Public Interest Energy Research (PIER) Program

FINAL PROJECT REPORT

INDUSTRIAL PROCESS STEAM GENERATION USING PARABOLIC TROUGH SOLAR COLLECTION

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PREFACE

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

The PIER Program conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy Innovations Small Grants
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

Industrial Process Steam Generation Using Parabolic Trough Solar Collection is the final report for the Reduce Natural Gas Use for Industrial Process Heat using High-Temperature Parabolic Trough Solar Collectors project (Contract Number 500-05-025) conducted by American Energy Assets, California L.P. The information from this project contributes to PIER's Industrial, Agriculture & Water End-Use Energy Efficiency and Renewable Energy Program.

For more information about the PIER Program, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-327-1551.

ABSTRACT

This final report details the results of a project to demonstrate the use of solar collectors that produce high temperature process heat for industrial use. This project consists of several phases, from contracting and feasibility, through design, construction, operation, and analysis of a system. This system is designed to produce 300 pounds per square inch (20 bar) pressure steam for a Frito-Lay® Inc. snack foods plant, offsetting natural gas usage by conventional fired boilers. This project intends to reduce natural gas demand in the plant, during peak summer days, by approximately 20 percent. Project goals include demonstration of a cost-effective and reliable source of high grade heat to reduce the environmental impact of the plant, and improve the reliability of the local natural gas delivery system by reducing peak demand.

Keywords: solar, parabolic trough, industrial solar, solar steam, solar thermal system, heat transfer, solar concentrators, solar field, high temperature hot water

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EXECUTIVE SUMMARY

Introduction

This project researched the viability of producing high temperature industrial process heat from the sun's energy. The installation of a large scale industrial solar thermal system provides an opportunity to evaluate the technical and economic hurdles of similar systems in California.

The research was performed through the design, construction, operation, and analysis of a high temperature solar thermal system at a Frito-Lay snack food plant located in Modesto, California. In this installation, high temperature water in excess of 232°C (450°F) is produced by a concentrating solar field, which in turn is used to produce approximately 300 pounds per square inch (20 bar) of process steam. The solar thermal system is intended to improve plant efficiency with minimal impact on day-to-day production operations. Process steam in the plant is used for cooking, which includes heating edible oil for frying, and heating baking equipment. Steam is also converted into hot water for cleaning and sterilization processes.

Purpose

This project demonstrates the feasibility of adding solar thermal energy to an existing manufacturing facility and to produce enough heat to reduce plant natural gas demand by up to 30 percent using energy from the sun. The project furthers Research, Development & Demonstration (RD&D) of high temperature process steam generation using renewable solar energy while improving the environment and public heath in the San Joaquin Valley. A key aspect of this project is its ability to operate as a large scale model for demonstration and analysis.

Project Objectives

The project intends to demonstrate the feasibility of these types of systems through the following goals:

1. Contract with the manufacturing customer to design and build a solar thermal system which meets the customer's requirements and the goals of this Public Interest Energy Research (PIER) project.
2. Design a system which meets the needs of the manufacturing facility.
3. Build and commission the system.
4. Install instrumentation and data collection equipment sufficient to use the system as a measurement and analysis platform.

5. Demonstrate the cost-effective construction and operation of a safe and reliable system.
6. Measure and analyze system performance over a period of several months.
7. Compare system performance to the existing system models.

Project Outcomes

The project system has been successfully built and operated and is being monitored and analyzed by the project team, as well as the National Renewable Energy Laboratory, on an ongoing basis. Beginning its second solar season of operation, the system's peak system energy output has been approximately 30 percent below project goals; however, ongoing monitoring and analysis will likely discover any deficiencies.

With respect to the specific project goals, to date the outcomes are as follows:

1. **Contract for Design and Construction**: All parties have been successful in contracting to build the project while meeting the basic requirements of this PIER project, including 54,500 square feet of solar panels with integration into existing plant steam and hot water systems.
2. **System Design:** The team was successful in designing a system which met the goals of the contract and this PIER project. The system design provided for adequate solar concentrator area as well as steam and hot water generation equipment to meet the goal of 20 percent to 30 percent reduction in plant natural gas requirements during peak summer days.
3. **Construction and Commissioning:** The full field was successfully approved by the customer and installed at the Modesto, California plant. Steam generation capacity connected to the field is capable of augmenting the high pressure steam supplied by the existing natural gas boilers. However, the project team and Frito-Lay elected to forego the installation of a low grade heat recovery system on the grounds of poor economic return. In lieu of the lower temperature heat exchanger a medium-pressure steam tie-in was added to the solar system allowing the system to produce slightly lower temperature process steam when load is available.
4. **Instrumentation and Data Collection:** Instrumentation and data collection systems were installed to provide sampling and logging throughout the system. In order to facilitate system performance and utilization analysis, temperatures, pressures, flows, solar intensity, sun position and field statuses are recorded and logged on an ongoing basis.

5. **Cost-effective, Safe, and Reliable Operation:**

    a. Final design, construction and startup cost of the project was $3.95 million, or $0.439 per British Thermal Unit per hour (BTU/hr), or $1,500 per kilowatt (kW) of design thermal output. This cost allows for a payback period below 10 years, depending on natural gas prices. In addition to offsetting natural gas consumption, the customer has realized federal tax credits for the installation, further reducing the effective project cost. These benefits make the investment cost effective per industry standards, provided that the system's performance goals are met. If the system performance is lower than expected or natural gas prices remain below $9 per million BTU, then the system payback could be extended.

    b. In its second solar season of operation the system has proven safe with no failures of high pressure equipment or controls.

    c. The solar thermal system automatically begins operation each morning and, once up to temperature, provides low and medium pressure steam into the plant in a reliable manner.

