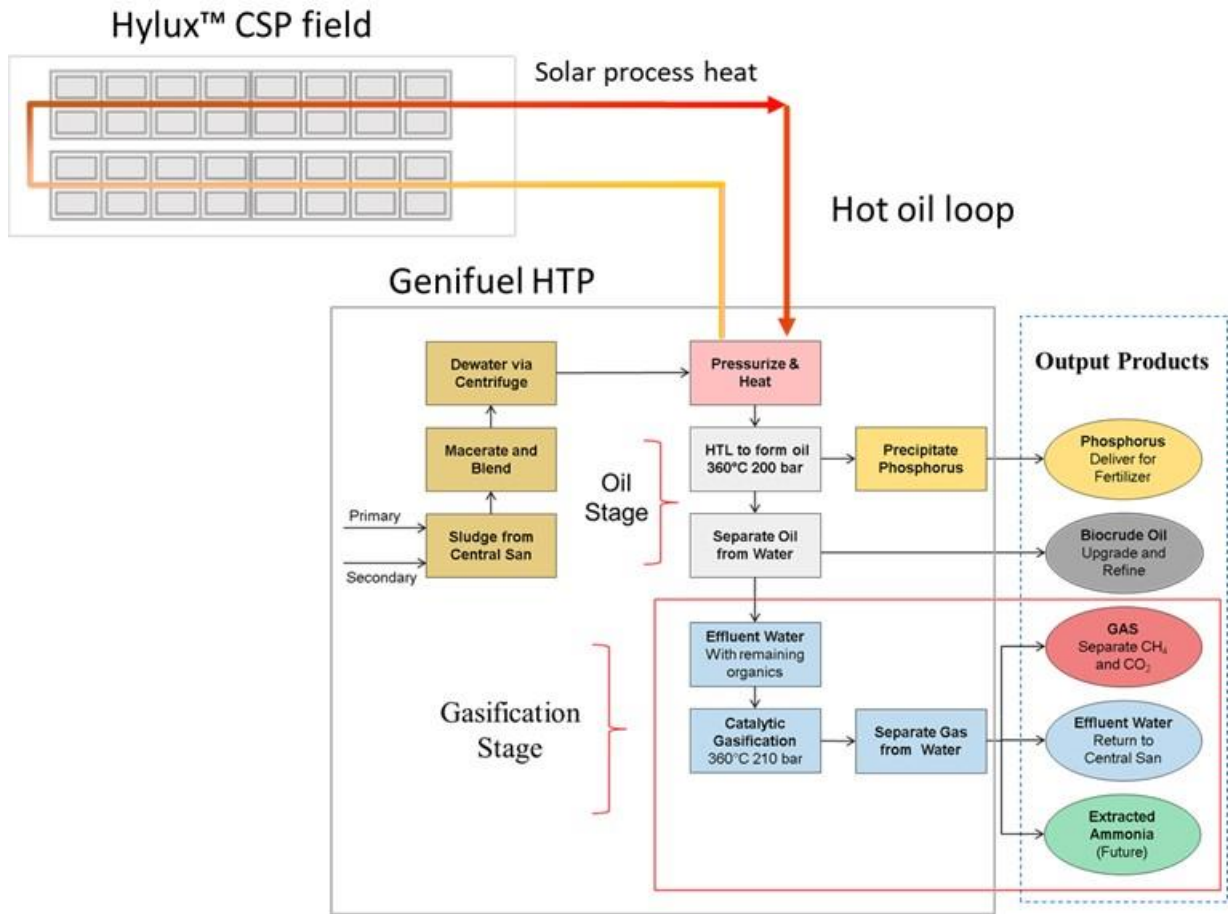
Hyperlight Energy's first generation concentrating solar power plant in Brawley, California.

Source: Hyperlight Energy

The pieces of this project fit together as in Figure 2. Thermal energy, in the form of hot oil, is circulated from the Hylux™ solar field to an inlet into the Genifuel HTP system. A heat exchanger is used to transfer heat to the feedstock and then the oil is circulated back to the solar field to be heated again.

¹ "Commercializing a Disruptively Low Cost Solar Collector," agreement number EPC-16-016.

Figure 2: Project Configuration



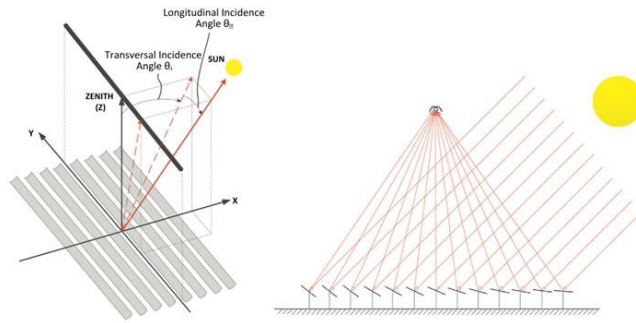
Source: Hyperlight Energy

Technology Gaps

Prior research funded by the Energy Commission to demonstrate the Hyperlight technology showed that extruded plastic pipe could achieve and maintain the optical accuracy needed for CSP.² As shown in the stylized diagram of linear Fresnel geometry (Figure 3), the majority of an LFR solar field consists of reflectors which aim the sun at the receiver. Consequently, the reflectors are the largest area of potential cost reduction; one of the largest areas for performance improvement, however, is the thermal performance of the receiver subsystem.

