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FINAL PROJECT REPORT

DEMONSTRATION OF COMBINED HEAT AND POWER WITH THERMAL STORAGE FOR MODERN GREENHOUSES

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PREFACE

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

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Demonstration of Combined Heat and Power with Thermal Storage for Modern Greenhouses is the final report for the Demonstration of Combined Heat and Power with Thermal Storage for Modern Greenhouses project (contract number PIR-11-023-01) conducted by Southern California Gas Company. The information from this project contributes to the Energy Research and Development Division's Environmentally Preferred Advanced Generation Program.

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ABSTRACT

This project successfully demonstrated a combined heat and power system, integrated with thermal energy storage, at Houweling's Tomatoes, a 128-acre California greenhouse. A natural gas engine-generator produces hot water to warm the greenhouse and electricity to power grow lights, plus carbon dioxide to accelerate photosynthesis. Thermal energy storage adds flexibility to the system, letting operators meet these loads more economically. Greenhouses use little electricity when grow lights are off, so surplus power is sold to the utility.

The design of the 4.2-megawatt demonstration unit was based on the customer's experience with two existing units, bringing total heat and power capacity at the host site to 12.6 megawatts. The combined heat and power system's net electrical generation efficiency was 38 percent; with 50 percent of the fuel's heat being recovered, the system's overall efficiency averaged 88 percent.

The market for combined heat and power in California greenhouses could exceed 2.2 gigawatts if projects can be developed more efficiently and less costly, without grid-connection and power-sale agreements delays.

For combined heat and power to infiltrate California's potential greenhouse market, technical and economic data must be verified, analyzed, and documented, then communicated to various audiences. Furthermore, it is essential to (1) streamline and expedite interconnection and power-sale agreements and (2) amend California's feed-in tariff rules to be more clear and advantageous to energy consumers. Also helpful would be a guidebook for navigating the grid-connection and power-sale agreement processes.

Keywords: combined heat and power, distributed generation, reciprocating engine, thermal energy storage, agriculture, greenhouse, carbon dioxide enrichment, interconnection, feed-in tariff, power purchase agreement

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EXECUTIVE SUMMARY

Background

Modern greenhouses were introduced in Northern Europe, where traditional farming is constrained by land area and climate. Within the glass-covered structure, the temperature, humidity, light, and carbon dioxide levels are controlled to optimize plant growth 24 hours a day, 365 days a year. Crops are grown hydroponically (without soil) through drip irrigation, delivering the right amount of water and nutrients to the plants at the right time.

Precise irrigation, coupled with rainwater collection, reduces water use by 83 percent compared to traditional farming (per unit weight of produce), and no chemicals are required to kill weeds. High-tech greenhouses can yield more than 24 times the produce than the same acreage of open land. Besides operating year-round, virtually immune to the weather or season, greenhouses can be sited closer to consumer markets, giving the produce a fresher taste and longer shelf life at a competitive price. Because of these advantages, the greenhouse farming concept has begun to migrate from Northern Europe to other parts of the world.

California's coastal climate provides ideal growing conditions for vegetables such as tomatoes, lettuce, bell peppers, and cucumbers, and well-suited to greenhouses. Some 538,000 acres of these vegetables – valued at $3.2 billion – were harvested in California in 2010. California's coast is also ideal for modern greenhouses, which requires heat mostly at night to maintain temperatures around 70°F (21°C). Currently, California has three mega-greenhouse complexes, each with more than 100 acres under glass. Many greenhouse operators inject carbon dioxide when photosynthesis is active to accelerate plant growth. Greenhouses use relatively little electricity unless grow lights are turned on at night or on overcast days to mimic daylight and extend the photosynthetic productivity of the plants.

Modern greenhouses, because they require temperature control and enriched carbon dioxide levels, can be a good application for combined heat and power technology. A natural gas-fueled engine-generator produces hot water to warm the greenhouse and electricity to power grow lights, plus carbon dioxide from the engine exhaust to accelerate photosynthesis.

Project Purpose

Southern California Gas Company demonstrated the economical operation of combined heat and power technology, integrated with thermal energy storage, at a state-of-the-art greenhouse complex. The greenhouse complex, operated by Houweling's Tomatoes, covers 128 acres in Camarillo, California. Beginning in 1996, Houweling's gradually built its greenhouse property starting with its first two engine-generators beginning operation in late 2011, and grow light installation soon completed afterward. The grid interconnection and power purchase agreements were signed in 2013, and the third combined heat and power system, the focus of this project, was commissioned in January 2014.

This project included optimizing the system for California's coastal climate, measuring the system's performance quantitatively, and complying with the state's environmental and utility regulations. In practice – heat, electricity, and carbon dioxide – do not usually occur at the same

time. The demand for carbon dioxide, for example – when plants are growing during the day or whenever grow lights are on – does not usually coincide with the greenhouse's demand for heat, which is mostly at night. The engine-generator's output in a combined heat and power system must be scheduled to meet these three loads in the most economical way.

If the engine's heat can be stored as hot water, the greenhouse operator has more flexibility to run the engine when electricity or carbon dioxide is required. Or, when the greenhouse's grow lights are off but the engine is running to supply heat or carbon dioxide, the operator must sell power to the electric utility.

The greenhouse operating strategy depends strongly on the value of this surplus power. For combined heat and power projects, a special feed-in tariff applies to exported power. The rate paid by utilities varies by the time of day (peak, mid-peak, off-peak, or super-off-peak) and the season of the year (summer or winter months). Also, the various utility charges that can be avoided by powering the grow lights on-site can greatly improve the economics of combined heat and power.

The project documented the hurdles involved in launching a combined heat and power system in a California greenhouse and the lessons learned along the way. These hurdles included connecting with the electric utility grid, reaching an agreement for surplus power export and sale, and analyzing complex feed-in tariff rates and other utility charges.

Project Process and Results

Combined heat and power systems are usually sized to match the thermal load of the application – for example in the Netherlands, the rule of thumb is 0.2 megawatt per acre under glass. Because California's coastal climate is more temperate, however, less heating capacity is required, and the project team determined that the rule of thumb is closer to 0.1 megawatt per acre.

A 4.2-megawatt engine-generator made by GE Jenbacher was selected for the combined heat and power unit being demonstrated in this project. GE's standardized platform for greenhouses combines in one package the engine, generator, catalytic converter, heat exchangers, and all of the balance-of-plant equipment and controls.

The Houweling's greenhouse complex already had two other 4.2-megawatt units in operation, for a total capacity of 12.6 megawatts. With 128 acres under glass, this is about 0.098 megawatt per acre – the first-of-its-kind benchmark case for coastal California. Each combined heat and power unit serves about one-third of the greenhouses. Only one of the six greenhouses at Houweling's is equipped with grow lights, however, the electrical load for only these lights is nearly 11.4 megawatts. The grow lights are not served by the electric utility, so they consume about 90 percent of the engine-generated power when they are turned on.

The engine-generators at Houweling's are integrated with three thermal energy storage tanks, each holding one million gallons of water. Houweling's also operates four condensing natural gas-fueled boilers, with, water circulating through a thermal loop connecting the engine, the greenhouses, and the thermal storage tank. The only way to cool the engine is to send hot water

to the greenhouse or to the storage tank. In other words, the engines cannot run when the greenhouse needs no heat and the storage tank is fully charged. The engine system incorporates catalytic after-treatment to remove harmful components from the exhaust before it is routed to the greenhouses.

The performance of the third combined heat and power unit was monitored from June 2014 through January 2015. The Houweling's system has been faultless except for routine scheduled maintenance. Net electrical efficiencies have averaged 38 percent, and overall efficiencies averaged 88 percent. After a utility rate increase in February 2015 for the baseline electric rate for the grow lights, the annual net revenue from CHP Unit 2 increased from $1.12 million to $1.42 million, decreasing the simple payback period from 4.7 years to 3.7 years.

During this demonstration, the agreements for grid interconnection and power sales took about three years to complete. This skewed the economic picture and contributed to the business risk of Houweling's investment. Houweling's had to coordinate with multiple regulatory, governmental, and utility groups on grid interconnection issues. Houweling's also incurred considerable engineering and legal expenses to obtain a reasonable price for the distribution line needed to export surplus power.

Benefits to California

Houweling's experience with the technology, along with the trove of data collected over the years, proved very useful to the project team during design, installation, and start-up. The market potential for combined heat and power technology in California greenhouses could exceed 2.2 gigawatts for four major crops. Small greenhouses, however, may not benefit from the same economies of scale as mega-greenhouses like Houweling's because of tariff, institutional and market barriers.. The simple payback for the 4.2-megawatt combined heat and power system demonstrated at Houweling's is expected to be less than four years, whereas a smaller system (one megawatt) would have an estimated payback of more than nine years.

Introducing greenhouse CHP technology to California agriculture could have other benefits. Vegetables grown in California greenhouses could increase the state's exports to neighboring states. Furthermore, other commercial buildings with noncoincident electrical and heating loads might benefit from CHP technology integrated with thermal energy storage.

Even with these challenges regarding delays to procur interconnection agreements and power sales, using advanced combined heat and power systems, like Houweling's have shown promise. To spur implementing more combined heat and power technology in California greenhouses, it is essential to continue technical and economic verification, improving institutional and regulatory, and outreach activities such as site visits.

CHAPTER 1: Introduction

Southern California Gas Company (SoCalGas), with funding from the California Energy Commission, conducted a combined heat and power (CHP) demonstration project at a 128-acre greenhouse complex in Camarillo, California, operated by Houweling's Tomatoes.

The technology demonstrated in this project could position CHP for the emerging high-tech greenhouse market in California. Some 538,000 acres of cucumbers, lettuce, bell peppers, and tomatoes – valued at $3.2 billion – were harvested in California in 2010. All of this produce is considered a good fit for modern greenhouses.

1.1 Project Goals

The goal of this project was to assess, design, and demonstrate the economical operation of CHP in a state-of-the-art greenhouse. This goal included implementing and monitoring a CHP system that is integrated with thermal energy storage (TES) and optimized for California's coastal climate and regulatory requirements. The project's end product is this report – a benchmarking study showing measured performance metrics, describing how hurdles were navigated, and laying out the methodology that was developed to optimize the greenhouse CHP system's design and operating strategy.

The primary objective of this project was to quantitatively measure the performance of an optimal CHP-powered greenhouse with maximum heat recovery, low heat loss, and integrated TES. The project team's approach included optimal sizing and operation of the CHP and TES equipment, along with enhanced heat recovery (condensing heat exchange).

The project objectives also included documenting the time and cost involved in these processes:

- Grid interconnection agreement with the electric utility, consistent with the still-evolving Rule 21 for exporting excess electricity to the utility grid
- Power purchase agreement with the electric utility through the new feed-in tariff for CHP, which was implemented by the California Public Utilities Commission (CPUC)

Table 1 lists the technical performance goals for the engine selected for this demonstration project. Goals included emissions of nitrogen oxides (NO_x), carbon monoxide (CO), and reactive organic compounds (ROCs)[1], as well as production of carbon dioxide (CO_2) for enriching the greenhouse atmosphere. Fuel consumption, efficiency, and heat rate are calculated using the higher heating value (HHV) of the natural gas fuel.

[1] Reactive Organic Compounds as defined by the Ventura County Air Pollution Control District: http://www.arb.ca.gov/drdb/ven/curhtml/r2.pdf

Table 1: Technical Performance Goals

Electrical	
Gross power output	4,347 kW_e
Ancillary power requirements	130 kW_e
Net power output	4,217 kW_e
Fuel consumption*	35.8 million Btu/hr (37.8 gigajoules/hr)
Net electrical efficiency*	40.2%
Net electric heat rate*	8,487 Btu/kW_{th}h (8,954 kilojoules/kW_{th}h)
Thermal	
Exhaust to 100°F (38°C)	9.9 million Btu/hr (10.4 gigajoules/hr)
Intercoolers plus lubricating oil	6.4 million Btu/hr (6.8 gigajoules/hr)
Engine jacket water	1.9 million Btu/hr (2.0 gigajoules/hr)
Total recovered heat	18.2 million Btu/hr (19.2 gigajoules/hr)
System	
Overall heat-and-power efficiency*	90%
Availability	95%
Net CO_2 production	455 lb/MW_eh (206 kilograms/MW_eh)
Environmental (permitted levels)[2]	
NOx**	5 ppm
CO**	80 ppm (see Note)
ROCs**	11 ppm
* Calculated using the engine fuel's higher heating value. ** Corrected to 15 percent oxygen.	
Note: In practice, carbon monoxide levels are kept below 1 ppm to protect the crops.	

Source: DE Solutions, Inc.

The system demonstrated in this project uses condensing heat recovery in the CHP equipment, a well-insulated TES system, and more efficient power dispatch and thermal load management. These improvements increase the system's overall efficiency from 79 percent to 88 percent (HHV).

1.2 Project Team

This collaborative project involved several key team members. All of them are committed to the to the project goal of increasing the likelihood of success for CHP technology integrated with TES in the California greenhouse market. The project team has the financial, management, and technical resources to advance the technology from demonstration to commercialization.

2

1.2.1 Prime Contractor

SoCalGas, the prime contractor, is the largest natural gas distribution utility in the United States, serving 20.1 million consumers. SoCalGas is closely aligned with the greenhouse industry, strongly supports the California Energy Commission's Natural Gas Research Program, and has provided match funding for many Commission projects. SoCalGas also has proven capabilities in developing technology, managing projects, and facilitating commercialization. SoCalGas is a California-based entity. SoCalGas has been involved in several other California Energy Commission projects.

Stephen Martz, SoCalGas, served as the Project Manager for this greenhouse CHP technology demonstration. Mr. Martz is SoCalGas's Senior Project Manager for Research, Development, and Demonstration (RD&D). He is the primary program manager for CHP and natural gas vehicle technologies. Mr. Martz has also served as a Project Manager for the SoCalGas Transmission Operations group, as well as the Operations Manager for the Aliso Canyon Storage Facility in Northridge, California. Mr. Martz holds a Bachelor of Science degree in Chemical Engineering from California State Polytechnic University, Pomona.

1.2.2 Other Project Team Members

Houweling's Tomatoes is one of the pioneers to recognize coastal California as a fertile location for state-of-the-art greenhouses, which were introduced in Northern Europe where farming acreage is limited. Houweling's is committed to making CHP an integral part of the company's greenhouse complex in Camarillo, California. Houweling's Nurseries Oxnard, Inc., is a California-based entity.

GE Jenbacher manufactures the high-performance CHP engine equipment used in Northern European greenhouses for CHP. An estimated 1,800 such engines are operating in the Netherlands and Belgium, not only serving greenhouses but also supplying about 20 percent of the two countries' electricity demand.

Western Energy Systems is the distributor of GE Jenbacher engines in the western United States. Western Energy Systems is a California-based entity.

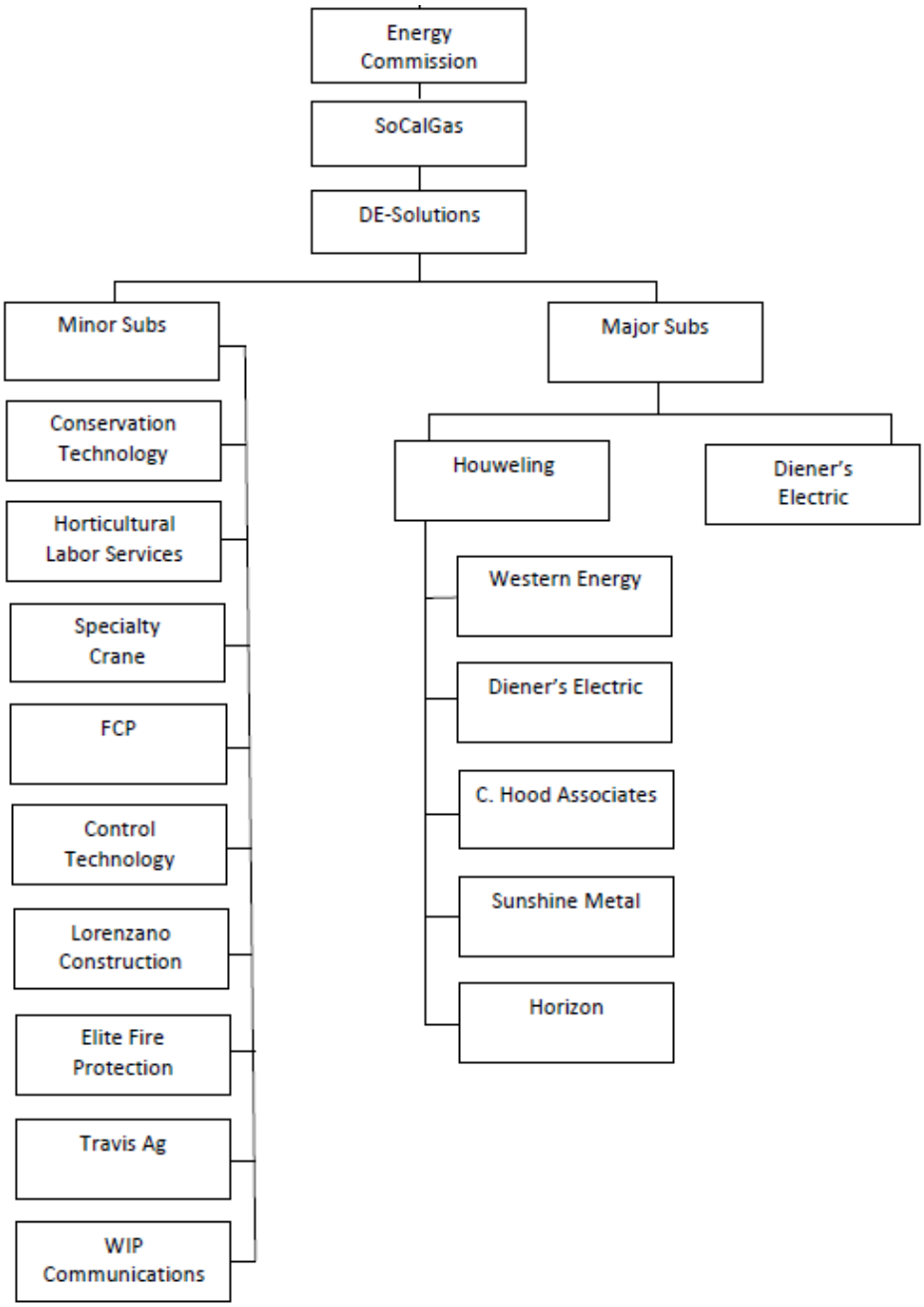
DE Solutions, Inc., is a professional services company meeting the needs of the distributed energy marketplace. Its services include technology development and deployment, application engineering, project management, market analyses, technology assessments, and business and market strategy support. DE Solutions, Inc. is a California-based entity.

Diener's Electric is a full-service electrical contracting firm that focuses on agricultural and industrial installation and maintenance. Its clients are primarily food processors, refrigerated storage companies, farming operations, water districts, and local industry. Diener's Electric is a California-based entity.

Conservation Technology is a consulting group that manages advanced energy projects and provides measurement and verification services. Conservation Technology is a California-based entity.

Figure 1 shows the team structure, and Table 2 describes the principal team members' roles.

Figure 1: Organizational Chart for Greenhouse CHP Project Team



Source: DE Solutions, Inc.

Table 2: Roles of Principal Team Members in Greenhouse CHP Project

Organization	Project Role
California Energy Commission	Contract manager and publisher of research results
SoCalGas	Prime contractor, match funder, project management, commercialization support
Houweling's Tomatoes	Demonstration site host, major CHP project funder, CHP system operator
GE Jenbacher	Power plant provider, greenhouse application experience
Western Energy Systems	GE Jenbacher distributor, application support
DE Solutions	Subcontract manager, technical advisor, administration, performance characterization, economic analysis, and project management support
Diener's Electric	Electrical engineering, high-voltage construction, grid interconnection agreement
Conservation Technology	Measurement & verification (M&V) including instrumentation procurement and installation, data collection and reporting

Source: DE Solutions, Inc.

CHAPTER 2:
Greenhouse Demonstration Site

2.1 Modern Greenhouses

Modern greenhouses were introduced in the Netherlands and other Northern European countries where traditional farming is constrained by land area and climate. The greenhouse shell is a glass-covered structure with complete climate and environmental control that optimizes temperature, humidity, light, and CO_2 levels (Figure 2). Crops are grown hydroponically (without soil) through drip irrigation, which delivers the right amount of water and nutrients to the plants at the right time. The greenhouse creates the ideal conditions for plant growth 24 hours a day, 365 days a year.

Figure 2: Houweling's Tomatoes Greenhouse

Source: Houweling's Tomatoes
Photo Credit: Houweling's Tomatoes

Precise irrigation, coupled with rainwater collection, reduces water use by 83 percent (per unit weight of produce), compared with traditional field farming, and no herbicides are needed to control weeds[3]. Modern greenhouses can yield more than 24 times the produce from the same acreage of open land farming[4]. Besides operating year-round, virtually immune to the weather or season, they can be sited closer to consumer markets, giving the produce a fresher taste and longer shelf life at a competitive price. Because of these advantages, the greenhouse farming concept has migrated from Northern Europe to other parts of the world, including California.

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[3] Source: Houweling's Tomatoes

[4] Source: Houweling's Tomatoes

California's coastal climate provides ideal growing conditions for vegetables such as tomatoes, lettuce, bell peppers, and cucumbers. Greenhouses are well-suited for growing these vegetable crops. California's agricultural sector generated revenue of $37.5 billion in 2010, of which $6.7 billion was for vegetable crops. Those suitable for greenhouse farming represent a significant portion of the vegetable crop revenue.

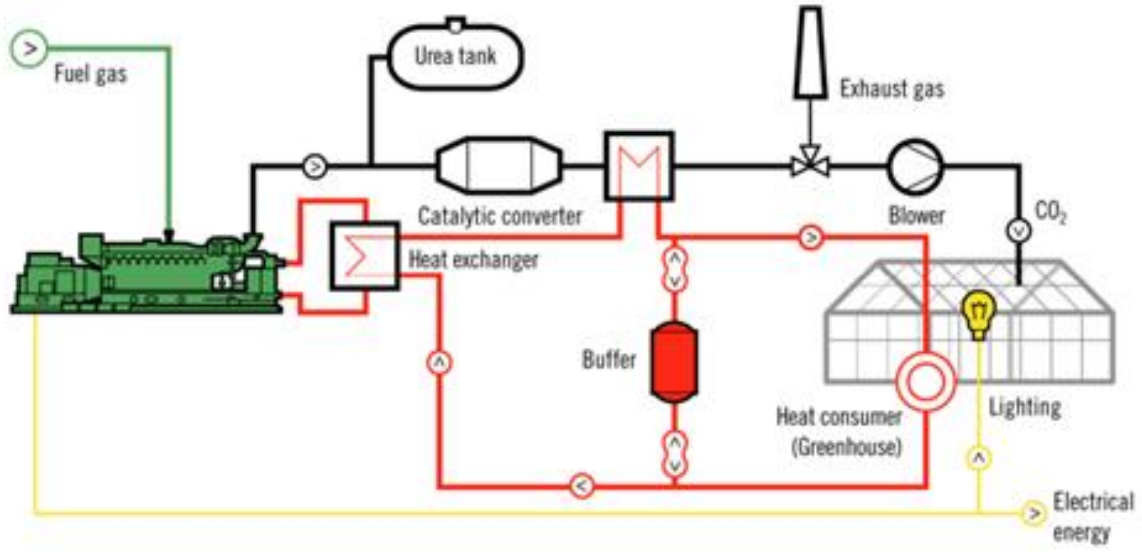
California's coastal region is also ideal for modern, high-tech greenhouses because of its temperate climate. Most of the time, greenhouses in the region require heat mostly at night to maintain temperatures around 70°F (21°C). Most greenhouses also need extra CO_2 to accelerate plant growth. Greenhouses use relatively little electricity except when grow lights are turned on at night to mimic daylight and extend the photosynthetic productivity of the plants.