6. **System Performance Measurement:** This project has been successful in collecting data for ongoing performance analysis. Current solar system energy performance is below expectations but improvement and analysis efforts continue. Approximately 86 percent of available energy has been utilized by the plant. Activities continue to improve utilization through operation and control adjustments.

7. **Performance Comparison to System Model:** The original feasibility model indicated an annual output of 14.7 billion BTUs per year (20 billion BTUs of natural gas reduction). The original system model varies from actual system capabilities in a few aspects, including the installation of a low grade heat recovery system. Peak performance to date has been approximately 30 percent below design output, which, in turn, is about 10 percent below the ideal peak performance model.

Recommendations

The project team recommends that current performance evaluation and tuning activities be carried out through the end of this solar season. This will allow a better understanding and optimization of performance and system utilization. Ongoing performance monitoring should continue during the lifetime of the project to assure efficiency levels are maintained. It is also recommended that similar industrial high temperature solar systems yet to be built include significant instrumentation and data collection capabilities so that the benefits of ongoing performance can be monitored and maintained.

Benefits to California

California's inland areas receive some of the highest levels of annual sun radiation in North America. This energy represents a resource to the citizens of California who can harvest it to produce high temperature process heat used by many industries throughout the state. Reducing industrial natural gas usage lowers manufacturing costs, making California more attractive for manufacturing companies that would provide jobs and boost tax revenue.

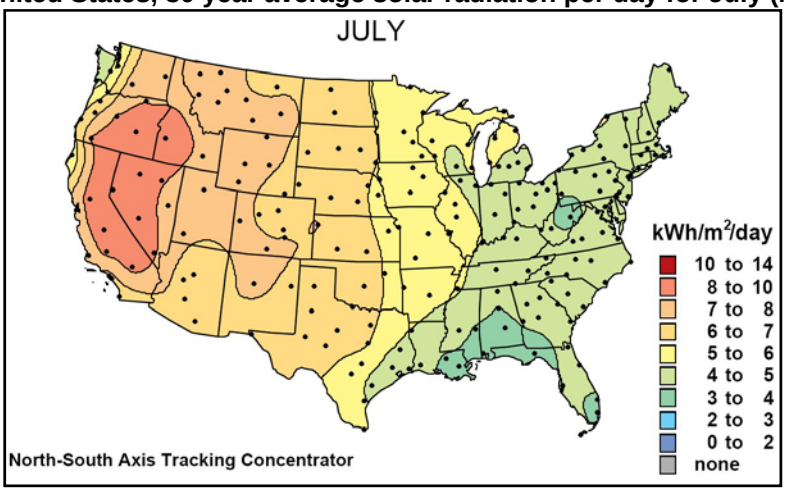
Industrial process heat generation through solar technologies provide an additional opportunity to reduce statewide greenhouse gas and chemical emissions caused by burning natural gas.

CHAPTER 1: Introduction

1.1 Background and Overview

Solar radiation is a readily available natural resource in many parts of North America, however, inland California has a much higher than average share of sunshine. Available energy for a single axis tracking surface for an average July day approaches 10 kilowatt hour (kWh) per square meter of collector area, more than double the daily intensity for gulf coast regions for example. Harvesting solar radiation has different technical hurdles depending on the final energy product.

Figure 1. United States, 30 year average solar radiation per day for July (NREL, n.d.)



Source: American Energy Assets, California L.P.

In the case of high temperature industrial process heat the high pressure system must be reliable, safe, cost-effective, and present minimal impact to other aspects of the manufacturing process. To make such systems palatable to industrial customers, downtime due to poor solar conditions, high winds, or system failure must not cause production losses.

1.2 Project Objectives

The primary objective of this project was to demonstrate the feasibility of a cost-effective industrial process heating system which offsets existing natural gas usage. The project is intended to further RD&D in this area by providing a working platform for measuring system performance and utilization by the plant. In addition to research the project is intended to directly reduce local emissions thus improving public health and environment in the San Joaquin Valley.

To complete these objectives the project intends to address the following specific goals:

1. **Contract for Design and Construction:** All involved parties were expected to enter into contract to design and build the solar thermal system and associated plant infrastructure. The contract had to meet the financial and performance goals of the customer while addressing the goals of this Public Interest Energy Research (PIER) project.

2. **System Design:** The project team was to complete a solar concentrated solar system design which augmented the plant's existing steam systems providing at least a 20 percent reduction in natural gas demand during peak summer days. Original feasibility models indicated that a system of this scale would produce enough usable heat to reduce plant natural gas usage by approximately 20 billion British Thermal Units (BTUs) annually.

3. **Construction and Commissioning:** Subsequent to the design, the project called for building the working system at the Frito-Lay plant in Modesto, CA. The project was to be commissioned and all equipment and instrumentation tested and verified through parametric analysis.

4. **Instrumentation and Data Collection:** In order to use this system as a platform to further Research, Development & Demonstration (RD&D), the project required extensive measurement and data collection systems to be installed.

5. **Cost-Effective, Safe, Reliable Operation:** The project required that such a system can be cost effective, safe and reliable while offsetting natural gas for high temperature process heat.

6. **System Performance Measurement:** This project called for ongoing measurement and analysis of energy provided by the system as well as the plant's utilization of available energy.