² California Energy Commission factsheet, "Combined Power's Hyperlight™ – A New Utility-Scale Concentrated Solar Power Technology," https://ww2.energy.ca.gov/publications/displayOneReport_cms.php?pubNum=CEC-500-2013-FS-003.

Figure 3: Line Drawing of Linear Fresnel Optics



Ray-tracing diagram showing the fundamental optics of a linear Fresnel reflector concentrating solar power system.

Source: National Renewable Energy Laboratory

Thermal Performance Gap

The thermal performance gap exists because previous work on this technology focused on the ability of the reflector system to hit a receiver. Almost no budget or schedule was available for receiver development. Consequently, almost no effort was spent on the effectiveness of the receiver in absorbing and converting light into usable energy. However, improvements in the performance of the receiver component can have a big effect on overall system performance.

One way to improve receiver performance is to minimize optical loss, sources of which are shown in Figure 4.

Figure 4: Optical Loss of Hylux™ System

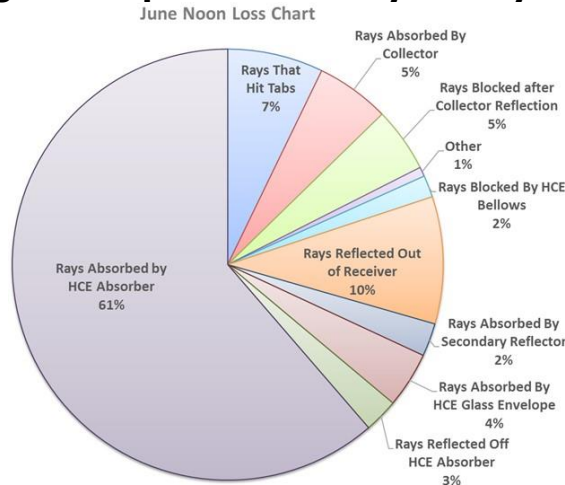


Chart shows the termination point of light incident on the primary collector by percent.

Source: Hyperlight Energy

Significant design effort was necessary to optimize the Hylux™ receiver subsystem. Another factor affecting performance relates to the Genifuel HTP system. The system operates at 360° C, if the hot oil supplied to it from the CSP field is for example 200° C, then the system’s internal, electrically powered trim heater is used to raise the feedstock to the operating temperature. This can represent a significant amount of energy, which would not be renewable energy input into the system. The amount of solar energy into the system is thus increased if the operating temperature of the CSP field is raised closer to 360° C. The primary

way to increase the operating temperature of the receiver (and the heat transfer fluid in it) is to reduce thermal loss. This strategy also improves energy capture, which has the additional benefit of improving economics.

Hydrothermal Processing System

Background

HTP technology was developed by the United States Department of Energy (USDOE) beginning in the 1970s, primarily at the Pacific Northwest National Laboratory (PNNL) using bench-scale and engineering-scale systems. In 2008, PNNL partnered with Genifuel Corporation to commercialize the HTP technology. The partners have won several awards including an R&D 100 Award in 2015 and a Federal Laboratory Consortium Award. The partners have also produced a system that generates biocrude (crude oil produced from organic feedstocks) from algae, with more than 2,000 liters of cumulative oil production. Also, in 2014 a research project sponsored by the Water Environment Research Foundation, USDOE, and United States Environmental Protection Agency (USEPA) demonstrated that HTP can convert wastewater sludge into biocrude and renewable natural gas (RNG) effectively and as predicted. The project that is the subject of this report builds on these and other prior efforts to advance the technology into early stage commercialization.

Technology

HTP uses temperature (350°C to 360°C), pressure (200-210 bar), and water in a continuous process that converts organic material into biocrude oil and natural gas, from a wide variety of feedstocks. In addition to wastewater solids, more than 100 different types of organic materials have been successfully tested and found to be viable feedstocks for HTP. The HTP conversion process is similar to the formation of fossil fuels, and typically converts between 40 percent and 50 percent of the dry mass of feedstock into biocrude, with another 20 percent to 30 percent converted to RNG (Figure 5).

