Honeywell

Modular Integrated Energy Systems

Final Report

June 20, 2006

Prepared for:

Oak Ridge National Laboratory
P.O. Box 2008
Building 3147
Oak Ridge, TN 37831

Prepared by:

Honeywell Laboratories
3660 Technology Drive
Minneapolis, MN 55418
Fax: (612) 951-7438

Honeywell

Modular Integrated Energy Systems

Final Report

Prepared for:

Oak Ridge National Laboratory
P.O. Box 2008
Building 3147
Oak Ridge, TN 37831

Prepared by:

Steve Gabel, Program Manager
(612) 951-7555
Honeywell Laboratories
3660 Technology Drive
Minneapolis, Minnesota 55418

June 20, 2006

Disclaimer

This report was prepared as an account of work sponsored by an agency of the United States Government. None of the following entities makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights: a) the United States Government, b) any agency, contractor, or subcontractor thereof, and c) any of their respective employees. Any use the reader makes of this report, or any reliance upon or decisions to be made based upon this report, are the responsibility of the reader. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or any agency, contractor or subcontractor thereof. The views and opinions of the authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Table of Contents

Section 1. Introduction 1
Section 2. Technology Development 3
2.1 IES Reference Designs 3
2.2 Exhaust-Driven Absorption Cooling Technology 13
2.3 IES Control Optimization 19
Section 3. IES Technology Field Demonstration 33
3.1 System Description 33
3.2 Site Description 37
3.3 Overview of Results 38
Section 4. Performance Monitoring 39
4.1 Field Monitoring Overview 39
4.2 Summary Performance Results 40
Section 5. Conclusions 51
5.1 Development of IES Reference Designs 51
5.2 Development of Exhaust-Driven Absorption Cooling Technology 51
5.3 Development of On-line Control Optimization Technology 52
5.4 IES Plant Operations 52
5.5 IES System Measured Performance 52

List of Figures

Figure 2-1. Reference Design Concept 4
Figure 2-2. System Arrangement: Reference Design R-2, R-4, and R-8 6
Figure 2-3. Scope of Reference Design R-2 8
Figure 2-4. General Arrangement Plan for Reference Design R-2 9
Figure 2-5. Chiller-Heater Internal Design 14
Figure 2-6. Exhaust-Driven Absorption Chiller 17
Figure 2-7. Exhaust-Driven Absorption Chiller Performance (June 2005) 17
Figure 2-8. CHP Control Optimization Concept 19
Figure 2-9. CHP Control Optimizer 21
Figure 2-10. CHP Control Optimizer: Equipment Schedule 22
Figure 2-11. Simulation of the CHP Control Optimizer 24
Figure 2-12. Ft. Bragg 82nd Central Heating Plant IES System 25
Figure 2-13. Simulation Input Data: Heating and Cooling Loads 26
Figure 2-14. Simulation Input Data: Electricity Real-Time Prices (RTP) 27
Figure 2-15. Simulation Input Data: Natural Gas Prices 28
Figure 2-16. Simulation Results: Operating Cost Savings 30
Figure 2-17. Simulation Results: Turbine-Generator Load Duration 31
Figure 3-1. Ft. Bragg 82nd Central Heating Plant IES System 33
Figure 3-2. Ft. Bragg 82nd Central Heating Plant IES System: General View 35
Figure 3-3. Ft. Bragg 82nd Central Heating Plant IES System Equipment Arrangement 36
Figure 4-1. IES System: Boundaries of the Performance Analysis 39
Figure 4-2. Energy Delivery Results, Summer 2004 40
Figure 4-3. Energy Delivery Results, Fall 2004 41
Figure 4-4. Operational Results, Fall 2004 42
Figure 4-5. Energy Utilization Results, Fall 2004 43
Figure 4-6. Energy Delivery Results, Winter 2005 44
Figure 4-7. Operational Results, Winter 2005 45
Figure 4-8. Energy Utilization Results, Winter 2005 46
Figure 4-9. Energy Delivery Results, Summer 2005 47
Figure 4-10. Operational Results, Summer 2005 48
Figure 4-11. Energy Utilization Results, Summer 2005 49

Acknowledgements

The project team would like to acknowledge the valuable support provided by other parties in our performance of this project and in the preparation of this report. Ron Fiskum (from the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy), along with Patti Garland, Bob DeVault, Jan Berry, Abdi Zaltash PhD., and Andrei Petrov PhD. (from Oak Ridge National Laboratory) provided a clear vision, steady guidance, and great technical support to the team throughout our work on this project.

Executive Summary

This document presents the results of the development and implementation of a set of packaging and related technologies for application to integrated energy systems (IES or CHP—cooling, heating and power). The project was funded largely by the U.S. Department of Energy, through Oak Ridge National Laboratory (ORNL), with significant cost sharing by the team of industry participants.

The objective of this project was to develop packaging and related technologies for large (1-5 MW) integrated energy systems and demonstrate the technologies in a field site installation. These systems are typically intended for central plant and district energy applications serving multiple buildings. The key technology development tasks in the project were:

- Develop a set of CAD-based modular "reference designs" for large IES systems
- Develop an exhaust-driven absorption chiller (with a capacity of 1000 Tons)
- Develop a supervisory control system having on-line control optimization capability

The project also included the following related technical work:

- Install the exhaust-driven absorption chiller and on-line control optimization technology at the field demonstration site (Ft. Bragg, NC).
- Monitor the performance of the IES installation for one year.

Standardized reference designs for large IES systems will provide lower installed costs and will also speed the acceptance of this technology in the marketplace. Streamlining the up-front design process is needed to produce the greatest benefit from IES technology. Designing these systems as a number of component modules (having appropriate interfaces and careful equipment matching), with each module corresponding to a piece of major equipment (i.e. gas turbine-generator, and absorption chiller-heater), simplifies the design and installation process by reducing the amount of site-specific engineering and site preparation required. The reference design development produced the following conclusions:

- This concept can help to reduce the complexity and installed cost of large IES systems. Our analysis showed that the use of reference design data could save up to 8% of a project's engineering costs through reductions in up-front project feasibility analysis, detailed design, and preparation of construction documents.
- Interconnection with building electrical and HVAC systems is a key project design task. Application of well-known engineering design practices (through resources provided in an earlier project report) can provide a good result.

The project team developed, built, and installed an exhaust-driven 1000 refrigeration ton (RT) absorption chiller. A similar design could be employed in implementing a chiller-heater unit.

The absorption cooling development produced the following conclusions:

- Exhaust-driven absorption cooling technology can be utilized to provide simpler IES system designs, especially if implemented as a chiller-heater by avoiding the use of a heat recovery steam generator in applications where steam is not required.
- The exhaust-driven chiller installed at the field demonstration site provided very good performance and met the design specifications. However, a small amount of regular maintenance is required in order to keep the unit operating at peak performance.

The IES control optimization concept considers the heating and cooling loads, utility rates (grid electricity and fuel prices), equipment characteristics, and weather data to determine how to best meet these loads using the IES equipment, electric grid power, and the non-IES heating and cooling equipment. This optimizer specifies the proper equipment set points for electric power generation, heating output, and cooling output. The set points are displayed as guidance to the plant operator. At the Ft. Bragg field site, all optimizer control actions were implemented manually by the plant operators. The control optimization development produced the following conclusions:

- A simulation analysis showed that on-line control optimization could deliver annual energy cost savings of approximately 6%, as compared with a user-defined "smart" operating strategy.
- On-line control optimization capability helped identify periods when it was not economical to operate the IES system due to high fuel prices or low thermal loads. Without optimization, these decisions may not otherwise be obvious to plant operators or energy managers.

Field performance monitoring work at the Ft. Bragg site produced the following conclusions:

- System-level and equipment-level performance can be measured and design intent verified with the proper amount of field instrumentation. Our site measurements showed that the design intent was met at the Ft. Bragg site.
- Monthly energy efficiencies of up to 80% (based on the lower heating value, LHV of the fuel input) are possible with IES technology, based on measured performance at the Ft. Bragg site. However, seasonal variations in energy efficiency are to be expected, due to varying thermal loads and equipment operating characteristics.

With the completion of this project, these IES technologies are now commercially available. These technical advances offer important economic benefits by reducing the installed cost and the operating cost of large IES systems. These benefits should serve to increase the application of large IES systems in the buildings sector.

Section 1. Introduction

This document presents the results of the development and implementation of a set of packaging and related technologies for application to integrated energy systems (IES, or CHP—cooling, heating and power). The majority of the project funding was provided by the U.S. Department of Energy through Oak Ridge National Laboratory (ORNL). The project team of industry companies also provided significant cost sharing for this development.

The objective of this project was to develop packaging and related technologies for large (1-5 MW) integrated energy systems and demonstrate the technologies in a field site installation. The installation site for the IES system was the 82nd Central Heating Plant at Ft. Bragg, NC. The 82nd plant serves a large number of barracks and other buildings with steam for heating and domestic hot water and chilled water for cooling.

The key technology development tasks in the project were:

- Develop a set of CAD-based modular "reference designs" for large IES systems
- Develop an exhaust-driven absorption chiller (with a capacity of 1000 Tons)
- Develop a supervisory control system having on-line control optimization capability
- Install the exhaust-driven absorption chiller and on-line control optimization technology at the Ft. Bragg field demonstration site. Monitor the performance of the IES installation for a period of one year.

The project team included: Honeywell Laboratories (control system development and project management), Broad USA (exhaust-driven absorption cooling technology), I.C. Thomasson Associates (development of the IES reference designs, and Ft. Bragg site engineering support), the Chelsea Group (system interfacing, and design engineering resources), North Carolina State University (data acquisition and data analysis support), and Honeywell Energy Services (energy savings performance contract with the U.S. Army for the IES installation at Ft. Bragg).

This final report is a summary of the project results. Other reports published earlier provide additional technical detail on the various elements of the technical work. These earlier reports are listed in Table 1-1 and can be accessed from the ORNL website at: http://www.ornl.gov/sci/engineering_science_technology/cooling_heating_power/pubs_ies.htm.

Table 1-1. Project Report Documents

Report Content	Report Title	Date	Report Filename
Reference Design Documentation	Modular Integrated Energy Systems, Task 5 Prototype Development, Reference Design Documentation	April 27, 2006	4000011476_Task5_RefDes_Apr06.pdf
Control Optimization Report	Modular Integrated Energy Systems, Task 5 Prototype Development, Control and Optimization Performance Report	May 5, 2006	4000011476_Task5_Optimizer_May06.pdf
Ft. Bragg IES System Performance Report, June thru December 2004	Modular Integrated Energy Systems, Task 6 Field Monitoring, Interim Report, Period Covered: June 2004–December 2004	March 24, 2005	82ndCHPperf_JunDec2004.pdf
Ft. Bragg IES System Performance Report, January thru April 2005	Modular Integrated Energy Systems, Task 6 Field Monitoring, Interim Report, Period Covered: January 2005–April 2005	July 22, 2005	82ndCHPperf_JanApr2005.pdf
Ft. Bragg IES System Performance Report, May thru August 2005	Modular Integrated Energy Systems, Task 6 Field Monitoring, Interim Report, Period Covered: May 2005–August 2005	April 28, 2006	82ndCHPperf_MayAug2005.pdf

The following sections of this document describe the technical work and the results of this project. Each section contains a tabular list of the key outcomes or “lessons learned” relating to that portion of the project.

Section 2. Technology Development

This project included significant development work in the following IES technologies:

- CAD-based modular reference designs for large IES systems,
- Exhaust-driven absorption cooling technology,
- Supervisory controls for IES systems, with on-line control optimization capability

The following sections describe the results of the technology development work.

2.1 IES Reference Designs

This section presents the results of the technical work performed in developing a set of modular reference designs for large IES systems.

Standardized, packaged IES modular systems will provide lower installed costs and speed the acceptance of this technology in the marketplace. Streamlining the up-front design process is needed to produce the greatest benefit from IES technology. The project team focused on IES modular systems in the 1-5 MW range, with 900 to 3000 tons of cooling. These systems are typically intended for central plant and district energy applications serving multiple buildings.

Because large IES system installation scenarios vary widely, packaging depends on modularity, namely the ability to construct a system by choosing from a selection of compatible components with standardized interfaces. Modularity is especially important for larger IES systems where the physical size of the equipment prohibits the manufacture and shipment of the entire system in one enclosure. Designing these systems as a number of component modules (having appropriate interfaces and careful equipment matching), with each module corresponding to a piece of major equipment (i.e. gas turbine-generator and absorption chiller-heater), simplifies the design and installation process by reducing the amount of site-specific engineering and site preparation required. This reference design concept is illustrated in Figure 2-1.

For a given field application, the building owner or cognizant engineer will select the proper reference design that would apply, based on an economic analysis. That economic analysis would utilize IES performance data which is included in each of the various reference designs.

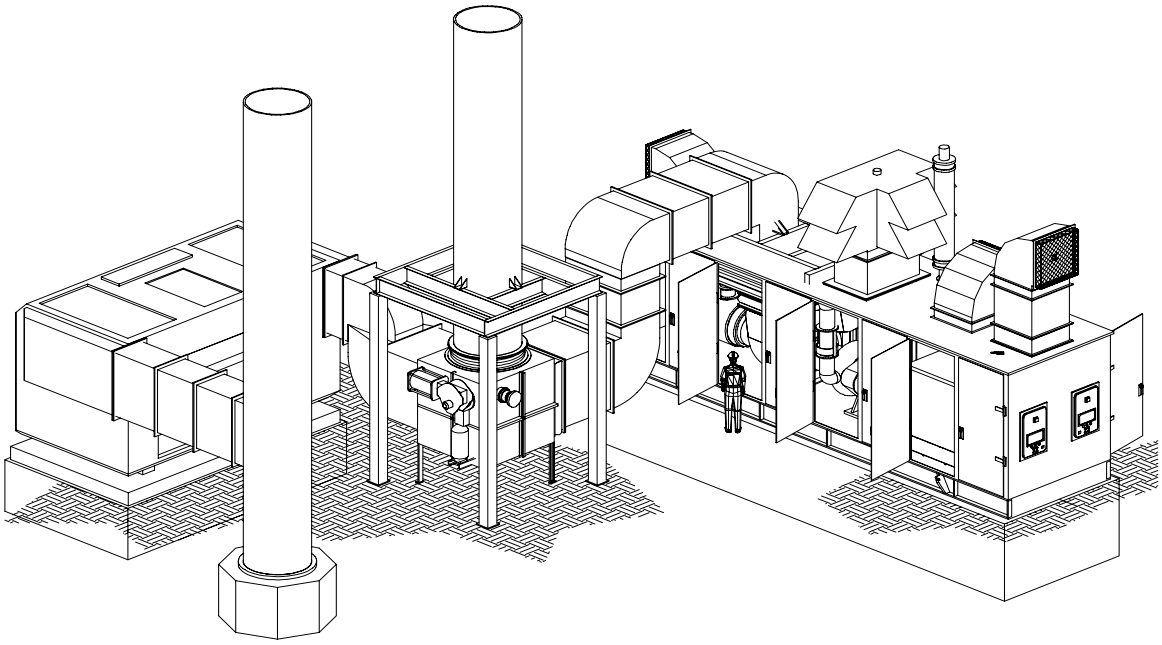


Figure 2-1. Reference Design Concept

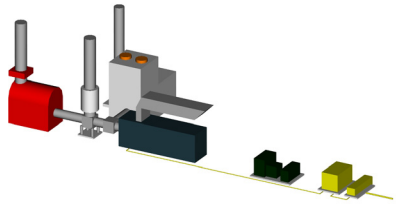
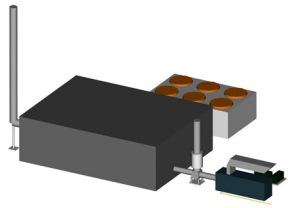
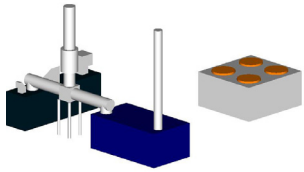
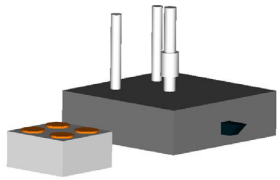
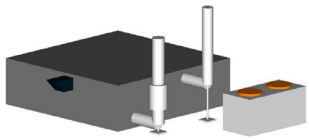
The benefits of applying a reference package design are:

- The amount of custom design work for a given site application is reduced. Modular reference designs provide IES systems that are more cost-competitive through a reduction in installed cost and optimal matching of equipment to the energy loads.
- Improved economics validate applications that are otherwise difficult to justify (from a purely economic standpoint). For these applications, the other benefits provided by IES technology (e.g., reduced emissions, improved indoor air quality, and increased energy efficiency) are thus made available to the central plant/building owner and occupants.
- Readily available reference designs can shorten the time required to perform the upfront analysis needed to quantify the economic and other benefits offered in each individual application, speeding the process of evaluating candidate IES applications.

2.1.1 Reference Design Overview

The reference designs were built around a gas turbine as the prime mover and an exhaust-driven absorption chiller (or chiller-heater). An overview of the designs is shown in Table 2-1.