7. **Performance Comparison to System Model:** Prior to beginning this project a model of system performance had been completed by the National Renewable Energy Laboratory, part of this project included evaluating the running system in comparison to the model.

CHAPTER 2:
Project Approach

2.1 Contract for Design and Construction

The first step in ensuring that building such a system in an existing industrial plant was to demonstrate that all parties could enter into an amicable contract to deliver and install the final project. The original feasibility model which drove the scope of the PIER project was to be the framework for a contract which insured cost-effective and reliable operation of the system.

2.2 System Design

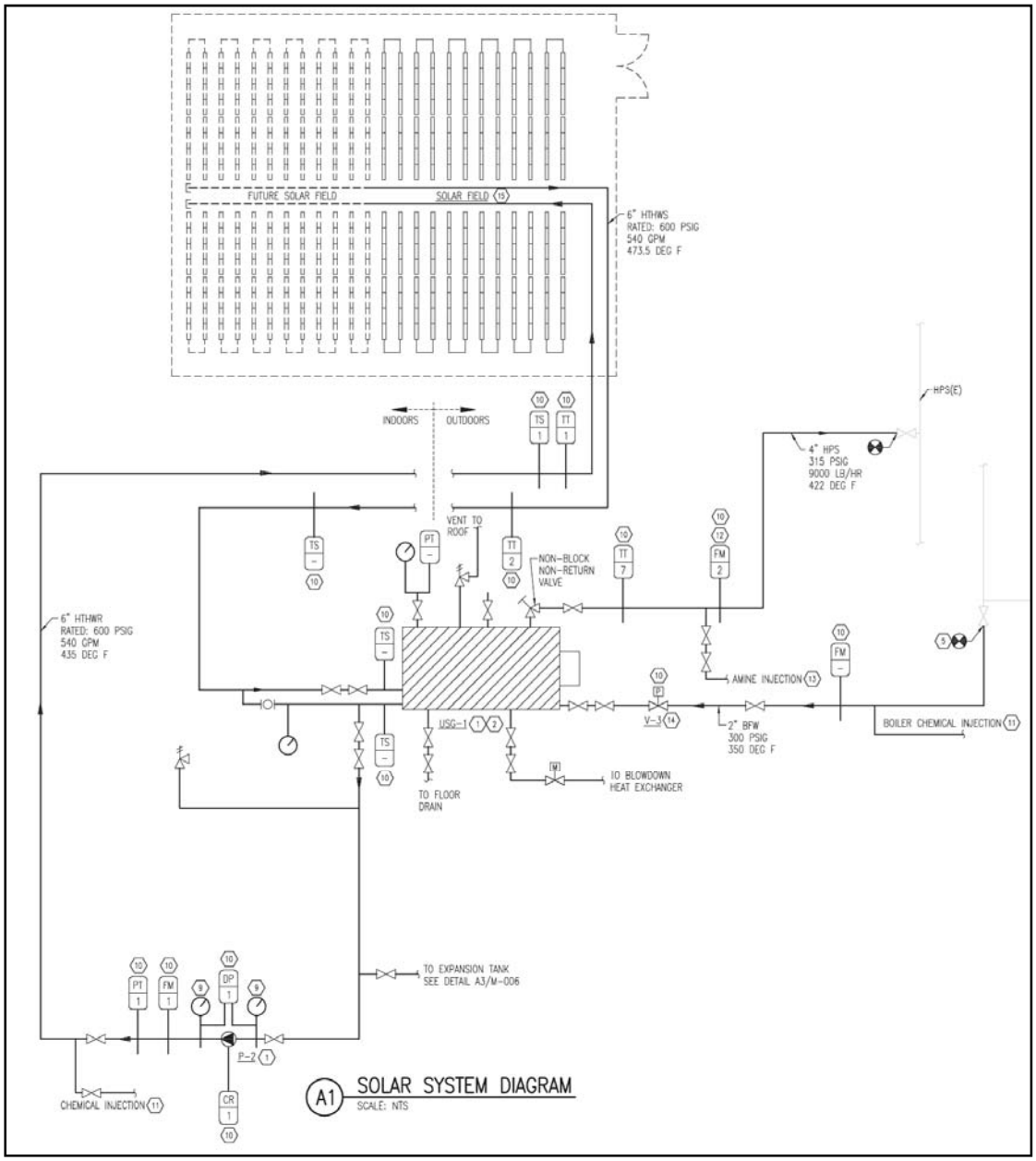
The design of this project was intended to meet the performance of this PIER project while providing for simple and reliable interconnection to the existing plant processes.

System design includes 54,528 square feet of total collector surface area installed on about 4.5 acres of vacant land to the east of the Frito-Lay plant. The total collector field is comprised of 384 individual parabolic trough collectors with a net aperture area of 142 ft^2 each. Each panel has a gross dimension of 20 ft wide by 7.5 ft in height. The panels are installed permitting rotation about a north-south axis, tracking the sun as it progresses from its morning to evening position each day. Individual collectors are piped in groups containing 16 in series, 24 of these series flow loops make up the total field (see Figure 2).

Each of the 24 parallel flow paths are driven by a separate motor and cable system which controls the angular position of the 16 panels independently of the remainder of the field. This segmented field operation permits for as little as 4 percent of the field to be down when washing or maintenance is required, allowing the rest of the field to operate. Each drive section utilizes photo-sensitive tracking eyes to maintain its focus on the sun as it moves across the sky.