Figure 5: Hydrothermal Processing Equipment



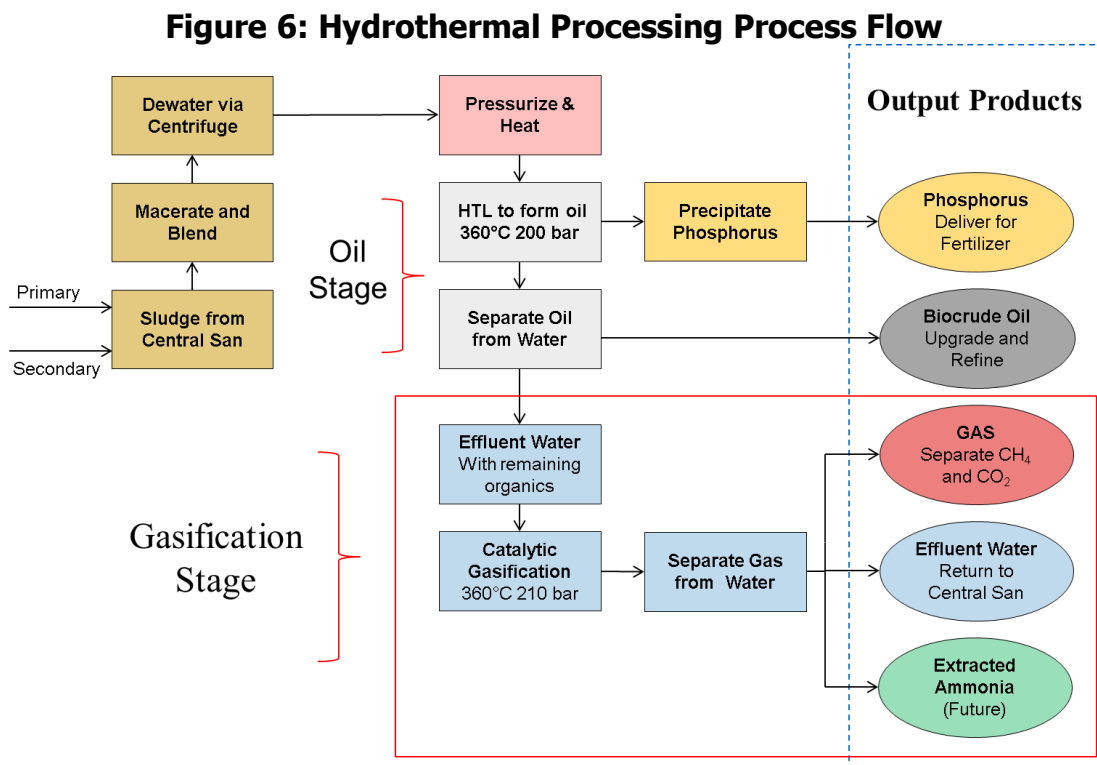
Source: Genifuel Corporation

The HTP portion of the Hyperlight project will produce both oil and gas. The biocrude oil is similar but not identical to fossil crude oil. It can be converted to finished fuels using conventional upgrading, followed by co-processing with petroleum in an existing refinery or other methods of conversion to finished fuels. The gas formed by the gasification section is a mix of methane and carbon dioxide in approximately a 65/45 ratio. The gas can be used directly, or upgraded to pipeline quality by removing carbon dioxide using a proven, fully commercial technology. The methane can then be injected as RNG into a natural gas pipeline.

In this project, the methane will not be injected into a pipeline because the gas volume is relatively small. Figure 6 shows a diagram of the HTP system, including primary inputs and outputs. It is also possible to configure the HTP system to produce only gas in the event that biocrude is difficult for a utility to handle; in this case, HTP would produce approximately 80 percent more gas than would digesters.

First Pilot Hydrothermal Processing System Installed in the Field

The largest HTP system currently in operation processes algae into biocrude and methane. The system was built for Reliance Industries Ltd. (RIL), which is one of the largest companies in India. RIL owns and operates natural gas production facilities as well as the Jamnagar Refinery that processes 1.2 million barrels of fossil crude oil per day. RIL was interested in the possibility of producing a biogenic substitute for both oil and gas to address growing concerns about fossil fuel emissions. The system is currently running in continuous operation processing algae (Figure 7).



Source: Genifuel Corporation

Figure 7: Operational Hydrothermal Processing System



Operational system in use by Reliance Industries Ltd.

Source: Genifuel Corporation

CHAPTER 2:

Project Approach

Building on the prior successful demonstration of the optical accuracy and robustness of HyLux™, this project intended to integrate CSP and HTP for the first time. Upgrading the receiver of HyLux™ was a focus of this project to maximize performance of the integrated system.

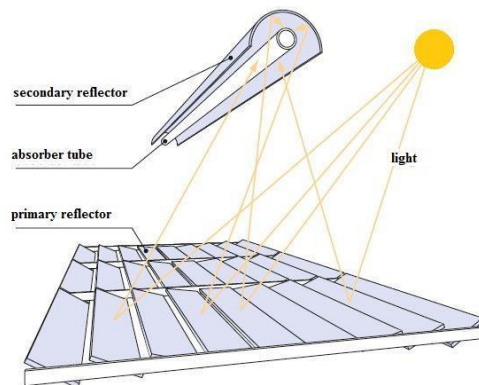
This chapter discusses the following steps in the project:

- Receiver design: focused on the design of the upgraded receiver subsystem.
- Balance of plant design: focused on the design of the heat transfer fluid subsystem.
- Third party procurement: procured equipment and supplies necessary to construct a half-acre system.
- Commissioning: testing, fine tuning and then operation of the system.
- Integration: integration with Genifuel HTP.

Receiver Design

The prototype system previously demonstrated³ focused on the reflector subsystem and not the receiver, which was not designed as a high-performance subsystem. In most LFR systems, there is an array of flat mirrors, the primary reflectors, which reflect sunlight onto a target, the receiver (Figure 8).

Figure 8: Traditional Linear Fresnel Reflector Layout



Source: Andreas Poullikkas

The receiver is generally composed of a secondary reflector and a heat collection element (HCE). There is a need for a secondary reflector because the image the primary reflectors put on the receiver is generally wider than commercially available off the shelf HCEs, and it is necessary to further concentrate this image down to the width of the HCE. In the prototype

³ California Energy Commission factsheet, "Combined Power's Hyperlight™ – A New Utility-Scale Concentrated Solar Power Technology," https://ww2.energy.ca.gov/publications/displayOneReport_cms.php?pubNum=CEC-500-2013-FS-003.

system, the secondary reflector had large losses and the HCEs were very poorly insulated. These two factors led to significant optical error from the secondary reflector and considerable thermal loss, which limited the upper operating temperature and thermal efficiency of the system. Although the receiver fit within the project budget for the prototype, it was not suitable for commercial applications.