Table 2-1. Reference Design Overview

Title	Arrangement	Description
R-1		5.7-MW Turbine, 1,000-ton chiller, outdoor installation with heat recovery steam generator (HRSG) and inlet air cooler, new chiller building, existing plant expansion
R-2		5.3-MW Turbine, 3,300-Ton Chiller-Heater, New Standalone Plant Building
R-4		4.6-MW Turbine, 1,300-ton chiller-heater, complete outdoor installation, auxiliaries installed in existing space
R-6		3.5-MW turbine, two 1,000-ton chiller-heaters (2000 tons total), new standalone plant building, dual chiller-heaters
R-8		1.2-MW turbine, 900-ton chiller-heater, existing plant expansion, all contained in existing space

Notes:

1. Reference Design R1 is patterned after the Ft. Bragg 82nd central heating plant application. The major equipment in R1 is sized to meet the heating and cooling loads for that specific site.
2. The electric output rating for Reference Design R1 has been increased by approximately 0.5MW due to the use of an inlet air cooler.
3. The HRSG package used in Reference Design R1, also includes associated equipment such as the duct burner, economizer, bypass diverter, stack silencer, etc.

The system arrangement for Reference Designs R-2, R-4, and R-8 is shown in Figure 2-2. (Note: The inlet air cooler is optional, depending on environmental conditions and energy cost considerations at each particular field site. Similarly, the need for a gas compressor will be dictated by the availability of high pressure natural gas at the site.) The system arrangements for the other reference designs vary somewhat from that shown in the figure below.

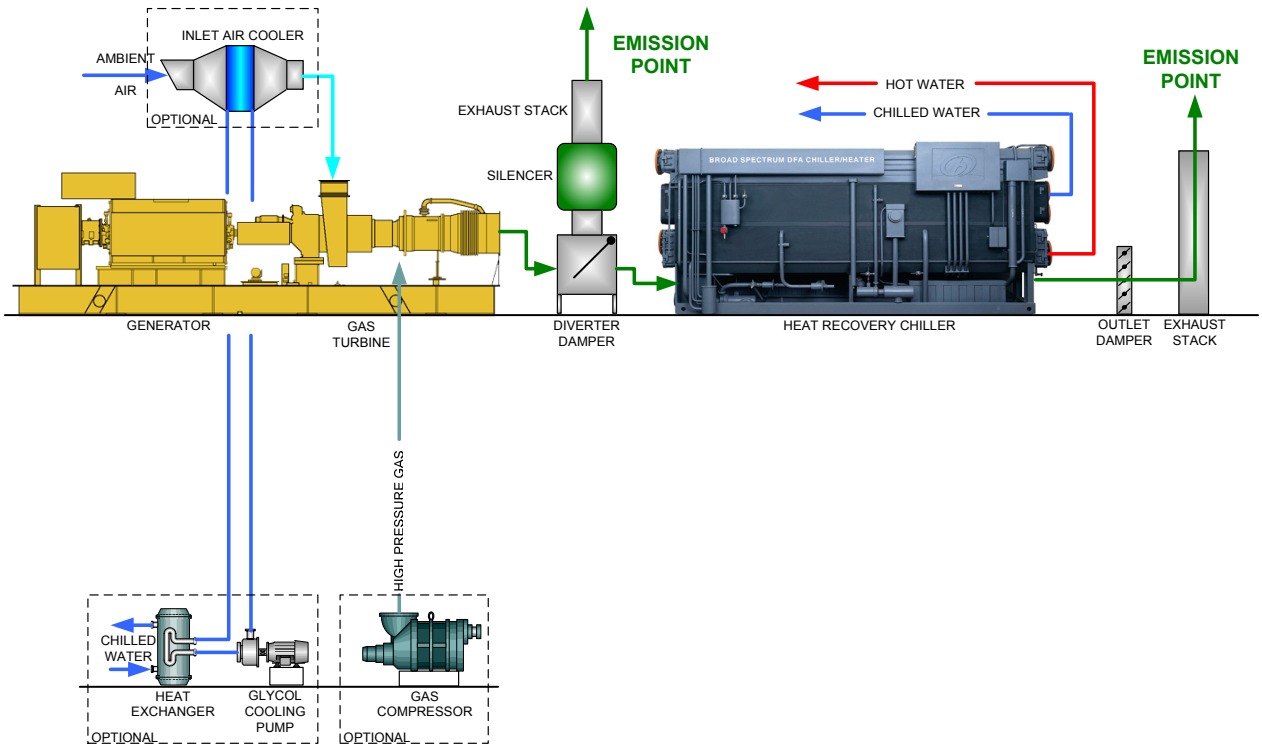


Figure 2-2. System Arrangement: Reference Design R-2, R-4, and R-8

2.1.2 Major Equipment

The major equipment used in the reference designs is described in Table 2-2.

Equipment from other suppliers can easily be applied in a specific IES application. These reference designs are examples that could be suitably altered by the user to incorporate other brands of major equipment.

Table 2-2. Major Equipment

Item	Manufacturer	Web link
Turbine generator	Solar Turbines	www.solarturbines.com
Absorption chiller	Broad Air Conditioning	www.broadusa.com
Heat recovery steam generator (HRSG) (used only in Reference Design R1)	Rentech	www.rentechboilers.com

2.1.3 Reference Design Concept

The key principles of the modular IES reference design concept are presented in the Table 2-3.

Table 2-3. Reference Design Concept and Limitations

Purpose	Packaging these systems into a number of component modules with each corresponding to a piece of major equipment (i.e. gas turbine-generator, heat recovery steam generator, absorption chiller or chiller-heater, and exhaust ductwork) simplifies the design and installation process by reducing the amount of site-specific engineering required.
Structure	The reference designs are developed as a set of individual designs of varying capacity (i.e. electric generating, heating, and cooling output). This set of designs spans the range of approximately 1-5 MW.
Primary user	A registered professional engineer (P.E.) with previous experience in CHP system design (or closely related expertise).
Other users	Facility engineers, energy managers and others who have a technical understanding of CHP systems may also make use of the reference designs in feasibility studies. However, all design work and use of the reference design should be performed under the direction of a registered P.E.
Design intent	The reference designs will not replace the need for direct technical oversight by a competent registered P.E. Any use of a reference design in a specific project must be performed under the direction of the cognizant P.E. and the resulting final project design is the sole responsibility of the P.E.
Compliance	These designs are offered for reference only. Compliance with all applicable local codes and standards is the responsibility of the cognizant P.E.
Application scenario	The reference designs describe the repeatable portion of the system that is not site specific. Application of a reference design to a specific site and the design of all interconnections to other systems and any additional equipment required will be performed by the cognizant P.E.
Design scope	The reference designs focus on the mechanical engineering design of these systems. Less emphasis is placed on the electrical design due to its site-specific nature.
Other disciplines	The reference designs do not include structural, architectural, or environmental elements. These other disciplines are the responsibility of the design engineering team for the specific project or site.
Equipment selection	The major equipment (gas turbine-generator, and absorption chiller or chiller-heater) have been carefully matched in order to maximize the system performance. Most of the reference designs utilize a chiller-heater configuration for simplicity and to minimize installed cost.
Technical support	No direct application support for the reference designs was offered as part of this DOE/ORNL project.
Communications and outreach	As part of the technology outreach efforts of the U.S. Department of Energy, these reference designs are useful to those who have previous experience with CHP system design as well as those who do not—including site owner decision makers.

2.1.4 Scope of the Reference Designs

The scope of the Reference Design R-2 is illustrated in Figure 2-3. The other reference designs have a similar scope.

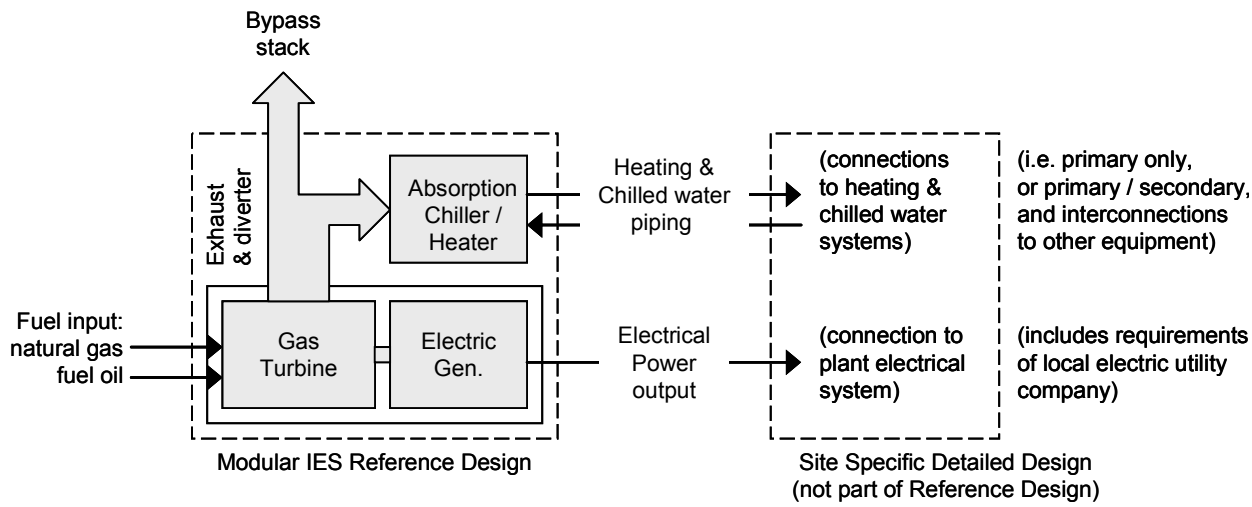


Figure 2-3. Scope of Reference Design R-2

2.1.5 Example Reference Design

As an example of the concept, the general arrangement site plan for Reference Design R-2 is illustrated in Figure 2-4.

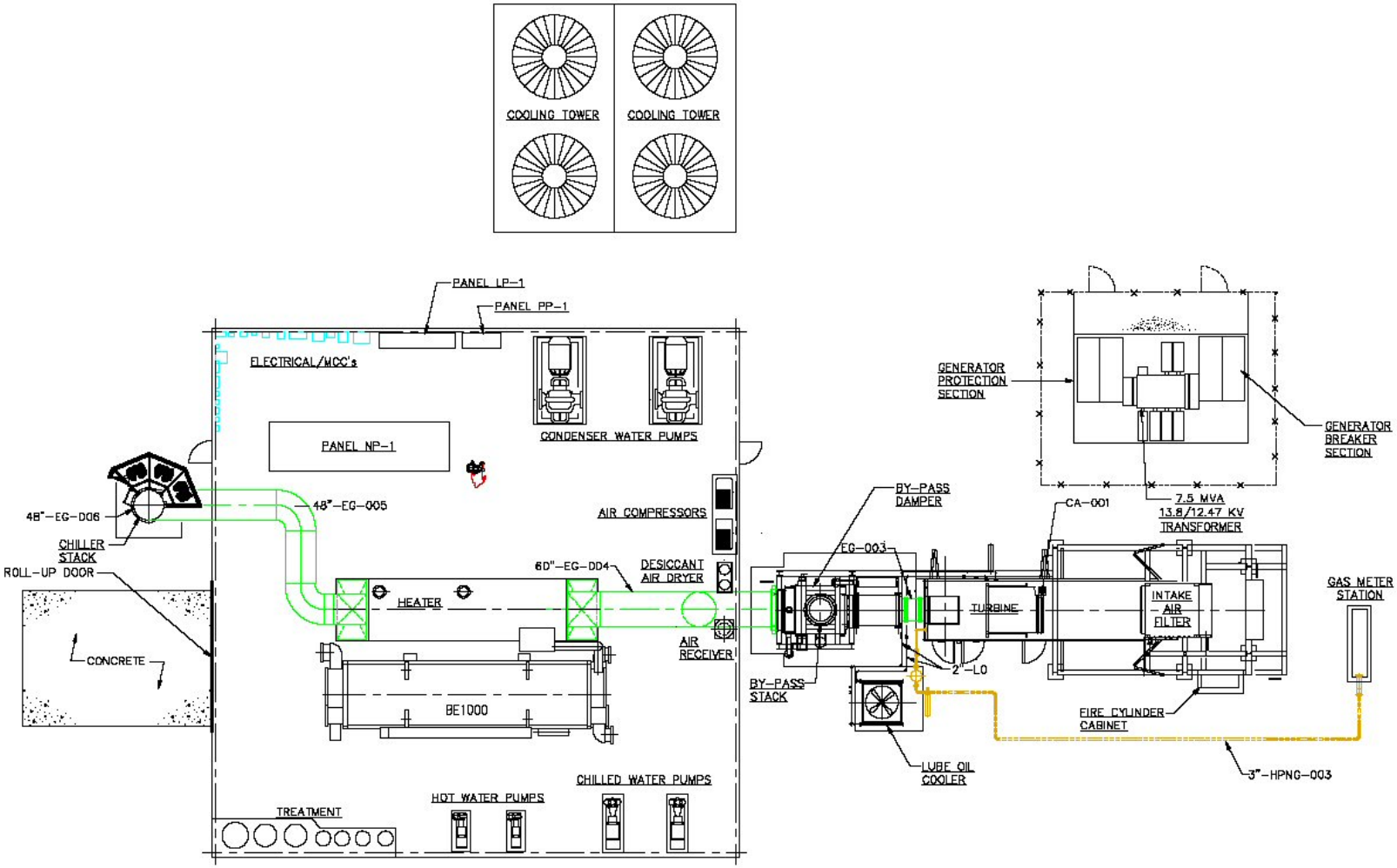


Figure 2-4. General Arrangement Plan for Reference Design R-2

2.1.6 Content of the Reference Designs

Reference designs are comprised of the design artifacts shown in Table 2-4.

Table 2-4. Reference Design Content

Item	Description
CAD Drawings	• Cover sheet, notes, symbols and nomenclature. • Piping and instrumentation drawing (P&ID) up to balance-of-plant (BOP) connections. This also includes a mass/energy matrix, showing performance data for winter, ISO, and summer conditions. • General arrangement of equipment (floor plan layout), including major equipment. Elevation views are also provided. • Plan view of BOP connections. • Electrical interconnect (one-line) from the generation equipment through the generation voltage switchgear. • Electrical power plan, including major equipment.
Description of major equipment (see Note 1)	For turbine-generator, absorption chiller, and HRSG: Excerpts from manufacturer's specification sheets: • Physical dimensions, weights, etc. • Nominal performance data.
Other technical data (see Note 1)	• Performance specifications for auxiliary equipment (i.e. cooling tower, pumps, etc.) (Note: These items are included for reference only. The performance requirements for a specific application will depend on the site characteristics, and should be specified by the P.E.) • Brief sequence of operation. This covers the turbine-generator and heat recovery portions of the system. (Note: The auxiliary cooling equipment (e.g. cooling tower, pumps, etc.) are not included in this sequence of operation. Operation of these systems will be similar to conventional practice, and should be specified by the P.E.)

Note 1: Equipment specifications and technical data are provided for Reference Design R-1 only. For technical data on the major equipment for the other reference designs, please refer to the manufacturers' websites.

2.1.7 Performance Estimates for the Reference Designs

Each reference design includes a system energy performance table. The following points should be noted in the use of this data:

- Values stated for "system useful energy conversion" are estimates of energy efficiency, which are based on the amount of turbine gross electrical energy output and the amount of turbine heat that is recovered and delivered to the chiller-heater for producing heating and/or cooling. Traditionally, this is accepted practice for many engineers in the industry.
- However, a more recent and complete description of overall system performance can be found in a document entitled "Distributed Generation Combined Heat and Power Long Term Monitoring Protocols" Interim Version, October 29, 2004, prepared by the Association of State Energy Research and Technology Transfer Institutions (ASERTTI) http://www.asertti.org . Using this standard, we can calculate a system efficiency figure as follows:

$$\text{System Efficiency} = \frac{\text{useful energy output from the system}}{\text{energy input (fuel)}} = \frac{\text{electric output + heating output + cooling output}}{\text{energy input (fuel)}}$$

This system efficiency value can be easily calculated from the data in the performance table in each reference design (Note: Inlet air cooling and system parasitic energy should be handled appropriately in performing this calculation. See the ASERTTI document for guidance.)

2.1.8 Site Specific Instrumentation Considerations

Instrumentation is a key part of any IES installation. When planning the instrumentation design for an IES project, the following points should be noted:

- The instrumentation shown in the reference designs is limited to that required for system control and operation purposes.
- The site owner and the cognizant engineer are encouraged to consider adding more complete instrumentation for use in more detailed performance monitoring. These types of instrumentation should be considered:
    - Turbine exhaust flow instrumentation
    - Water flow instrumentation (i.e. chilled water, condenser water, hot water, etc.)
    - Additional temperature and pressure instrumentation
    - Instrumentation to measure parasitic power

2.1.9 Key Results

Reference designs provide a viable approach to packaging large IES system applications. This concept can help to reduce the complexity and installed cost of these systems. Our analysis of the engineering work involved in a large IES system application showed that the use of reference design data could save up to 8% of a project's engineering costs. (These savings relate to the typical engineering activities of up-front project feasibility analysis, detailed design, and preparation of construction documents.)

The project team worked with program managers at Oak Ridge National Laboratory and the U.S. Department of Energy to disseminate reference designs for use by interested parties in the IES industry.

In performing this work, the project team identified a number of lessons learned that can help other engineers in the industry. A list of these key outcomes is shown in Table 2-5.

Table 2-5. Key Outcomes of the Reference Design Task

Key Outcome	Remarks
1. Project managers must carefully check local codes and standards.	See guidelines elsewhere in the full report on the reference designs.
2. A gas compressor may be required (application dependent).	Some sites will need a compressor to achieve the gas pressure required for delivery to the gas turbine.
3. Interconnection with local electric utility is a key project design task.	Very important planning and design issue. This has been a barrier to IES system development in some areas in the past, but recent standards work is helping to eliminate this problem.
4. Interconnection with building HVAC systems is a key project design task.	Another key planning and design issue. Smart use of well-known HVAC design practices can provide a good result.
5. Chiller-heater arrangement is a good application for exhaust-driven absorption cooling technology	For applications that do not require steam, a chiller-heater based design results in a simpler, lower cost IES system.