Hot water exiting the field at up to 246°C (475°F) is piped in a closed loop to the plant where it enters a shell and tube heat exchanger which boils water, producing steam between 290 and 300 psig. This steam is fed into the common plant high pressure steam header for use in the plant's processes. The design calls for the water exiting the shell and tube exchanger at approximately 216°C (420°F) to enter a second heat exchanger which is used to produce low grade heat for cleaning activities when possible. After exiting the second heat exchanger the water is returned to the field for re-heating.

Figure 2. Solar system piping and instrumentation



Source: American Energy Assets, California L.P.

Water was selected as a heat transfer media because of both excellent heat transfer properties and low environmental risk in the event of a system leak. Including the solar field and transmission piping, the system includes approximately 6,600 gallons of water in the closed high temperature loop. The water in the closed loop is continuously circulated during operation with no loss or makeup. In order to keep the water in the loop from flashing, or boiling, the system includes a 3,000 gallon expansion tank with pressure controls and nitrogen injection to ensure the system pressure stays above the water flashpoint plus an additional safety margin of

25 psig. As a result of the high temperature operation, the loop and associated equipment will operate at approximately 600 psig. The expansion tank also accommodates approximately 1,700 gallons of water volume expansion as the system heats from a cold idle state to full operating temperature.

Plant requirements called for the field to be built over 1,500 feet from the plant, where the steam generator is located, necessitating a very large volume in the closed loop.

After the design phase was completed Frito-Lay elected to pursue construction of the field in three phases:

- Phase 1 consisted of half of the field, 192 collectors, and the steam heat exchanger rated for the full 384 collector capacity as well as pumping and associated plant steam interconnections.
- Phase 2 was the construction of the remaining 192 collectors which were to be tied into the existing phase 1 field with no changes to the plant.
- Phase 3 was the addition of a hot water heat exchanger which allowed the field to generate lower temperature hot water into a system used for periodic cleaning and sanitation of the processing area and equipment.

2.3 Construction and Commissioning

Frito-Lay approved the construction of phase 1 which was completed and commissioned on April 2008. The field was built including the designed 192 collector modules. Plant pumping, piping and the steam heat exchanger were all built to handle the full 384 panel field.

Figure 3. Solar field collectors facing noon-time sun

Photo Credit: American Energy Assets, California L.P.

Phase 2 was approved and built in time for system startup and commissioning at the end of July 2008. Phase 2 included an additional 192 collector modules for a total solar field of 384 collectors and 54,528 ft^2 of total concentrating surface.

Figure 4. Collector field tracking eastern morning sun

Photo Credit: American Energy Assets, California L.P.

Frito-Lay elected not to pursue the phase 3 addition of a hot water exchanger and connections to the plant clean-in-place (CIP) system. The hot water heat exchanger and low grade heat dump were amongst the original project goals. However, the project also required that the system was built to be cost-effective for the manufacturing customer. In this case the project team learned that these goals were in conflict. Review of the phase 3 portion of the project indicated that the occasional CIP load would not offset the cost of the addition equipment required.

In place of the CIP hot water exchanger a low pressure control valve was added to the solar steam generator allowing the solar system to provide either high pressure (300 psig) or low pressure steam (90 psig) into two separate plant headers. Adding the lower pressure steam sink allows the solar field to operate with a 165°C (330°F) field inlet temperature, 32°C (90°F) lower than required for high pressure steam. The lower operating temperature allows the system to operate with reduced thermal losses and a shorter warm-up period each morning. Like the original CIP water sink the project team did not expect the 90 psig steam load to be available at all times. The cost of this addition was much lower than the full CIP integration and the expected cost recovery period was short.

2.4 Instrumentation and Data Collection

In order to meet the specific requirements of this PIER project the solar system was installed with instrumentation and data collection capabilities beyond what was required for normal day

to day operation. Original construction of the field included instrumentation and data collection equipment such that data collection began on the day of initial startup. Much of the instrumentation and its installation have been independently reviewed by the National Renewable Energy Laboratory (NREL) for accuracy and location.

2.4.1 Field Loop Test

In order to provide sub-field performance measurements, one of the 24 parallel flow paths in the field was outfitted with additional instrumentation. Other than this single loop, performance can only be measured for the whole field in aggregate when all 24 loops are operating.

2.4.2 Temperature Measurement

Temperature through the closed loop system is monitored by resistive thermal devices (RTDs) in temperature wells located at six points around the loop. The RTDs in the field loop support the calculation of temperature rise through the field as well as system losses and steam generator performance. Loop temperature is read in and out of the steam generator, in and out of the field, and in and out of the test loop.

In addition to the solar field loop, in-well RTDs are present in the boiler feed-water into the steam generator and in the steam supplied by the steam generator.

Each of the 24 individual flow loops in the field has two surface-mounted thermocouples for providing feedback on a per-loop basis. These sensors are primarily intended to provide high temperature limit shutdown in the event of flow loss through any segment of the field.

2.4.3 Pressure Measurement

For both over pressure safety and performance measurement, system pressures are measured on the expansion tank, in and out of the field loop pump, into the field, and on the steam header exiting the steam generator.

Because of the criticality of maintaining loop pressure high enough to avoid vaporizing the loop water, the pressure at the highest temperature point in the system is continuously monitored and controlled, if needed, by the expansion tank's nitrogen system.

2.4.4 Flow Measurement

Flow rates are measured at three locations in using vortex shedding velocity meters: (1) steam flow from the steam generator, indicated in lb/hr; (2) flow through the closed field loop, indicated in gallons per minute (gpm); and (3) flow through the field test loop, indicated in gpm.