This project's intent was to design and implement a high-performance receiver subsystem. As shown in Figure 8, the receiver has two main components: the absorber tube and the secondary reflector. High temperature and high efficiency were the goals. For the absorber tube, the project team selected commercially available off-the-shelf HCE technology (Figure 9) was selected.

Figure 9: Heat Collection Element



Source: Schott Solar

Commercially available off-the-shelf HCEs employ a vacuum envelope and a spectrally selective coating that results in low thermal loss. Although HCEs of this design are globally available, they are more expensive than the prototype system's receiver and difficult to acquire in small quantities.

Besides thermal loss, there is optical loss—specifically, rays missing the HCE. This is addressed by adding a curved mirror secondary reflector to the design (Figure 8). The time and cost associated with designing and sourcing this type of component was the obstacle in the development of the prototype system. There are few global suppliers that make curved glass mirrors, and those that do prefer large order sizes. The current project was specifically proposed with sufficient budget and schedule to succeed in this process.

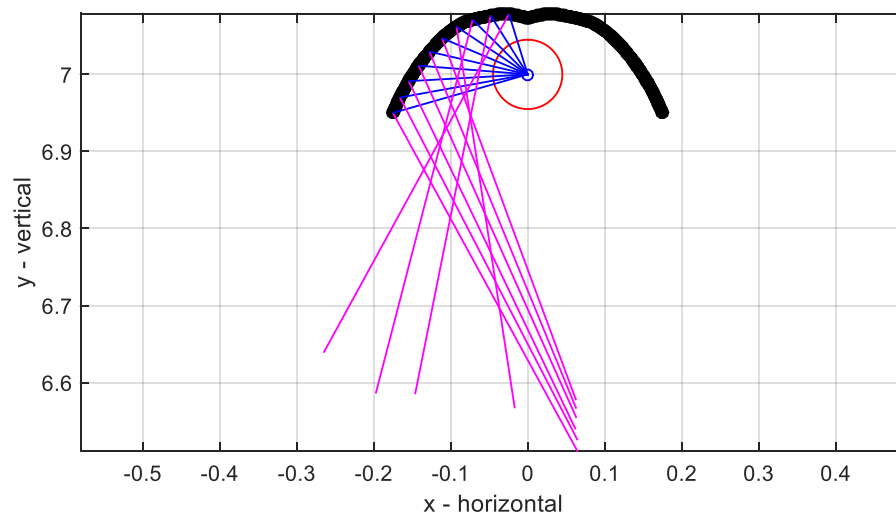
Optimized Secondary-Reflector Profile

The typical secondary reflector design approach in CSP is to start with a paraboloid cross section and make minor adjustments to parabola parameters. However, this is not the optimal design approach for an LFR. The reason is that parabolas are excellent at focusing parallel rays on a common point, but the incident light in an LFR receiver is not parallel; rather, the incident light will have an acceptance angle of up to 90°. Therefore, an alternate design approach is needed. Project partner NREL developed and has filed patents for a specific design approach for LFR secondaries.

By employing the new adaptive optimization method developed by NREL, an optimized secondary-reflector shape can be determined based on the Hyperlight Energy collector configuration. One optimum profile is illustrated in Figure 10. The pink and blue lines show the

ray-tracing technique to develop a surface, rather than starting with a surface, and then applying ray tracing to characterize its performance.

Figure 10: Optimized Linear Fresnel Reflector Secondary Concentrator



Optimized secondary-reflector shape for the Hyperlight Energy collector using the absorber with a diameter of 0.09 m. The pink lines are principal incidence direction that the secondary surface will reflect to the absorber center and the blue lines are the target reflection direction to the absorber center.

Source: NREL

Balance of Plant Design

This part of the project was focused on designing the heat transfer fluid (HTF) handling subsystem, including pumps, heat exchangers, valves, and controls. While no fundamental innovation was involved here, it was still necessary to customize the various components and their configuration to match the thermal and other performance characteristics of the solar array. Further, it was necessary to plan for relevant market sectors in terms of temperatures, fluids, controls, and other considerations.

The design of an HTF system is difficult and complex. The original intent of the project was to design a system capable of 400°C. This is the highest temperature at which thermal oil can be used. The higher the temperature, the more commercial applications open up and the more efficiently one can operate a power generation plant. A key issue here was that the project team's core competence was reflector design, not HTF system design. Although the team engaged consulting help, there were no consultants that could be familiar with the performance characteristics of a brand new LFR system. The team needed an HTF subsystem to be able to build a complete CSP system, but did not know the precise characteristics of the new CSP technology to be able to move through the design process of the HTF system. For this reason, it took a long time to establish a baseline design suitable for quote. Up to that point, from proposal development through final contract signature for the project, the team had estimated the cost of the HTF system based on percentages of cost associated with other CSP plants built and documented in the literature. The researchers knew that because the other plants were much larger than the one being proposed for this project, the percentages would also be larger. The team increased the percentages used in estimating the cost of the

HTF system, but there was no way to know how much increase would be enough. When the cost quote for the HTF system eventually came in, it was more than twice the team's highest original estimate. This cost differential presented the project team with its first large problem because the project budget could not accommodate the cost quoted for the HTF system.