2.2 Exhaust-Driven Absorption Cooling Technology

This section presents the results of the technical work performed in developing exhaust-driven absorption cooling technology for large IES systems. The project team developed, built, and installed a 1000 ton absorption chiller, which is driven directly from exhaust produced by a large gas turbine generator. This was the first exhaust-driven absorption chiller of this size. A similar design could be employed in implementing a chiller-heater unit, using the exhaust-driven approach. The following sections describe the development of this technology.

2.2.1 Background

Absorption technology has been in commercial use since the late 1800s, and continues to offer key energy efficiency advantages due to its ability to recover (otherwise wasted) heat to produce cooling for commercial and industrial applications. Recent innovations in the fields of metallurgy, instrumentation, heat exchanger designs, chemistry, improved cycles, and controls have provided steady improvements in performance.

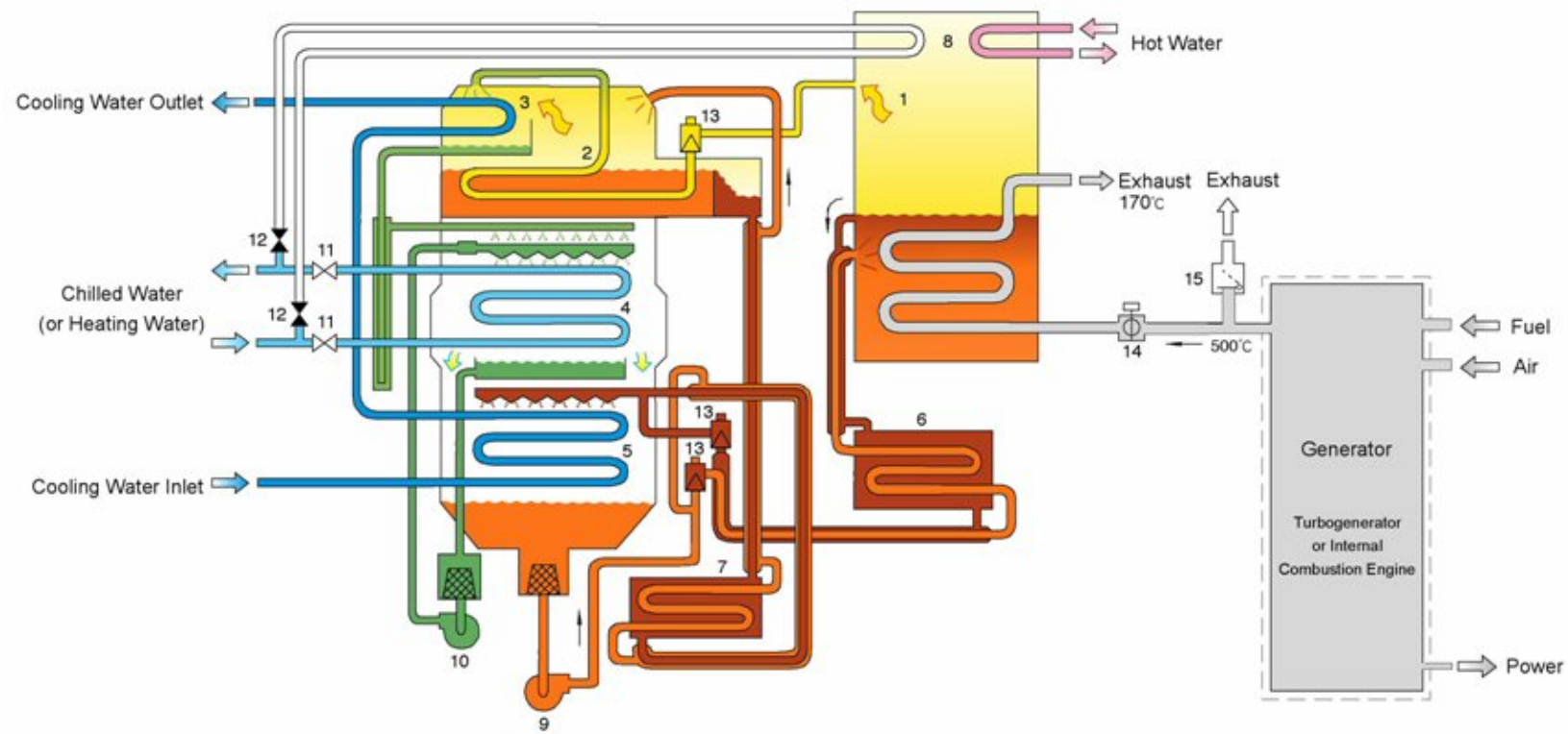
Traditionally, absorbers were used only to produce chilled water as chiller equipment for building cooling. Recent advances in absorption technology allow them to be used also as heating equipment, in a "chiller-heater" arrangement—eliminating the need for a separate boiler to provide heating for building HVAC applications. These chiller-heater designs are able to provide chilled water for summer air-conditioning applications as well as hot water heating for winter space heating needs.

2.2.2 Development Objective

Commercially, absorption chillers or chiller-heaters use steam, hot water, or fossil fuel (natural gas or fuel oil) as their primary source of energy. Hence, most previous IES plant designs that employed absorption chillers typically have a heat recovery steam generator (HRSG) or heat recovery hot water heater to produce hot water or steam as the primary heat source to the absorption chiller. Additionally, this equipment is used in the winter to provide hot water or heating water for building HVAC applications.

This technology development work was focused on developing an exhaust-driven design that could provide simpler IES system designs. This work built upon proven double-effect absorption cooling technology which was originally applied in a direct gas-fired design. This approach employs a lithium bromide / water solution as the working fluid inside the unit.

A schematic of the exhaust-driven chiller-heater internal design is shown in Figure 2-5.



Legend:		
Concentrated Solution Diluted Solution Hot Water Refrigerant Vapor Refrigerant Cooling Water Chilled Water	1. High-Stage Generator 2. Low-Stage Generator 3. Condenser 4. Evaporator 5. Absorber 6. High-Temp. Heat Exch. 7. Low-Temp. Heat Exch. 8. Water Heater	9. Solution Pump 10. Refrigerant Pump 11. Chilled Water Valve 12. Heating Water Valve 13. Cool./Heat. Switch Valve 14. Exhaust Motor Valve 15. Auto Exhaust Damper

Figure 2-5. Chiller-Heater Internal Design

This development used a standard, direct-fired 1,000 RT absorption chiller-heater design with a modified high-stage generator that was suitable for taking 900-950ºF exhaust gases of the requisite quantity. Typically, the design considers ~330-340ºF as the exhaust exit temperature from the absorber after heat recovery in the cooling mode (or 290-300ºF in the heating mode). The performance specifications are shown in Table 2-6.

The waste-heat-fired absorption chiller-heater requires 9,250 thousand Btu/hr (MBH) of heat to produce 1,000 RT of chilled water at 44ºF. Table 2-6 shows the performance of the 1,000 RT absorber chiller-heater design with 8,560 MBH of heating capacity at a 180ºF hot water temperature.

Table 2-6. Chiller-Heater Design Performance

	Units	Specification
Output		
Cooling capacity	RT	1,000
Cooling capacity	kW	3,520
Heating capacity	MBH	8,560
Chilled Water Circuit		
Outlet temperature / Inlet temperature	ºF	44 / 54
Chilled water flow	GPM	2,397
Cooling Water Circuit		
Outlet temperature / Inlet temperature	ºF	95 / 85
Flowrate	GPM	4,085
Heating Water Circuit		
Outlet temperature / Inlet temperature	ºF	180 / 160
Flowrate	GPM	855
Exhaust Gases (Heat Input)		
Inlet temperature	ºF	932
Heat input	MBH	9,250
Electrical Requirement		
Power consumption	kW	8.8

2.2.3 Design Highlights

This exhaust-driven approach resulted in a higher volume and lower temperature of exhaust, as compared to a direct natural-gas-fired design. As a result, the design of the high-stage generator (HSG) was modified to accommodate the increased volume of turbine exhaust (while adhering to the maximum backpressure requirement of the gas turbine). Hence, the standard turbulators in the high-stage generator were modified to meet the exhaust pressure drop requirement.

While the design had to provide good heat recovery performance, manufacturing cost was an important consideration in the design of the HSG. Hence, the design sought to limit the amount of lithium bromide working fluid inventory required (due to its cost). The resulting design was relatively compact, while still providing the required heat transfer surface area for recovery of heat from the turbine exhaust. In addition, the internal flow patterns inside the HSG were carefully designed in order to obtain optimum heat and mass transfer.

The exhaust gas side was appropriately designed to handle the large volume of flue gas effectively. To attain a degree of evenness in the flow of exhaust gases, the exhaust gas inlet box area was increased to create an enhanced plenum effect. Also, the turbulator design was modified to achieve evenness in the flue gas path.

Finally, modifications in the unit's internal control logic accommodated the change to turbine exhaust firing.

2.2.4 Implementation

The design described above was constructed at the Broad Air Conditioning factory and delivered to the Ft. Bragg site for installation. This unit was a chiller design (as the site requirements for steam would not accommodate a chiller-heater unit). However, this site did provide an excellent application for the exhaust-driven approach. A photo of the chiller as installed at Ft. Bragg is shown in Figure 2-6.

2.2.5 Field Installation and Performance Monitoring

The exhaust-driven absorption chiller was installed at Ft. Bragg in May 2004. Field monitoring was performed throughout the cooling seasons of 2004 and 2005. Operating experience showed that the unit was able to produce 990+ tons of cooling output, depending on actual cooling load conditions. In addition, the measured coefficient-of-performance (COP) met the design specifications (COP=1.20 at design). This field experience verifies the design intent for the unit. Field experience to date has been very good, validating the exhaust-driven design approach. A plot of measured performance data for June 2005 is shown in Figure 2-7.

Figure 2-6. Exhaust-Driven Absorption Chiller

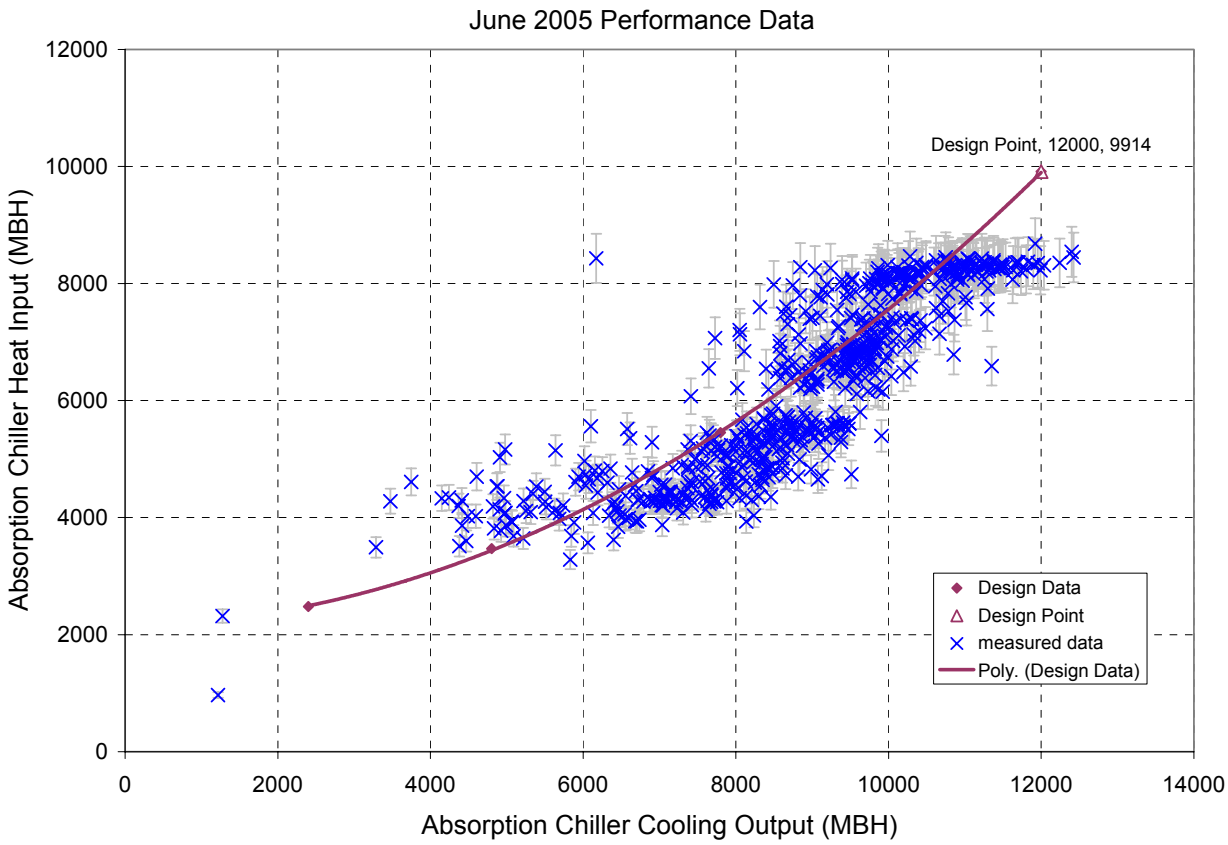


Figure 2-7. Exhaust-Driven Absorption Chiller Performance (June 2005)

2.2.6 Key Results

The exhaust-driven absorption cooling technology offers distinct advantages for large IES system applications. In performing this work, the project team identified a number of lessons learned, which can help other engineers in the industry. A list of these key outcomes is shown in Table 2-7.

Table 2-7. Key Outcomes of the Absorption Chiller Development Task

Key Outcome	Remarks
1. No special training needed for plant operators or service personnel.	This type of equipment is very similar to the more common steam-driven or gas-fired absorption chiller technology.
2. A few items of spare equipment were required to perform routine maintenance on the unit.	These items were procured from the chiller manufacturer at a reasonable cost.
3. Some regular maintenance was required to keep the unit operating at peak performance.	For example, it is necessary to periodically remove non-condensibles from the chiller.
4. Exhaust-driven absorption cooling technology can provide simpler IES system designs, especially if implemented as a chiller-heater (by avoiding the use of an HRSG) in applications where steam is not required).	An exhaust-driven design approach lends itself well to the development of a chiller-heater unit

2.3 IES Control Optimization

This section presents the results of the technical work performed in developing the IES control optimization technology, which was implemented as the "CHP Manager" software. This work included a simulation of the performance of the control optimization function. The simulation computed the energy cost savings provided by the optimizer (as compared with the "best" conventional operating strategy as defined by the CHP plant operators at Ft. Bragg).

2.3.1 CHP Control Concept

The IES control optimization function considers the heating and cooling loads, utility rates (grid electricity, and fuel prices), equipment characteristics, and weather data to determine how to best meet these loads using the IES equipment, electric grid power, and the non-IES heating and cooling equipment. The CHP Manager's optimizer specifies the proper set points for electric power generation, heating output, and cooling output. These set points are displayed as guidance to the plant operator. At the Ft. Bragg field site, all optimizer control actions were implemented manually by the plant operators. (Note: As part of this project, control interfaces have been implemented to enable automatic operation of optimizer control actions in the future, if desired).

The design approach for the CHP supervisory control and optimization software are shown in Figure 2-8 and Table 2-8.

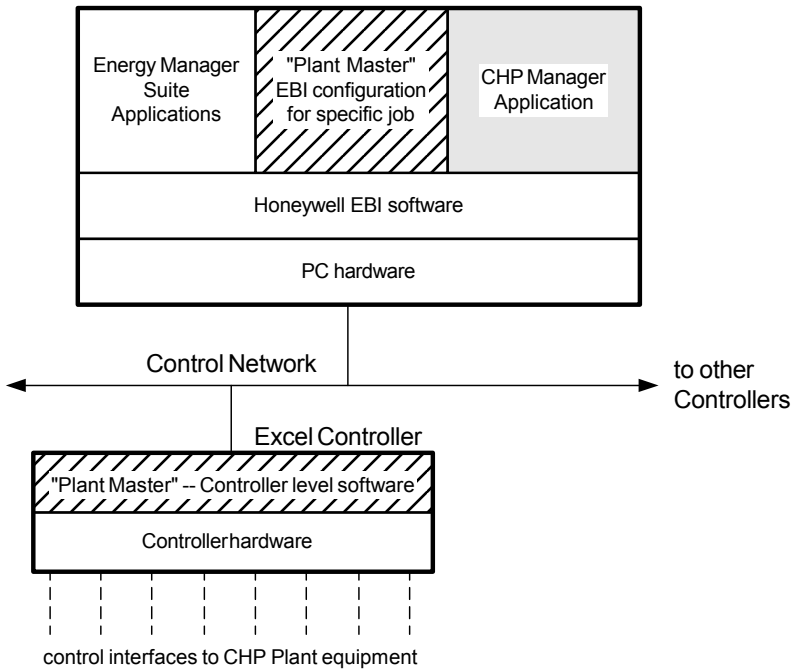


Figure 2-8. CHP Control Optimization Concept

Table 2-8. Control System Functional Elements

Control Function	Description
CHP Manager	Software that optimizes the operation of a CHP system (i.e. determine optimal equipment operating schedules and set points, etc.). Designed to collaborate with EBI and Energy Manager.
Enterprise Building Integrator (EBI)	Honeywell supervisory control and data acquisition (SCADA) control system product. This is the control front end and user interface for the plant operators. The term EBI also refers to the overall integrated control system, including the DDC controllers in the plant.
Energy Manager	Related Honeywell product software (designed to collaborate with EBI) that provides a suite of energy services functions (i.e. meter reading, energy cost calculation, reporting, etc.).
Plant Master	Control functions, displays, reports, and other functions of EBI that are custom configured for the CHP System. This includes all of the customary SCADA functions that are normally found in a CHP control installation. The Plant Master is independent of the CHP Manager
Plant controllers	Distributed controllers located in the plant. For connection to sensors and actuators installed in the plant.
Unit controllers	Factory supplied controllers in the turbine-generator, HRSG / duct burner, absorption chiller, electric chiller and other CHP equipment. These low-level controls govern the operation of the equipment and provide all of the customary equipment protection functions.