2.4.5 Solar Intensity Measurement

To measure the input solar intensity to the system several devices have been utilized throughout the project. A shadow-band pyranometer, which is mounted to the surface plane of the field test loop, allows measurement of solar beam intensity directly in the plane of the

rotating collector. A more accurate calibrated rotating shadow band pyranometer is installed in the field for measuring solar beam intensity in the horizontal plane regardless of the origination of the collector. Additionally, analysis has been performed using a normal incidence pyrheliometer which requires manual orientation to the sun.

2.4.6 Data Collection

Data from all system sensors is monitored and logged in at least one minute intervals and stored for ongoing analysis. Higher frequency, four to six second, interval data is recorded for several system parameters including solar tracking. System data has been collected and archived since the initial startup.

2.5 Cost Effective, Reliable, and Safe Operation

In order to provide a cost-effective system, components were chosen which provided the necessary output with reduced initial and long term costs. For example, unlike some systems which use large steel lattice collector structures with glass mirrored reflectors, the system was constructed using lighter weight, and smaller, aluminum structures with silver film reflective material. The silver film significantly reduces the weight and structural requirements while the aluminum structure maintains the rigidity and shape of the parabolic surface. These materials sacrifice some amount of optical performance over similar mirrored technologies but improve the cost performance for installations of this scale. Rather than gas-filled or vacuum enclosures around the absorber tubes, this project utilized simpler semi-sealed anti-reflective coated glass tubes to reduce both convective and radiative losses from the high temperature absorber tubes.

Project goals required reliable operation including smooth startup during proper solar conditions as well as shutdown for inclement weather and low solar conditions. To meet this goal the system was designed to calculate the sun angle during all daytime hours. From known sun angles the system determines startup and shutdown time each day based on panel height, row spacing, and associated panel shading. As the day length changes throughout the year the system automatically chooses the optimum start minute. The solar field control system also monitors available sun intensity assuring that the field is put into stow mode when adequate sun is not available for an extended period.

System operation is monitored both by the onsite control system and remote personnel to maximize field operating hours and quickly address any issues. Field statuses such as drive motor activity, drive position, and sun tracking are displayed on consoles for local and remote operators.

Safety is a great concern when operating over two miles of solar fields and distribution piping at 600 psig. Several precautions have been taken in the design and operation of the system to ensure safety.

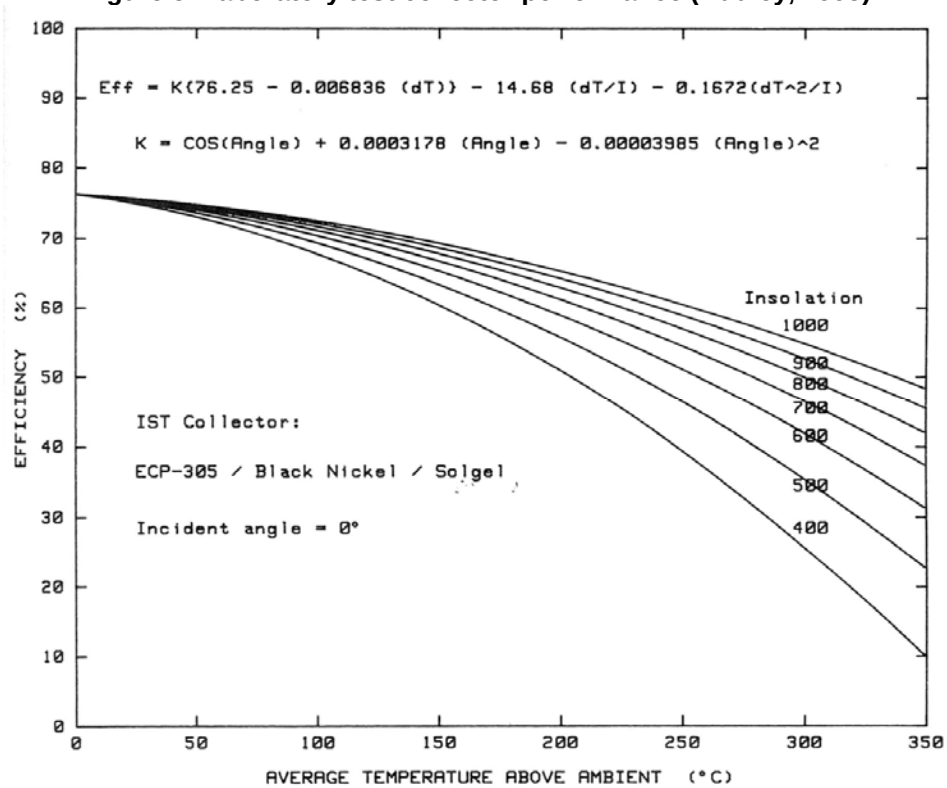
- Seamless extruded tubing is used for the thin walled absorber tubes to assure adequate pressure rating.

- The system controls provide for field and pump shutdown in the event of high pressure or temperature which is monitored at several points in the system.
- The expansion tank is equipped with a nitrogen injection system which monitors the system temperature and pressure assuring that the system pressure exceeds the required liquid saturation pressure at all times.
- An uninterruptable power supply system is used to assure the field can drive to stow position in the event of a power outage, preventing the field from being focused on the sun with no power for flow at the pump.
- Wind speed is motored to provide shutdown and assure that the field panels are not left in a vulnerable position during high wind conditions.
- Pressure relief valves have been placed throughout the loop to assure controlled pressure relief in the event of over pressurization.