Modern greenhouses, because they need temperature control and enriched CO_2 levels, can represent a good application for CHP. Their demand for CO_2, however – during the day and at night if grow lights are on – does not generally coincide with the need for heat (mostly at night). Also, greenhouse CHP needs a market outlet for excess electricity when the grow lights are off. To solve these issues, TES can decouple a greenhouse's heating load from its CO_2 requirement. Furthermore, the CPUC recently introduced a feed-in tariff (FIT) for CHP, which helps make the technology economically viable in California greenhouses.[5]

CHP integrated with TES (Figure 3) has already proven to be an economically promising technology for the evolving greenhouse industry in the Netherlands. An engine-based CHP system would operate during daylight hours and inject cooled exhaust into the greenhouse to enrich CO_2 levels. Heat from the engine and from its exhaust gases is captured and sent to a TES tank ("buffer"), which can supply heat to the greenhouse at night. Because the greenhouse's electricity demand is modest (unless grow lights are on), most of the generated electricity would be sold back to the grid at the favorable FIT rates.

[5] CHP Feed-in Tariff: http://www.cpuc.ca.gov/PUC/energy/CHP/feed-in+tariff.htm

Figure3: CHP with TES Schematic



Source: DE Solutions, Inc.

2.2 Site Layout and Existing Equipment

Houweling's Tomatoes began evolving its California greenhouse presence in the mid-1990s. At the time, CHP was a compelling energy-efficiency concept proven in the Netherlands, but not ready for implementation in California. Besides the lack of a FIT, the key missing element was a CHP sizing methodology that reflects the differences in thermal load requirements between the Netherlands and coastal Southern California.

Houweling's 128-acre greenhouse complex in Camarillo was built in six phases, with grow lights added incrementally (Table 3). Houweling's design and layout called for three CHP units. The first two (CHP Units 1 and 3) began operating in 2011. The third, CHP Unit 2, is the focus of this Natural Gas Research project.

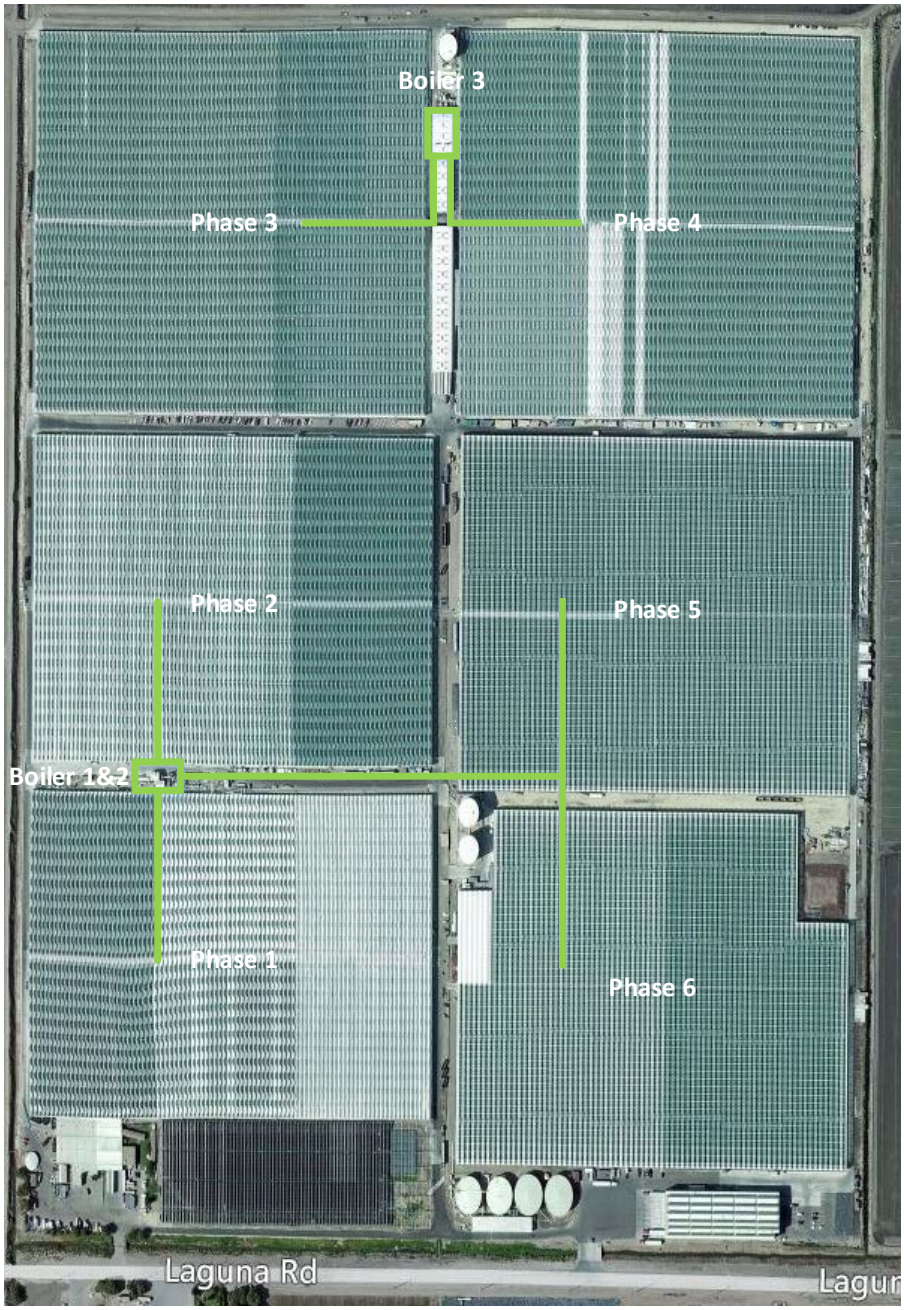
Table 3: Chronology of Houweling's Greenhouse Evolution

Year	Construction Build-Out
1996	Phase 1
1998	Phase 2
1999	Phases 3 and 4
2008	Phases 5 and 6
2010	Phase 2 grow lights – Section 1
2011	Phase 2 grow lights – Section 2
2011	CHP Units 1 and 3 commissioned
2012	Phase 2 grow lights – Section 3
2013	Grid interconnection and export agreements
2014	CHP Unit 2 commissioned

Source: Houweling's Tomatoes

The greenhouse complex (Figure 4) incorporates two boiler houses. Each boiler house contains two 30.3 MMBtu/hr condensing natural gas-fueled boilers. One boiler house serves Phases 1, 2, 5, and 6 of the greenhouse complex (that is, the southern two-thirds of the area). The second boiler house serves Phases 3 and 4 (the northern third). The complex also has three tanks for TES, each holding 1 million gallons of water, and three tanks for supplemental CO_2 enrichment, each holding 12,500 gallons (50 tons) of liquid CO_2.

Figure 4: Satellite View of Houweling's Camarillo Greenhouse Complex



Sources: DE Solutions, Inc.; Houweling's Tomatoes; Google Earth
Photo Credit: Google Earth

The high-pressure sodium grow lights were installed in the Phase 2 greenhouse over a three-year period beginning in 2010. Each of the three grow-light sections requires about 3,792 kilowatts electric (kW_e) for a total of 11,377 kWe (equivalent to 11.4 megawatts electric (MW_e)). Power for the first section of grow lights was initially supplied by the electric utility. After Section 2's grow lights were installed, CHP Units 1 and 3 were commissioned. Each unit can

generate 4.2 MW_e, so they began powering Section 1 and 2's grow lights in isolation from the grid. The interconnection and export agreements with the electric utility were not executed until September 2013, just before CHP Unit 2 became operational.

2.3 Baseline Operating Strategy

The project team documented greenhouse energy usage without any CHP equipment ("pre-CHP") to establish a baseline for the design, operation, and performance of the CHP units. The greenhouse operators enhance productivity and product quality according to the following key operating criteria:

- During periods of photosynthesis (daylight and grow-light operation), CO_2 levels are boosted from the 300—350 ppm range to 700—800 ppm. This increases productivity by about 25 percent. Although ambient CO_2 levels outside the greenhouse are closer to 400 ppm, the photosynthesis process depresses CO_2 levels inside the greenhouse without active CO_2 injection.
- Temperatures inside the greenhouses are kept at a minimum of 63°F (17°C) to avoid condensation and to minimize plant disease. The preferable night-time temperature is around 70°F (21°C).
- When the greenhouse interiors reach 67°F (19°C) during the day, vents in the greenhouse roof are opened to bring in outside air and dampen the heating effect of solar insolation. Mechanical cooling is not provided, so the temperature inside the greenhouse can float higher during the daytime. Infrequently, when the plants are exposed to temperatures around 95°F (35°C) or higher, the photosynthesis process slows considerably, and the plants focus on water intake.
- Run-time priority for the boilers is during photosynthesis periods, when the cooled CO_2-rich boiler exhaust is injected into the greenhouse and recovered heat is used to either warm the greenhouse or charge the TES tanks for night-time heating.
- Supplemental CO_2 is injected as needed during photosynthesis, and boilers are operated at night whenever the TES charge is insufficient.

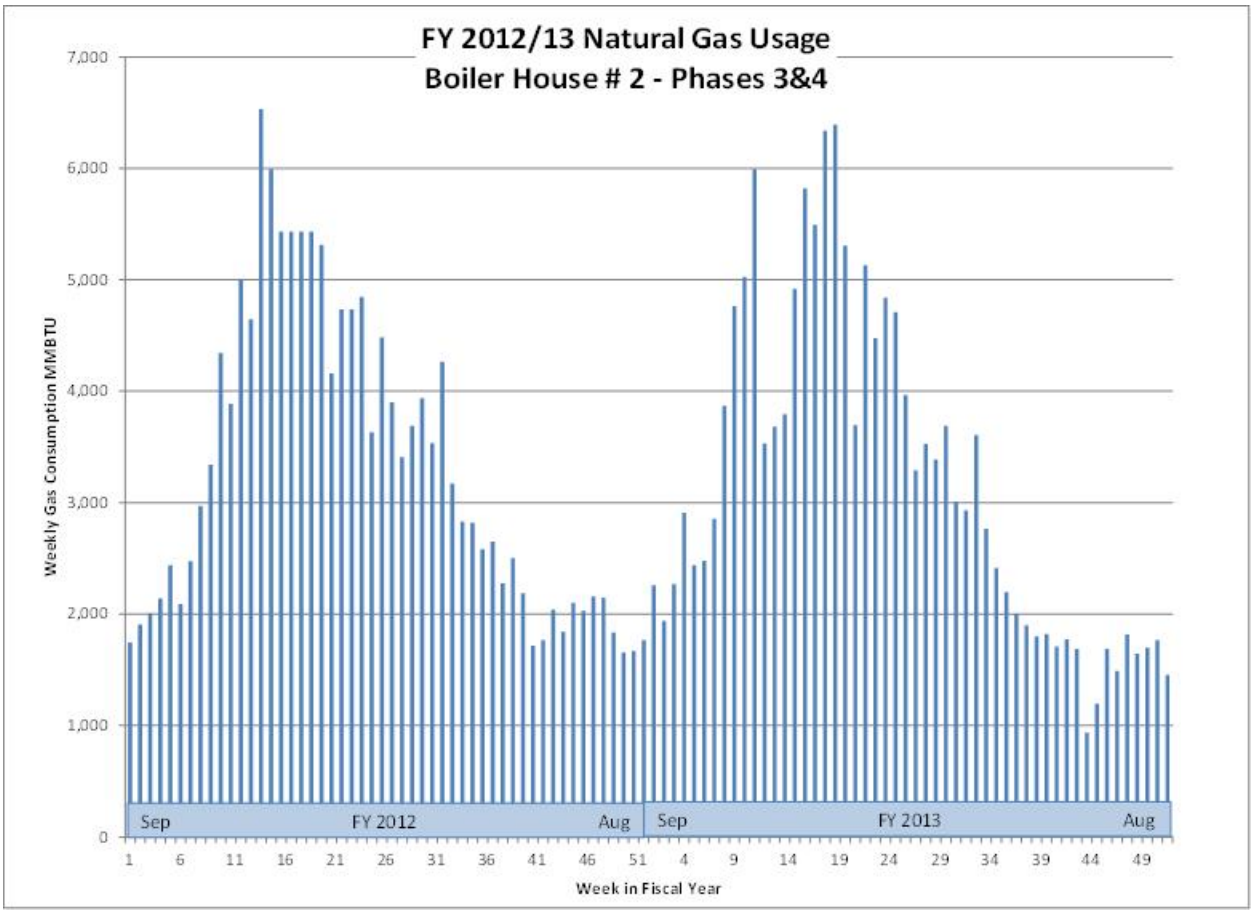
2.4 Energy and CO_2 Loads

The historical data are based largely on weekly or monthly logs that lack the granularity of a data acquisition system. The focus of this discussion is on energy and CO_2 usage patterns before any CHP equipment was installed, and in particular Phases 3 and 4 – the greenhouses that would eventually be served by CHP Unit 2, the last one installed and the subject of this Natural Gas Research project. The data are for fiscal years 2012 and 2013 (September 2011 through August 2013).

Figure 5 displays the weekly natural gas usage of the two 30.3 MMBtu/hr boilers serving Phases 3 and 4. As expected, gas use is much higher in the winter than summer. The best operating window for the boilers is during daylight hours when the cooled exhaust enriches the

photosynthesis process. Most of the heat from the boilers is stored in the TES tanks during the day and extracted at night to keep temperatures inside the greenhouse at 63°F to 70°F (17°C to 21°C). In the two-year period analyzed, summer gas fuel usage averaged about 11 MMBtu/hr (equivalent to 3.2 megawatts thermal (MW_{th})), whereas in the winter, it spiked into the range of 30 MMBtu/hr (12.4 MW_{th}), a difference of about 19 MMBtu/hr (9.2 MW_{th}) between summer and winter.

Figure 5: Pre-CHP Natural Gas Usage



Source: Houweling's Tomatoes

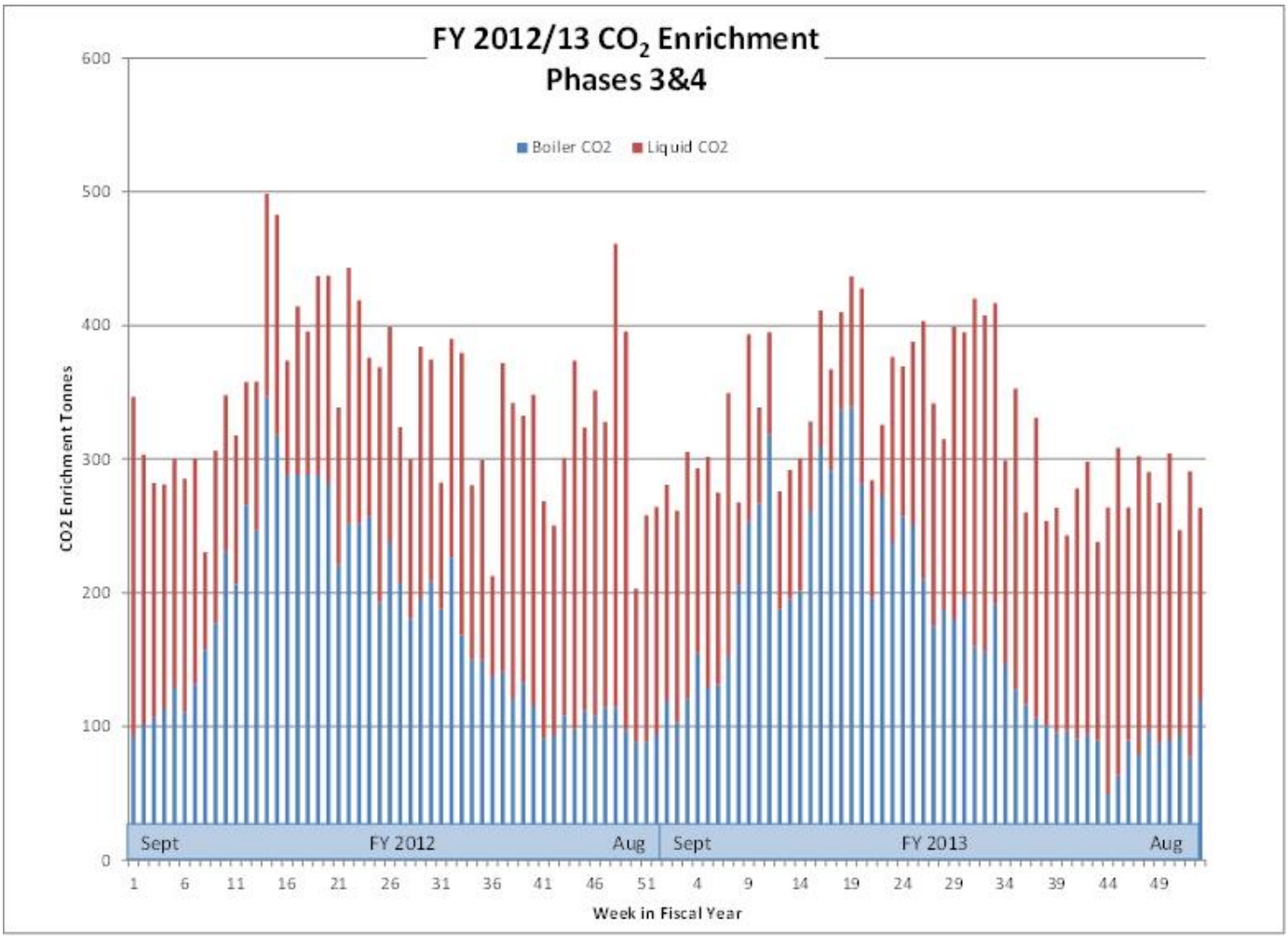
Figure 6 illustrates the weekly contribution of the boiler exhaust plus liquid CO_2 injection toward CO_2 enrichment for accelerated photosynthesis. It should be noted that the boilers were likely used sometimes at night during the winter. This would negate some of their contribution to the photosynthesis process, because these greenhouses have no grow lights for night-time operation.

Figure 7 shows monthly electricity consumption on-site for the five largest electric meters. Only one of these meters is for Phases 3 and 4, but all site loads are shown because several are unassociated with a particular greenhouse phase. Typical electricity consumption for a month is

about 800 kW_eh, or an average 1.1-MW_e demand. This is very small in relation to the average weekly thermal demand, which varies from 3 to 12 MW_{th} just for Phases 3 and 4.

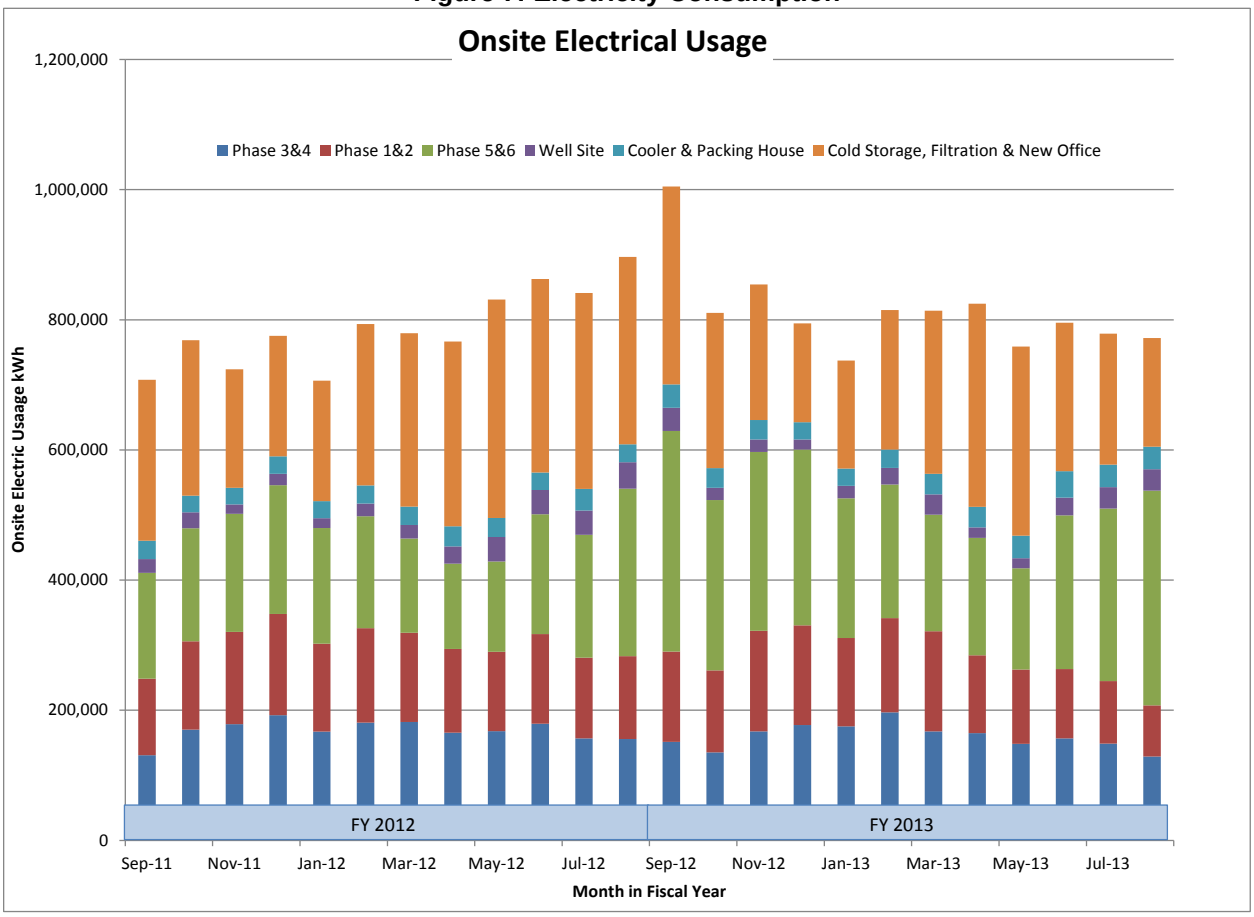
Figure 7 does not contain any data on the grow lights. For a brief period, electricity for the grow lights in Section 1 of Phase 2 was supplied by the electric utility grid. After Section 2's grow lights were added in 2011, CHP Units 1 and 3 were started up and were used exclusively to power the grow lights until the interconnection line and agreement were completed in September 2013. Likewise, Section 3 of the grow lights was added when CHP Unit 2 was started up. Each grow light section consumes about 3,792 kW_e, for a total power draw of 11,377 kW_e (11.4 MW_e).

Figure 6: CO_2 Enrichment Levels



Source: Houweling's Tomatoes

Figure 7: Electricity Consumption



Source: Houweling's Tomatoes

2.5 Environmental Considerations

The operating air permit from Ventura County Air Pollution Control District (VCAPCD) limits site air criteria pollutant emissions as follows in Table 4.

Table 4: Site Emission Limits

Permitted Emissions	tons/yr	lb/hr
Reactive organics	5.28	3.1
Nitrogen oxides	10.36	22.59
Particulate matter	3.76	2.76
Sulfur oxides	0.28	0.53
Carbon monoxide	72.59	45.61
Ammonia	4.76	1.47

Source: Ventura County Air Pollution Control District Permit to Operate

In addition, the boilers and CHP units have the following emission limits (Table 5).