2.3.2 CHP Control Optimization

The CHP Manager software employs the services of EBI and Energy Manager to optimize the operation of a CHP system. The optimizer function periodically computes the optimal operating set points for the CHP equipment. The update frequency is typically set to one hour. A high-level overview of the CHP Manager's optimizer is shown in Figure 2-9.

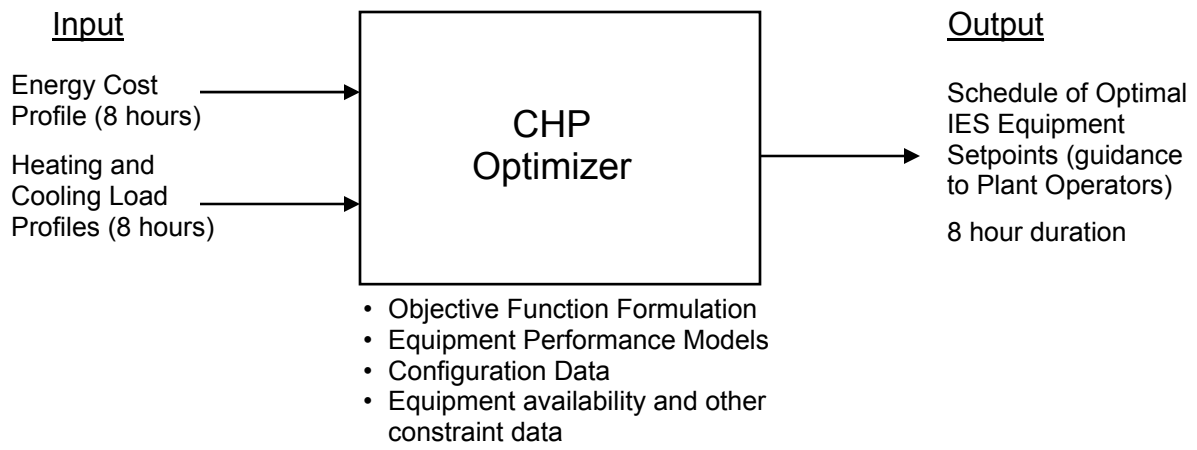


Figure 2-9. CHP Control Optimizer

2.3.3 Optimization Formulation

The CHP Manager's optimizer function is formulated as a constrained economic optimization problem. This function is structured as follows:

- Objective: Minimize the cost of operation incurred via fuel oil costs (natural gas and fuel oil), and electric utility real-time price of electricity (RTP) costs
- Constraints, subject to a requirement to satisfy the heating load and cooling loads, and a set of CHP equipment operating constraints
- Decision variables consist of equipment operating setpoints for each item of CHP equipment in the system

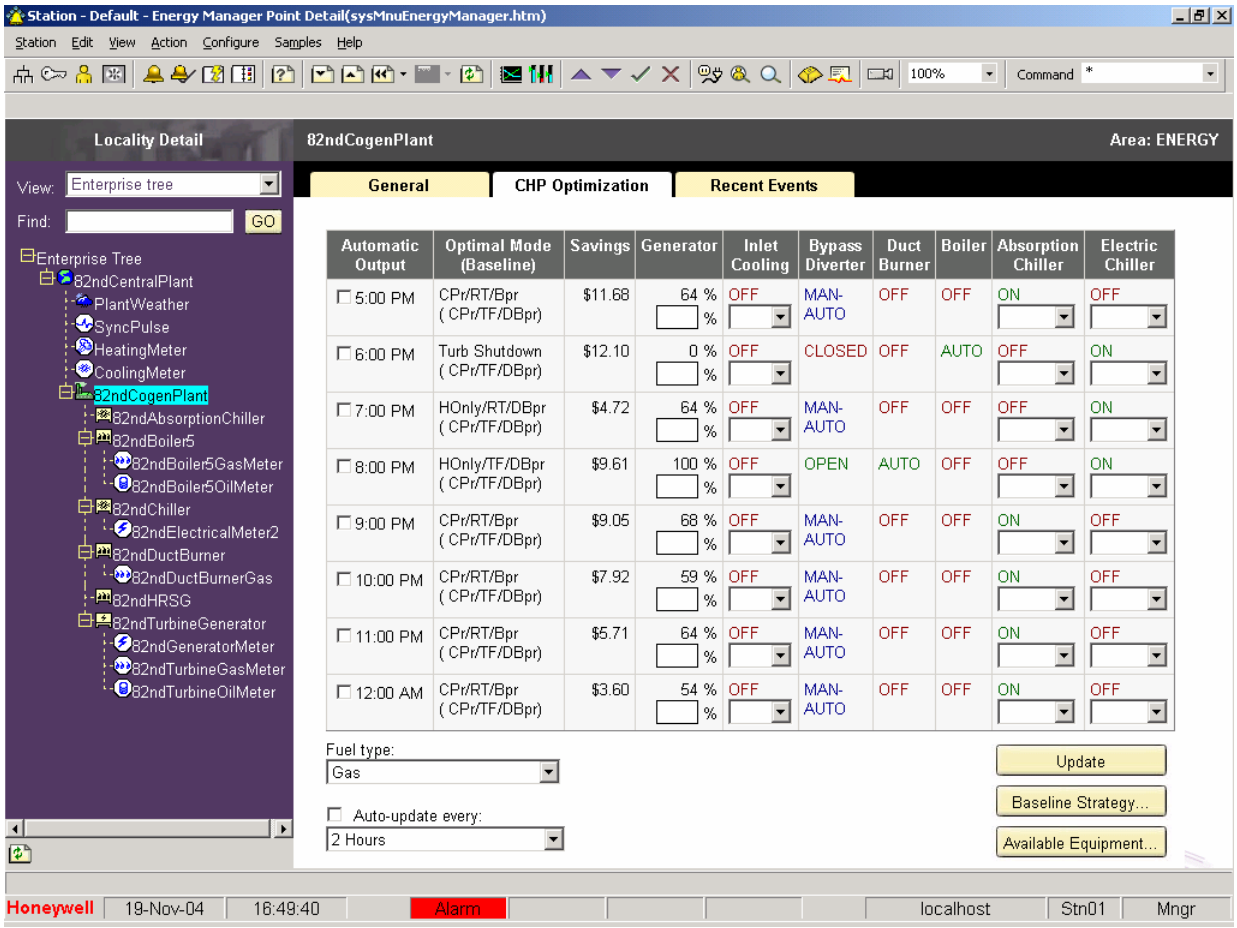
2.3.4 CHP Manager Features

The key features of the CHP Manager are:

- User interface, graphic displays, trend plotting, and historization (for CHP optimization functions)
- CHP equipment performance models
- Interfaces with Plant Master physical input-output (I/O) points and pseudo I/O points to achieve control of the manipulated variables to optimize the operation of the plant.
- Interfaces with the Energy Manager software (to receive energy prices, load forecasts, equipment model data, weather forecast data, etc.).
- Configured at the field site as part of the overall control system installation and commissioning (after commissioning and acceptance of the Plant Master)
- Note: The CHP Manager is not required for performing basic CHP operating strategies (these can be accomplished by the Plant Master)

2.3.4.1 Equipment Schedule

The Equipment Schedule is the key output from the CHP Manager's optimizer and is the primary operator interface for the software. This display shows the optimizer's recommended equipment setpoints for the next eight hours. An example display is shown in Figure 2-10. This is the primary display used by the plant operators to determine the optimum operating schedule for the CHP plant.



Automatic Output	Optimal Mode (Baseline)	Savings	Generator	Inlet Cooling	Bypass Diverter	Duct Burner	Boiler	Absorption Chiller	Electric Chiller
5:00 PM	CPr/RT/Bpr (CPr/TF/DBpr)	$11.68	64 % %	OFF	MAN-AUTO	OFF	OFF	ON	OFF
6:00 PM	Turb Shutdown (CPr/TF/DBpr)	$12.10	0 % %	OFF	CLOSED	OFF	AUTO	OFF	ON
7:00 PM	HOnly/RT/DBpr (CPr/TF/DBpr)	$4.72	64 % %	OFF	MAN-AUTO	OFF	OFF	OFF	ON
8:00 PM	HOnly/TF/DBpr (CPr/TF/DBpr)	$9.61	100 % %	OFF	OPEN	AUTO	OFF	OFF	ON
9:00 PM	CPr/RT/Bpr (CPr/TF/DBpr)	$9.05	68 % %	OFF	MAN-AUTO	OFF	OFF	ON	OFF
10:00 PM	CPr/RT/Bpr (CPr/TF/DBpr)	$7.92	59 % %	OFF	MAN-AUTO	OFF	OFF	ON	OFF
11:00 PM	CPr/RT/Bpr (CPr/TF/DBpr)	$5.71	64 % %	OFF	MAN-AUTO	OFF	OFF	ON	OFF
12:00 AM	CPr/RT/Bpr (CPr/TF/DBpr)	$3.60	54 % %	OFF	MAN-AUTO	OFF	OFF	ON	OFF

Figure 2-10. CHP Control Optimizer: Equipment Schedule

2.3.4.2 Equipment Models

The CHP Manager's optimizer utilizes mathematical models of the plant equipment. These models describe the energy efficiency of the equipment as a function of other pertinent variables (e.g. absorption chiller refrigeration tons output vs. exhaust heat input).

2.3.4.3 Fuel and Electricity Costs

Nominal prices for natural gas and fuel oil are manually entered. They are typically expressed in units of dollars per decatherm ($/DT). As these prices vary over time, their values can be updated in the system. The latest value is always used for optimization, and a history of prices is maintained for cost reporting.

The post at Ft. Bragg purchases electricity under a two-part rate tariff. A portion of the energy charge is determined by a real-time price for energy consumption above a specified contract base load. Similar to fuel price data, the real-time pricing cost of electricity is stored in the system. The RTP values are automatically downloaded from the energy provider via the Internet; therefore, no manual data entry is required.

2.3.4.4 Fuel Switching

The plant operator uses Plant Master Fuel to manually switch between natural gas and fuel oil for all plant equipment. The plant operator's procedures for fuel switching follow the standard practice as defined by the 82nd Central Heating Plant operations manager (i.e. plant operator walk-around, auxiliary equipment checks, local start/stop commands, etc.).

2.3.5 CHP Optimizer Performance

The project team performed an analysis of the expected annual performance of the optimization technology included in the CHP Manager software. This analysis consisted of an annual simulation of the operation of the CHP Manager software, as driven by a set of input historical data taken from the Ft. Bragg IES system. The key output was the expected operating cost savings provided by the optimizer compared with a baseline CHP operating strategy defined by a knowledgeable plant operator. The baseline CHP operating strategy was defined with the assistance of the plant operators at Ft. Bragg. No comparison was made to a non-CHP system.

2.3.5.1 Structure of the Simulation

The simulation performed an hour-by-hour analysis of the operation of the CHP Manager's optimizer function driven by a year-long (from 2002) set of input historical data taken from the Ft. Bragg IES system. (Note: The simulated optimizer utilized the same functionality as that in the actual CHP Manager software.) The structure of the simulation is shown in Figure 2-11.

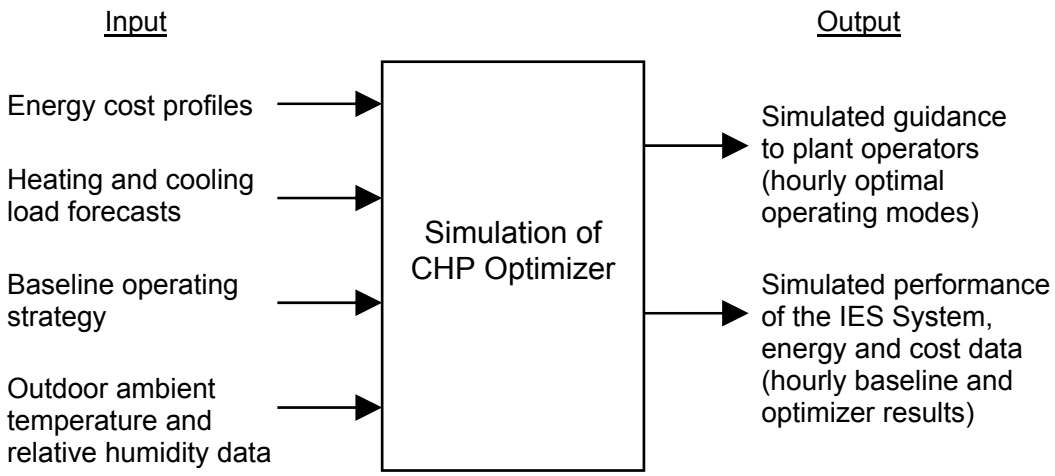


Figure 2-11. Simulation of the CHP Control Optimizer

2.3.5.2 CHP System Description (Ft. Bragg site)

The Ft. Bragg 82nd Central Heating Plant IES system was used as a test case for the annual performance simulation work. This system is described in the following paragraphs.

2.3.5.2.1 System Arrangement

A block diagram of the Ft. Bragg 82nd Central Heating Plant IES system is shown in Figure 2-12. The major equipment in the system consists of a 5.7 MW gas turbine generator, a 1000 ton exhaust-driven absorption chiller, a heat recovery steam generator (HRSG), and a duct burner.

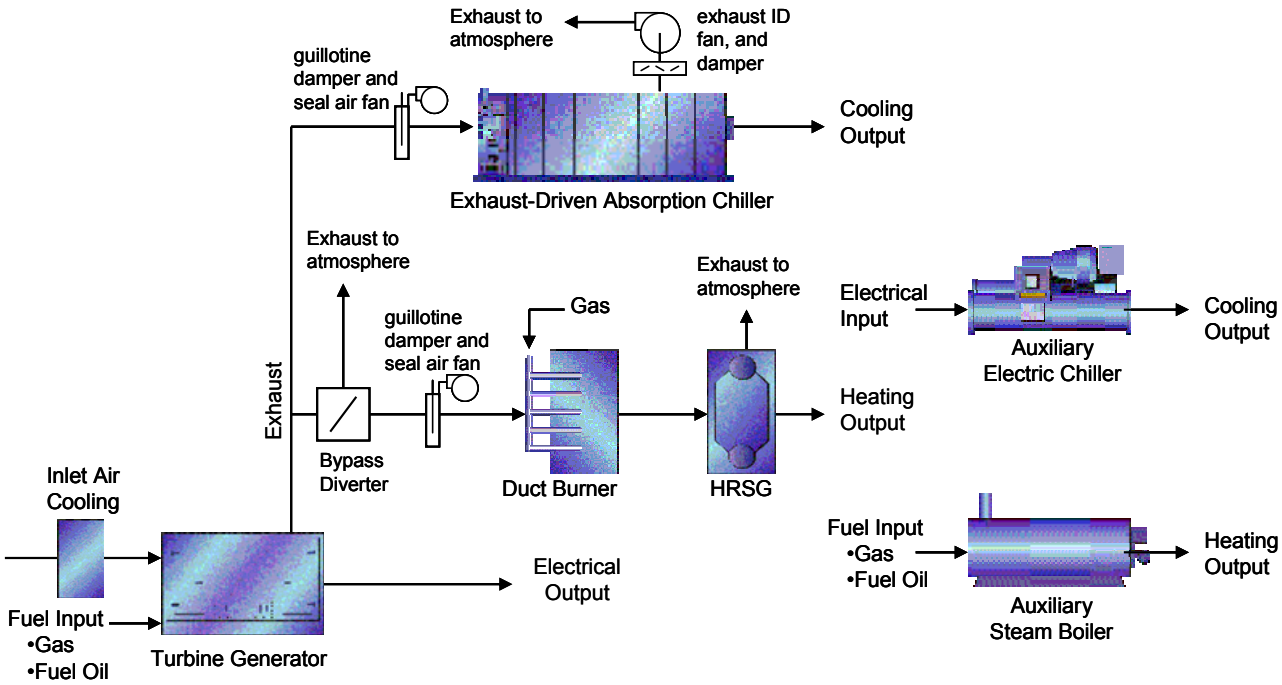


Figure 2-12. Ft. Bragg 82nd Central Heating Plant IES System

2.3.5.3 Simulation Input Data

Input data for the simulation was made up of actual historical data taken from the Ft. Bragg IES system. Highlights of this data included:

- Thermal load data. A plot of the heating and cooling load data is shown in Figure 2-13. The numbering of hours from 1 to 8760, spans the period from January 2002 thru December 2002. The loads are given in thousands of Btu per hour (MBH).
- Energy price data. A plot of the electric real-time price data is shown in Figure 2-14. A plot of the natural gas price data is shown in Figure 2-15.
- Baseline CHP operating strategy:
  - Winter/high heating loads: Heat load following or heating priority with duct burner preference. Similar for transition from winter to summer.
  - Summer/high cooling loads: Cool load following, or cooling priority with duct burner preference (over boiler). Similar for transition from summer to winter.