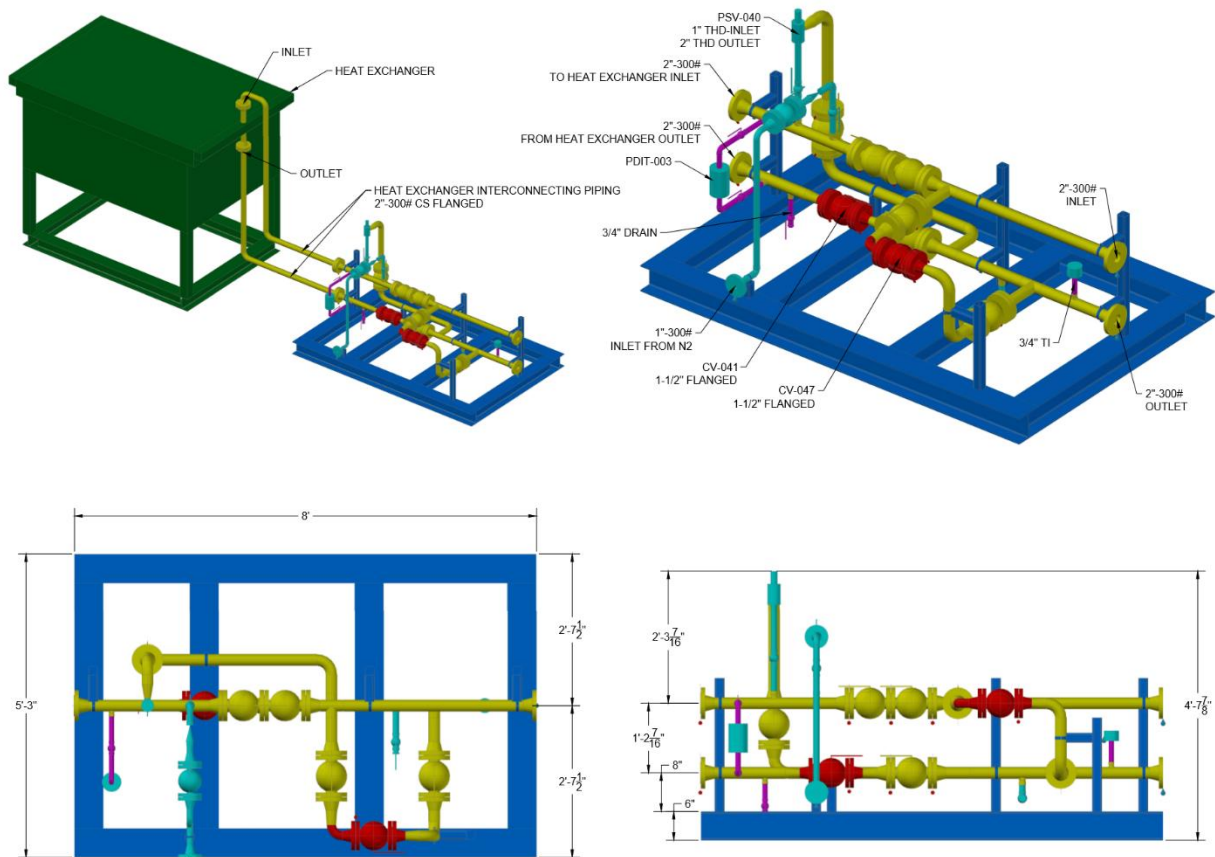
The solution was to switch to a less expensive design that would use a different HTF with a temperature limit of 300°C rather than 400°C. This reduced the cost of the HTF system enough to make it feasible to build if other changes were made. The main other change needed was to reduce the demonstration site size from one acre to a half acre. This, along with other cost saving strategies identified by the team, brought the budget back to a manageable level. The project team had always planned for the HTP system to be able to operate at night (without the CSP system) so the system included a trim heater. The trim heater would be sufficient to raise the temperature of the HTP system from the CSP limit of 300°C up to 360°C. For this reason, the reduced temperature input to the Genifuel HTP system was acceptable. The resulting HTF system design, which is much simpler than the original 400°C design, is shown in Figure 11 on the following page.

This situation generated one of the key takeaways of this entire project: it is the project team's opinion that it is likely not feasible to go above 300°C for projects on the scale of one acre or less for any CSP technology that uses thermal oil.

Third Party Procurement

Procuring parts from the global CSP supply chain and other industrial sectors is difficult for an emerging technology developer. The largest possible order size for a small-scale developer such as Hyperlight Energy is a fraction of the smallest size vendors typically consider and are set up to service. While not part of the fundamental technology development process, procurement is still essential to prove out the technology and must be considered. Also, the project team faced other supplier challenges including a breakage rate of more than 10 percent in the HCEs sent from one supplier, and the exit from the curved mirror business by a supplier the team had been working with for a year. These supply-chain challenges caused delays in the schedule that were impossible to anticipate.

Figure 11: Heat Transfer Fluid Processing Skid



These engineering drawings show the general layout of the oil-processing skid, containing a pump, two control valves, two safety relief valves, inlet and outlet sensor arrays, and a large oil-air heat exchanger to vent heat when the HTP skid is not in operation.

Source: Hyperlight Energy

Commissioning

Hydrothermal Processing System Testing

After construction of the CSP system was completed (Figure 12), the project team conducted two testing campaigns for the HTP system (Figure 12, Figure 13) after the initial commissioning. The first campaign used algae as a feedstock because the test was performed at the factory in Los Angeles County where the system was built, and the factory owner did not want dairy manure in the facility. The second campaign was performed after the containerized system was moved to Brawley, California in proximity to dairies which could provide the feedstock for the second test.