Table 5: Equipment Emission Limits[6]

Emissions	CHP, ppm @ 15% O_2	Boilers, ppm @ 3% O_2
Reactive organics	11	N/A
Nitrogen oxides	5	40
Carbon monoxide	80	250
Ammonia	10	N/A

Source: Ventura County Air Pollution Control District Permit To Operate

Furthermore, to maintain the company's standard for product quality, Houweling's Tomatoes maintains a carbon monoxide emission limit of 3 ppm at 3 percent oxygen, equivalent to 1 ppm at 15 percent oxygen. The boilers are equipped with ultra-low CO burners designed specifically for greenhouses. The lean-burn engines are fitted with selective catalytic reduction to control emissions of NO_x, CO, ammonia, reactive organics, and methane (see section 3.1.3 for more detail). When the CHP engines are started, their exhaust must be bypassed to the atmosphere until the cleanup system gets up to temperature and reduces CO to levels acceptable for injection into the greenhouse. This usually takes between 35 and 45 minutes. Greenhouse gas emissions are discussed in section 3.2.3.

2.6 Implications of Existing Loads for CHP Operation

Prudent CHP systems are designed to match the thermal load of the application, as is the case with greenhouses designed for Northern Europe. Given the moderate California coastal climate, however, the CHP sizing per acre is smaller. Whereas the rule of thumb in the Netherlands is 0.2 MW_e per acre, the sizing for CHP in coastal California is closer to 0.1 MW_e per acre.

With the demonstration CHP unit added, the Houweling's greenhouse complex would reach a total CHP capacity of 12.6 megawatts. With 128 acres under glass, this works out to 0.098 megawatt (electric) per acre – a first-of-its-kind benchmark case for coastal California.

The TES system at Houweling's Camarillo greenhouse complex was sized and built before the commitment to proceed with a third CHP unit. The CHP system was not designed to dump recovered heat, so its run-time in the summer is limited when the export price for CHP electricity is at its highest. Thus CHP dispatch has to be orchestrated precisely to maximize export sales revenue.

[6] Per the Permit To Operate, the boilers are subject to VCAPCD Rule 35. The emission limits on the natural gas engines are applied as BACT, which is more stringent than VCAPCD Rule 74.9 and the EPA New Source Performance Standard (NSPS) Subpart JJJJ limits.

CHAPTER 3:
CHP System Design

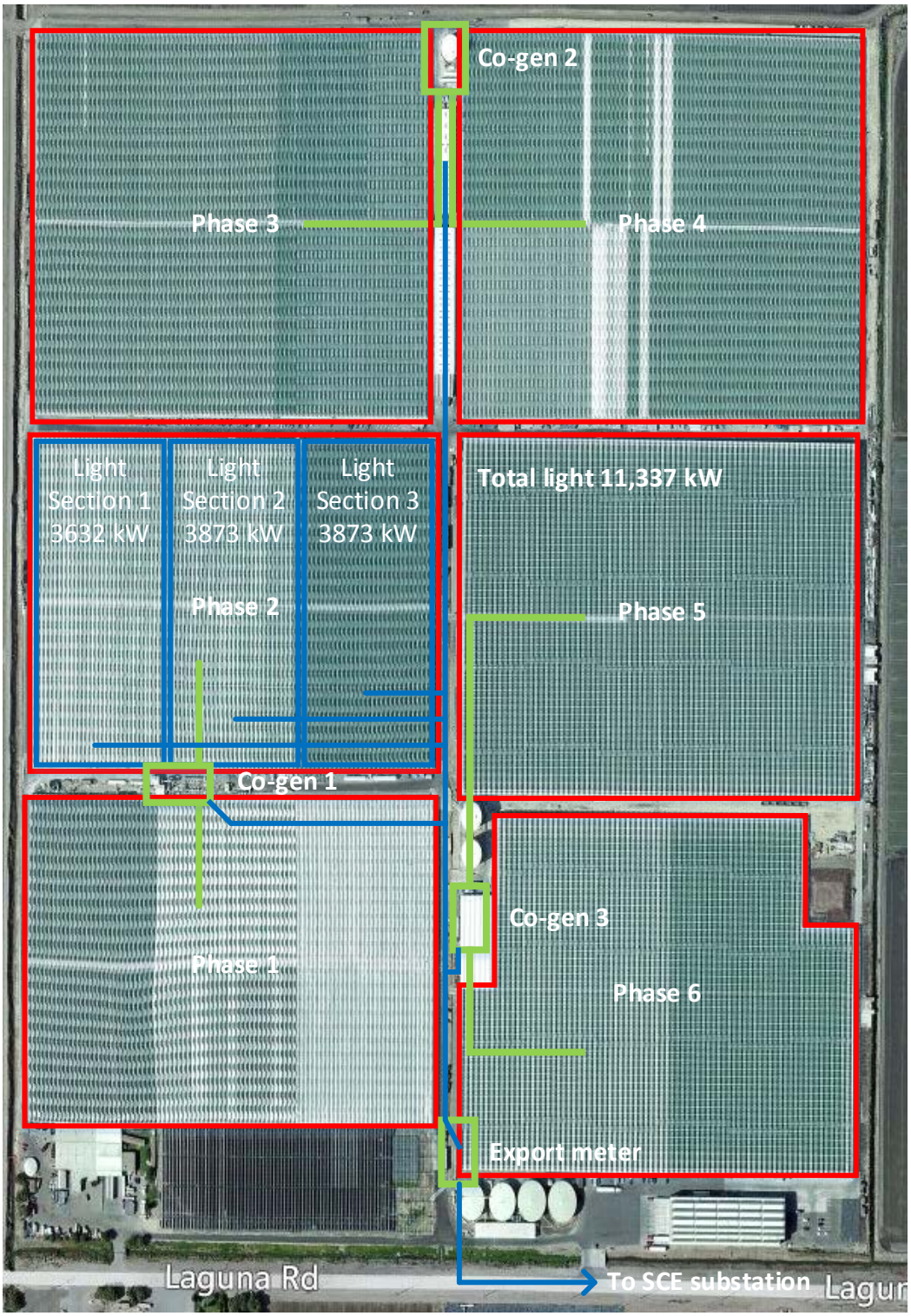
As noted earlier in section 2.1, the demand for CO_2 enrichment in modern greenhouses – during the day and at night if grow lights are on – does not generally coincide with the need for heat (mostly at night). TES can resolve this issue by decoupling a greenhouse's heating load from its CO_2 requirement.

The project team developed a design for a CHP unit to provide heat, CO_2, and power to Houweling's Tomatoes' 128-acre greenhouse complex in Camarillo. CHP Unit 2, the focus of this Natural Gas Research project, was the last of three CHP units to be installed and commissioned at the site, bringing total system capacity to 12.6 MW_e. The three CHP units each serve about one-third of the greenhouse area. The complex also includes two boiler houses, three hot-water TES tanks, and six liquid CO_2 storage tanks (described earlier in section 2.2).

A marked-up satellite view of Houweling's Tomatoes' Camarillo greenhouses, shows the location of the CHP unit installed for this demonstration ("Co-gen 2" at the top of the figure) (Figure 8). The 4.2-MW_e GE Jenbacher engine-generator joins two other CHP units on the site, labeled "Co-gen 1" and "Co-gen 3," each with 4.2-MW_e capacity. (For consistency's sake, these systems will be called CHP Units 1, 2, and 3.) CHP Unit 2 specifically provides hot water and CO_2 to the two greenhouses at the northern end of the site, an area of about 44.5 acres.

Grow lights are installed in just one of the six greenhouses on the site. Figure 9 shows the greenhouse complex at night with the grow lights illuminated. The power from the three CHP units is either sold back to the electric utility during the day or used to power the grow lights at night or on overcast days. The grow lights are connected to all three CHP units and are not served by the utility, so they can be powered only by the CHP-generated electricity. When the grow lights are on, they consume about 90 percent of the entire CHP system's 12.6-MW_e generating capacity. Any power generated in excess of the grow lights' demand is exported to the utility on a 16.8-kVA (kilovolt-amperes) distribution line. All of the other electric loads at Houweling's are served from a one-MW_e solar photovoltaic array, supplemented by power purchased from the utility.

Figure 8: Demonstration Site Diagram at Houweling's Tomatoes (Camarillo, California)



Sources: Houweling's Tomatoes; Google Earth
Photo Credit: Google Earth

Figure 9: Elevation View of the Site from the South at Night

Source: Houweling's Tomatoes
Photo Credit: Houweling's Tomatoes

3.1 System Description

3.1.1 Engine-Generator

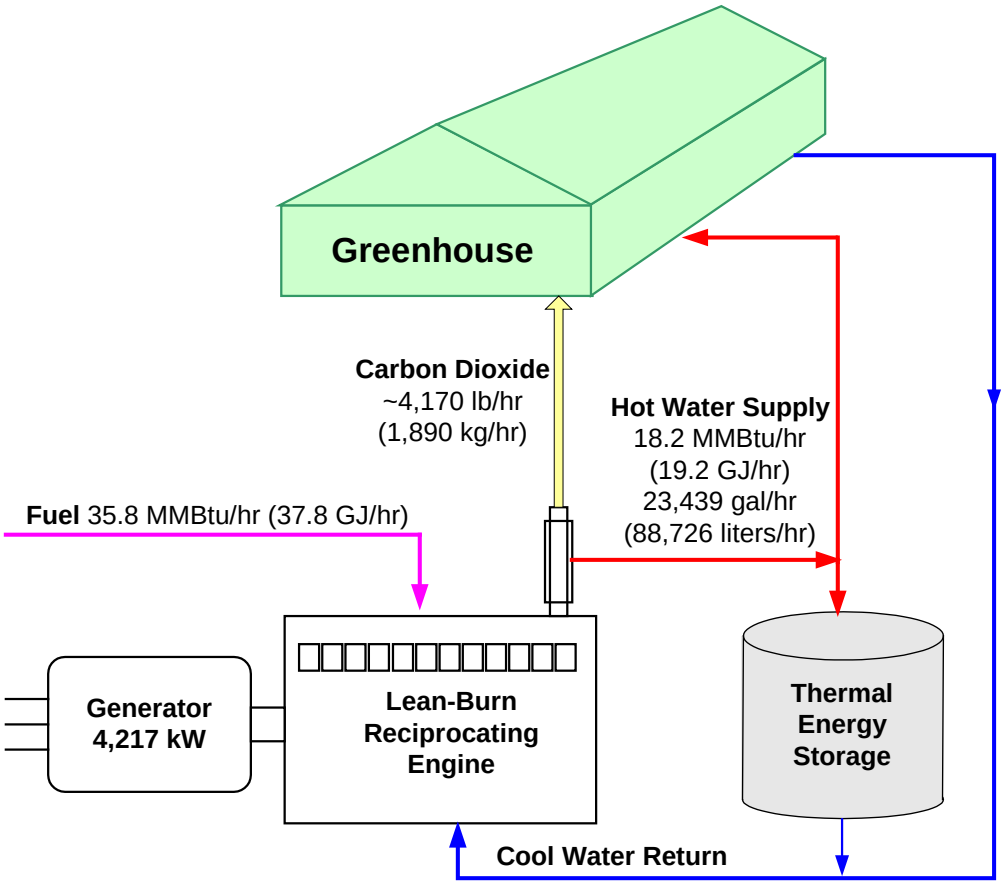
Table 6 summarizes the GE Jenbacher engine specifications. Complete specifications and other technical data for the CHP unit appear in Appendix A. Figure 10 illustrates the CHP system and its nominal energy balance, as well as the CO_2 mass flow. (Not shown are the boilers and CO_2 tanks that back up and supplement the CHP unit.) The lean-burn reciprocating engine operates at a constant engine speed of 1,500 rpm. A simple gearbox converts the engine shaft speed to the generator's 1,800 rpm. The engine is turbocharged with two, two-stage intercooled turbochargers.

Table 6: Engine Specifications

Manufacturer	GE Jenbacher
Engine type	J 624 GS-H01
Fuel type	natural gas
Net generator capacity	4,217 kW_e
Fuel consumption (HHV)	35.8 MMBtu/hr
Thermal energy output	18.2 MMBtu/hr
Compression ratio	12.5
Gearbox ratio	1:1.2
Mean effective pressure	348 psi
Length	378 inches
Height	101 inches
Working principle	4-Stroke
Configuration	V 60
No. of cylinders	24
Bore	7.48 inches
Stroke	8.66 inches
Engine displacement	9,135 cubic inches
Starter motor output	20 kW_e
Width	83 inches
Mean piston speed	433 inches/sec

Sources: GE Jenbacher; Houweling's Tomatoes

Figure 10: Conceptual Design of CHP Unit 2

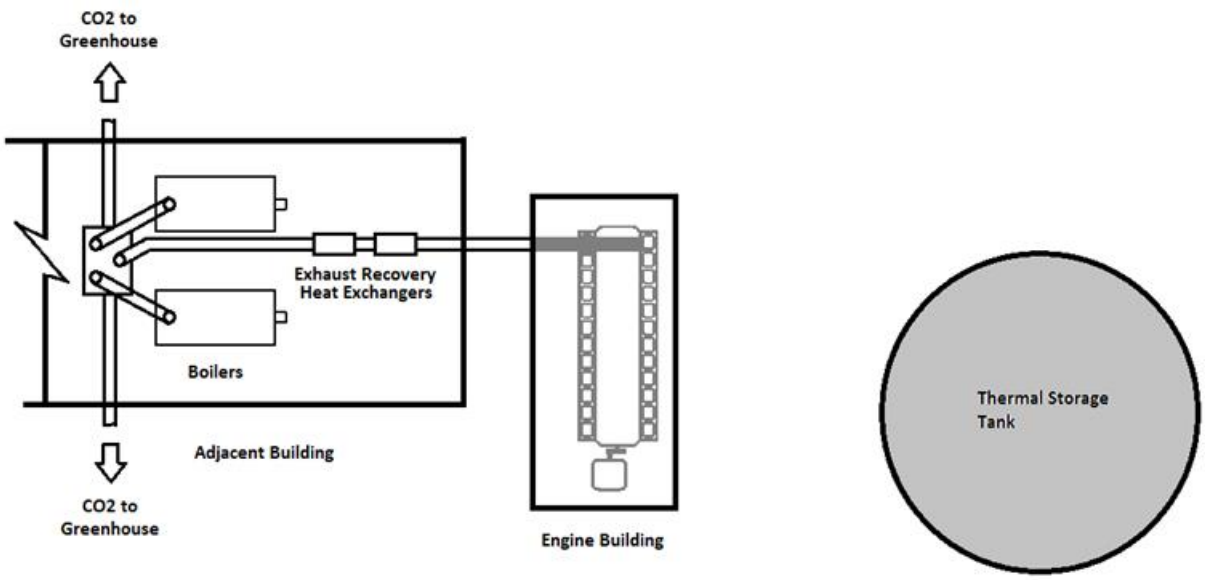


Source: DE Solutions, Inc.

3.1.2 Heat Recovery and Exhaust Management

Figure 11 sketches the plan view of the site for CHP Unit 2. The engine building contains the engine, its gearbox and generator, its primary controls, intake manifolds, turbochargers, and exhaust manifolds. Exhaust is collected from the turbochargers and transported into another, larger building that contains the equipment for heat recovery, emission controls, boilers, and CO_2 collection. CO_2 is distributed from this building to the two northern greenhouses.

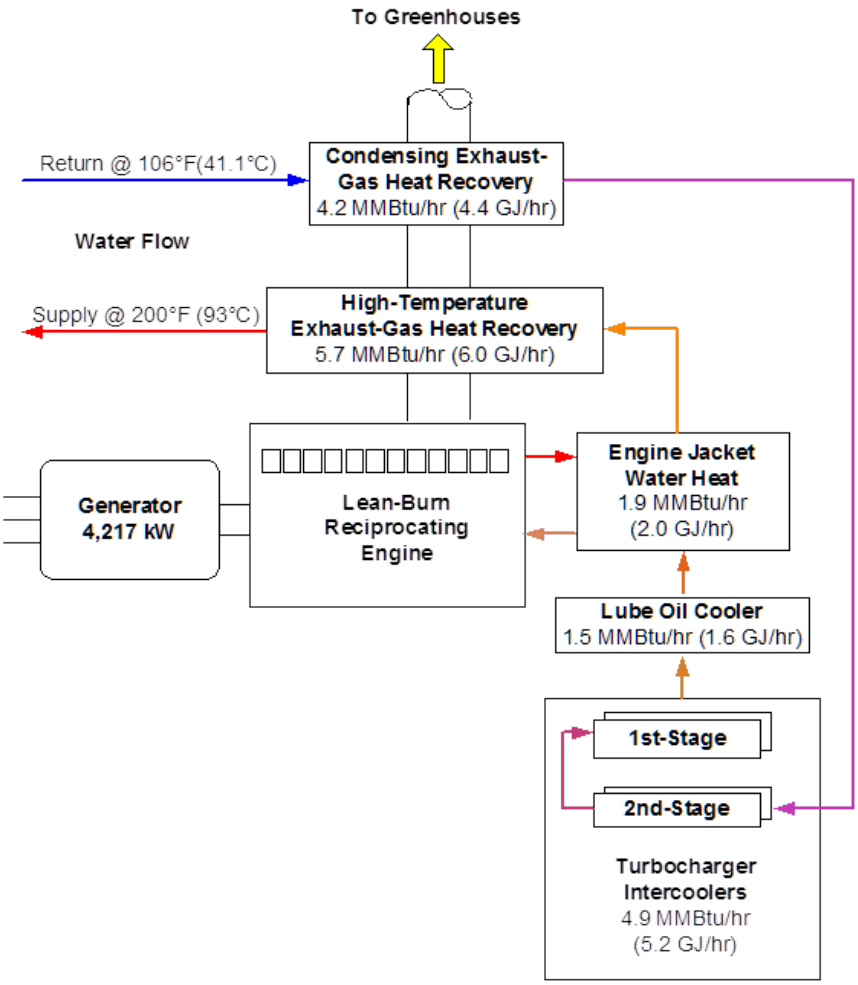
Figure 11: Plan View of CHP Unit 2 (not to scale)



Source: DE Solutions, Inc.

Figure 12 illustrates schematically how heat is recovered from the engine. Hot water is circulated in a thermal loop throughout the greenhouse to warm the air inside. The cool return water first enters the condensing heat exchanger, which reduces the engine's exhaust temperature to below its dew point (nominally 100°F, or 38°C). This somewhat warmer water is heated further, first by the compressed air emerging from the turbochargers' second stages and then by the air from the turbochargers' first stages. Next, heat from the engine's oil cooler and then from the engine jacket are added to the water in the thermal loop. The high-temperature exhaust recovery heat exchanger is the final stage of heat input, bringing the water up to around 200°F (93°C). This hot water is then routed back to the two northern greenhouses, the TES tank or both.

Figure 12: Thermal Energy Resource Detail



Source: DE Solutions, Inc.

3.1.3 Emission Control

The COdiNO$_x$® exhaust treatment system, which was designed specifically for greenhouses, was selected for this CHP demonstration. The engine exhaust is first treated by an oxidation catalyst to reduce CO emissions. Urea is then injected, and the exhaust passes through a selective catalytic reduction (SCR) unit to remove NO$_x$. A second oxidation catalyst eliminates ammonia slip and further reduces CO to near-zero (nondetect) levels. This conditioned exhaust goes through the condensing heat exchanger and is then ducted to the greenhouse to raise the interior's CO_2 concentration, which accelerates plant growth. (The exhaust stream can be supplemented with more CO_2 from liquid storage as required.) Exhaust is not allowed to flow to the greenhouses until the exhaust temperature reaches 635°F (335°C), where the COdiNO$_x$ comfortably maintains NO$_x$ below 5 ppm and CO near zero (less than 1 ppm). This usually takes between 35 and 45 minutes from a cold start.

Table 7 lists the major equipment to this CHP demonstration project.

Table 7: Demonstration System Equipment List

Supplier	Equipment Description
GE Jenbacher	Exhaust gas manifold Control panels Generator gearbox Engine Main gas train Pre-chamber gas train Tecjet Sundries and small parts Treadles
Hanwel Environment & Energy	COdiNO_x control panel COditheen retro panel Oil system tank & piping Urea tank components
VD Berg	Exhaust silencer Filter box Exhaust gas cooler CO_2 pipe and valve COdiNO_x inlet and outlet Stack Condensate collection vessel Condenser skid Exhaust system materials
Isotech	Exhaust isolation components
Ebro	CO_2 valve
Alfen	Sicuro 25 connection box Sicuro 25 stack MV cables
Hamer	Oil piping bundle

Source: Houweling's Tomatoes

Appendix B presents detailed drawings of the following equipment:

- Exhaust purifier sequence (to scale)
- Piping and instrumentation diagram (complete thermal schematic around engine)
- Site plan of entire greenhouse complex showing location of CHP Unit 2
- Top view of CHP Unit 2 including plumbing
- Hot water and instrumentation schematic
- COdiNO_x housing drawings

- Different views of CHP Unit 2 including plumbing (three views including isometric)
- Electrical drawings
- Engine and enclosure plan view
- Engine piping and instrumentation diagram

Appendix C contains the legal and regulatory documents involved in the design and planning of the system, including the following:

- Ventura County Air Pollution Control District's permit to operate (April 14, 2008)
- Ventura County Air Pollution Control District's authority to construct (Sept. 21, 2011)
- Power purchase agreement executed in accordance with the California state legislature's Assembly Bill (AB) 1613
- Signed application for Houweling's limited exemption from the California Air Resource Board (ARB) cap-and-trade program
- Utility generator interconnection agreement

3.2 Greenhouse Integration and Controls

3.2.1 Electrical Interconnection

The CHP Unit 2 engine/generator set is connected electrically both to the greenhouse facility's distribution system and to a purpose-built utility distribution line that can export the entire generating capacity of all three CHP engines (12.6 MW_e). The greenhouse's electrical distribution system is also connected to the utility's local distribution system but is limited by a circuit breaker to a total input of 450 kW_e (see second bullet below).

3.2.2 CHP Operating Strategy

The CHP system was designed to operate within the following constraints:

- The only way to cool the CHP engines at Houweling's greenhouse complex is to send the engine's hot water to the greenhouses or the TES system. If the greenhouses do not need heat or if the TES system is fully charged, then engine cooling might be insufficient, and the engines would automatically shut down to avoid overheating.
- Houweling's opted not to connect the grow-light load (11.4 MW_e) to the utility grid. This power can come only from the CHP engines on-site. Houweling's contracts for 450 kW_e of service on the grow-light circuit to start the engines. An automatic breaker will open if the greenhouse's distribution system applies a load to the electric utility above 450 kW_e.
- Providing CHP power to the grow lights during off-peak hours is economically advantageous compared with selling power to the utility.

- When the grow lights are on, the amount of power available for sale to the utility is small (1.3 MW_e).
- Houweling's must give the electric utility two hours' notice before reducing power sales to accommodate the grow lights. In practice, Houweling's provides this information to the utility as soon as grow-light operation is scheduled.
- The best time to sell power to the utility and provide CO_2 to the greenhouses does not coincide with their need for heat. As noted earlier, the TES system helps to resolve this issue.

A typical weekday operation at the greenhouse starts at 8:00 a.m., when the utility's FIT payment rises to the mid-peak rate (as opposed to the off-peak rate in effect as early as 9:00 p.m. the night before). At this time in the morning, thermal energy is already flowing from the TES system to the greenhouses, which have probably been receiving heat throughout the night. If the CHP engine is not already running, it is started and warmed up in time to reach full power by 8:00 in the morning. As noted earlier, the engine exhaust bypasses the greenhouse for about 35 to 45 minutes until the CO$diNO_x$ system is also warmed up and CO emissions are acceptable.

The exhaust is then diverted to manifolds near the floor of the greenhouse that direct the cooled, CO_2-laden exhaust to the plants. The thermal loop water begins to flow from the TES tank through the heat exchangers as shown above in Figure 15. The flow rate for this coolant is roughly 23,400 gallons per hour (Figure 13 above), or 430 gallons per minute. The hot water leaves the high-temperature exhaust recovery heat exchanger and either recharges the TES tank or is routed directly to the greenhouses. All of the CHP engine's power at this time is exported to the utility.