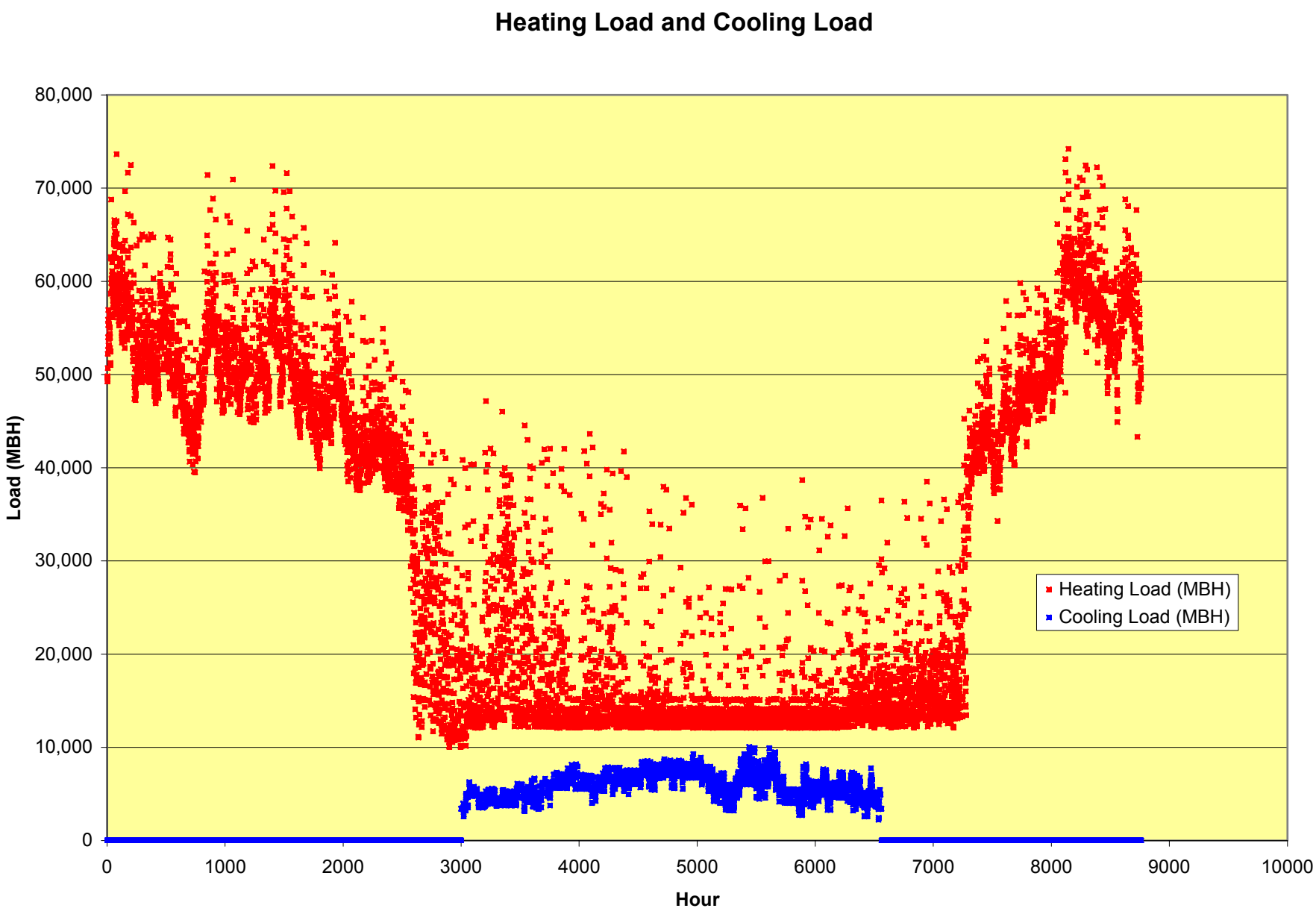


Figure 2-13. Simulation Input Data: Heating and Cooling Loads

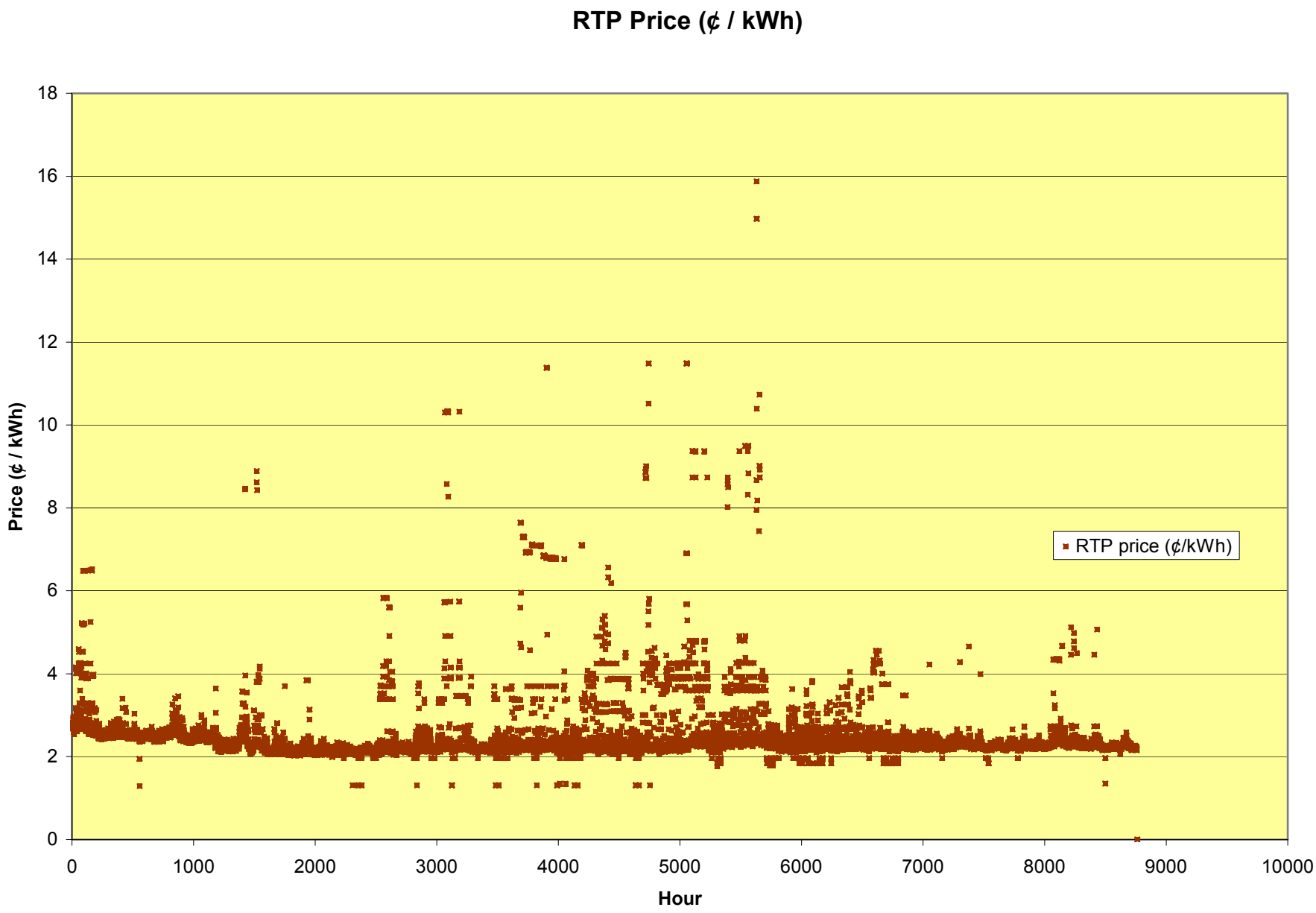


Figure 2-14. Simulation Input Data: Electricity Real-Time Prices (RTP)

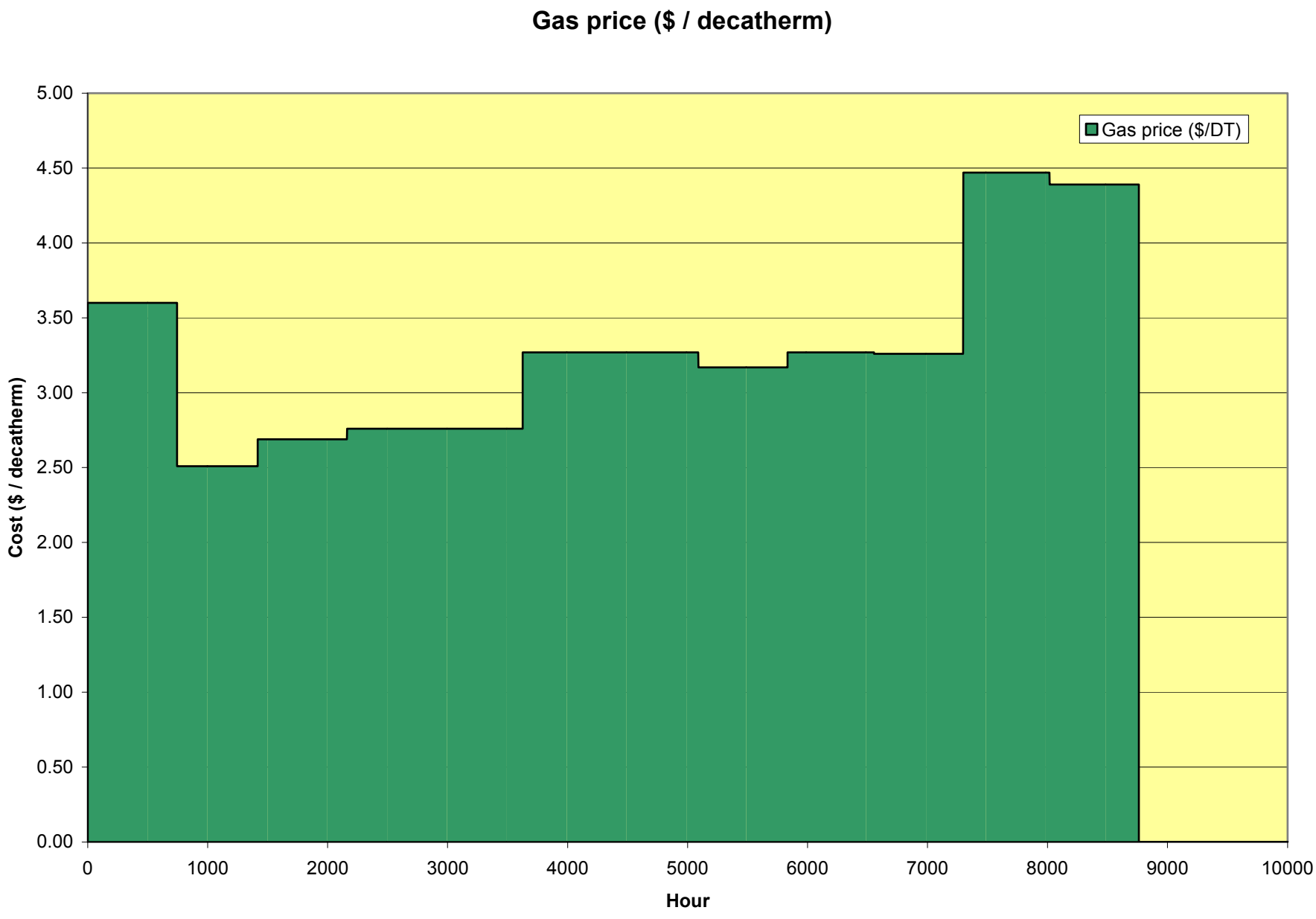


Figure 2-15. Simulation Input Data: Natural Gas Prices

2.3.5.4 Simulation Results

The key output results of the simulation are presented in the following paragraphs.

2.3.5.4.1 Operating Cost Savings

A plot of the hourly operating cost savings (as compared with the "smartest" user strategy that would be employed by a knowledgeable plant operator) is shown in Figure 2-16. (The numbering of hours from 1 to 8760, spans the period from January 2002 thru December 2002.)

2.3.5.4.2 Turbine Load Duration Curve

A plot of the cumulative load duration for the turbine generator (electric output) is shown in Figure 2-17.

2.3.5.4.3 Discussion of Simulation Results

The simulation showed that the CHP Manager's optimizer could deliver an annual cost savings of approximately 6% over and above the "smart" user-defined strategy of operation (based on the 2002 input data used to drive the simulation).

The savings plot also shows that 61% of the above annual savings resulted from the optimizer's ability to judiciously identify opportunities to shut the turbine down. This condition would occur when the fuel prices are high, and as a result, do not provide an economic incentive to operate the turbine and the CHP system. Also, 28% of the above savings resulted from appropriate identification of periods to operate inlet air cooling for the turbine. The remaining 11% of the savings resulted from judicious modulation of the turbine output set point.

The user-defined baseline operating strategy provided a lower bound on the savings delivered by the CHP Manager. (Note: There will be many hours during a typical year when the cost savings will be zero).

The load duration curve for the turbine generator shows that the optimizer recommends that the turbine be shutdown for approximately 19% of the year. Most CHP plant operators recognize that there are certain periods when economics do not justify operating the system. The CHP Manager helps operators identify those periods more precisely.