The first test was configured (with the aid of the control system, shown in Figure 15) to produce biocrude oil from algae, while the second test was configured to produce methane gas but no oil. A third test that could produce both oil and gas together was possible but was not required since the team felt it would produce little additional information.

Figure 12: Concentrating Solar Power Construction Complete



Hylux™ on sun.

Source: Hyperlight Energy

Figure 13: Container at Factory at Start of Fabrication



Containerized HTP system at factory.

Source: Genifuel Corporation

Figure 14: Container after Completion of Fabrication, Ready for Operations



Inside of containerized HTP system at factory.

Source: Genifuel Corporation

First Campaign

The first test to produce biocrude from algae was conducted in Los Angeles County in January 2019. The test run included 21 continuous hours of feed with 10 hours for heat-up and cool-down (continuous run time 31 hours). The purpose was to produce oil, with a planned pumping rate of 2,100 milliliters per hour (mL/h) that increased to 3,000 mL/h after 17 hours online. The feedstock was mixed at approximately 13.9 percent solids, and the run was conducted at 360°C and 203 bar (2,950 psi) (Figure 15).

The results of the testing included production of 4.5 pints (2.1 L) of biocrude oil at a calculated conversion rate of algae to oil approximately 40 percent (Figure 17). The process also produced approximately 11 gallons (57 L) of hydrothermal liquefaction (HTL) effluent for the gas formed by the catalytic hydrothermal gasification (CHG), which will be added to HTL effluent water from other runs later, and the effluent water would be used for the CHG run in Brawley (the containerized system for this test, and the piping integrating it with the CSP system are shown in Figure 19). The team also collected samples of dry algae, feed slurry, blowdown solids, biocrude oil, and effluent water.

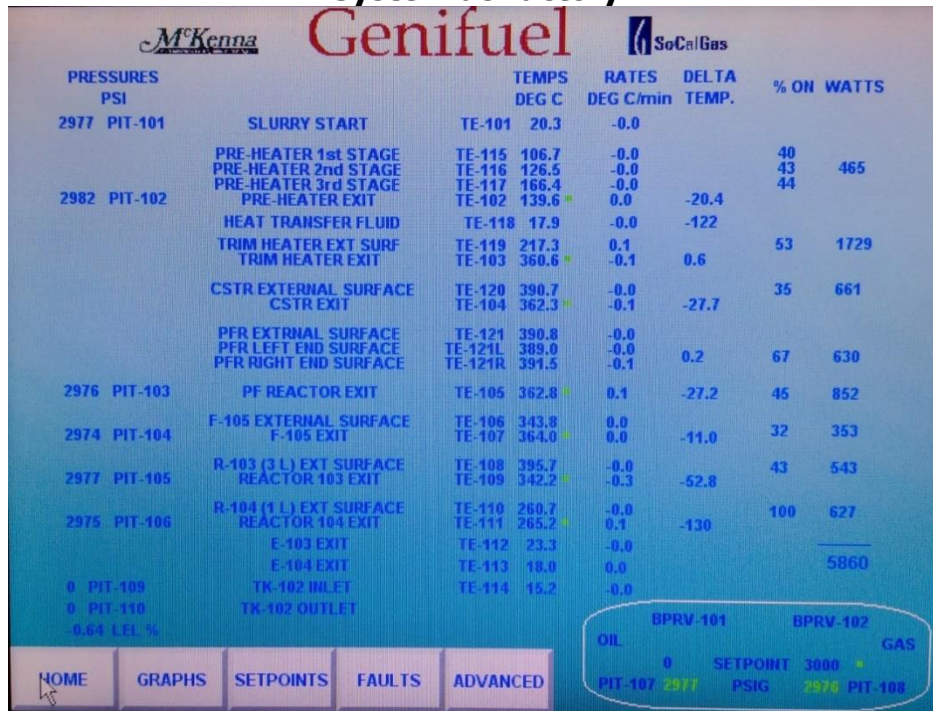
Figure 15: Algae Feedstock Ready for Testing



View of feedstock tank inside containerized HTP system at factory. Approximately 11 gallons (42 L) of feedstock ready to feed to HTL; container is 50 L; approximately 14 percent solids in algae slurry; approximately 36 L was pumped.

Source: Genifuel Corporation

Figure 16: View of Control Screen inside Containerized Hydrothermal Processing System at Factory



An automated controller manages system operation.

Source: Genifuel Corporation

Figure 17: Output of Biocrude inside of Containerized Hydrothermal Processing System at Factory



Just over four pints of oil was produced from the algae.

Source: Genifuel Corporation

Second Campaign

The second test to produce methane gas from dairy manure (collection of manure shown in Figure 17 and Figure 18, manure itself shown in Figure 20 and Figure 21) was conducted in Imperial County in March 2019. The test ran with 10 continuous hours of feed plus 8 hours for heat-up and cool-down for a total continuous run time of 18 hours. The planned pumping rate was 2,000 mL/h, which was maintained throughout the run. The feedstock was mixed at approximately 8 percent solids, and the run was conducted at 360°C and 203 bar (2,950 psi). The run produced approximately 20 cubic feet of gas composed of 65 percent methane and 35 percent carbon dioxide (Figure 23).

Figure 18: Dairy Manure Feedstock Collection



Rob van Ommering in Lakeside, California supplied the first feedstock sample.

Source: Genifuel Corporation

Figure 19: Second Feedstock Sample Supplied by Bullfrog Farms



Michele and Richard van Leeuwen of Bullfrog Farms in Imperial, California supplied the second sample feedstock.