During the electric utility's summer season (June – September), the FIT paid by the utility increases to the on-peak rate at noon. Of course, engine operation continues uninterrupted. During the utility's winter season (October – May), the FIT remains at the mid-peak rate. At some time in the morning, the greenhouse's need for heat is satiated and hot water stops flowing to the greenhouses from the TES tank. Meanwhile, the engine continues to recharge the TES tank. At 6:00 p.m. in the summer, the on-peak rate ends, and the FIT paid by the utility returns to the mid-peak rate.

When the sun goes down and the grow lights are turned on, power sales fall considerably, with most of the CHP-generated power being consumed by the grow lights. This electricity would otherwise have been purchased on the utility's TOU-PA-3 tariff (time-of-use pumping and agricultural rate option). Although this avoided power purchase is usually at the utility's off-peak rate, the CHP system's marginal generation cost is only about \$0.027/kW_eh. Thus it makes sense to continue generating power for the grow lights rather than purchasing it. Besides, Houweling's had decided not to serve the grow lights from the utility grid, thus avoiding the standby rates and additional departing load charges imposed by the utility's TOU-8 primary rate.

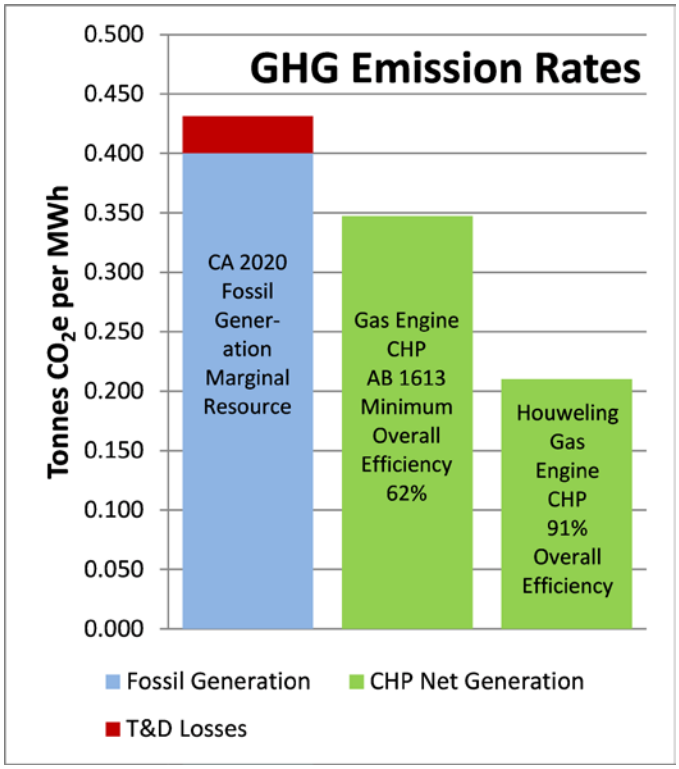
As the grow lights are switched off some time before dawn, the engine might be shut down if the greenhouse needs no heat and the TES system is fully charged. A special effort is made, however, to keep enough capacity available in the TES tank so that the engine can run and power the grow lights at night.

3.2.3 Greenhouse Gas Considerations

Two important greenhouse gas (GHG) emissions rules were considered during the CHP Unit 2 design – the efficiency threshold defined by the California AB 1613 legislation (CHP Feed-in Tariff) and the cap-and-trade threshold.[7]

AB 1613 has a minimum overall efficiency threshold of 62 percent, which results in a smaller GHG footprint than the marginal generation resource as defined by the California ARB and the CPUC. Houweling's CHP specification, which includes condensing exhaust-gas heat recovery, exceeds 90 percent HHV efficiency. Figure 13 shows the net GHG emissions of Houweling's CHP specification compared with California's 2020 marginal resource and the minimum required performance under AB 1613. As shown, Houweling's specified GHG emission rate is half that of California's 2020 marginal generation resource.

Figure 13: GHG Emission Comparison



Sources: California State Legislature Assembly Bill 1613; California Air Resources Board; California Public Utilities Commission; Houweling's Tomatoes

[7] California ARB cap-and-trade program: http://www.arb.ca.gov/cc/capandtrade/capandtrade.htm

In Houweling's 2012 GHG summary report to ARB, 24,388 tonnes of CO_2 emissions were documented. (Metric tonnes are fairly close to U.S. tons, at a ratio of 1.1 to 1.) This is below the cap-and-trade threshold of 25,000 tonnes for covered entities and includes emissions from partial operation of the first two CHP units. In 2013, with the CHP system operating at higher capacity, documented emissions were 29,326 tonnes of CO_2, exceeding the 25,000-tonne threshold. Without the CHP system, however, GHG emissions would still be below the covered-entity threshold, entitling Houweling's to a limited exemption during the first three compliance periods (through 2020) as long as subsequent annual reported data continue to qualify for the limited exemption. As a noncovered entity, the allowance cost for natural gas use will be phased in to the natural gas prices beginning in 2015. The percent of the allowance cost passed through (consigned) to natural gas customers by year is shown in Table 8.

Table 8: Allowance Cost Consigned to Natural Gas Prices

	Compliance Period					
	2			3		
Year	2015	2016	2017	2018	2019	2020
Percent Consigned	25%	30%	35%	40%	45%	50%

Source: California Air Resources Board

3.3 Operations

3.3.1 Sequence of Operation

CHP Unit 2's engine is operated remotely and scheduled by Houweling's Manager of Energy and Water Conservation (Richard Vanderburg). Power sales to the electric utility can be initiated on the hour and are typically scheduled a few minutes prior. Upon a signal from the computer, the engine begins its starting sequence. As the engine warms up, the exhaust bypasses the greenhouse until the catalysts in the $COdiNO_x$ cleanup system reach activation temperature. A monitoring system continuously tracks NO_x and CO in the exhaust. The presence of CO even in small quantities could damage the crop. When the exhaust reaches a high enough temperature to ensure that the $COdiNO_x$ system has reduced CO and NO_x emissions to safe levels, the control system actuates a damper that routes exhaust to the greenhouses.

To make use of the CO_2, the plants must be photosynthesizing. For the northern greenhouses (Phases 3 and 4), which have no grow lights, this means after dawn or before dusk. These greenhouses are supplied with CO_2 by CHP Unit 2. The emission monitors can stop allowing engine exhaust into the greenhouse if any upset in the catalytic after-treatment system results in unacceptable levels of CO. If this occurs, the exhaust is released to the atmosphere while the engine continues running. This type of fault must be resolved by human intervention before the exhaust can be routed again into the greenhouses.

In the central greenhouse with grow lights (Phase 2), the CHP engines must be running for the grow lights to operate. If anyone tries to turn on the grow lights while the engines are not running, an error message appears, calling for the start of the engines. There is an optional mode in which the engines are automatically started whenever the grow lights are turned on. As a practical matter, however, this mode has been disabled because the engines need to operate in a more stable manner. If the grow lights are on and the operator wants to turn them off, it would be convenient to shut the engines down at the same time. If engine shutdown is not desired, it is important to schedule the shutdown of the grow lights and provide the utility with sufficient notice that the utility grid will be receiving an additional 11.4 MW_e.

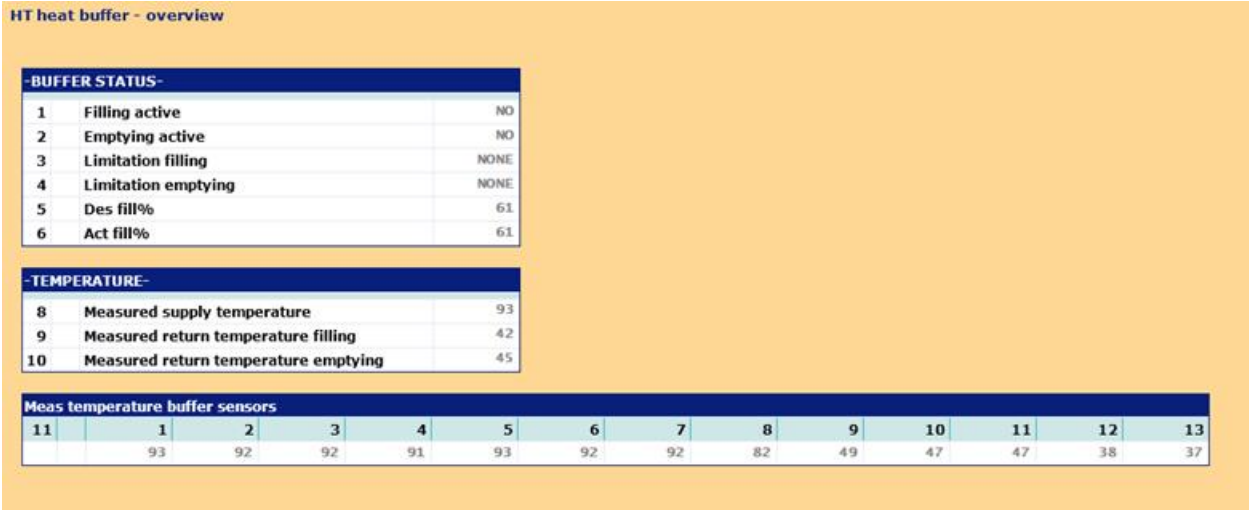
As noted earlier, the only way to cool the CHP engine is to send heated water to the greenhouse or TES tank and receive cooled water in return. During the shoulder months and particularly during the summer, Houweling's typically must limit the CHP engine's operation because the TES tank gets fully charged. At night, the priority for the engine's power is the grow lights. The exhaust from CHP Unit 2, however, is not ducted to the greenhouse with grow lights, so this unit's exhaust does not provide fertilization value and the CO_2 must be released to the atmosphere. Each day, Mr. Vanderburg reviews how much cooling water is available in the TES tank and schedules the engines accordingly. During the winter, the engines can often run around the clock because the greenhouses require more heat and thus the TES tank can take more hot water.

The engines shut down when they receive a scheduled signal from the greenhouse energy management system. Upon receiving the signal, the engine goes into its programmed shutdown sequence. It is then on standby to start again upon a signal from the computer. Once a shutdown occurs, however, the engine should remain down for at least two hours.

3.3.3 Management of TES

Figure 14 shows the computer screen that Houweling's uses to establish the engine's run schedule by checking the TES status. At the instant shown on this screen, the TES tank was being neither charged nor discharged. If the engine was running, hot water was being routed directly to and from the greenhouses. Operational limitations within the system did not exist at that moment; the tank was desired to be charged to 61 percent of its capacity, and it was charged to that percentage. The TES tank has a supply water temperature of 199°F (93°C). The return water temperature from the greenhouses is 113°F (45°C). The temperature near the bottom-left of the screen (buffer 1) is the temperature at the top of the TES tank.

Figure 14: TES Status Screen (Temperatures in °C)



HT heat buffer - overview

-BUFFER STATUS-		
1	Filling active	NO
2	Emptying active	NO
3	Limitation filling	NONE
4	Limitation emptying	NONE
5	Des fill%	61
6	Act fill%	61

-TEMPERATURE-		
8	Measured supply temperature	93
9	Measured return temperature filling	42
10	Measured return temperature emptying	45

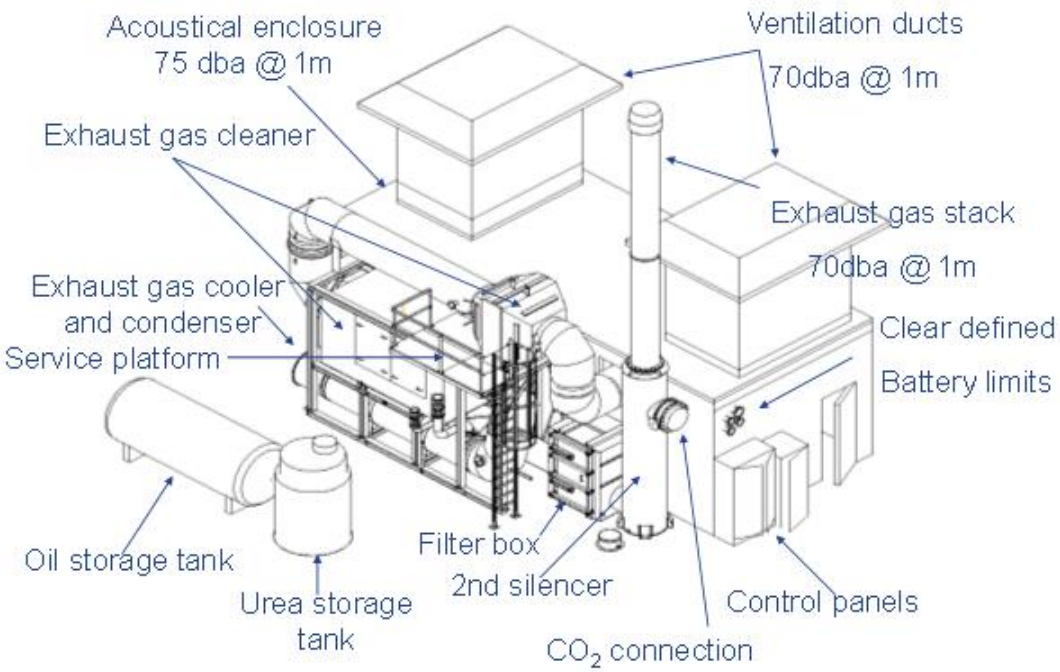
Meas temperature buffer sensors													
11	1	2	3	4	5	6	7	8	9	10	11	12	13
	93	92	92	91	93	92	92	82	49	47	47	38	37

Source: Houweling's Tomatoes

CHAPTER 4:
Installation and Commissioning

GE Jenbacher (GE) and Western Energy Systems (WES) provided the vast majority of the CHP equipment and installation and commissioning services. The GE/WES scope of supply was the focus of the project team's Commissioning Plan. GE has developed a standardized greenhouse CHP platform (Figure 15). This system combines in one package the engine, generator, emission control, heat exchangers, and all of the balance-of-plant equipment and controls.

Figure 15: GE's Standardized Greenhouse CHP Platform



Sources: GE Jenbacher; Houweling's Tomatoes

The efficiency of the engine-generator set is specified around 40 percent, calculated using the natural gas fuel's HHV. Heat is recovered from the first- and second-stage intercoolers, the lube oil cooler, the jacket water, and the exhaust (including the latent heat of condensation), pushing the overall CHP efficiency above 90 percent HHV. Table 9 lists the GE Jenbacher engine's key performance specifications. Table 10 summarizes the scope of supply. The CHP system runs more in the colder months because the greenhouses need more heat. During the summer, the run time is limited because of lower heat demand. The run-time priority in summer months is to power the grow lights at night when needed; otherwise, the run-time priority shifts to the electric utility's on-peak and mid-peak hours.

Table 9: CHP System Performance Specifications

GE Jenbacher 624 CHP Engine	
Fuel input (lower heating value)	32.2 MMBtu/hr
Fuel input (HHV)	35.8 MMBtu/hr
Fuel input (HHV)	10,501 kW_e
Gross electrical output	4,347 kW_e
Parasitic power	130 kW_e
Net electric output	4,217 kW_e
Thermal recovery	
Intercoolers (1st + 2nd stage)	4.86 MMBtu/hr
Lube oil cooler	1.51 MMBtu/hr
Jacket water	1.90 MMBtu/hr
Exhaust to 100°F	9.90 MMBtu/hr
Total heat output	18.17 MMBtu/hr
Total heat output	5,326 kW_{th}
Performance metrics	
Net electrical efficiency (HHV)	40.2%
Net overall efficiency (HHV)	90.9%

Sources: GE Jenbacher; Houweling's Tomatoes

Table 10: Scope of Supply

Standardized Scope GE	WES, Houweling's, and Local Suppliers/Contractors
Predefined greenhouse module (engine and generator)	***Electrical***
Diane XT (CO_2, fertilizer, auxiliaries)	Switchgear substation, step-up transformers
Gas train	Generator power cables, surge suppressor
Exhaust gas system	Integration with existing grid
Oil system, fresh and waste oil tanks	***Integration with the greenhouse***
Piping, hot-water and low-water temperature circuit	Connection to hot-water/low-water circuit
Heat recovery, exhaust gas cooler/condenser	Connection to CO_2 from engines
Insulation (water and exhaust)	Connection to existing gas system
Control cable works	Connection to greenhouse computer/software
CO_2, fertilizer/emission guarding system	***Civil***
Urea tank	Building, concrete floor, etc.
Commissioning	***General***
Engineering, project management, supervision	Permits, local code requirements
	Technical compliance
	Interconnection study
	Assembly, construction on-site
	Transportation, off-loading

Sources: DE Solutions, Inc.; GE Jenbacher; Western Energy Systems

4.1 Hardware Installation and Startup

The timeline in Table 11 tracks the major construction events for the installation and commissioning of CHP Unit 2. Commissioning was completed in January 2014 (see section 4.2).

Table 11: Installation Schedule

Date, 2013	Milestone
Feb	Procured major equipment (CHP package, switchgear, transformers)
Apr	Groundbreaking
May	Completed site preparation
Jun	Began fabrication of building
Jul	Fabricated and erected building
Aug	Delivered engine-generator set to site
Aug	Completed heat recovery connections to engine system
Aug	Connected piping from CHP building to greenhouse heating system
Aug	Installed CO$diNO_x$ exhaust after-treatment system
Aug	Completed installation of low- and medium-voltage distribution system
Sep	Installation completed
Sep	Commenced commissioning
Oct	Operation of the engine began
Nov	AB 1613 contract signed with electric utility

Source: DE Solutions, Inc.

GE has a 170-page startup manual with detailed technical instructions, but the document is not intended for external distribution. To convey the magnitude of the startup process, Table 12 shows the manual's table of contents.

Table 12: Startup Instructions

Startup Checklist: Technical Instructions, Table of Contents	
1.	Stamford Generator
2.	SIMATIC S5
3.	EBG charger
4a.	SEG MRN 2 mains decoupling relay
4b.	SEG-mains decoupling relay MRN3
4c.	SEG-mains decoupling – generator protection relay MRG3
5.	Circuit breaker monitoring during individual synchronization
6.	Circuit breaker monitoring – common and individual synchronization
7.	Leonhard ASG 410 synchronizer
8a.	PROTRONIC 100 Controller general
8b.	SIPART DR Controller generally
9.	Checking protection against electric shock (safety precautions)
10.	Manual start
11.	Frequency converter ABB - Sami GS
12.	Checking computer/bus interface with customer-provided master control
13a.	Parameterizing IQ 750 (JW 320)
13b.	Parameterizing IQ 724 (JW 620)
13c.	IC900/910 – ignition system with CAN-Bus
13d.	IC900/910 – double ignition system (Redundant)
13e.	IC912 – double ignition system (extended firing time)
14.	Generator negative sequence
15.	Servo amplifier for Heinzmann actuator StG 10 and StG 30
16.	Instructions for adjusting gas mixer actuator
17.	Voltage relay with evaluation of symmetrical components SEG MRU1
18.	Voltage balance relay
19.	Transfer Program to OPS
20.	ABB-Generator
21.	Basic setting, parameterizing control and monitoring instruments
22.	Cable support for Leroy Somer MV/HV Generators
23.	Differential protection relay XD1-T
24.	Gas leakage monitoring device BIAS 4
25.	SR current limiting controller (A.v.K.)

Source: GE Jenbacher

In part because of GE's standardized greenhouse CHP platform, along with Houweling's experience installing the first two CHP units, the construction process was well-organized and on schedule. The system was successfully started up in accordance to the procedures outlined

in the Commissioning Plan discussed above. Figures 16 -22 show photographs of CHP Unit 2 on-site.

Figure 16: Engine-Generator Set (Left and Right-Hand Views)

Source: Houweling's Tomatoes
Photo Credit: Houweling's Tomatoes

Figure 17: Control Room

Source: Houweling's Tomatoes
Photo Credit: Houweling's Tomatoes

Figure 18: CHP Unit 2 Building with Exhaust Duct to Boiler House

Source: Houweling's Tomatoes
Photo Credit: Houweling's Tomatoes

Figure 19: Exhaust Treatment System and Heat Exchangers

Source: Houweling's Tomatoes
Photo Credit: Houweling's Tomatoes

Figure 20**: CO_2 Transport from Exhaust Heat Exchanger to Greenhouse**

Source: Houweling's Tomatoes
Photo Credit: Houweling's Tomatoes

Figure 21: CO_2 Intake to Greenhouse

Source: Houweling's Tomatoes
Photo Credit: Houweling's Tomatoes

Figure 22: CO_2 Distribution Ducts in Greenhouse (Below Plants in Metal Frames)

Source: Houweling's Tomatoes
Photo Credit: Houweling's Tomatoes

4.2 Commissioning

Once the CHP system was started up, the commissioning protocol (Table 13) called for a series of measurements to be recorded and compared against the specifications. Except for the valve stem measurements, all measurements were taken during engine operation. Table 14 lists the instrument readings.

Upon completion of the measurements taken per the commissioning protocol, an acceptance report was prepared noting any defects that needed follow-up attention. The acceptance report with defects noted (Figure 23) was signed by GE, by the client (Houweling's), and by the Project Manager (WES). Figure 24 shows the final signed acceptance report noting that the defect had been rectified. CHP Unit 2 was commissioned in January 2014.

Table 13: Commissioning Protocol

Commissioning protocol:

Keyword:	Houweling, Camarillo, CA	Design No.:	
Generator type:	J624GS-H01	Year of construction:	2013
Type/version:	JMS624GS-NL	Country of installation:	CA, USA

Software version B&R/SAM	RPS:	(computer-controlled control)	3.2.3o
	VISU:	(Dia.ne visualisation)	3.2.3o
	MMU:	(Multi-function transducer)	.02 / 3.36
	ZÜND:	(Ignition)	7.17
	MONIC:	(Ignition visualisation)	
	KLS98:	(Knock control)	
	TEC:	(Tecjet)	2.07
	SAM:		
	EMS3000:		
Software version Siemens/B&R	Sps:	(PLC control)	0.3
	Syn:	(Synchronisation)	
	Stat:	(Station control)	
	?		