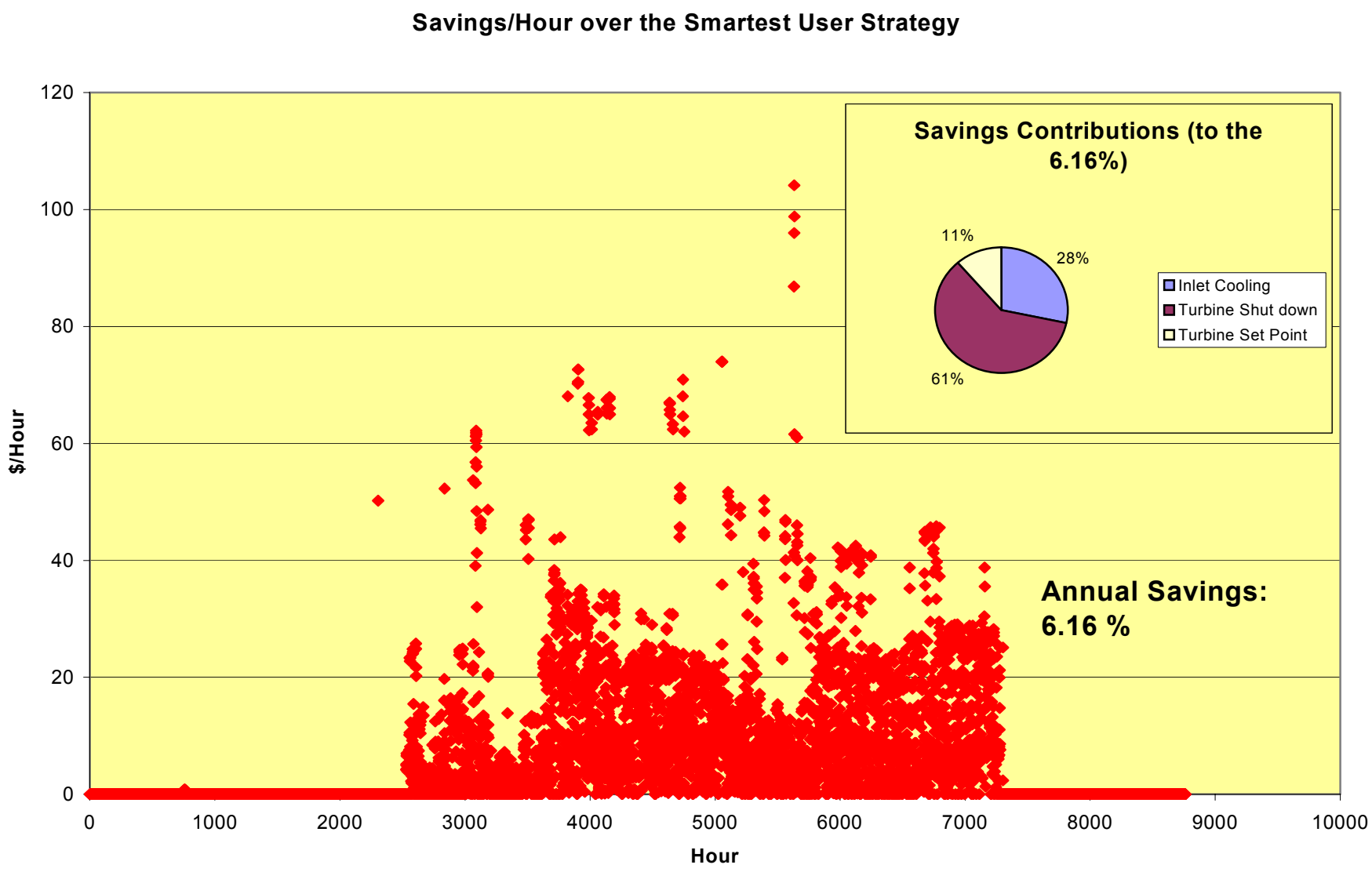


Figure 2-16. Simulation Results: Operating Cost Savings

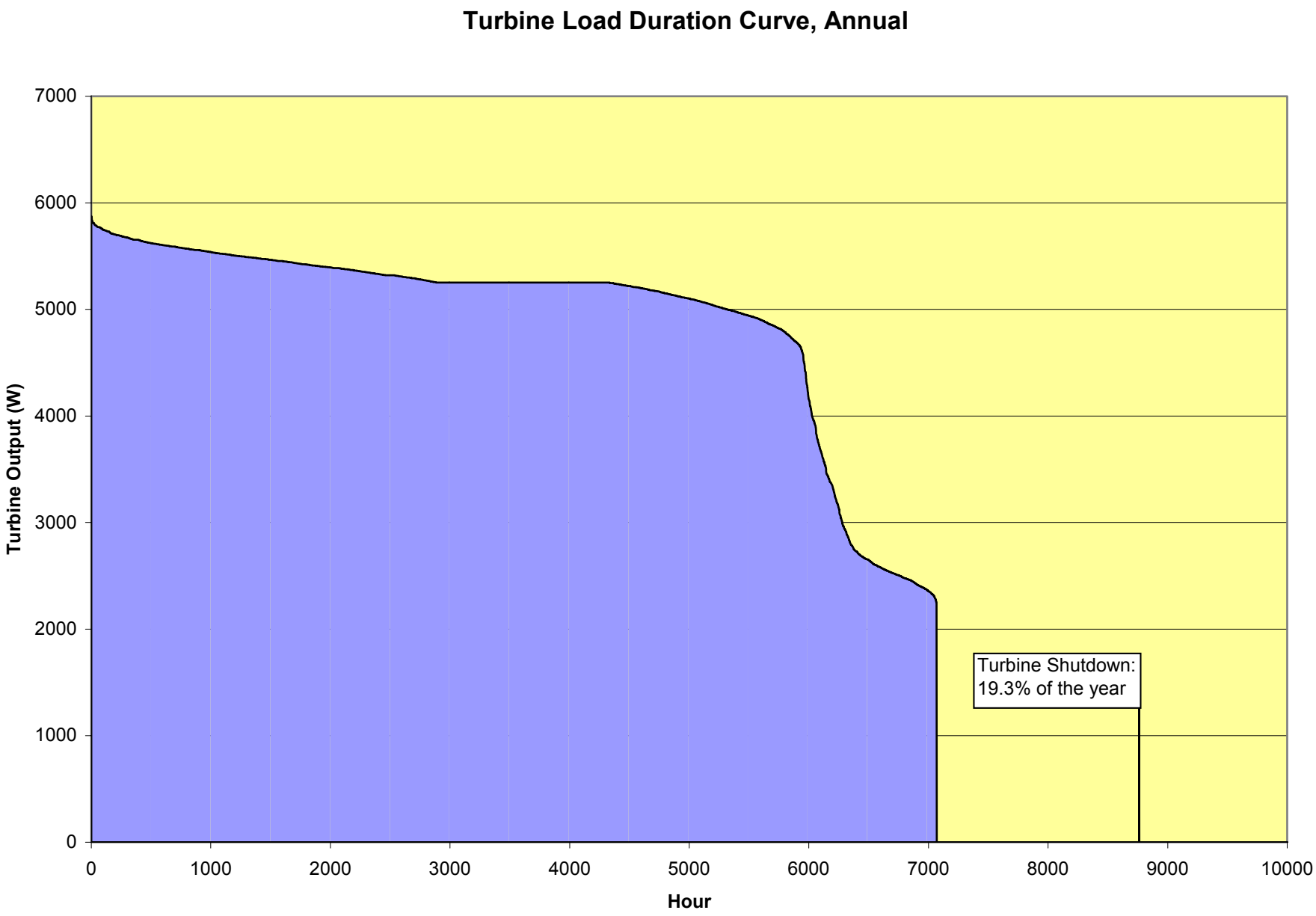


Figure 2-17. Simulation Results: Turbine-Generator Load Duration

2.3.6 Field Observations

The CHP Manager software was installed in June 2004 at the Ft. Bragg site. Following commissioning and user training, the software was placed into operation. Observations in 2004 and 2005 showed that the software produced optimal control recommendations consistent with those predicted during our off-site simulation work.

As expected, observations showed numerous periods when the user-defined best operating modes were sub-optimal. During these periods, plant operators were able to take advantage of the recommended optimal operating setpoints (provided by the optimizer), as described in the previous sections of this report.

It should be noted that the enterprise-level (base-wide) energy management at Ft.Bragg seeks to make the best operating decisions from an overall base-wide perspective. As such, this is a higher-level objective—and at times will override (or re-direct) operating policies at the plant level. For this reason, there are periods when enterprise-level decisions will determine the actual plant operating strategy for the 82nd Central Heating Plant.

Based upon observations in 2004 and 2005, field experience with the software has been good—demonstrating that the CHP Manager software is an important element of the plant operations strategy employed by the energy managers at Ft Bragg. This software provides the operating staff with an important tool for use in their objective of managing energy efficiency and operating cost on the post.

2.3.7 Key Results

Supervisory control optimization can offer operating cost advantages for large IES system applications. In performing this work, the project team identified a number of lessons learned, which can help other engineers in the industry. A list of these key outcomes is shown in Table 2-9.

Table 2-9. Key Outcomes of the Control Optimization Task

Key Outcome	Remarks
1. Enterprise-level operating objectives can sometimes override plant-level optimization.	While this is not a frequent occurrence, it is to be expected occasionally.
2. Each IES site will need a “champion” on its operating staff who is dedicated to using the optimizer software.	Like any new technology, it can be difficult to find someone on the staff who has the time and the desire to use a new tool on a continuing basis.
3. Instrumentation is a key system component.	Good quality, well calibrated instrumentation will help in achieving the benefits of control optimization.

Section 3. IES Technology Field Demonstration

The Ft. Bragg 82nd Central Heating Plant served as the field site for the installation and demonstration of the absorption chiller and supervisory control optimization technologies that were developed under this project. This site also provided an excellent case study for IES technology application in general. The following sections describe the installation site.

3.1 System Description

A block diagram of the Ft. Bragg 82nd Central Heating Plant IES system is shown in Figure 3-1.

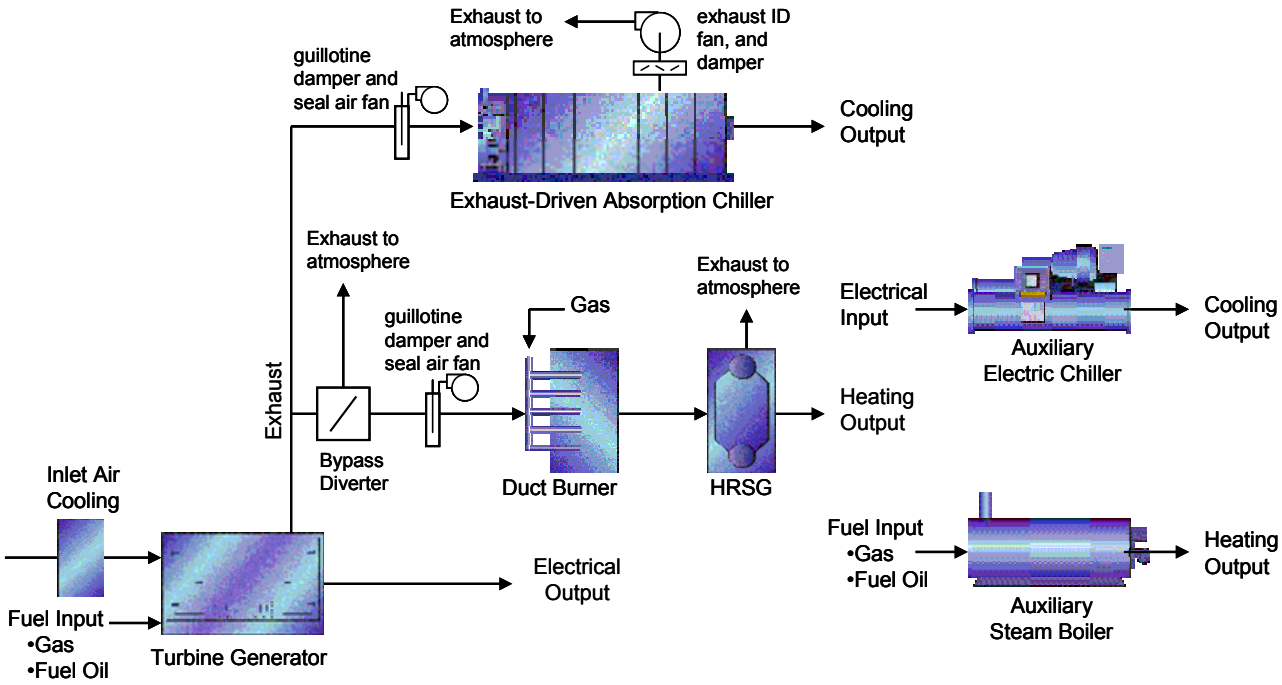


Figure 3-1. Ft. Bragg 82nd Central Heating Plant IES System

The major IES equipment in the system is described in Table 3-1.

The major auxiliary equipment in the system is described in Table 3-2.

Table 3-1. Ft. Bragg Site Major IES Equipment

Equipment	Description
Gas turbine	one Solar Turbines, Taurus 60 dual-fuel gas turbine (4160 volt, 3 phase, nominal 5.7 MW electrical output), with SoLoNox burner technology www.solarturbines.com
Absorption chiller	one Broad Air Conditioning, 1000 tons capacity, exhaust-driven, 44F/54F CHW design, 85F/95.2F CDW design www.broadusa.com
Heat recovery steam generator (HRSG)	one Rentech Boiler Systems, type "O" shop-assembled, 28,700 pph at 125 psig (unfired), 81,200 pph (fired) www.rentechboilers.com
Duct burner	one Coen, rated at 55.2 MMBH on natural gas www.coen.com

Table 3-2. Ft. Bragg Site Key Auxiliary Equipment

Equipment	Description
Boiler	one English, rated at 60,000 pounds of steam per hour, 125 psig
Electric chiller	one, Trane, 800 tons nominal capacity

The equipment installation is shown in Figure 3-2.

The physical arrangement of the equipment is shown in Figure 3-3.

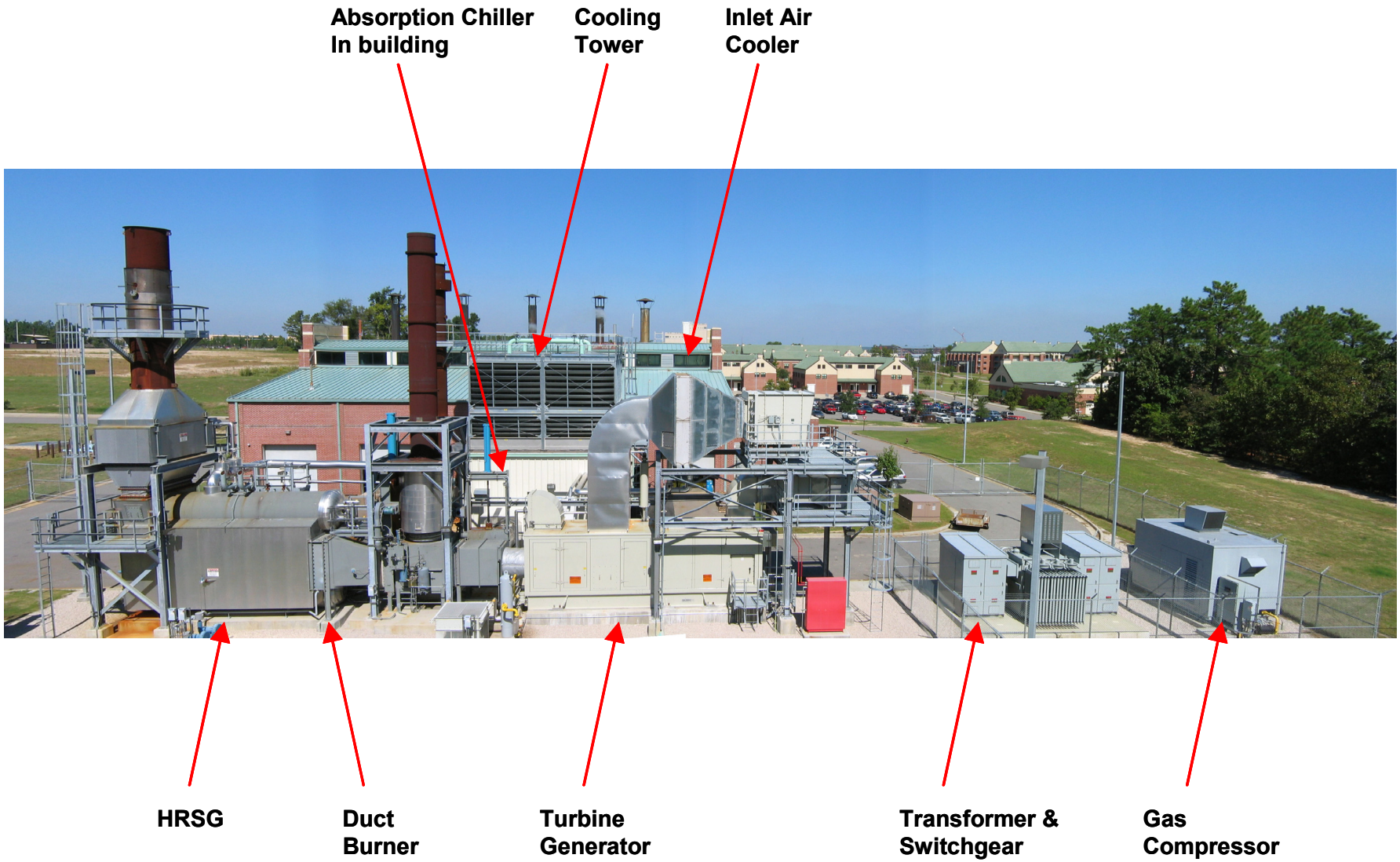


Figure 3-2. Ft. Bragg 82nd Central Heating Plant IES System: General View

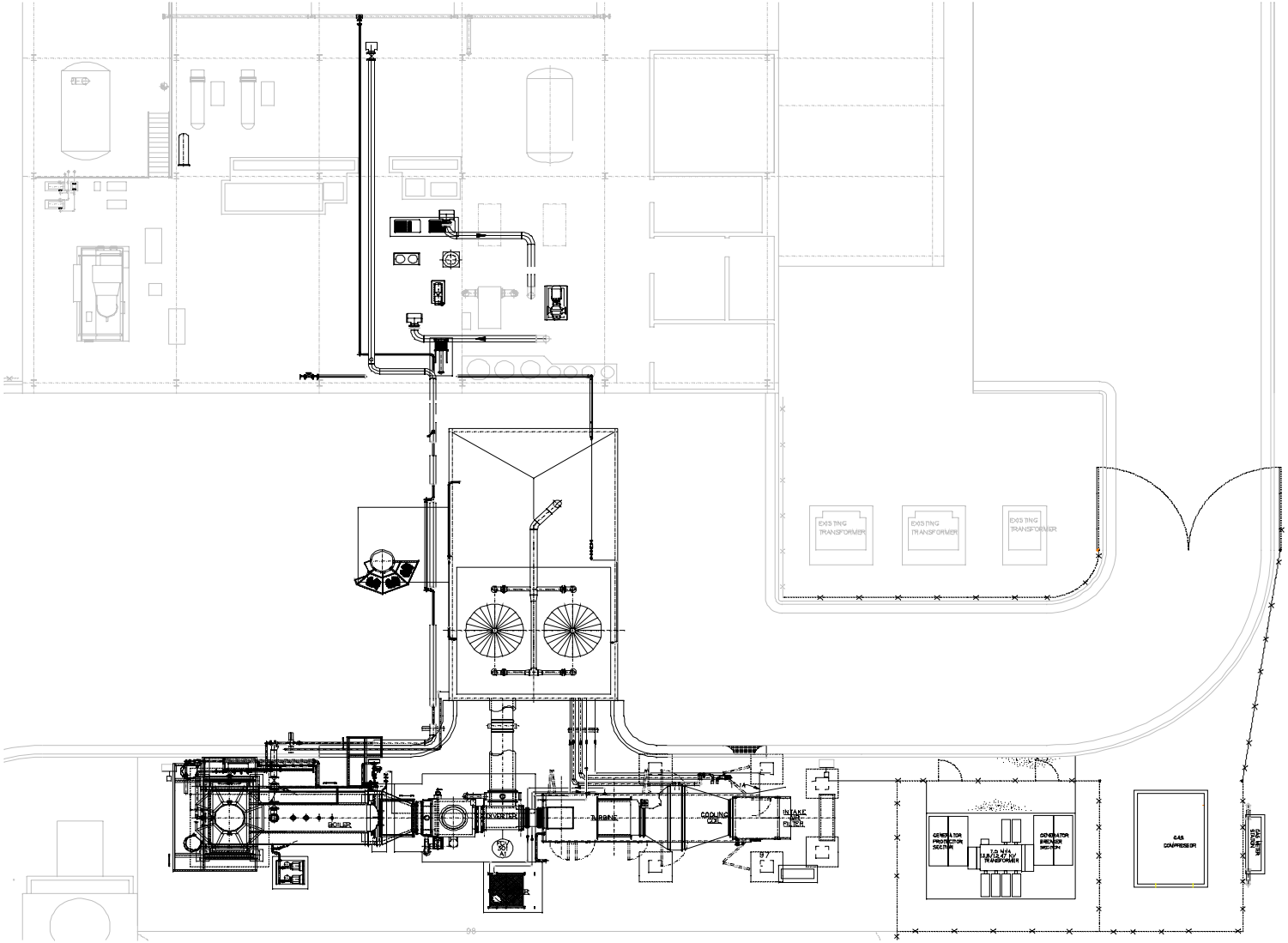


Figure 3-3. Ft. Bragg 82nd Central Heating Plant IES System Equipment Arrangement

3.2 Site Description

The following sections present a background description of the IES project at Ft. Bragg.