2.6 System Performance Measurement

System performance monitoring has been a continuous event since initial project startup. As part of this project ongoing performance measurement has been conducted by several parties. Parabolic trough solar concentrators have been actively used for capturing thermal energy from the sun for over 20 years. As such, performance metrics for these systems have been well established in the research community. Performance measurement for this project utilized methods and standards established by the research community.

Figure 5. Laboratory test collector performance (Dudley, 1995)



Source: American Energy Assets, California L.P.

The model PT-1 parabolic trough system supplied by IST/Abengoa Solar had previously been tested by Sandia National Labs in 1995 (Dudley, 1995). The published report included operating the collectors in a controlled environment to calculate the performance characteristics of the system. The tests included independently varying each of the operating characteristics that impact the performance of a single axis tracking solar concentrator which include:

- Delta T - the difference in temperature between the solar fluid and the ambient air (signified as "dT" and expressed °C as in Figure 5).
- Incidence angle – the angle at which the sun rays impact the collector in the non tracking direction. If the sun position is normal to the plane of the collector then the incidence angle is zero. Since the Modesto field tracks the sun east to west the incidence angle is driven primarily by the sun's seasonal path across the sky which is more toward the south during the winter months and closer to directly overhead during the summer. Incidence angle modifier is the impact of incidence angle on system performance; this is indicated as "K" as in Figure 5 and is a unit less variable.
- Insolation - the intensity of the sun beam's energy at ground level. Insolation is indicated here as "I" and expressed in Watts per square meter of concentrating surface (W/m^2).

The results of the 1995 tests are the formulas and plot expressed in Figure 5. These formulas were used to define the system performance for the models on which system feasibility and anticipated output were based.

2.7 Comparison to System Model

Multiple feasibility models of the solar system built in Modesto have been developed prior to construction. Modeled annual system output ranged from 13.8 billion BTU/ year to 14.7 billion BTU/year of recoverable solar thermal energy. Using an anticipated net efficiency of 75 percent for the existing natural gas boilers, this yields the previously indicated 18 billion BTU/ year to 20 billion BTU/ year of expected natural gas reduction.

Two of the models were published by Dr. Andy Walker and Dr. Chuck Kutscher of NREL (Walker, et al., 2007). In the paper Dr. Walker presented a customized annual simulation which utilized an 8 year average of solar intensity data. The simulation computes the sun position, including incidence angle, for every hour of the simulation year. Intensity data provided by the average data set is used to determine the input energy to the system and the efficiency is calculated using parameters from the Sandia tests. The results of the model indicated an estimated annual energy output of 14.7 billion BTU/ year from the Modesto solar field.

In comparison, Dr. Kutscher computed annual output using empirical modeling equations published by the Solar Energy Research Institute's Industrial Process Heat design handbook (Kutscher, 1982). Dr. Kutschers emperical model computed total annual heat output of 14.5 billion BTU/year, very close to the hourly simulation. The empirical model neglects the effects of piping heat losses during operation and overnight.

Comparison of actual performance to the system models requires evaluation of (1) net efficiency of the system under specific conditions compared to the formulas expressed in Figure 5 and (2) total energy output of the field over the course of a month or year to that anticipated by the annualized models.

Since there are some differences between the components of the installed system and the models, then the approach will also include making the corresponding adjustments to the models.

CHAPTER 3: Project Outcomes

3.1 Contract for Design and Construction

American Energy Assets (AEA) and Frito-Lay Inc. were successful in contracting to build the solar field in a manner which met the goals of this PIER project while focusing on the financial and performance goals of the plant. The contract called for a solar field consisting of 54,500 ft^2 of concentrating collectors, high pressure steam supply at 300 psig, and lower grade heat in the form of hot water for cleaning or boiler feed water preheating.

Industrial Solar Technologies, now part of Abengoa Solar Inc. (ASI), was to provide the design and fabrication of the collector equipment, drives, and sun tracking controls through a sub-contract with AEA. Abengoa Solar was to provide the model PT-1 parabolic trough solar concentrating system similar to the system utilized in the Sandia tests.

As such the project was successful in meeting the goal of contracting for the construction of the system in a manner which met the needs of all parties involved.

3.2 System Design

System design followed the scope and scale of the project in a similar manner to the contract. The team was successful in designing both the solar field and the associated plant heat recovery equipment which would meet the project and contract goals. The plant steam recovery equipment was designed to a capacity of 9,000 lb/hr of sustained system output with over 10,000 lb/hr of capable steam output at the steam generator.

Design hurdles were nothing out of the ordinary for a project of this scope and included: adequate structural design for the seismic zone 4 build site, complexity of managing system pressures due to the use of water as a solar heat transfer fluid, and adequate materials for high operating pressures and temperatures.

3.3 Construction and Commissioning

Prior to construction of the designed system the project was broken into three phases. The project was successful in building the first two phases of the project which included the full 54,500 ft^2 solar field and plant steam recovery system.

The third phase of the project, which was the addition of the hot water recovery system for plant clean-in-place water, was not built. Since the goals of the project were to produce a cost-effective system, the project was successful in identifying that this portion did not meet the customer's return on investment goals. The loss of this source of low grade heat recovery would, however, negatively impacts the annual output of the system compared with the project goal.

In lieu of the CIP heat exchanger a medium pressure steam tie-in was added to make up some of the lost heat recovery opportunity. As such the project team was successful in meeting the requirements for interconnection to the plant's existing infrastructure.