		Engine No.				
			1032813			
Engine No.			1032813			
Operating hours	Bh					
Number of starts						
Power, electric	kW		4347			
Voltage - average value	V		14170			
Current - average value	A		179			
Zero conductor current	A		1			
Cos phi	Ind/Kap		Ind 0,995			
Exciter voltage	V		24,9			
Mixture temperature	°C		52.8			
Charge pressure	mbar		5748			
Gas-mixer position / TEC	mm / %		27.7			
Throttle valve position	%		98.0			
Flow-Tech position	%		5.9			
After cooler differential pressure, mixture side	mbar		42/33			
Mixture cooling water temperature, intake, stage 1	°C		55 / 55			
Mixture cooling water temperature, intake, stage 2	°C		55 / 50			
Engine cooling-water temperature	°C		82.0			
Engine cooling-water pressure	bar		2.29			
Oil temperature	°C		68.2			
Oil pressure	bar		4.11			
Gas pressure before pre-pressure controller	mbar		3250			
Gas pressure after pre-pressure controller	mbar		110			
Pre-combustion chamber differential pressure	mbar		-1478			
Gas pressure before differential-pressure controller	bar		5515			
Methane content (CH4)	%		n/a			
Gas temperature before activated carbon filter	°C		n/a			
GET: Engine Type						
GET: Camshaft offset	° v OTH					
GET: Knock limit						
GET: Pulse slope retard						
GET: Pulse slope forward						

Sources: GE Jenbacher; Houweling's Tomatoes

Table 13: Commissioning Protocol, continued

Commissioning protocol:

		Engine No.									
				1032813							
Cylinder temp. 1/2	°C			549	548						
Cylinder temp. 3/4	°C			544	548						
Cylinder temp. 5/6	°C			548	548						
Cylinder temp. 7/8	°C			550	552						
Cylinder temp. 9/10	°C			551	550						
Cylinder temp. 11/12	°C			550	547						
Cylinder temp. 13/14	°C			548	547						
Cylinder temp. 15/16	°C			551	552						
Cylinder temp. 17/18	°C			549	552						
Cylinder temp. 19/20	°C			556	556						
Cylinder temp. 19/20	°C										
Cylinder temp. 19/20	°C										
Cylinder temp. 21/22	°C			553	554						
Cylinder temp. 23/24	°C			549	547						
Ignition-voltage requirement min/max	kV			9.3	15.7						
Ignition point	°KWvOT			24							
Hot water forward temperature	°C			95.2							
Hot water return temperature	°C			54.2							
Exhaust-gas heat exchanger - tube-plate temperature	°C			n/a							
Drive side (DS) generator bearing temperature	°C			64.1							
Non-drive side (NDS) generator bearing temperature	°C			53.6							
Generator winding temperature 1	°C			81.6							
Generator winding temperature 2	°C			84.3							
Generator winding temperature 3	°C			80.3							
Exhaust-gas temperature before heat exchanger	°C			371							
Exhaust-gas temperature after heat exchanger	°C			62 / 46							
Cooling water inlet temperature at exhaust-gas heat exchanger	°C			70							
Cooling water outlet temperature at exhaust-gas heat exchanger	°C			95							
Differential pressure across flame trap, mixture side	mbar			7.4							
Differential pressure - exhaust-gas heat exchanger	mbar			15.4							
Differential pressure - catalytic converter	mbar			24							
Exhaust-gas backpressure after exhaust-gas turbocharger	mbar			67.1							
O2 value	Vol./%			10.8							
CO value (related to 5% O2)	mg/Nm³			456							
NOx value (related to 5% O2)	mg/Nm³			489							
Engine cooling water - concentration test	Vol./%			50							
Product applied / additive		Chevron Dexcool									
Mixture cooling circuit (2nd stage) concentration test	Vol./%			n/a							
Product applied / additive		n/a									
Intake temperature at engine air-filter intake	°C			28							
Generator cooling-air intake temperature	°C			15.2							
Crankcase pressure (at dipstick)	mmWS			-42 mBar							
Engine-room pressure	mbar			0							
Valve noise (KLS 98)	mV			n/a							
Zero pressure controller setting	mm/U			n/a							

Sources: GE Jenbacher; Houweling's Tomatoes

Table14: Instrument Readings

GE Jenbacher

Instrument Readings List		
Client Name	Houweling Greenhouse Engine 2	
Jenbache Engine #	K 214	
Date	9/26/2013	
Technician	Rene Vermue	
Operating Hours	10	hours
Gas mixer Position	35.7	%
Throttle Valve Position	100	%
Turbocharger bypass mode	9.4	%
Exhaust backpressure after turbo	77	mbar
Exhaust backpressure after silencer	51.4	mbar
Exhaust backpressure after SCR	n/a	mbar
Exhaust backpressure after pre-cooler	n/a	mbar
Exhaust backpressure after COdiNOx	26.9	mbar
Exhaust backpressure after flue gas cooler	17.7	mbar
Exhaust backpressure after condenser	7.6	mbar
Exhaust backpressure after soot filter	0.9	mbar
Average outlet temperature	552	°C
Exhaust temperature before turbo	552	°C
Exhaust temperature after turbo	378	°C
Exhaust temperature after pre-cooler	n/a	°C
Exhaust temperature after COdiNOx	377	°C
Exhaust temperature after sensible HX	109	°C
Exhaust temperature after condensing HX	39	°C
Outside temperature	21	°C
Temperature at air filter	26.4	°C
Comments		

Source: GE Jenbacher

Figure 23: Acceptance Report Noting Defect

Form of Equipment Acceptance Report

Client: WESTERN ENERGY SYSTEMS GE Jenbacher-Order: 4075

Order No.|
Confirmation of Order No.:

Keyword | Site: HOUWELING 3-3

Set type: JMS 624 GS-N.L Design No.: J K214

Set No.: 1032801 Engine No.: 1032813 Generator-No.: 604687-1

Scope of supply: Above mentioned equipment has been found in full accordance with the specification of order.
The equipment has been commissioned and all functions have been thoroughly examined

Result: ☐ No defects have been found:
☒ Following defects have been found:

GE Responsibility: FINAL COMMISSIONING OF THE CODINOX SYSTEM

Customer Responsibility: ENGINE WILL REMAIN BLOCKED UNTIL THE UNDER VOLTAGE TRIP COIL IN INSTALLED IN THE GCB.

EHS:

In consequence of the commissioning the equipment has been taken over on: 01-10-2013
(Hand-Over DATE)

WARRANTY TERMS according to the terms and conditions of the sales contract. Warranty period begins on above mentioned date and ends as specified in the contract.

On behalf of Client:	On behalf of Project Manager:	On behalf of GE Jenbacher GmbH & CO OG
Name in capital letter	Name in capital letter	Name in capital letter
Richard Vandersburg		RENE VERMUE

Source: DE Solutions, Inc.

Figure 24: Acceptance Report Noting Defective Part Replaced

Form of Equipment Acceptance Report

Client: WESTERN ENERGY SYSTEMS GE Jenbacher-Order: 4075

Order No.|
Confirmation of Order No.:

Keyword | Site: HOUWELING 3-3

Set type: JMS 624 GS-N.L Design No.: J K214

Set No.: 1032801 Engine No.: 1032813 Generator-No.: 604687-1

Scope of supply: Above mentioned equipment has been found in full accordance with the specification of order.
The equipment has been commissioned and all functions have been thoroughly examined

Result: ☐ No defects have been found:
☒ Following defects have been found:

GE Responsibility: FINAL COMMISSIONING OF THE CODLNOX SYSTEM

Customer Responsibility: ENGINE WILL REMAIN BLOCKED UNTIL THE UNDER VOLTAGE TRIP COIL IN INSTALLED IN THE GCB.

EHS:

UVT COIL INSTALLED. BREAKER OPERATION OK.

In consequence of the commissioning the equipment has been taken over on: 01-10-2013
(Hand-Over DATE)

WARRANTY TERMS according to the terms and conditions of the sales contract. Warranty period begins on above mentioned date and ends as specified in the contract.

On behalf of Client:	On behalf of Project Manager:	On behalf of GE Jenbacher GmbH & CO OG
Name in capital letter	Name in capital letter	Name in capital letter
Richard Vanderburg	JOEL FORTY	RENE VERMUE

Firmenbuchgericht Innsbruck | Firmenbuchnummer FN 36326 a | DVR 008 8916 | UID: ATU31786303 | IBAN: AT37 1100 0012 7002 2500

Source: DE Solutions, Inc.

CHAPTER 5: Performance Monitoring

The energy infrastructure of Houweling's Camarillo greenhouse complex is designed and operated for maximum efficiency. The CHP units run only when the greenhouses need heat or when the TES tank has the capacity to store more heat – and when the photosynthesis process is active and can benefit from CO_2 injection. The CHP engines' recovered heat and CO_2 (except when powering Phase 2 grow lights) are always used within the greenhouse complex. The boilers and liquid CO_2 tanks are there to supplement and back up the CHP units.

5.1 Monitoring Plan and Instrumentation

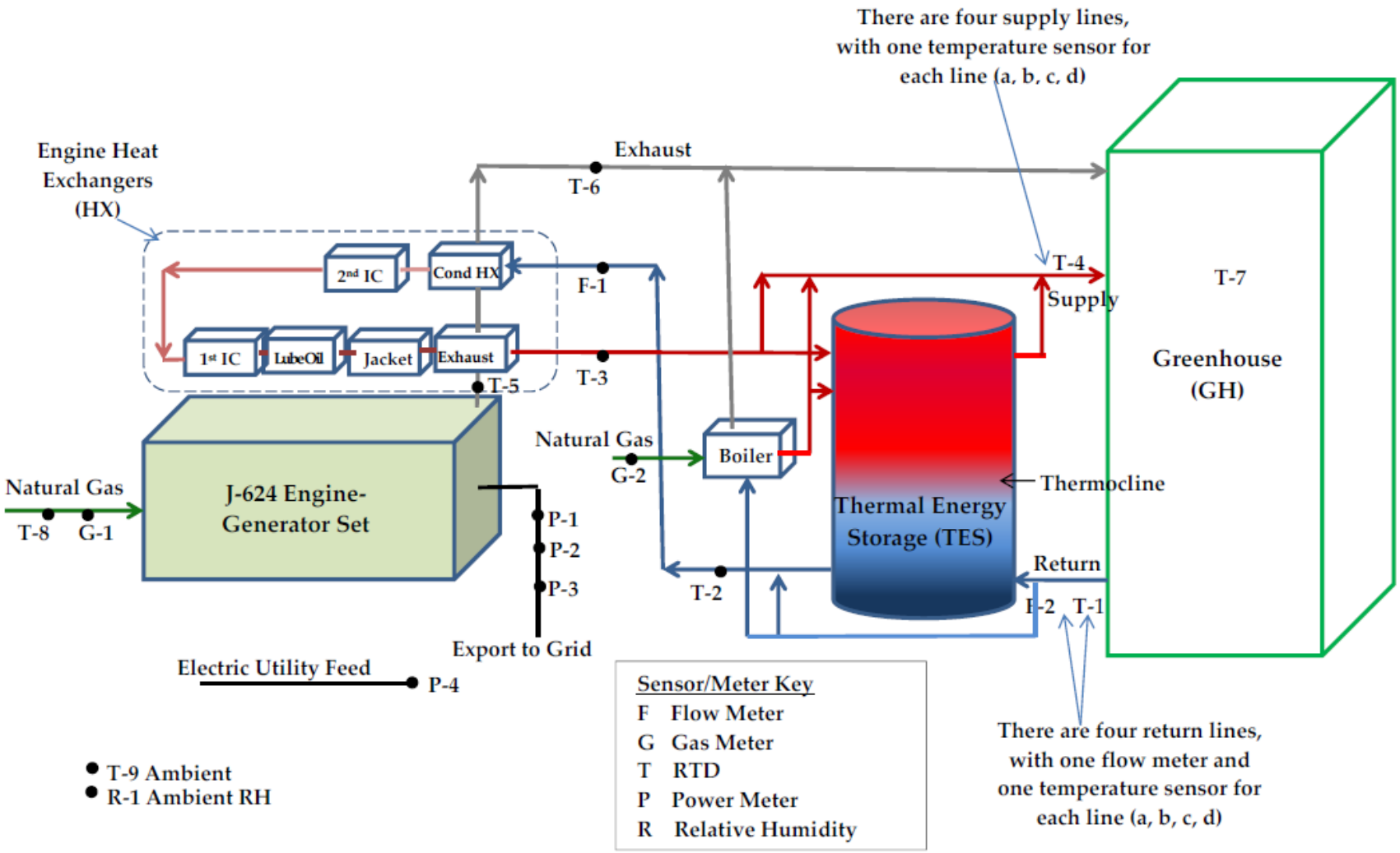
The monitoring plan describes the approach to monitoring the performance of CHP Unit 2, which was commissioned in January 2014 and serves the northern third of the greenhouse area (about 44.5 acres under glass). The monitoring system is intended to collect the measured data necessary to quantify the technical and economic performance of the CHP system. The monitoring plan conforms to the long-term monitoring protocol of the Association of State Energy Research and Technology Transfer Institutions (ASERTTI).[8]

The monitoring team took advantage of some sensors already in place which Houweling's uses to monitor and manage operations. Houweling's greenhouse automation system (Priva) was used to collect and store performance data for CHP Unit 2. Newly installed sensors were tied into Houweling's Priva data collection system, and access was granted to Conservation Technology for data collection and formatting. The logistics involved in installing new sensors, gaining access to existing sensor outputs, and learning data correction factors took longer than anticipated. The complete data acquisition system became fully functional on June 1, 2014.

The CHP system and other equipment at the greenhouse complex have been described in chapters 2 and 3. A simplified schematic of the CHP system along with instrumentation points is shown in Figure 25. Table 15 lists the instrumentation used for monitoring the performance of CHP Unit 2. Appendix D contains more detailed specification sheets for the instrumentation.

[8] ASERTTI DG/CHP Long Term Monitoring and Testing Protocol: http://prod-http-80-800498448.us-east-1.elb.amazonaws.com/w/images/3/32/Lt_monitoring_protocol_nov08.pdf

Figure 25: Process and Instrumentation Schematic



Sources: DE Solutions, Inc.; Conservation Technology

Table 15: CHP Unit 2 Instrumentation List

Sensor ID	Priva Register	Description	Sensor Type	Units
T-1 a, b, c, d	9	Hot water (HW) return from greenhouse (GH) to TES	RTD (resistance temperature detector	°F
T-2	14	HW return from TES to engine heat exchanger (HX)	RTD – liquid	°F
T-3	17	HW temperature leaving engine HX	RTD – liquid	°F
T4 a, b, c, d	10	HW from TES to GH	RTD – liquid	°F
T-5	40	Engine exhaust leaving engine	RTD – air	°F
T-6	34	Engine exhaust leaving engine HX	RTD – air	°F
T-7	23, 24, 25 & 26	GH interior	RTD – air	°F
T-8	20	Natural gas temperature	RTD – air	°F
T-9	21	Ambient	RTD – air	°F
F-1	13	HW return from TES to engine HX	Insertion flow meter	gpm
F-2 a, b, c, d	36, 37, 38 & 39	HW return from GH to TES	Insertion flow meter	gpm
G-1	18	Natural gas to engine	Coriolis flow meter	SCFM
G-2		Natural gas to boilers	Rotary meter	SCFM
P-1	11	Gross electric power output	Electric meter	kW_eh
P-2	35	Parasitic electric power demand	Electric meter	kW_eh
P-3	16	Grow lights	Electric meter	kW_eh
P-4	15	Remaining on-site electric loads	Electric meter	kW_eh
R-1	22	Relative humidity	RH meter	%
NGHHV		Natural gas (HHV)	Supplied by SoCalGas	Btu/scf
		NO_x and CO emissions	Continuous emissions monitoring system	ppm

Sources: DE Solutions, Inc.; Conservation Technology

5.2 Data Collection and Analysis

Performance data are periodically downloaded by Conservation Technology for data reduction and analysis. The Priva automation system scans each data point at five-second intervals. All readings are averaged, summed, or calculated for each 1-minute interval. The automation system holds more than 30 days of recorded data if communications are lost. The data are downloaded from the automation system at least once a day via the Internet connection and loaded into a database for long-term storage. An operational log is maintained to track scheduled and unscheduled outages. This information is also entered into the database.

Houweling's maintained the automation system over the eight-month performance monitoring period. Conservation Technology periodically checked the CHP website to ensure that the system was operating properly. In the event of a data collection or sensor issue, Houweling's staff was contacted to make the repair.

Temperature sensors were compared to readings with handheld instruments, power transducer readings were also compared to handheld power readings. Where feasible, flow readings were checked with ultrasonic flow meters.

5.3 Measured Performance Results

Figures 26-35 present the performance data on CHP Unit 2 collected from June 2014 through January 2015.

Figure 26 shows the net power output consistently producing electricity in the 4.3—4.5 MW_e range. The CHP system shut down at night and on some weekends during the warmer months. Two unscheduled maintenance periods occurred in July and August, both related to the under-voltage trip relay. Because CHP Unit 2's engine was an early production model, it fell victim to a design deficiency in the connecting-rod crankshaft bearing, which caused the engine to fail. GE Jenbacher quickly readied a replacement engine that was transported to Houweling's in Camarillo, installed, and commissioned within two months of the failure. Since the new engine was commissioned, it has run without incident and with more up-time due to the need for additional heat during cooler weather.

Figure 27 illustrates fuel consumption and thermal recovery. Typical values were 39 MMBtu/hr HHV for natural gas consumption and 19.5 MMBtu/hr for recovered thermal energy. This means that about 50 percent of the natural gas fuel's higher heating value is being recovered for use by the greenhouses.

Figure 28 displays the HHV efficiency of the CHP system. The net electrical efficiency stayed close to 38 percent (slightly below the performance specifications), and the net overall efficiency averaged about 88 percent.

Figure 29 shows the ambient and greenhouse temperatures over the course of the monitoring period. Ambient temperatures varied from 34°F to 94°F (1°C to 34°C). Greenhouse temperatures seldom dropped below 60°F (16°C) and peaked as high as 100°F (38°C).

The next two graphs zoom in on performance during two representative weeks of operation in 2014. Figure 30 covers the week of June 8—14. The CHP system operated during the day and shut down in the evenings. When operating, the CHP unit produced a net 4.35 MW_e and 5.75 MW_{th} (19.6 MMBtu/hr) of hot water, which was either transferred to the TES tank or sent directly to the greenhouses.

Figure 31 covers the week of November 9—15. The CHP units were running longer to satisfy demand for heat. Also, the grow lights were on to compensate for the shorter days. For both weeks, the boilers were used only minimally to supplement heat production from the CHP unit. Figure 32 and Figure 33 show details of energy generation and use on the Wednesday of each representative week.

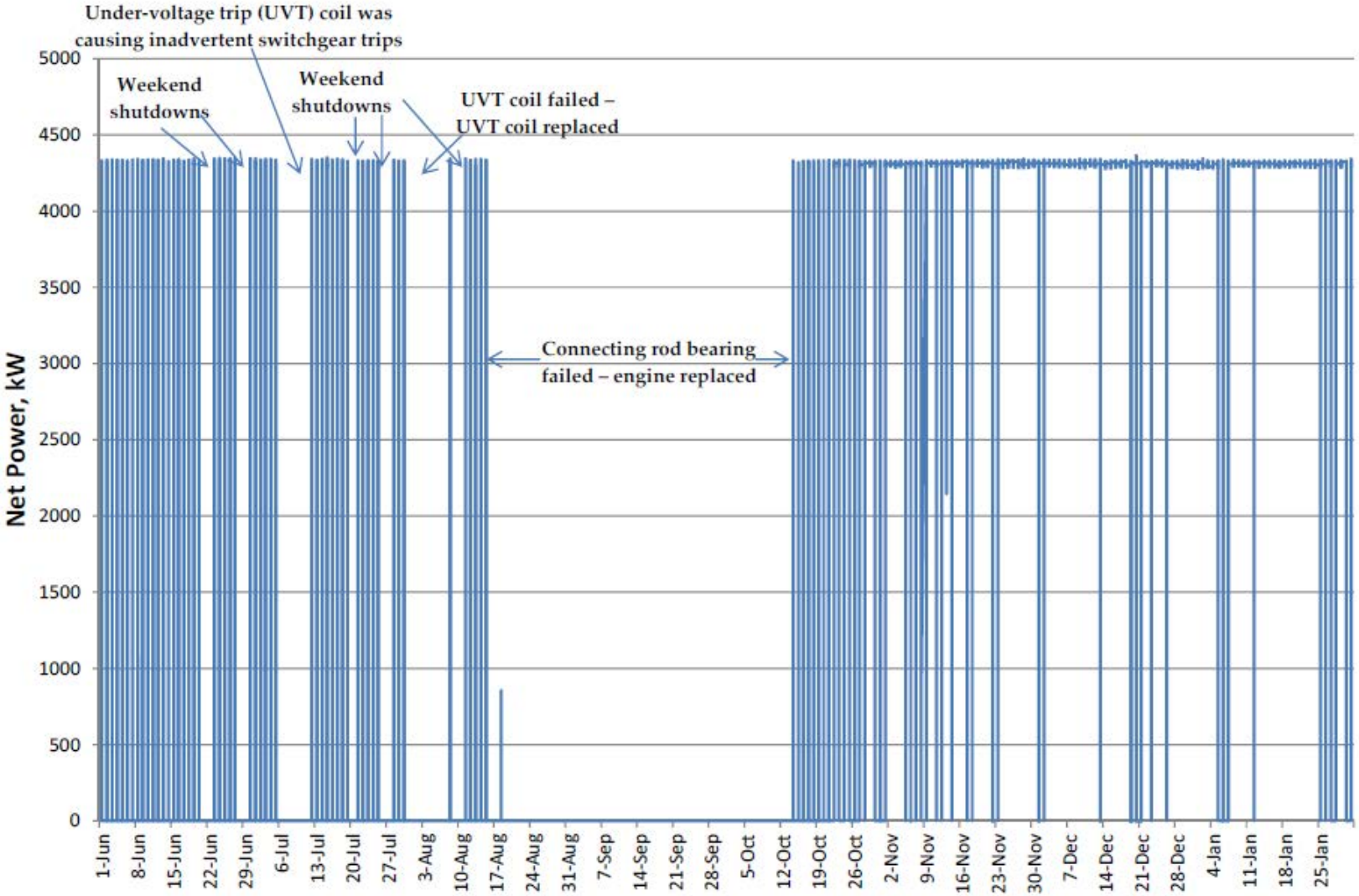
During engine startup, the exhaust is diverted from the greenhouse to the ambient air via a bypass damper, which remains closed until the COdiNO_x emission control system has been

fully activated and the emissions (particularly CO) are at near-zero levels, presenting no risk to the crops. Then the damper is opened, and the exhaust is routed to the greenhouse.

Figure 34 illustrates the warmup and activation process for three different temperatures conditions at engine start-up. These conditions are primarily a function of how long the engine has been off. In this graph, warm-up times vary between 35 and 45 minutes.

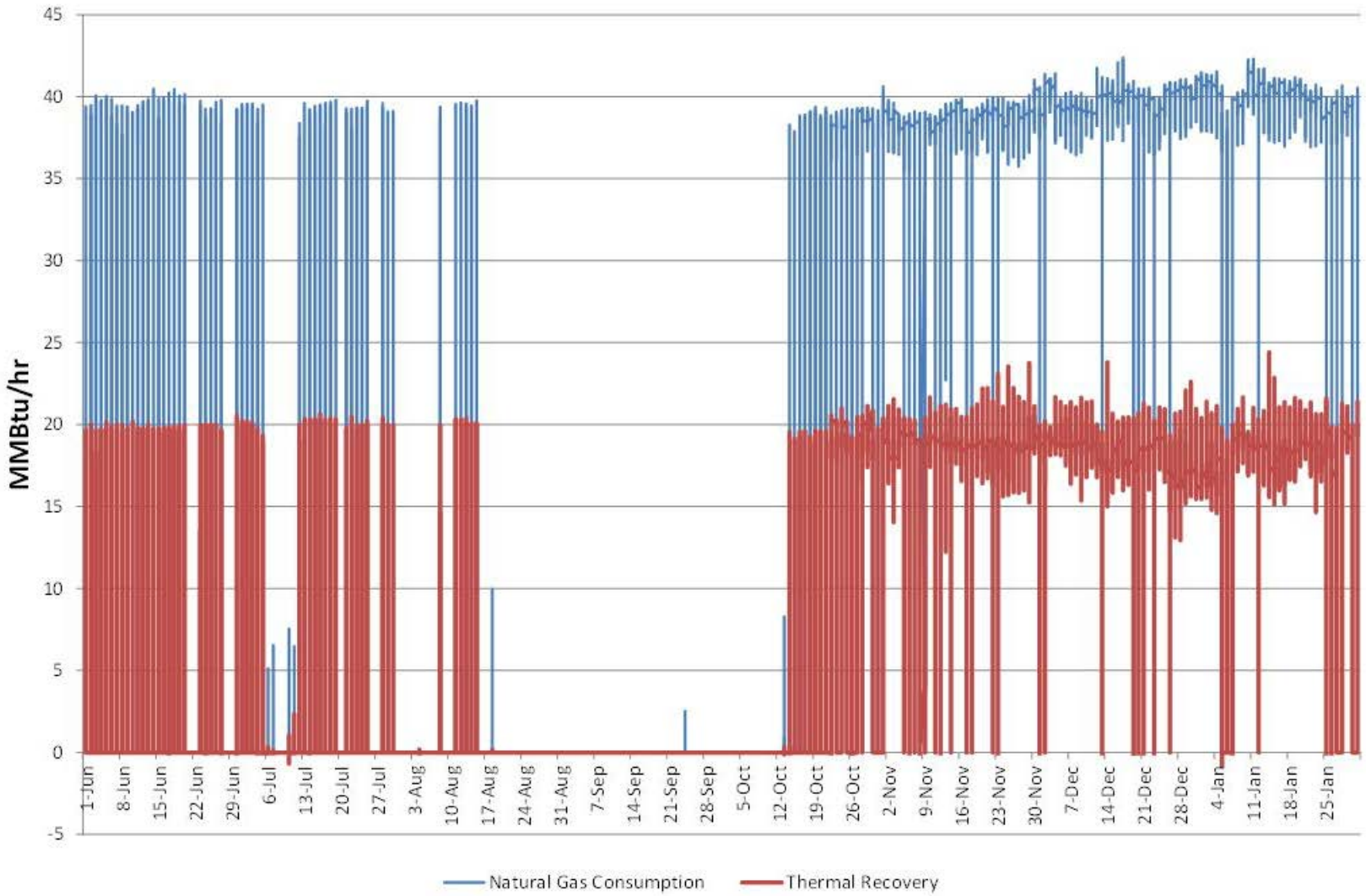
Figure 35 displays representative emission values for NO_x and CO, expressed in ppm corrected to 15 percent oxygen. Over the two 15-minute measurement periods shown, the average NO_x emissions were comfortably below the 5-ppm limit, and CO levels were less than 1 ppm (nondetectable amounts) necessary to protect the crops, which is far below the air permit limit of 80 ppm.