Source: Genifuel Corporation

Figure 20: Containerized System Installed in Brawley, California for Second Test



Hydrothermal processing and concentrating solar power system integration.

Source: Genifuel Corporation

Figure 21: Dairy Cow Manure Ready for Feedstock Preparation



Source: Genifuel Corporation

Figure 22: Fibrous Dairy Manure



Dairy cow manure is quite fibrous, requiring careful preparation.

Source: Genifuel Corporation

Figure 23: Gas Bladder Filling with Gas



Gas bladder for collection of produced renewable natural gas. The system produced approximately 20 cubic feet in this run. Hyperlight system is in background with pipes to HTP system for hot oil heat.

Source: Genifuel Corporation

CHAPTER 3:

Project Results

The goals and objectives of this project from the original statement of work were to:

- Integrate CSP and HTP into a single system (achieved)
- Process dairy manure into RNG and bio-crude (achieved)
- Determine the operating conditions that produce optimal yields of RNG and bio-crude (not achieved)
- Determine the best strategy for storing diurnal CSP heat for the HTP continuous system (not achieved)
- Better understand the economics of integrated CSP/HTP systems sited at dairy farms and determine the optimal mix of RNG to bio-crude for maximum economic viability (achieved)

The integrated system was run on March 19, 2019, with the purpose to produce methane gas. Because it was a particularly cloudy day, although thermal oil from the solar array was run through the HTP skid the temperature was insufficient to measure solar heat input into the process. However, the HTP system (which was designed to operate with or without solar heat) still functioned. The system ran for 10 continuous hours of feed with 8 hours for heat-up and cool-down for a total continuous run time of 18 hours. The planned pumping rate was 2,000 mL/h which was held at this rate throughout the run. The feedstock was mixed at approximately 8 percent solids. The run was conducted at 360°C and 203 bar (2,950 psi), and produced around 20 cubic feet of gas composed of 65 percent methane and 35 percent carbon dioxide.

The run established successful completion of the project goals of integrating HTP and CSP and processing dairy manure into RNG and biocrude.

The team originally intended to continue to run the integrated system to determine operating conditions that produce optimal yields of RNG and bio-crude as well as the optimal strategy to store diurnal CSP heat for continuous HTP operation. However, the project schedule did not allow for the additional run time, so the system will be run again in the future with these goals in mind.

The team analyzed the economics of integrated CSP-HTP systems sited at dairies and produced a report during the project that clearly showed that the economics of such a strategy depend heavily on project scale, with most dairies not large enough to achieve the economies of scale needed to make this approach cost effective.

CHAPTER 4:

Technology/Market Transfer Activities

Knowledge Transfer via Public Reports

HTP was developed over 40 years by USDOE, primarily at the Pacific Northwest National Laboratory (PNNL). Genifuel was formed in 2006 to produce renewable fuels from wet waste feedstocks. The two parties have worked together since 2008 on a wide variety of projects. With respect to knowledge transfer, one advantage of the cooperation between PNNL and Genifuel is that almost all of the work is published, since it is partly produced with public money from USDOE. Published work is available on a USDOE-maintained website accessible through PNNL. A small sampling is shown below:

- PNNL-18944 Final Report on Gasification Project⁴
- PNNL-24386 CHG for Cleanup⁵
- PNNL-25464 Sludge TEA Final⁶

Similar to the reports generated by PNNL, many findings and technology descriptions are published in peer-reviewed journals and are available online by services such as Elsevier, such as:

- Elsevier Waste to Energy Paper from PNNL⁷
- IECR paper #4⁸
- IECR #6 paper⁹
- CHG biomass #7 paper¹⁰

⁴ https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-18944.pdf.

⁵ https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-24386.pdf.

⁶ https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-25464Rev1.pdf.

⁷ Elsevier; Renewable and Sustainable Energy Reviews 82 (2018) 2640–2651; Waste-to-Energy biofuel production potential for selected feedstocks in the conterminous United States; Skaggs et al

⁸ Ind. Eng. Chem. Res. 1994,33, 566-574; Chemical Processing in High-pressure Aqueous Environments. 4. Continuous-Flow Reactor Process Development Experiments for Organics Destruction; Elliott et al.

⁹ Ind. Eng. Chem. Res. 1999, 38, 879-883; Chemical Processing in High-Pressure Aqueous Environments. 6. Demonstration of Catalytic Gasification for Chemical Manufacturing Wastewater Cleanup in Industrial Plants; Elliott et al.

¹⁰ Ind. Eng. Chem. Res. 2004, 43, 1999-2004; Chemical Processing in High-Pressure Aqueous Environments. 7. Process Development for Catalytic Gasification of Wet Biomass Feedstocks; Elliott et al

A major report on the use of hydrothermal processing for wastewater sludge was prepared by the Water Research Foundation and is available free of charge¹¹. This 185-page report was prepared by an independent third-party and contains copious technical information about the hydrothermal technology and processing.

Knowledge Transfer via Universities and Conferences

Genifuel presents at university-sponsored conferences such as the conference on Renewable Natural Gas at University of California, Riverside in 2017. Genifuel also speaks widely at technical conferences on the topics of wastewater, renewable fuels, and other potential feedstocks such as algae. Genifuel is also an exhibitor at the annual wastewater industry conference (WEFTEC), and has participated in the preparation of technical papers for the proceedings section of WEFTEC for several years. In total, the conferences at which Genifuel has been an exhibitor, presenter, or contributor have provided a total audience of more than 50,000 highly qualified attendees. Genifuel intends to continue with these activities, and to broaden the topics to other conferences including dairy production.