3.4 Cost-Effective, Reliable, and Safe Operation

3.4.1 Cost-Effective

Final design, construction and startup cost of the project was $0.439 per BTU/hr ($1,500 per kW) of design thermal output. In addition to natural gas offset, the customer has realized federal tax credits for the installation further reducing the effective project cost. Net payback was originally estimated at about 7 years, provided system performance goals are met and the system is cost-effective by the customer's payback standards. If the system performance is below expected and/or natural gas prices remain below $9/MMBTU then the system payback will be extended.

Because the project team was unsuccessful in installing the complete heat recovery system some of the assumed recoverable heat will not be available. Project cost was reduced somewhat by not installing the CIP water system, however, the loss in annual output may not warrant this exclusion over the long run.

3.4.2 Reliable

The system has encountered some mechanical failures as expected for a project of this scope. Upon entering the second solar season of operation the system is starting up successfully according to the calculated sun position each morning.

The project team has encountered some unforeseen hurdles in the way the conventional gas boilers unload with the addition of steam from the solar field. Difficulties primarily exist in conditions when plant load is very low and load available for the two natural gas boilers is below minimum throttling capabilities. The team expects these limitations can be resolved by adjustments to plant operations. If not, unfortunately, during periods of low-load the solar field output will have to be throttled back from its full potential. To date these issues have reduced the available operating time of the system and potential energy recovery during operating hours.

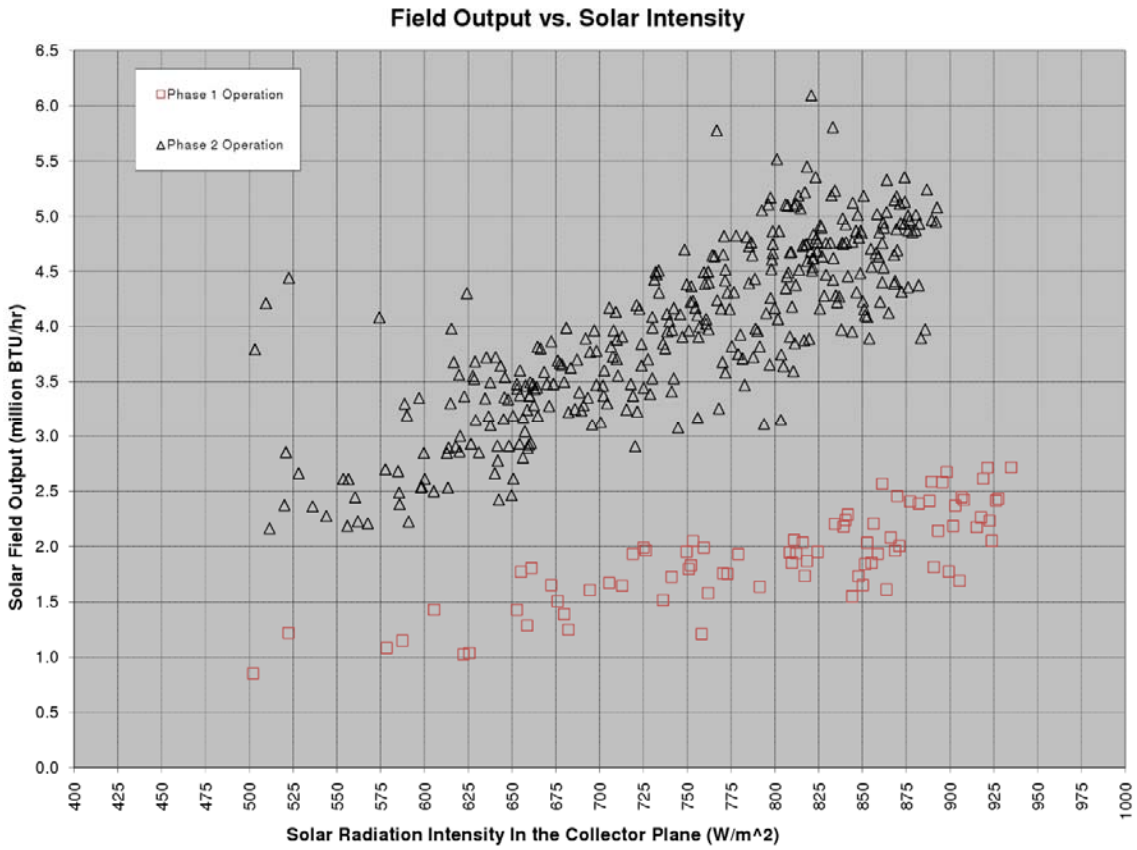
3.4.3 Safe Operation

In its second solar season of operation the system has proven safe with no failures of high pressure equipment or controls.

3.5 System Performance Measurement

Performance of the system in the 13 months following the startup of phase 1 are illustrated in Figure 6. The field was shutdown as planned between November and March due to inadequate solar conditions.

Figure 6. Solar field performance as of 5/28/2009



Source: American Energy Assets, California L.P.

Peak system performance is behind expected output levels by about 30 percent, under like conditions. Several efforts are ongoing to identify sources of performance deficiency including the evaluation of: final optical accuracy of the field, sun tracking effectiveness, optical material efficiencies, washing procedures and soiling abatement.

Performances of the test loop, under improved conditions, indicate full field performances of 9 million BTU/hr to 10 million BTU/hr under idealized sun conditions are achievable with the installed system.