Figure 26: Net Power Output



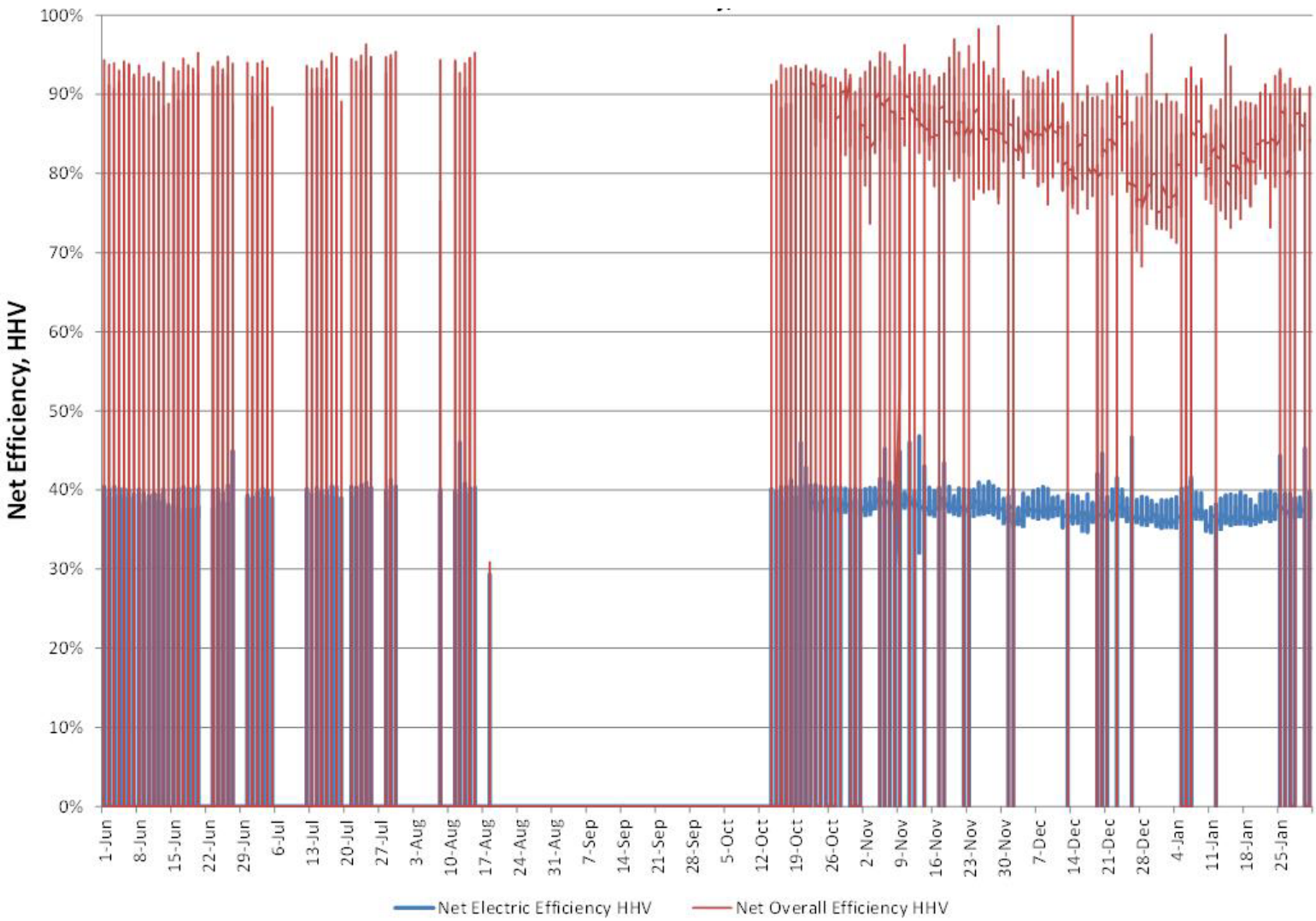
Sources: DE Solutions, Inc.; Conservation Technology

Figure 27: Fuel Consumption and Thermal Recovery



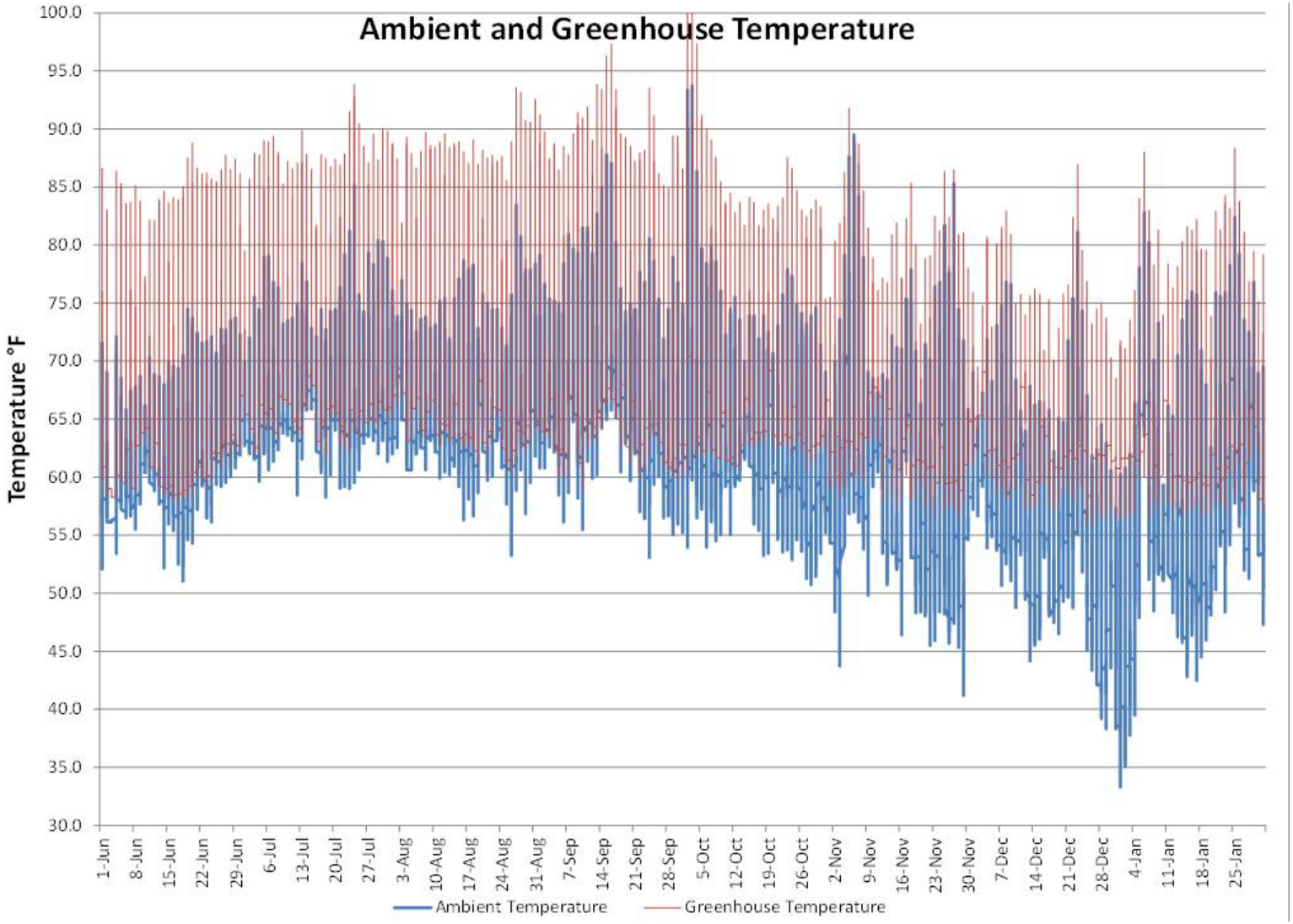
Sources: DE Solutions, Inc.; Conservation Technology

Figure 28: Net CHP Efficiency (HHV)



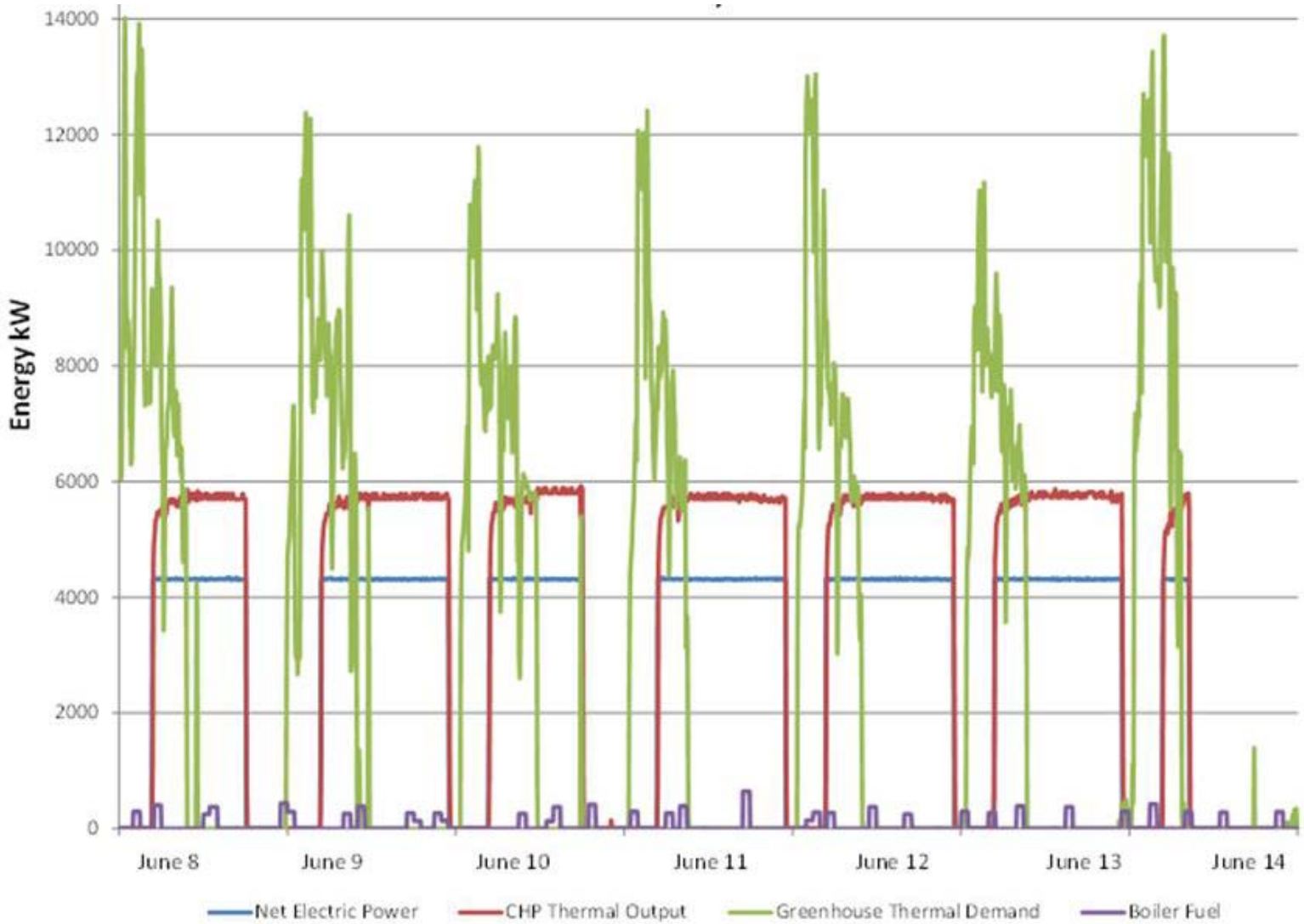
Sources: DE Solutions, Inc.; Conservation Technology

Figure 29: Ambient and Greenhouse Temperatures



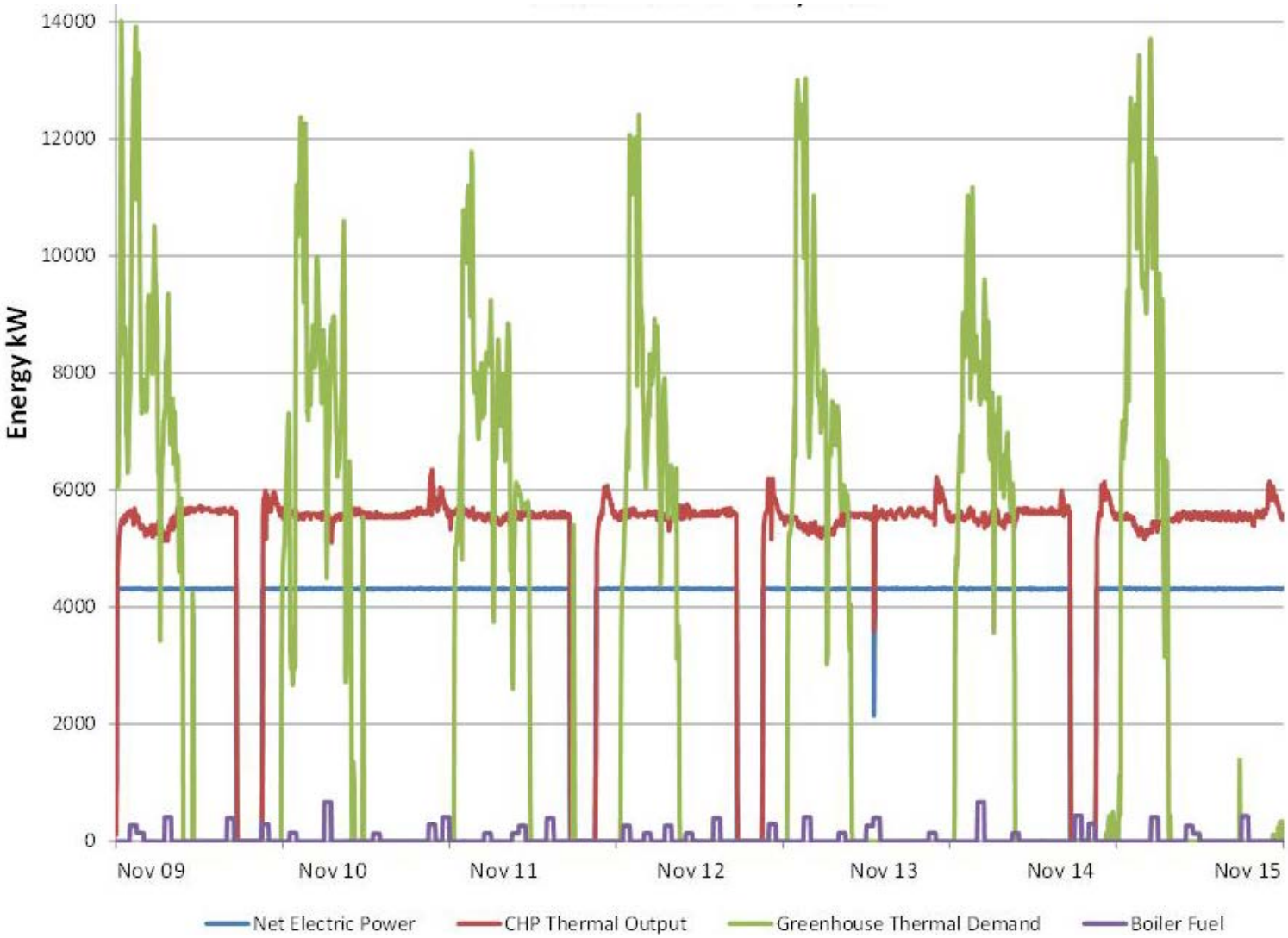
Sources: DE Solutions, Inc.; Conservation Technolog

Figure 30: Energy Generation and Use (June 8—14, 2014)



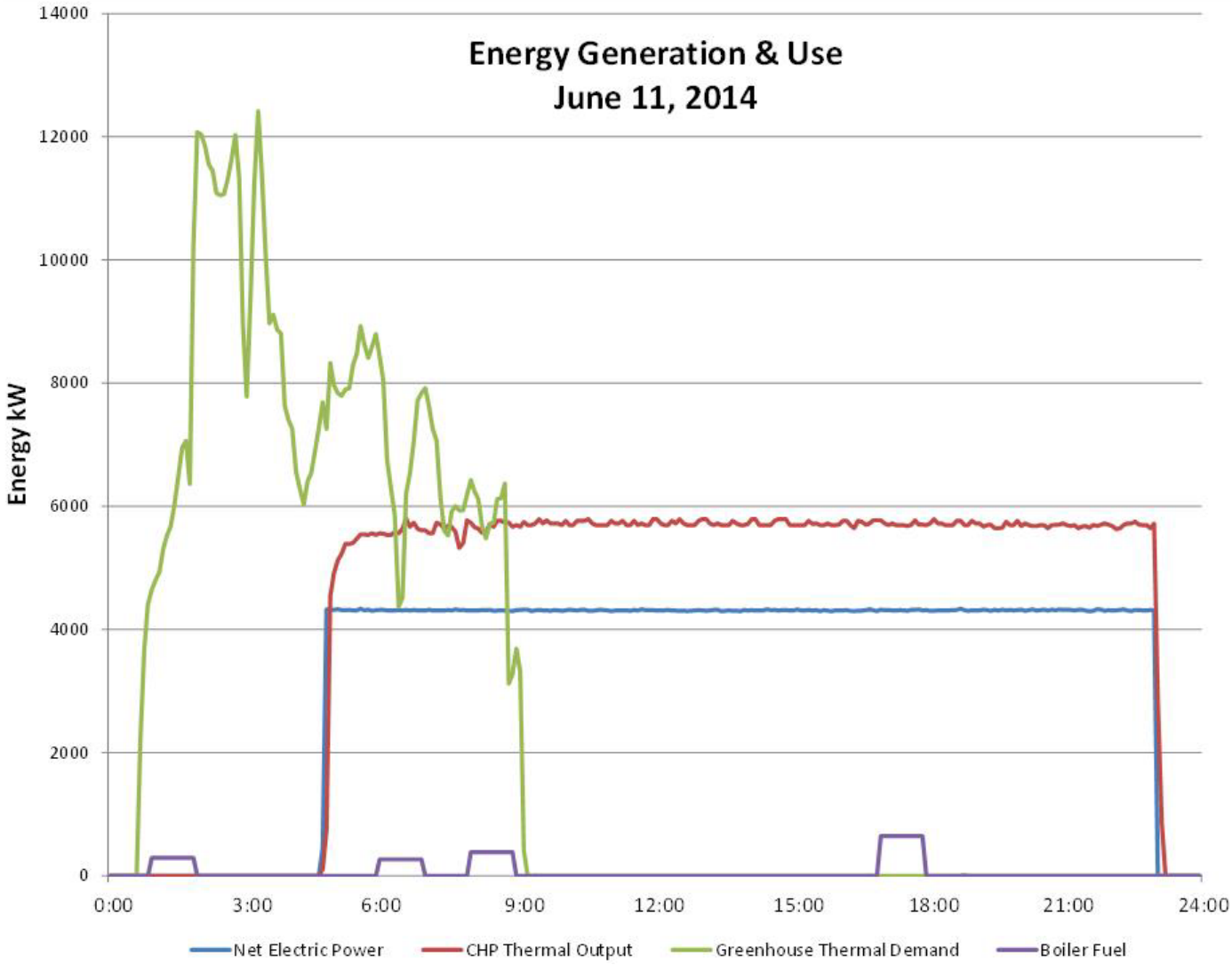
Sources: DE Solutions, Inc.; Conservation Technology

Figure 31: Energy Generation and Use (November 9—15, 2014)



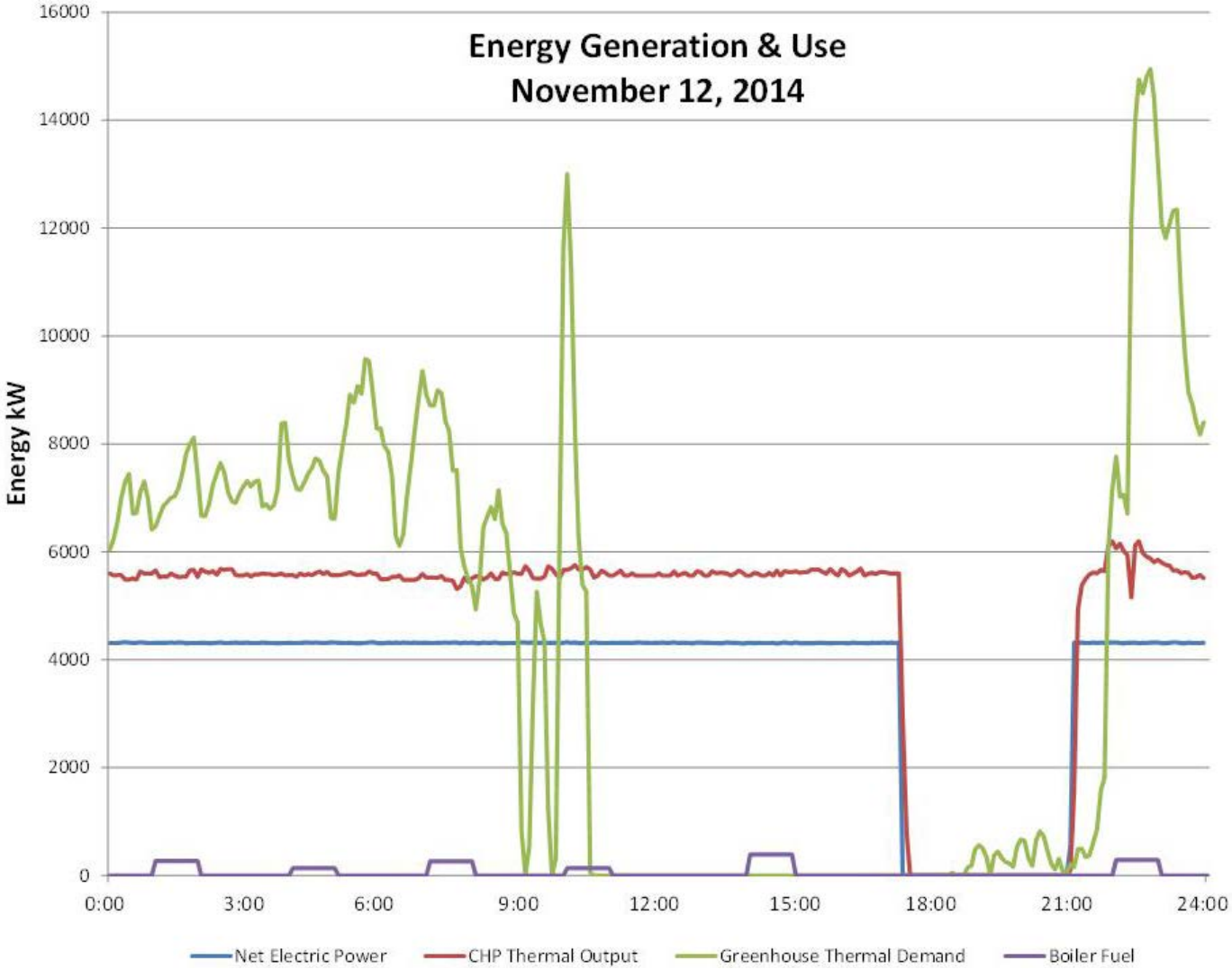
Sources: DE Solutions, Inc.; Conservation Technology