Operator Training

In addition to information presented to wide audiences, Genifuel also prepares training materials for personnel who will operate and maintain the system. This manual allows the operators to use the automated control system as well as manual controls when required. Each operator's training includes ample hands-on time with personnel already familiar with system operation. This process has already been followed for training of two new operators for Genifuel HTP.

Technical Training

In addition to operator training, more detailed instruction is needed for engineers or technicians who will diagnose problems and make repairs or design changes if needed. The primary vehicle for technical training is the Piping and Instrumentation Diagram. This level of training must be accomplished either by Genifuel or by the Technical Manager of the fabrication company, which is McKenna Engineering in Carson, CA.

Safety Training

The primary vehicle for safety training is the hazard and operability (HAZOP) study, a standard part of most process equipment design and fabrication. Genifuel and the equipment fabricator (McKenna Engineering) conducted a HAZOP review for the CHPDS, and are in the process of updating it with changes made during the commissioning of the system. This final report is also one avenue of knowledge dissemination.

¹¹ <https://www.werf.org/I/itemdetail?productcode=LIFT6T14PDF&ORDERLINEID=3E8BFE32-6C89-4D3F-8F80-09243492153>.

CHAPTER 5:

Next Steps

Given the Food Production Investment Program and a project with Saputo Cheese plant in Tulare, Hyperlight Energy is turning its focus to commercialization. With a large project on the horizon in the San Francisco Bay Area for the Genifuel HTP system, that is the appropriate focus for Genifuel Corporation at this time as well.

The Hyperlight team plans to fix a sensor issue identified in the commissioning of the system and continue with data collection. Additionally, the team plans to continue to run the CSP portion of the system in conjunction with the hydrothermal processing. However, the project team believes there is not enough work still to be done on this technology to justify another R&D grant. Although improvements to the technology will always be useful, it is time to commercialize and realize improvements through that process (e.g., through learning by doing). Another CSP company, Solar Reserve, won a multi-million dollar grant from the U.S. Department of Energy to improve its tracking system. Solar Reserve has a large solar thermal plant in Crescent Dunes Nevada and is still doing R&D. Similarly, Hyperlight is planning to continue technology improvement.

CHAPTER 6:

Benefits to Ratepayers

This project had significant benefits to California ratepayers by advancing the state of the art of the CSP industry. In conjunction with another EPIC-funded project, the funding provided by this project allowed Hyperlight Energy to build a half-acre demonstration site in Brawley, California to prove lower bounds on the performance and cost-effectiveness of the Hyperlight Hylux™ solar technology. The data obtained as a result of this project show that concentrated solar power reflector and receiver system for generating electricity and process heat, at scale, will be a cost-competitive alternative to natural gas for industrial process heat, enhanced oil recovery, and ultimately electricity generation. Future installations of the technology could replace current or planned fossil-fuel burning heat sources, reducing California's greenhouse gas emissions and natural gas consumption.

Further, CSP can play an important role in reaching the state's goal to have 100 percent of total retail sales of electricity come from renewable energy and zero-carbon resources by 2045. Perhaps the greatest challenge in reaching that goal is addressing the variability or intermittency of most forms of renewable generation. To address this issue, California will likely need to add significant amounts of cost-effective energy storage. Currently, the only form of energy storage that is cheap enough to be practical is thermal energy storage: storing a hot fluid and converting it into electricity on demand. CSP is highly complementary with thermal storage because it is a power source that can heat a storage medium to very high temperatures to allow for efficient storage.

In addition to the long-term environmental benefits to California, this project also generated short- and long-term economic benefits in the form of jobs. The project generated 9 jobs during execution, and has led to projects that will lead to 10 full time jobs in California, with far greater potential with continued deployment. In conjunction with another EPIC project related to this technology, Hyperlight Energy developed methods to produce many of the primary components of the CSP system locally, which will lead to local manufacturing jobs as project components are fabricated. Furthermore, at present all planned Hylux™ installations are in California, promising additional in-state employment for the installation of the various projects.

Additionally, the project at San Diego State University's satellite campus in Brawley led directly to securing a commercial project that will result in 18,000 million British thermal units of thermal energy generated per year and approximately 1,800 tons of carbon dioxide emissions reductions per year.

LIST OF ACRONYMS

Term	Definition
Bar	The atmospheric pressure at sea level, equal to 14.5037738 pounds per square inch.
C	Centigrade
CH ₄	Methane
CHG	Catalytic hydrothermal gasification
CO ₂	Carbon dioxide
CSP	Concentrating solar power
EPIC	Electric Program Investment Charge
HAZOP	Hazard and operability (study)
HCE	Heat collection element
HTF	Heat transfer fluid
HTL	Hydrothermal liquefaction
HTP	Hydrothermal processing
L	Liters
LFR	Linear Fresnel reflector
mL/h	Milliliters per hour
NREL	National Renewable Energy Laboratory
P&ID	Process and instrumentation diagram
PNNL	Pacific Northwest National Laboratory
Psi	Pounds per square inch
R&D	Research and development
RIL	Reliance Industries, Ltd.
RNG	Renewable natural gas
USDOE	United States Department of Energy
USEPA	United States Environmental Protection Agency
WEFTEC	Water Environment Federation Technical Exhibition and Conference