The 82nd Central Heating Plant is the largest of 14 central plants on the post. This IES system is an important element of the Army's strategy to improve energy efficiency and reduce operating cost at Ft. Bragg. The project was a combination of an energy savings performance contract (ESPC) between the Army and Honeywell (providing the turbine generator, HRSG, and other components), and the IES R&D project funded by the DOE's Office of Distributed Energy Resources and administered by Oak Ridge National Laboratory (providing the absorption chiller and advanced controls).

The 82nd plant provides district heating and cooling to serve a large number of barracks and other buildings with 125 psig steam for heating, 170 deg. F. hot water (converted from steam), and 45 deg. F. chilled water for cooling. The plant originally contained five large water tube steam boilers. Four of these boilers were poorly performing, unreliable and in need of replacement. This condition provided an excellent application for installing an integrated energy system (or cooling, heating, and power system).

The IES equipment is fired with natural gas, and can also be fired with fuel oil as a backup fuel source. The plant also includes an auxiliary steam boiler and an auxiliary electric centrifugal chiller, for backup or to provide additional capacity when required. The IES system has an electrical generating capacity of 5250 kW, and a heating capacity of 28,700 lbs. per hour of steam at nominal ambient conditions (60 deg. F.). The plant serves a steam heating load during the winter months, and a year-around heating load for domestic hot water and food service needs. Cooling is provided during the spring, summer, and early fall.

The IES system operates in a base load condition, essentially offsetting some of the electric demand on the post. The balance of the electric load is purchased from the local electric utility. During periods of low heating load, the heating demand is less than the maximum thermal output of the IES system. During periods of high heating load, the auxiliary duct burner is employed to increase the output of the HRSG. At present, all of the cooling load for the building served can be satisfied by the 1000 ton absorption chiller.

This project contributed significantly to the post's energy security initiative. The on-site generation capacity of this IES system is a valuable asset that can be used to mitigate the effects of utility plant outages and other disruptions on the electrical grid.

The key dates in the history of the project are:

- Design phase & approvals: 2002 and early 2003
- Construction: 3Q2003 and 1Q2004
- Startup and commissioning: 2Q2004
- Commercial operation: June 1, 2004

3.3 Overview of Results

The Ft. Bragg site provided an excellent vehicle for demonstrating and assessing the value of IES technologies. Based on our experience at the Ft. Bragg site, the project team identified a number of lessons learned that can help other engineers in the industry. A list of key outcomes relating to IES site-specific design work is shown in Table 3-3.

Table 3-3. Key Outcomes of the Field Demonstration Work

Key Outcome	Remarks
1. Commissioning is a very important part of an IES installation project.	As with any building or plant level energy system.
2. Guillotine dampers can be made to perform in an exhaust-driven chiller application. (Note: A guillotine damper is needed to protect the absorption chiller from hot exhaust gases, when the chiller is not in operation.)	There is no need for specially designed guillotine dampers, although there may be a need to carefully adjust the damper slide mechanism during plant commissioning.
3. Additional instrumentation (beyond that required for control purposes) is a valuable part of an IES project.	Additional sensors provide more information to plant operators and energy managers, about equipment and system operating performance.

A list of key outcomes relating to IES plant operations is shown in Table 3-4.

Table 3-4. Key Outcomes of the Field Demonstration Work

Key Outcome	Remarks
1. Site operating staff should maintain a proper inventory of critical spare parts or plan carefully to be sure they are procured before they are needed. Examples are air and fuel filters, and other key consumables.	Poor planning can result in lost operating time of the IES system from unplanned outages caused by a lack of the necessary spare parts.
2. High fuel prices (vs. electric prices), during periods of low thermal loads can make it uneconomical to operate the IES system.	This illustrates the benefit of having control optimization capability.
3. If not carefully planned, emissions permitting can delay startup.	Begin the permitting process early, and follow up to make certain that all requirements are met prior to completion of the site construction work.
4. Interconnection with local electric utility (protective relaying, etc.) is a key element of an IES project.	Coordination with the electric utility on commissioning the interconnection is one of the key elements of plant startup.

Section 4. Performance Monitoring

This project included a period of field performance monitoring for the IES System at the Ft. Bragg 82nd Heating Plant. During the period of June 2004 thru August 2005, various performance data were collected and analyzed for the following purposes:

- Field monitoring of absorption chiller performance.
- Measurement of IES system operational performance in an actual site application (Ft. Bragg 82nd Heating Plant).

Details of performance results at an equipment level are contained in the separate performance reports that were published earlier in this project.

4.1 Field Monitoring Overview

A description of the Ft. Bragg 82nd Heating Plant IES system is presented in the previous section of this report. A system block diagram showing the performance analysis boundaries is shown in Figure 4-1. The definition of system efficiency is taken as: (useful energy output) / (total energy input from fuel).

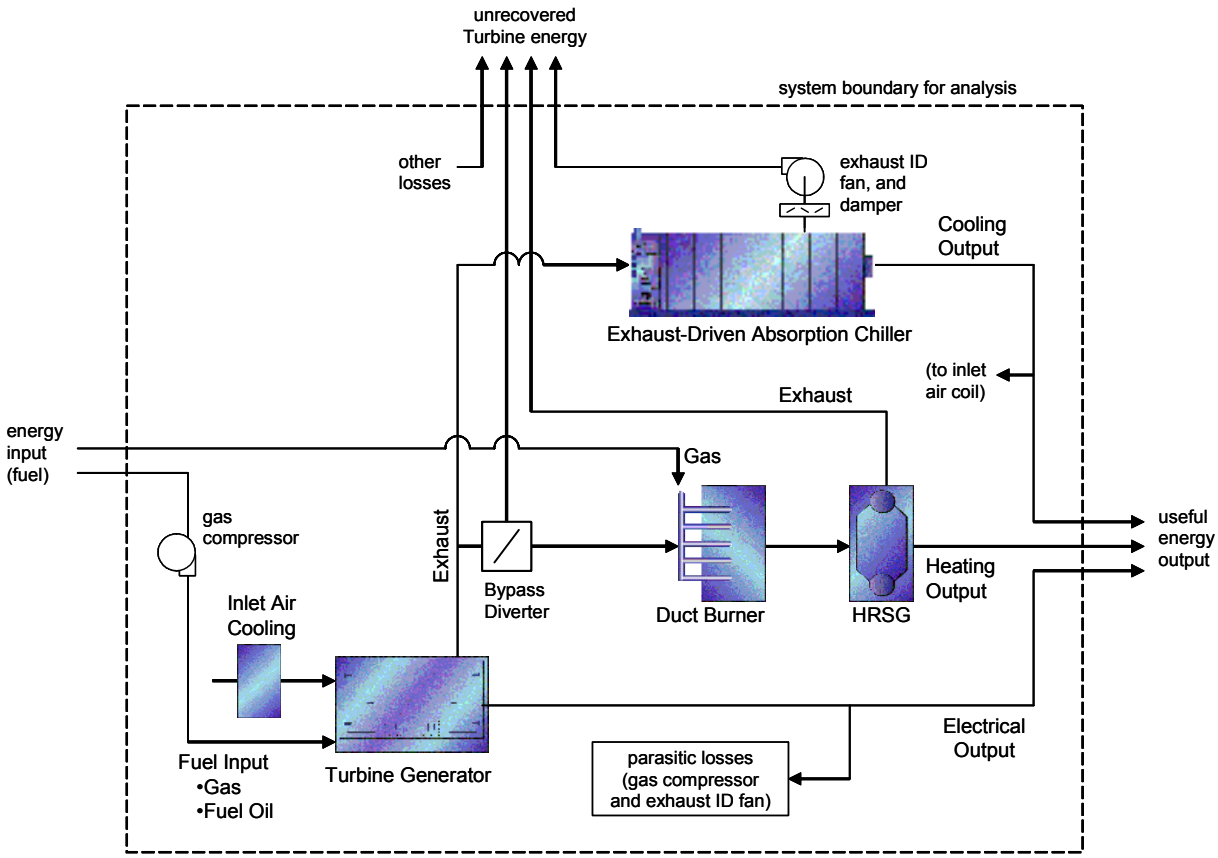


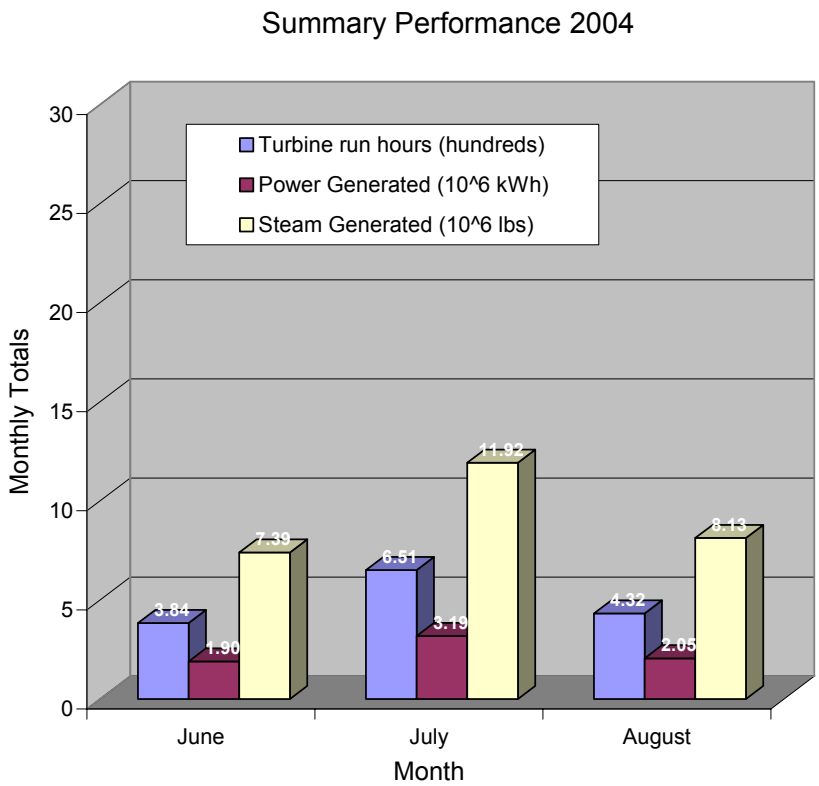
Figure 4-1. IES System: Boundaries of the Performance Analysis

4.2 Summary Performance Results

Measured performance results are presented in the following sections, arranged by season. Additional in-depth performance data can be found in other project report documents listed in Section 1 of this report.

4.2.1 Summary Performance Results: Summer 2004

A high-level summary of energy delivery results for the summer months of 2004 is shown in Figure 4-2. (Note: During this period, the system experienced some periods of downtime due to extended commissioning activity and delays in acquiring an emissions operating permit.)

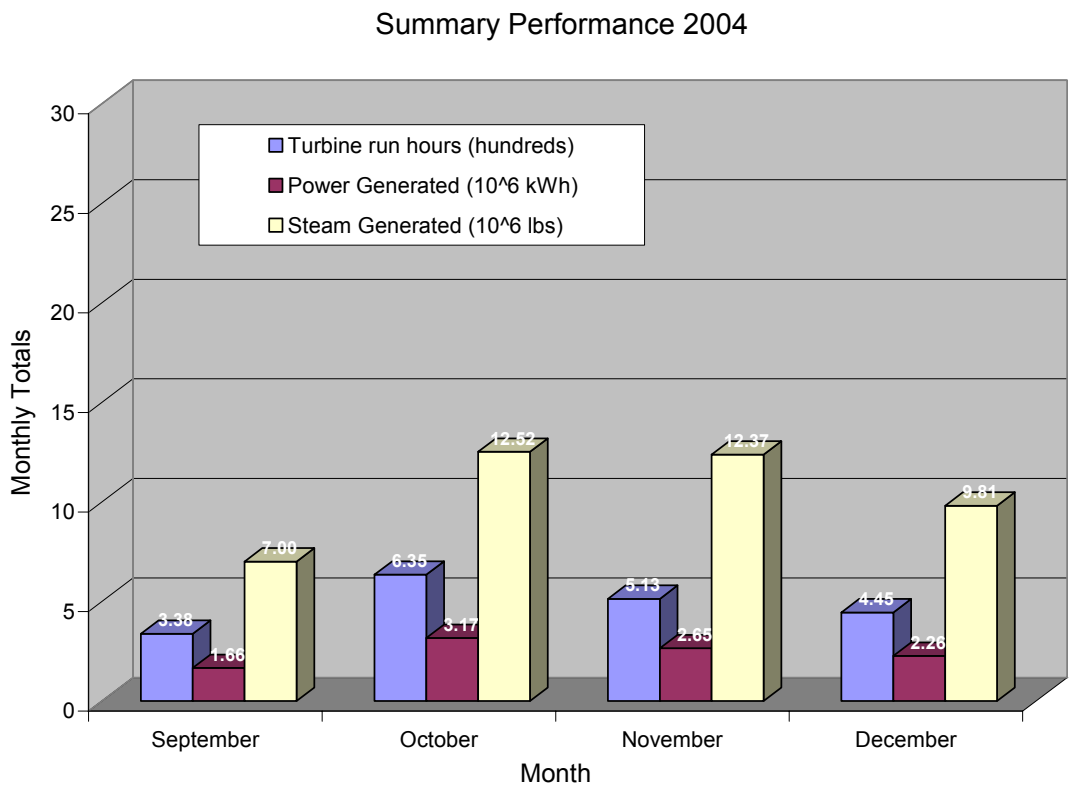


	Summary Performance Data		
Month	Turbine run hours	Power Generated (kWh)	Steam Generated (lbs)
June	384	1,904,408	7,392,141
July	651	3,189,374	11,923,695
August	432	2,053,839	8,130,529

Figure 4-2. Energy Delivery Results, Summer 2004

4.2.2 Summary Performance Results: Fall 2004

A high level summary of energy delivery results for the fall months of 2004 is shown in Figure 4-3.

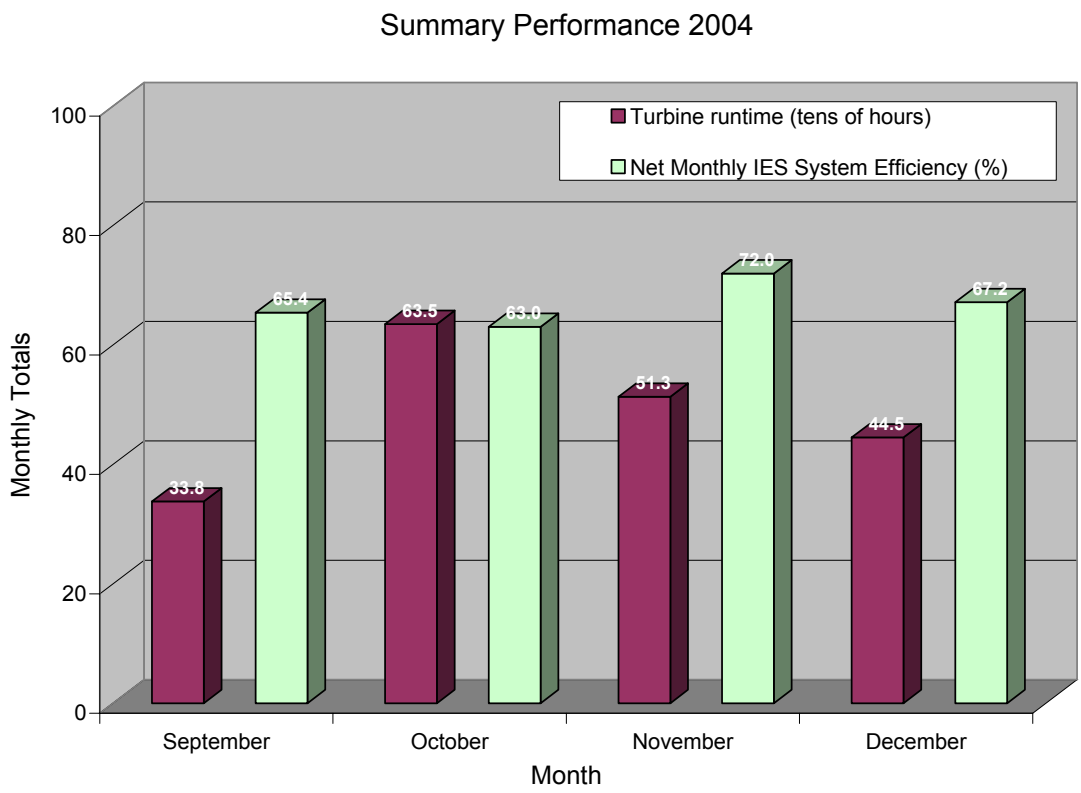


	Summary Performance Data		
Month	Turbine run hours	Power Generated (kWh)	Steam Generated (lbs)
September	338	1,664,393	7,001,374
October	635	3,169,605	12,520,358
November	513	2,654,199	12,374,470
December	445	2,262,950	9,808,411

Figure 4-3. Energy Delivery Results, Fall 2004

A high-level summary of operational results for the fall months of 2004 is shown in Figure 4-4.