Figure 32: Energy Generation and Use (June 11, 2014)



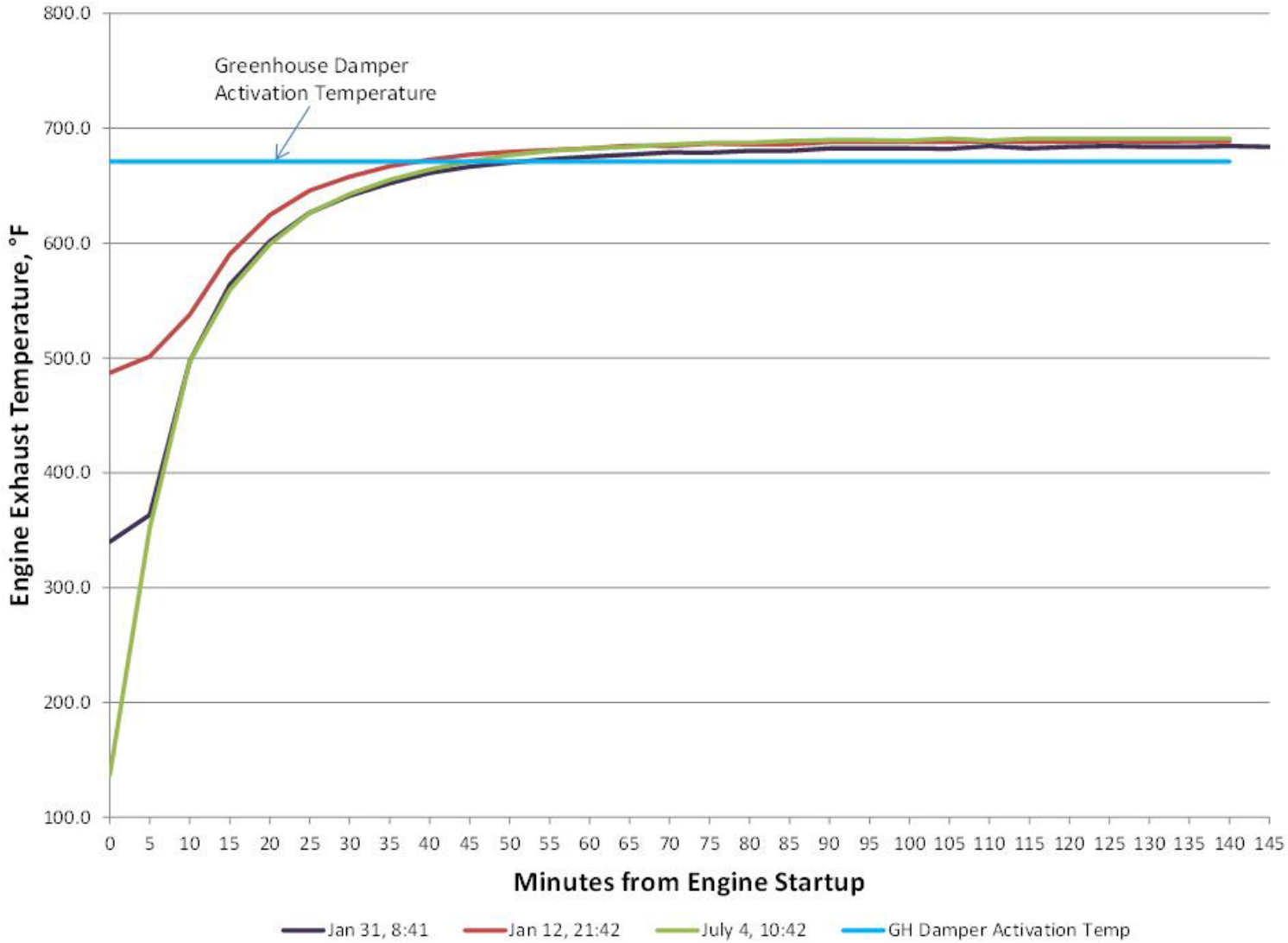
Sources: DE Solutions, Inc.; Conservation Technology

Figure 33: Energy Generation and Use (November 12, 2014)



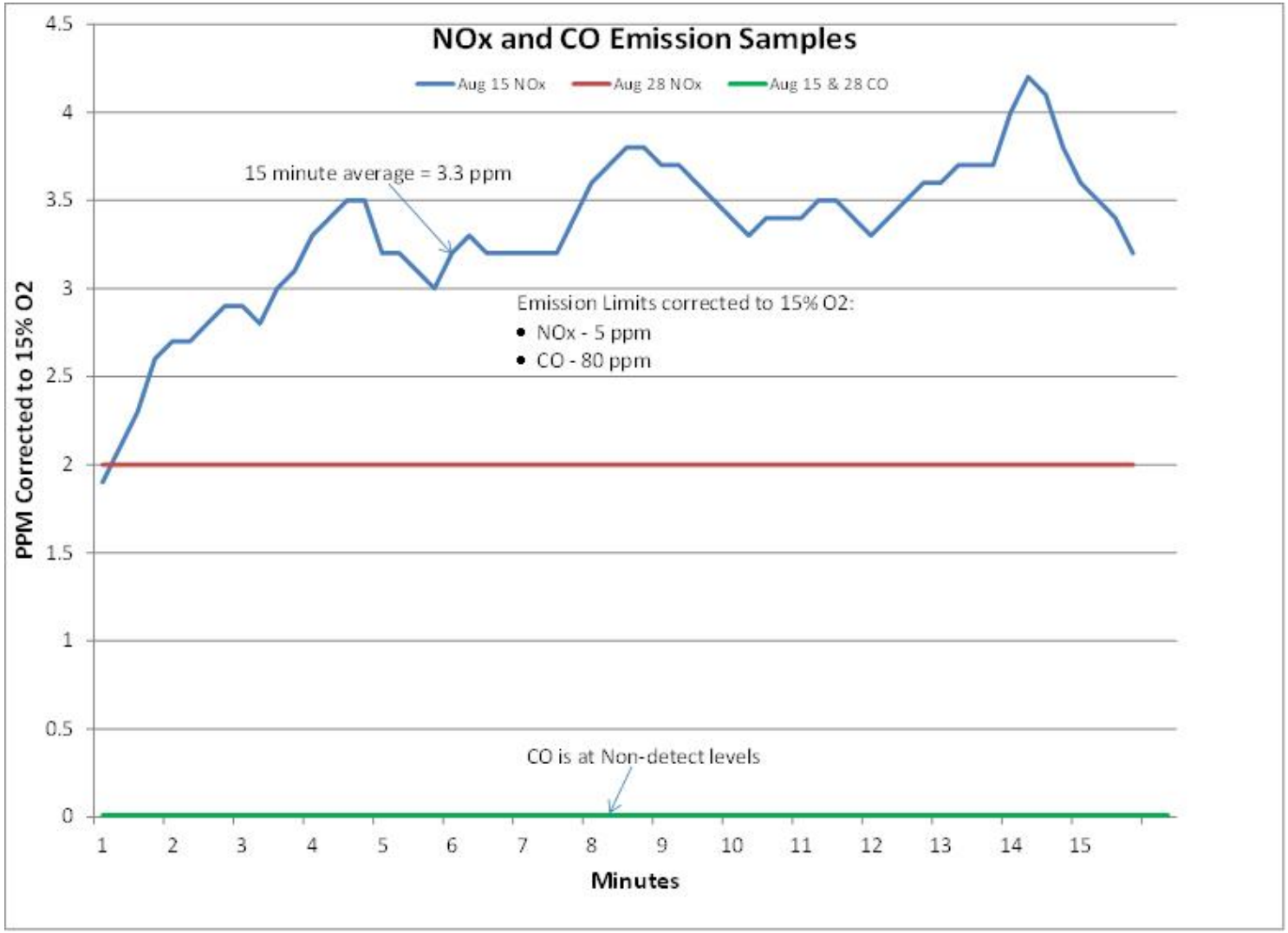
Sources: DE Solutions, Inc.; Conservation Technology

Figure 34: Greenhouse Exhaust Bypass Damper Activation



Sources: DE Solutions, Inc.; Conservation Technology

Figure 35: Representative Emission Measurements



Sources: DE Solutions, Inc.; Conservation Technology

Table 16 compares average measured values against the CHP system specifications. Power output, fuel consumption, and recovered heat were all a bit higher than specified, while measured efficiency was somewhat lower than the specifications. This resulted in higher CO_2 emission rates, but still considerably below the avoided emission benchmark for 2020 and the minimum acceptable performance level permitted under AB 1613, as illustrated in Figure 36.

Table 16: Measured Performance vs. Specifications

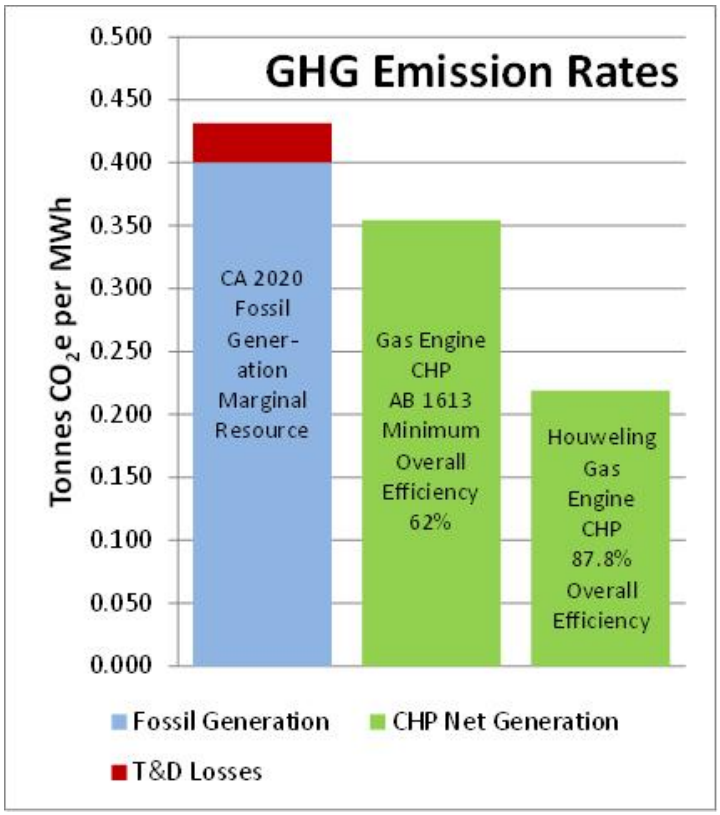
Performance Parameter	Specification	Measured	
		Range	Average
Electrical			
Gross power output, kW_e	4,347		4,350
Ancillary power requirements, kW_e	130	38—42	40
Net power output, kW_e	4,217	4,280—4,340	4,310
Fuel consumption, MMBtu/hr*	35.8	38.5—39.4	39.2
Net electrical efficiency*	40.2%	36%—39%	37.5%
Net electrical heat rate, $Btu/kW_{th}h$*	8,487		9,100
Thermal			
Total recovered heat, MMBtu/hr	18.2	19.0—20.4	19.7
System			
Overall heat-and-power efficiency*	90%	85%—90%	87.8%
Availability	95%		N/A
Total CHP CO_2 production, lb/MW_eh	993		1,064
Net CHP CO_2 production, lb/MW_eh	455		482
Environmental (permitted levels)			
Nitrogen oxides, ppm**	5	2.0—3.3	2.7
Carbon monoxide, ppm**	80 (see Note)	< 1	< 1

* Calculated using the engine fuel's higher heating value.
** Corrected to 15 percent oxygen.

Note: In practice, carbon monoxide levels are kept below 1 ppm to protect the crops.

Source: DE Solutions, Inc.

Figure 36: Comparative GHG Emission Rates

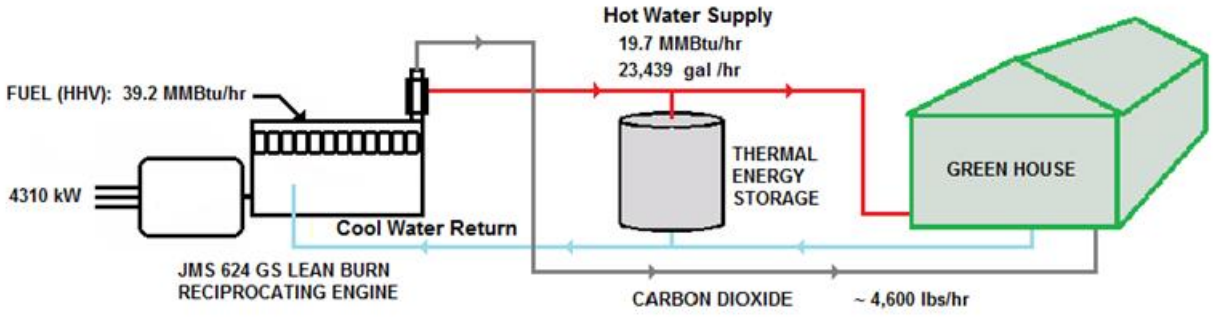


5.4 Economic Performance

5.4.1 Assumptions

This analysis forecasts the financial performance of CHP Unit 2 for calendar year 2015, based on the system's demonstrated performance to date. Figure 37 includes the important system metrics that were assumed in this analysis. (This figure appeared previously but is repeated here for easy reference.) Table 17 lists other specific assumptions.

Figure 37: Schematic of CHP Unit 2 at Houweling's Tomatoes



Source: DE Solutions, Inc.

Table 17: Base Case Assumptions

SoCalGas distribution tariff[9]	GT-F
Electric utility avoided tariff[10]	TOU-PA-3
Electric utility standby tariff[11]	TOU-8-S Primary
Base case price of natural gas	$3.85/MMBtu
Average marginal cost of generation*	$0.026/$kW_eh$
Calculated average gross value of power generated**	$0.074/$kW_eh$
* Including standby and departing load charges. ** Power sold under the FIT or avoided purchases under TOU-PA-3.	

Source: DE Solutions, Inc.

As noted earlier, the only way to cool the engine is to heat the greenhouses or charge the TES tank. The engine, when it is running, is expected to run at full power, with all of its recovered thermal energy being profitably used. If the greenhouses do not require heat and the TES is fully charged, the engine must shut down to avoid overheating.

5.4.2 Analysis of Expected Economic Performance

Two years' worth of weekly boiler fuel data, taken before CHP Unit 2 was installed ("pre-CHP"), were used to establish the engine's operational profile. The operation of the grow lights in Phase 2 was forecast, based on operational data to date coupled with insight provided by Houweling's staff. CHP Unit 2 was assumed to meet one-third of the grow lights' load of 11,377 kW_e. Because the only source of power for the grow lights is the three engines, CHP power was assumed to be prioritized to meet the needs of the grow lights when they are on.

The year was split into three bins. Bin 1 included the four summer months of the electric utility's summer season, June through September. Bin 2 included the shoulder months of October, November, April, and May. Bin 3 included the winter months of December through March. Table 18 shows the load factor of engine power for each of the bins, driven by the forecast need for greenhouse heating. It also shows the assumed daily hours of grow-light operation.

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[9] SoCalGas GT-F, Firm Intrastate Transmission Service: https://www.socalgas.com/regulatory/tariffs/tariffs-rates.shtml

[10] SCE TOU-PA-3, Time-of-Use, Agricultural and Pumping: https://www.sce.com/wps/portal/home/regulatory/tariff-books/rates-pricing-choices/agricultural-pumping-rates/

[11] SCE TOU-8-S, Time-of-Use, Seasonal: https://www.sce.com/wps/portal/home/regulatory/tariff-books/rates-pricing-choices/business-rates/

Table 18: Engine Load Factor and Grow-Light Schedule

	Load Factor, %	Grow-Lighting, hr/day
Bin 1 (June – Sep.)	51	5
Bin 2 (Oct. – Nov. and April – May)	81	10
Bin 3 (Dec. – March)	99	11

Sources: GE Jenbacher; Houweling's Tomatoes

In this analysis, the TES tank accommodated the use of thermal energy noncoincidentally with power generation. This allowed any available engine hours to be scheduled in an economically optimal fashion, because heat can be either used or stored. Power not used on-site for the grow lights is exported under the utility's FIT. The remaining hours of engine operation, at full load, are then scheduled to maximize revenue earned under the FIT.

Table 19 shows the FIT rates as a function of season and time of use. The seasons defined are the same as those used for the utility's TOU-PA-3 sales rate. Houweling's cannot offer "fixed-capacity" export of electricity, so all power is sold to the utility at the FIT rate for "energy-only" deliverability status. For the purposes of this economic analysis, it is assumed that power for the grow lights would have been purchased under the TOU-PA-3 agricultural rate.

Table 19: Seasonal Time-of-Use Feed-in Tariffs

Time of Use	Summer (June – Sep)	Winter (Oct – May)
	$/kWh	
On-peak	0.059376	N/A
Mid-peak	0.060446	0.054562
Off-peak	0.051352	0.053492
Super off-peak	N/A	0.049212

Source: DE Solutions, Inc.

Table 20 shows the rates used in this analysis for the grow lights' avoided power (11,377 kW_e). The power for the grow lights was assumed to be used at night, during off-peak or super-off-peak hours. Because the grow lights use only CHP-generated power, the facilities charge that would ordinarily be assessed by the utility against the grow lights' consumption can be avoided completely.

Table 20: TOU-PA-3 Avoided Tariff Rates

Avoided Costs	Summer (June – Sep)	Winter (Oct – May)
Off-peak energy, $/kW$_e$h	0.06078	0.06657
Facilities charge, $/kW$_e$ per month	8.09	8.09

Source: DE Solutions, Inc.

Even while the grow lights are on, some excess power is still available for sale to the electric utility. The amount of excess power from CHP Unit 2 is 518 kW_e, equal to the engine's capacity minus one-third of the grow lights' load:

$$4{,}310\ kW_e - (11{,}377\ kW_e / 3) = 518\ kW_e$$

Table 21 shows the energy revenue earned by CHP Unit 2 for power sales under the FIT, plus the value of the avoided facilities charge (under the TOU-PA-3 tariff) that results from running the grow lights on CHP-generated power over the two-year forecast period. The fuel cost and FIT energy rate calculations assume a $3.85/MMBtu natural gas price.

Table 21: Two-Year Generation Earnings

	Grow Lights Off			Grow Lights On		FIT Earnings	Avoided Tariff (TOU-PA-3 Off Peak)
	FIT Tariff						
	On-peak	Mid-peak	Off-peak	Off-peak	Super off-peak		
Time of Use	$						
Bin 1 (June – Sep.)	294,830	219,590	6,297	36,844	0	557,562	290,428
Bin 2 (Oct. – Nov. and April – May)	0	469,201	112,370	28,998	40,017	650,586	600,844
Bin 3 (Dec. – March)	0	569,847	117,945	36,247	40,017	764,057	660,929
Avoided facilities charge	N/A	N/A	N/A	N/A	N/A	N/A	736,319
Totals						**1,972,205**	**2,288,520**

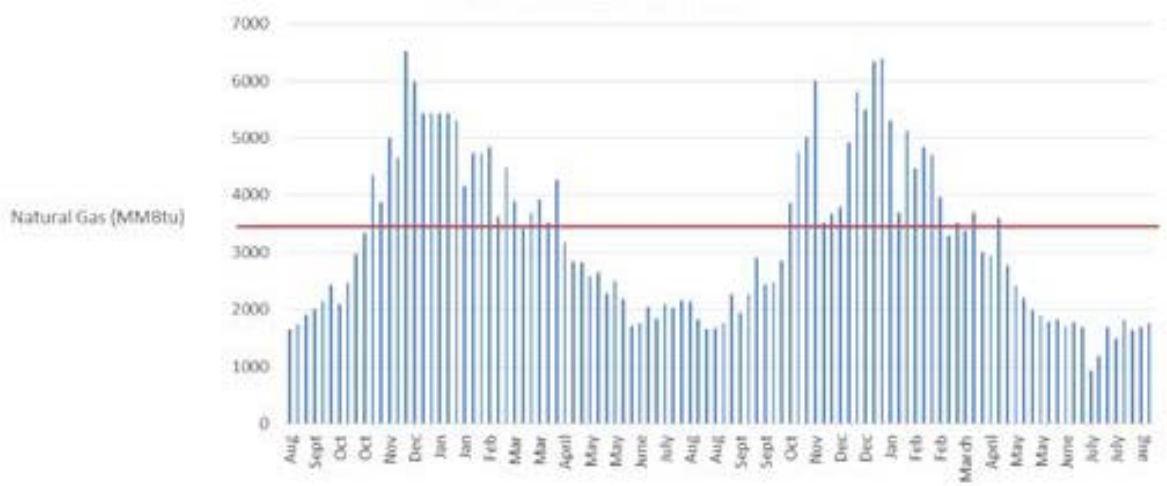
Source: DE Solutions, Inc.

To calculate the value of the CHP system's CO_2 production, it was necessary first to calculate the number of hours over the forecast period that the CO_2 could be profitably used. The plants can take advantage of the additional CO_2 only while photosynthesis is under way, that is, during the day or under the grow lights. CO_2 for the Phase 2 greenhouses (the only ones with grow lights) is already being provided by CHP Unit 1. Therefore, during daylight is the only time that CO_2 is needed from CHP Unit 2 for the northern greenhouses that it serves, and of course the CO_2 is available only when Unit 2's engine is running during the day.

In this analysis, the need for CO_2 and the need for engine heat were forecast to coincide for 5,853 hours over the two-year period. The amount of hourly CO_2 that could be credited to CHP Unit 2 equals the hourly generation of CO_2 from the engine minus the CO_2 that had previously been provided by the existing boilers (for an equivalent heat output). The net hourly amount of CO_2 credited to CHP Unit 2 in this analysis was 0.85 tonnes per hour, at a value of $0.0417/lb or $91.91/tonne, which is what Houweling's pays to purchase liquid CO_2.

As has been alluded to before, the value assigned to the CHP unit's thermal energy assumes that a good deal of the heat supplied by the boilers in the past will now be provided by the engine instead, because the engine will be thermally loaded preferentially before loading the boilers. Figure 38 shows boiler fuel consumption data for the two-year period. The existing condensing boiler efficiency was estimated to be 90 percent. The load factors of the engine, reflecting these boiler loads. The horizontal red line in the figure indicates what the CHP engine could provide if it ran full-time, 168 hours per week. If the engine is running, however, all of its thermal energy must be used or stored, otherwise the engine would automatically shut down to avoid overheating.

Figure 38: Weekly Boiler Fuel Consumption (Fiscal Years 2012 and 2013)



Source: Houweling's Tomatoes

Table 22 shows miscellaneous assumed and calculated values for the two-year period. Table 23 breaks out the project's capital cost by major category. Table 24 summarizes the project's expected economic performance; the capital cost is adjusted for a 10 percent investment tax credit. Table 25 summarizes the pro forma cash-flow analysis, which uses conventional financial metrics for a private-sector project assuming 100 percent equity financing. The pro forma discounted cash-flow details can be found in Appendix E.