Annual plant utilization of energy available from the field is approximately 86 percent to date. Expected utilization was 100 percent. The primary reason for slightly reduced utilization is minimum firing capabilities of the plant's natural gas boilers. Control changes can be made to plant operations allowing at least one of the boilers to power down completely in order to keep sufficiently load on the second boiler while the field is operating and total plant load is low. Additionally due to steam leakage into the condensate system from major process equipment the plant is not able to utilize heat from the field's 90 psig steam system.

3.6 Comparison to System Model

The final constructed test system varies from the system models in several ways which reduce the potential annual output of the system compared to the models. The primary gaps between the annual models and the system as built include:

- No low grade heat dump due to removal of CIP system from the scope limits annual heat recovery potential. The addition of a medium pressure tie-in to the plant makes up for some portion of the expected loss in heat recovery.
- The addition of over 1,000 ft of distribution piping was required increasing system volume, warm-up time, and thermal losses.
- Due to local environmental conditions soiling impacts measured in the field have been significantly more than anticipated by the models, reducing the potential output by as much as 6 percent over the model.
- Mechanical and control limitations in the field prevented the test system from operating as many hours per day as modeled.

The net impact of these differences has been evaluated by Dr. Andy Walker of NREL through modifications to his original hourly system model. In total the above issues represent approximately 39 percent reduction in ideal annual peak performance energy output from the field. This results in a revised expected natural gas offset of 12 billion BTU/year, significantly below the project goal of 20 billion BTU/year.

In addition to the above model gaps, which primarily address the annualized performance, there are gaps in the calculated peak performance of the models. The models use the original Sandia Laboratory test efficiency parameters to determine the output of the system under various sun conditions. Field design expected that the real-world collector performance would be somewhat below the idealized laboratory tests. However, the field models expect near ideal output under all solar conditions. As a result, the models over-predict the expected field performance on an hour by hour basis. This means that a system designed to meet the peak performance goals will fall short of the modeled annual output for reasons additional to the model gaps indicated above, even with 100 percent utilization by the plant.

CHAPTER 4:
Conclusions and Recommendations

4.1 Conclusion

Overall the project was successful in meeting the PIER project goals with the exception of energy recovery to date.

Conclusions to the seven specific project goals are as follows:

1. **Contracting:** The parties involved were successful in contracting to install to complete the system and meet the original PIER project goals. Completing the contracting process demonstrated that the project could be made viable to the manufacturing customer from a business perspective.
2. **Design:** The completed design met all aspects of the original PIER project, further demonstrating feasibility of this type of system for high temperature industrial process heat.
3. **Construction:** While the constructed system was required to deviate from the original project goals the system was installed in the scale of the original project. Reductions in final constructions scope, however, will result in reduced annual energy savings.
4. **Instrumentation:** The project was successful in installing instrumentation and data collection systems that have made research and analysis possible.
5. **Demonstration:** While the system has operated in a reliable and safe manner, overall return on investment is expected to be lower than forecast due to feasibility model assumptions and deviations from the original project scope.
6. **Performance Measurement:** Performance measurement activities continue into the system's second solar season of operation. While peak performance has been measured below design goals activities continue to improve system efficiencies.
7. **Model Comparison:** Current expected output is approximately 39 percent below modeled due to the removal of the CIP system, current plant utilization levels, and performance expectations of the models compared to actual designed performance.

4.2 Recommendations

The project team recommends that performance evaluation and efficiency improvement activities continue through this solar season. Additionally, performance monitoring should continue for the operating life of the project to assure maintained performance.

To accurately evaluate the system performance against baseline models, efforts should be made to adjust and reapply the models using the design capabilities of the installed system.

4.3 Benefits to California

California's inland areas receive some of the highest levels of annual sun radiation in North America. This energy represents a resource to the citizens of California which can be harvested to produce high temperature process heat used by many industries in the state. Reducing industrial natural gas usage lowers manufacturing costs, thus making California more attractive for manufacturing companies, providing jobs, and boosting tax revenue.

Industrial process heat generation through solar technologies provide an additional opportunity to reduce statewide greenhouse gas and chemical emissions caused by burning natural gas.

REFERENCES

Dudley, Vernon E. 1995. *Test Results Industrial Solar Technology Parbolic Trough Solar Collector.* Albuquerque, NM : Sandia National Laboratories, 1995. SAND94-1117.

Kutscher, Charles F. et al. 1982. *Desgn Approaches for Solar Industirla Process Heat Systems: Nontracking and Line-Focus Collector Technologies.* Golden, CO : Solar Energy Research Institute, 1982. SERI/TR-253-1356.

NREL. n.d.. Atlas For The Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors. [Online] n.d. [Cited: May 26, 2009.] http://rredc.nrel.gov/solar/old_data/nsrdb/1961-1990/redbook/atlas/colorpdfs/85.PDF.

Walker, Andy and Kutscher, Chuck. 2007. *Design and Analysis of a Large Solar Industrial Heat Plant for Frito Lay in Modesto California.* Golden, CO : NREL/ASME, 2007. ES2007-36050.

GLOSSARY

Abengoa	Abengoa Solar Inc.
AEA	American Energy Assets, California L.P.
BTU	British thermal unit
Frito-Lay	FRITO-LAY, INC.
ft^2	square feet
gpm	gallons per minute
m^2	square meter
NREL	National Renewable Energy Laboratory
psig	pounds per square inch gauge pressure
RD&D	research, design, and demonstration
RTD	resistance temperature detector
kW	kilowatt