Table 22: Miscellaneous Economic Parameters (Fiscal Years 2012 and 2013)

Fuel cost per hour	$171.33
Maintenance cost per hour	$54.69
Marginal cost of generation	$0.026/$kW_e$h
Departing load and standby charges	$433,922
Hours of operation	13,396
Total cost of operation	$3,461,823
GHG reimbursement under AB 1613	$39,566
Total gross revenue	**$6,304,183**
Total net revenue	**$2,842,360**

Source: DE Solutions, Inc.

Table 23: Capital Cost Summary

Equipment and Materials	
GE JMS 624 standardized greenhouse CHP platform	$2,433,260
Building materials	161,600
550 kVA transformer and splice/communication vaults	345,970
Switchgear and 480-Volt transformers	132,690
Utility grid interconnection	226,670
Miscellaneous	480,530
Subtotal equipment and materials	*$3,780,720*
Balance of Scope of Supply	
Engineering	361,090
Project management	308,310
Construction	1,212,170
Commissioning	138,870
Subtotal supply balance	*$2,020,440*
Total	**$5,801,160**

Source: DE Solutions, Inc.

Table 24: Summary of Expected Economic Performance

Estimated capital cost	$5,801,160
Investment tax credit (10%)	–580,116
Project capital cost	$5,221,044
Total annual net revenue	$1,421,180
Simple payback	3.67 years

Source: DE Solutions, Inc.

Table 25: Pro Forma Cash-Flow Summary

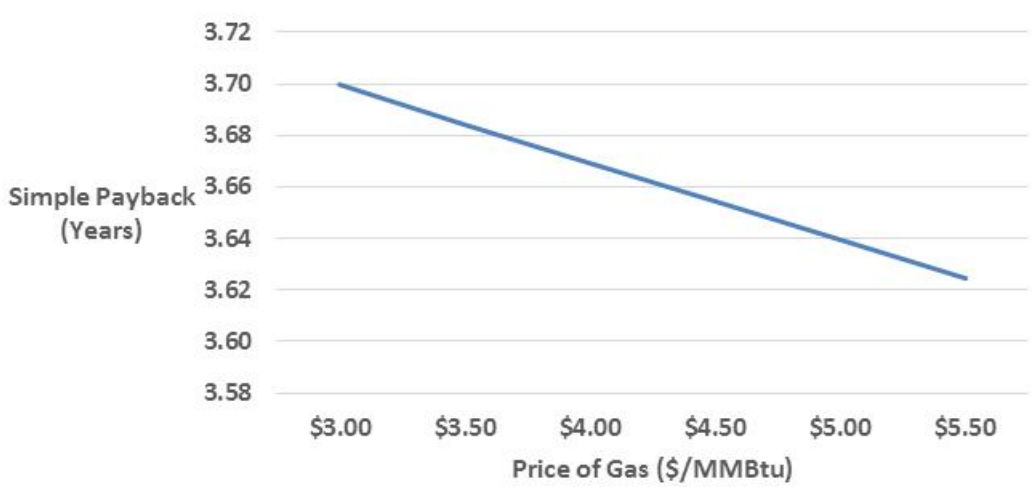
Initial investment	$5,221,044
After-tax internal rate of return (IRR)	22.64%
Years to capital recovery	4.0

Source: DE Solutions, Inc.

5.4.3 Sensitivity Analysis

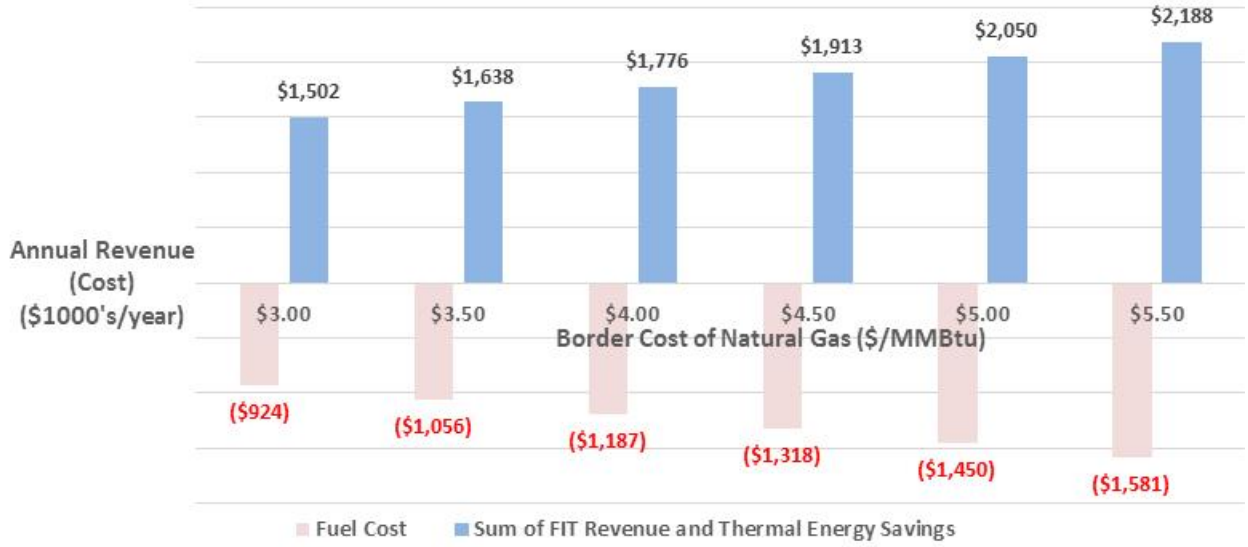
Figure 39 illustrates the sensitivity of the project economics to the price of fuel. The project's simple payback actually varies inversely with the price of fuel. Figure 40 unpacks the data in Figure 39, showing how three metrics vary with the price of natural gas. The price of engine fuel obviously varies with the cost of natural gas, but so does the value of the thermal energy and thus the savings from heat recovery. Also, the FIT revenue varies with the price of gas. For a very efficient CHP system such as this one, the aggregate change in the value of power sold under the FIT and the thermal energy savings more than compensate for higher engine fuel costs.

Figure 39: Variation of Simple Payback with the Cost of Gas



Source: DE Solutions, Inc.

Figure 40: Variation of Fuel Cost, FIT Revenue, and Thermal Energy Savings with the Cost of Gas



Source: DE Solutions, Inc.

CHAPTER 6:
Transferring Technology to Market

6.1 Market Potential

The core CHP technology being demonstrated in this Natural Gas Research project was developed by GE Jenbacher for applications in Northern Europe. The project team aimed to develop and demonstrate a benchmark for applying the technology in California's climate in compliance with local environmental regulations and utility requirements.

The technology demonstrated in this project will position CHP for the emerging high-tech greenhouse market in California. The market for CHP in modern greenhouses is quite large. According to *California Agricultural Statistics – 2010 Crop Year*, about 538,000 acres of cucumbers, lettuce, bell peppers, and tomatoes were harvested in California that year.[12] All of this production, valued at $3.2 billion, is considered a good fit for modern greenhouses. As shown in Table 26, the greenhouse acreage for an equivalent amount of production is about 21,500 acres. The CHP potential is estimated at just over 2,200 MW_e. (These calculations assume that greenhouses yield 24 times more produce per acre than open land and that greenhouses require about 0.1 MW_e of CHP capacity per acre, as noted in Chapter 2.)

Table 26: California Greenhouse Market Potential

Crop	Area Cultivated (2010)		Greenhouse Equivalent Area*		Value, $ million	Combined Heat and Power Potential, MW_e
	Acres	Hectares	Acres	Hectares		
Cucumbers	3,200	1,300	133	54	16	13
Lettuce	206,500	83,570	8,604	3,482	1,642	860
Bell peppers	20,400	8,260	850	344	228	85
Tomatoes	308,000	124,600	12,833	5,194	1,274	1,283
Total	**538,100**	**217,800**	**22,421**	**9,073**	**3,160**	**2,242**
* Based on a 24:1 ratio of open-land vs. greenhouse area.						

Source: US Department of Agriculture, California Office; thermal requirement estimates.

The introduction of greenhouse CHP technology to California agriculture could have other benefits as well. Vegetables grown in California greenhouses could increase the state's exports

[12] *California Agricultural Statistics – 2010 Crop Year* https://www.nass.usda.gov/Statistics_by_State/California/Publications/California_Ag_Statistics/Reports/2010cas-all.pdf

to neighboring states. Furthermore, other commercial buildings with noncoincident electrical and heating loads might benefit from CHP technology integrated with TES.

Currently, California has three "mega"-greenhouse complexes, each with more than 100 acres under glass. So far, Houweling's Tomatoes is the only one to implement CHP. The other two are younger greenhouse operations that are still assessing CHP technology. Although the growth of mega-greenhouses in California is limited, a significant population of smaller greenhouses in the state have thermal profiles that would match well with CHP systems ranging in size from 0.4—3.0 MW_e. Table 27 summarizes the market data for SoCalGas's territory and provides an estimate based on extrapolating these data to the entire state. (Only greenhouses without CHP are included in the table; Houweling's is excluded.) The economics of CHP technology would be more challenging for smaller greenhouses, however, because capital, operating, and maintenance costs would be relatively higher while earnings from the FIT would remain the same (see section 6.2 below). Also, not all of these smaller greenhouses need CO_2 enrichment.

Table 27: Existing Greenhouses in SoCalGas Territory and State Estimate

	CHP Size Range, MW_e	No. of GH	CHP Potential, MW_e
Existing SoCalGas Territory Greenhouses	>10	2	30
	1—3	19	31
	0.4—0.99	22	12
Total		**43**	**73**
California statewide estimate		**86**	**146**

Source: DE Solutions, Inc.

6.2 Hypothetical Case for Smaller CHP Project

As part of its analysis, the project team investigated the potential economics of a CHP system that is a scaled-down version of the one built at Houweling's. This analysis used the specifications of a real Jenbacher engine with a capacity of about 1 MW_e (1,127 kW_e, net of parasitics). Figure 41 illustrates the important system metrics. Table 28 presents the base case assumptions, and Table 29 shows other important economic parameters.

Figure 41: Hypothetical 1-MW$_e$ CHP System

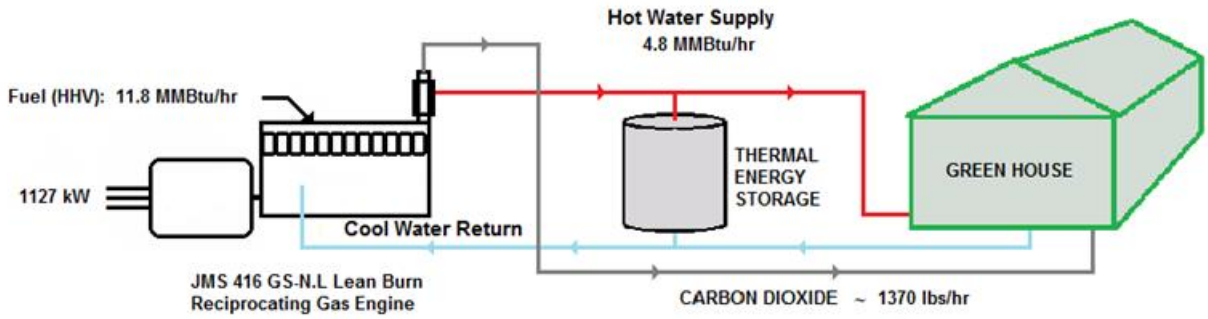


Table 28: Base Case Assumptions

SoCalGas distribution tariff	GT-F
Electric utility avoided tariff	TOU-PA-3
Electric utility standby tariff	TOU-8-S Primary
Base case price of natural gas	$3.85/MMBtu
Average marginal cost of generation*	$0.041/kW$_e$h
Calculated average gross value of power generated**	$0.074/kW$_e$h
* Including standby and departing load charges. ** Power sold under the FIT or avoided purchases under TOU-PA-3.	

Source: DE Solutions, Inc.

Table 29: Miscellaneous Economic Parameters for a Two-Year Period

Fuel cost per hour	$51.91
Maintenance cost per hour	$21.83
Marginal cost of generation	$0.041/kW$_e$h
Departing load and standby charges	$113,496
Hours of operation	13,396
Total cost of operation	$1,101,286
GHG reimbursement under AB 1613	$12,309
Total gross revenue	**$1,617,896**
Total net revenue	**$516,609**

Source: DE Solutions, Inc.

Table 30 displays the economic results of this analysis. The hypothetical 1-MW$_e$ system would not be expected to perform nearly as well as the Houweling's CHP project based on the same

FIT. The smaller system's payback would be much longer because its first cost and maintenance costs are higher and its overall efficiency lower.

Table 30: Economic Results for Hypothetical 1-MW_e System

Project capital cost	$2,536,475
Total annual net revenue	$258,305
Simple payback	9.82 years

Source: DE Solutions, Inc.

6.3 Challenges to Commercial Deployment

A number of regulatory, institutional, and market barriers mired the CHP demonstration project at Houweling's and will continue to cause concern for similar projects. Furthermore, economic barriers remain for smaller, existing greenhouses, which would not benefit from the same economies of scale as mega-greenhouses.

Specifically, the following barriers confronted the Houweling's project team:

- The process of obtaining a grid interconnection agreement that included exporting power back to the grid was unnecessarily delayed, lasting three years and resulting in excessive cost.
- The time and cost required to negotiate and execute the power purchase agreement also was excessive, taking about three years.
- The grid interconnection agreement was overly complex, and the process required Houweling's to coordinate not only with the electric utility and the CPUC, but also with the California Independent System Operator (ISO) and the Federal Energy Regulatory Commission (FERC). Also, Houweling's had to deal with many different people within the electric utility because the company's affiliate transaction rules precluded direct coordination between the utility's power procurement group and its transmission and distribution group.
- The electric utility originally priced the distribution extension to the nearby substation at triple the amount that was eventually negotiated. Houweling's incurred considerable engineering and legal expenses to obtain a reasonable price for the line.
- The cost and schedule associated with the electric utility interfaces were not resolved before the project team had to decide whether to proceed with CHP installation. This delay kept the economic outcome of the project unclear until well after the first two CHP units were commissioned.
- The FIT provided by AB 1613 was only marginally workable for mega-greenhouses at the time of construction. The delays and needless expenses imposed by the electric utility contributed unnecessarily to the business risk of the investment decision, and

they raise doubt about the wisdom of structuring a project that depends on FIT earnings for economic viability. Houweling's was the first end-user to take advantage of AB 1613 since the FIT took effect; although a few other FIT projects have been started or planned since then, the underwhelming response suggests that the law in practice is not living up to its full intent.[13] It should be noted that increases in the electric utility's agricultural rates in early 2015 have improved the economics considerably.

Houweling's experience will likely make the other two mega-greenhouses more cautious toward CHP and will hinder smaller greenhouses from installing CHP without a more favorable FIT, coupled with initiatives to expedite interfacing with electric utilities. As noted above, a smaller CHP system would have much poorer economics than a multi-megawatt project such as Houweling's. Please refer to Chapter 7 for the project team's solutions and recommendations on how to overcome these challenges.

6.4 Market Transfer Activities

Table 31 summarizes the status of the project team's technology transfer actions as of February 2015 (partial list).

[13] As of September 2015, six facilities are certified under the AB 1613 program for a total of 39.1 MW_e. Source: California Energy Commission staff, http://www.energy.ca.gov/renewables/tracking_progress/documents/combined_heat_and_power.pdf

Table 31: Technology Transfer Status

Outreach Events	Dates	Presenters/Exhibitors
Houweling's Ribbon-Cutting – CHP Units 1 and 3; Camarillo, California	Aug 2012	Casey Houweling (Houweling's Tomatoes) Al Clark (Western Energy Systems)
SoCalGas CHP workshop presentation on Houweling's CHP journey	Sep 2012	Casey Houweling
Case study brochure (Western Energy Systems)	Feb 2014	Western Energy Systems
Exhibits with Western's brochures available as handouts: California League of Food Processors, AEE West Coast Congress, California Resource Recovery Conference, others	2014 & 2015	
Website link to brochure & YouTube video	2015	
Energy Solutions Center – Technology & Market Assessment Forum; Los Angeles	Oct 2014	Scott Nolen (GE); Monica Houweling (Houweling's Tomatoes)
Combined Heat and Power Association (CHPA) Conference	Oct 2014	Steve Hall (Western Energy Systems)
Case study brochure (SoCalGas)	Nov 2014	SoCalGas
Presentation at Consortium of Energy Efficiency	Jan 2015	Steve Martz (SoCalGas)
SoCalGas's brochure featured at Tulare Agriculture Show	Feb 2015	SoCalGas
Regular participation at California Farm Bureau meetings to educate members on the benefits of CHP in greenhouses	2014 & 2015	D. Carrell & J. Catanzaro (SoCalGas)
International Colloquium on Environmentally Preferred Advanced Power Generation (ICEPAG)	Mar 2015	Keith Davidson (DE Solutions)
Advocacy Actions	Dates	Organization/Representative
Comments to CPUC regarding ineffectiveness of AB 1613 program and recommended amendments	Dec 2013	California Clean DG Coalition
Energy Commission Staff Workshop on CHP to support California's energy & environmental goals	Jul 2014	Casey Houweling

Outreach Events	Dates	Presenters/Exhibitors
Meeting with Energy Commission Chair Weisenmiller regarding project barriers that cost precious time and money to resolve	Jul 2014	Casey Houweling & Dave Carrell (SoCalGas)
Comments to Energy Commission in response to Staff CHP Workshop	Aug 2014	California Clean DG Coalition

Source: DE Solutions, Inc.

CHAPTER 7:
Conclusions and Recommendations

7.1 Observations and Conclusions

CHP's market potential in California greenhouses could exceed 2.2 gigawatts. A number of regulatory, institutional, and market barriers, however, confront CHP projects, and smaller, existing greenhouses would not benefit from the same economies of scale as mega-greenhouses.

During this CHP demonstration project, the processes of reaching agreements for grid interconnection and power purchase were time-consuming and expensive.. This clouded the economic picture and contributed to the business risk of Houweling's investment. Houweling's had to coordinate with multiple regulatory, governmental, and utility groups on grid interconnection issues. Finally, Houweling's incurred considerable engineering and legal expenses to obtain a reasonable price for the distribution line needed to export surplus power.

The demonstrated performance of Houweling's CHP system has been outstanding since early product design deficiencies were rectified. Subsequent to installation of the new engine in early October 2014, the availability of the CHP system has been faultless except for routine scheduled maintenance. Net electrical efficiencies have averaged 38%, and overall efficiencies have averaged 88% (both HHV). After a utility rate increase in February 2015 for the baseline electric rate for the grow lights, the annual net revenue from CHP Unit 2 increased from $1.12 million to $1.42 million, decreasing the simple payback period from 4.7 years to 3.7 years.

Overall, the delays and expenses involved in this CHP demonstration will likely raise doubt about the wisdom of structuring a project that depends on FIT earnings for economic viability. Houweling's experience will likely make other mega-greenhouses more cautious and will hinder smaller greenhouses from installing CHP without a more favorable FIT, coupled with initiatives to expedite interfacing with electric utilities.

7.2 Recommendations

Advocacy, technical and economic benchmarking, and outreach activities are recommended to spur implementation of CHP technology in California's greenhouse community. These recommendations encompass energy research and development organizations, CHP engineers and developers, CHP equipment suppliers, the agricultural and greenhouse industries, and governmental agencies. Many such activities to spur further implementation of CHP in California greenhouses are under way or planned and are listed below.

7.2.1 Technical and Economic Verification

- Instrumentation, data collection, and analysis of key performance metrics, including:
  - Fuel consumption
  - Production of electricity and heat

    - Electric and overall efficiency
    - Emissions
- Economic analysis
    - Capital cost breakdown
    - Operating costs
    - Operating savings
- Documentation of technical and economic performance

7.2.2 Outreach and Communication

- Case studies and project profiles for distribution via websites, e-mail, and conferences
- Presentations, papers, and exhibits at agricultural, energy, and environmental conferences
    - SoCalGas Energy Resource Center (ERC) workshops
    - U.S. DOE CHP Pacific Technology Assistance Partnership (TAP) seminars
    - Industrial Environmental Association (IEA) and California Manufacturers & Technology Association (CMTA) annual conference
    - Association of Energy Engineers (AEE) West Coast Energy Management Congress and Exhibit
- Press releases
- Videos
- Site visits and tours
- Meetings with government officials
    - California Energy Commission
    - California ARB
    - CPUC
    - Governor's office
    - State legislature
- Meetings with electric, gas, and combination utilities
- Meetings with prospective end-users, project developers, and business partners
- Meetings with advocacy organizations

- California Clean DG Coalition (CCDC)
- California Cogeneration Council (CCC)
- California Manufacturers Technology Association (CMTA)

As a result of this CHP demonstration experience, the project team recommends the following institutional and regulatory improvements:

- Streamline and expedite the processes for interconnection and power purchase agreements
- Require the electric utility to provide a single point of contact for the customer to work with throughout the interconnection process
- Hold the host electric utility responsible for coordinating with the governmental and regulatory agencies involved in the interconnection agreement
- Amend the AB 1613 rule to be more advantageous and straightforward to energy consumers
- Develop a guidebook for navigating the AB 1613 interconnection maze and explaining the power purchase agreement terminology

GLOSSARY

Term	Definition
AB	Assembly Bill
AEE	Association of Energy Engineers
ARB	California Air Resources Board
ASERTTI	Association of State Energy Research and Technology Transfer Institutions
Btu	British thermal unit
Btu/scf	Btu per standard cubic foot
CCC	California Cogeneration Council
CCDC	California Clean DG Coalition
CEMS	continuous emissions monitoring system
CHP	combined heat and power
CHPA	Combined Heat and Power Association
CMTA	California Manufacturers & Technology Association
CO	carbon monoxide
CO_2	carbon dioxide
CPUC	California Public Utilities Commission
ERC	Energy Resource Center (SoCalGas)
FERC	Federal Energy Regulatory Commission
FIT	feed-in tariff
GH	greenhouse
gpm	gallons per minute
GHG	greenhouse gas
GJ	gigajoules
GTI	Gas Technology Institute
HHV	higher heating value

HW	hot water
HX	Heat exchanger
ICEPAG	International Colloquium on Environmentally Preferred Advanced Power Generation
IEA	Industrial Environmental Association
IRR	Internal rate of return
ISO	Independent System Operator
kVA	Kilovolt-amperes
kW_e	Kilowatts electric
kW_eh	Kilowatt-hours electric
lb	Pound
LHV	Lower heating value
kg	Kilogram
M&V	Measurement & verification
MMBtu	Million Btu
MMBtu/hr	Million Btu per hour
MW_e	Megawatts electric
MW_{th}	<egawatts thermal
MW_eh	Megawatt-hours electric
N/A	Not applicable or not available
NG	Natural gas
NO_x	Nitrogen oxides
O_2	Oxygen
ppm	Parts per million
PURPA	Public Utility Regulatory Policies Act
QTO	Qualified thermal output
R&D	Research and development

RD&D	Research, development, and demonstration
ROC	Reactive organic compound
RTD	Resistance temperature detector
SCFM	Standard cubic feet per minute
SCR	Selective catalytic reduction
SoCalGas	Southern California Gas Company
TAP	Technology Assistance Partnership (U.S. Department of Energy)
TES	Thermal energy storage
TOU	Time of use (utility rate or tariff)
TOU-PA-3	Time-of-use pumping and agricultural (utility rate or tariff)
WES	Western Energy Systems
yr	Year

APPENDICES

A CHP Unit 2 Engine Specifications

B CHP Unit 2 Equipment Drawings

C Legal and Regulatory Documents

D Instrumentation Specifications

E Pro Forma Cash-Flow Details

These appendices are available as a single, separate volume, publication number CEC-500-2016-049-AP.