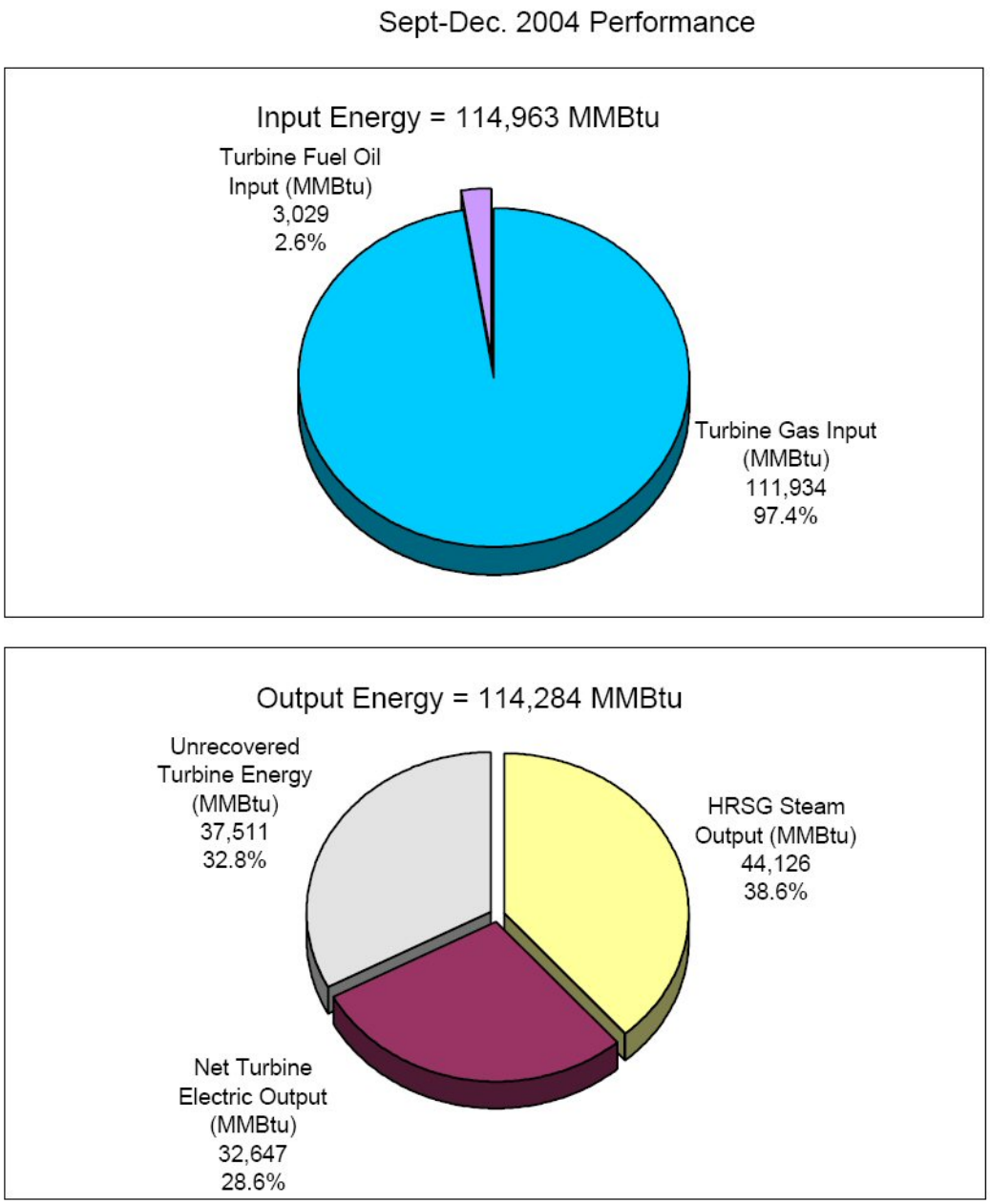
The IES system energy efficiency is based on the lower heating value (LHV) of the fuel input. Energy efficiency calculations were made in accordance with "Distributed Generation Combined Heat and Power Long Term Monitoring Protocols" Interim Version, October 29, 2004, prepared by the Association of State Energy Research and Technology Transfer Institutions (ASERTTI) http://www.asertti.org .



	Summary Data	
Month	Turbine run hours	Net Monthly IES System Efficiency (%)
September	338	65.4
October	635	63.0
November	513	72.0
December	445	67.2

Figure 4-4. Operational Results, Fall 2004

A high level summary of energy utilization results for the fall months of 2004 is shown in Figure 4-5.



Net IES Efficiency

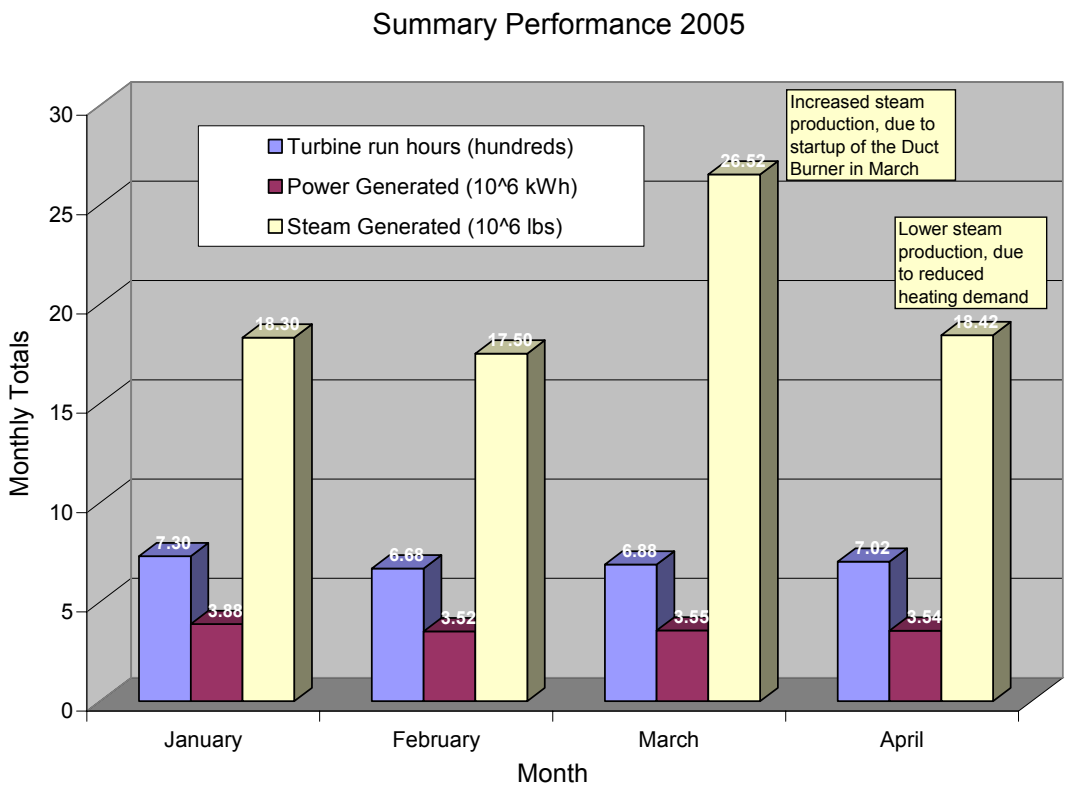
$$n_{CHP\cdot NET} = \frac{NET\ P_{REAL}(kW) + P_{QNET}(kW)}{P_{FUEL\cdot INPUT}(kW)} \times 100$$

= 66.8%

Figure 4-5. Energy Utilization Results, Fall 2004

4.2.3 Summary Performance Results: Winter 2005

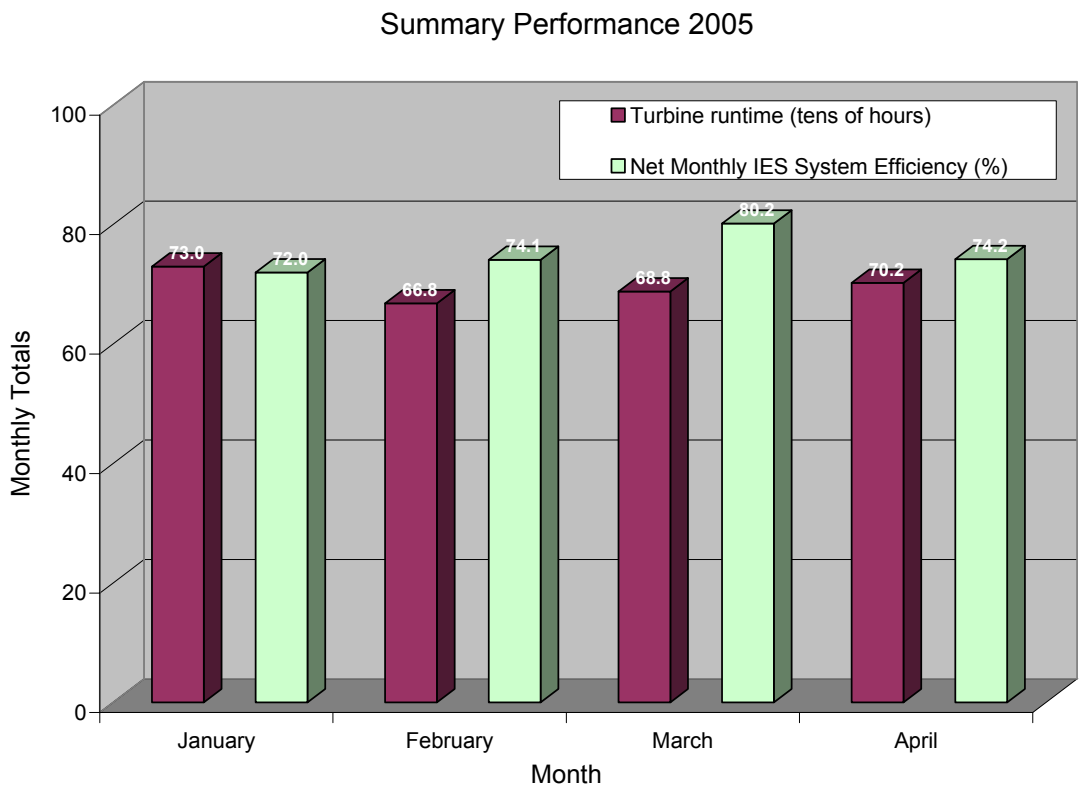
A high-level summary of energy delivery results for the winter months of 2005 is shown in Figure 4-6.



	Summary Performance Data		
Month	Turbine run hours	Power Generated (kWh)	Steam Generated (lbs)
January	730	3,876,281	18,302,123
February	668	3,515,882	17,495,770
March	688	3,553,763	26,515,075
April	702	3,543,983	18,422,213

Figure 4-6. Energy Delivery Results, Winter 2005

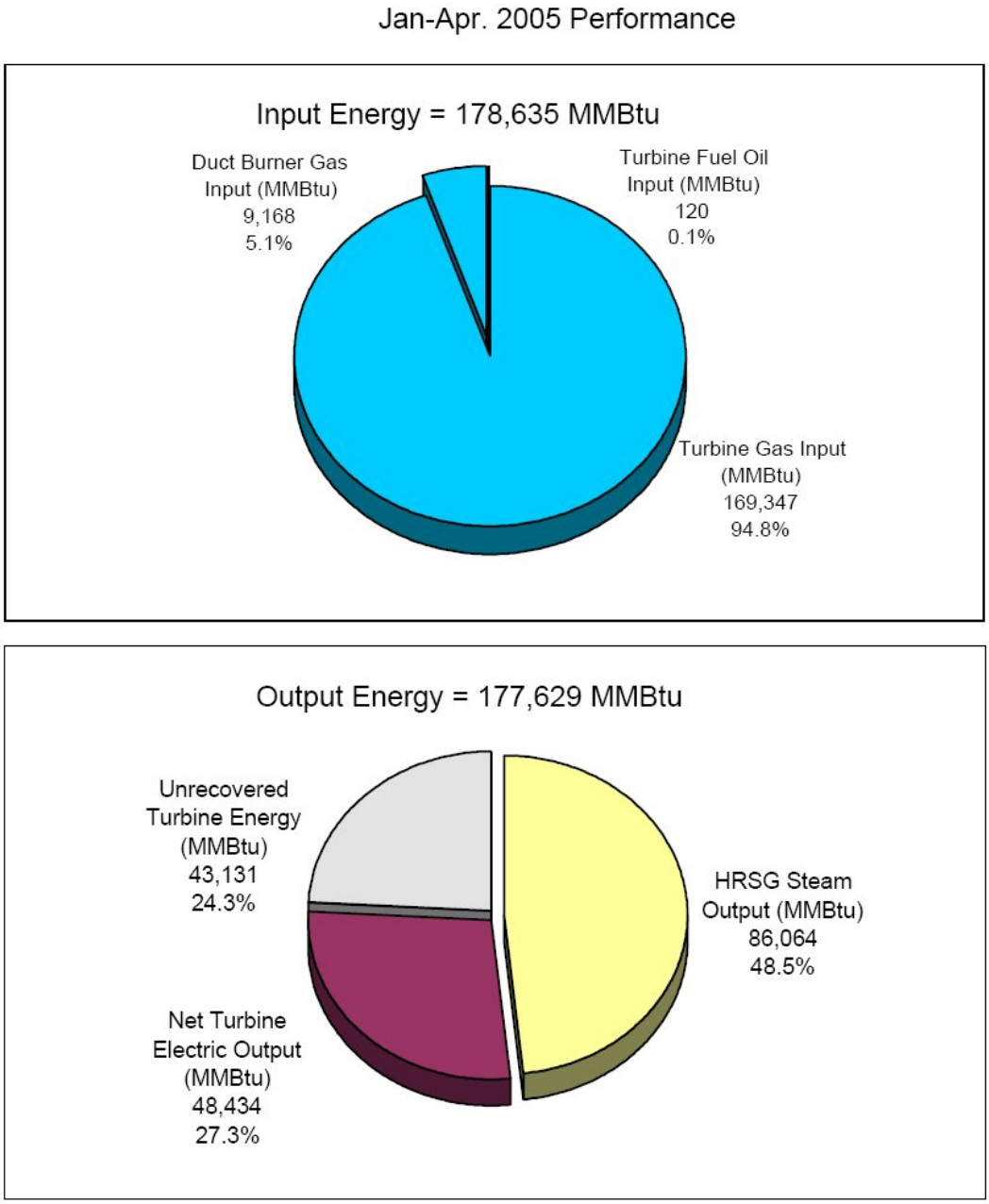
A high-level summary of operational results for the winter months of 2005 is shown in Figure 4-7. The CHP system energy efficiency is based on the LHV of the fuel input.



	Summary Data	
Month	Turbine run hours	Net Monthly IES System Efficiency (%)
January	730	72.0
February	668	74.1
March	688	80.2
April	702	74.2

Figure 4-7. Operational Results, Winter 2005

A high-level summary of energy utilization results for the winter months of 2005 is shown in Figure 4-8.



Net IES Efficiency

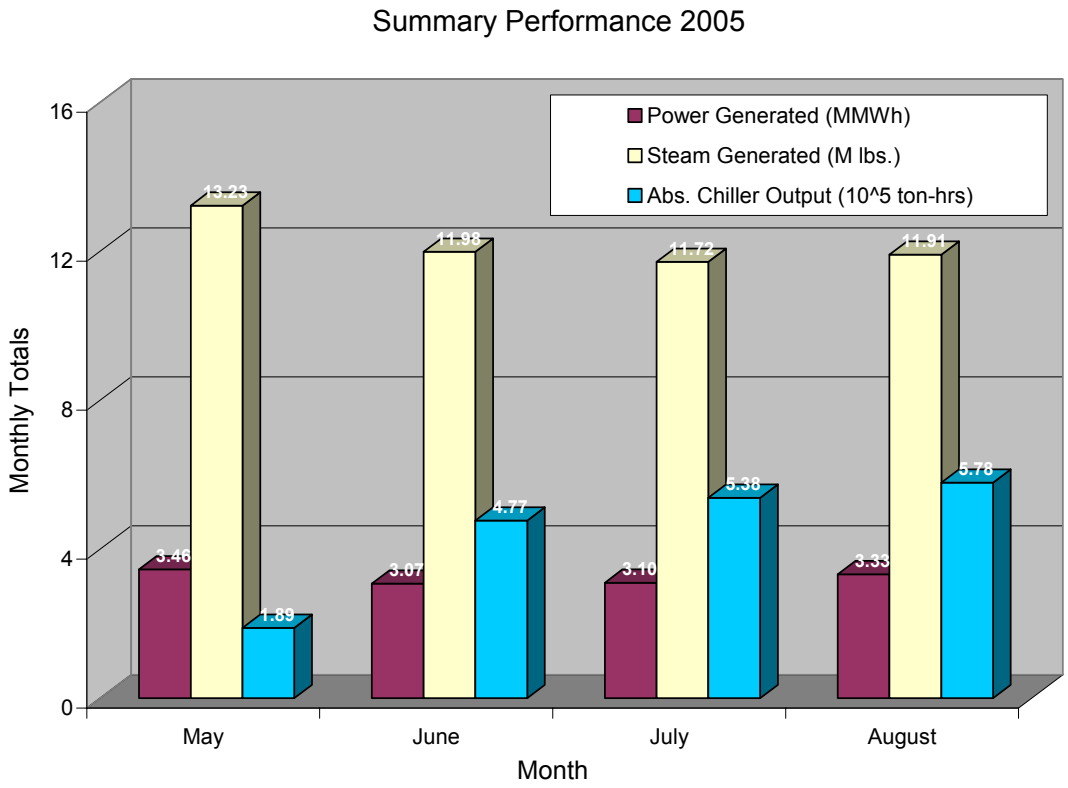
$$n_{CHP\text{-}NET} = \frac{NET\ P_{REAL}(kW) + P_{QNET}(kW)}{P_{FUEL\text{-}INPUT}(kW)} \times 100$$

= 75.3%

Figure 4-8. Energy Utilization Results, Winter 2005

4.2.4 Summary Energy Performance Results: Summer 2005

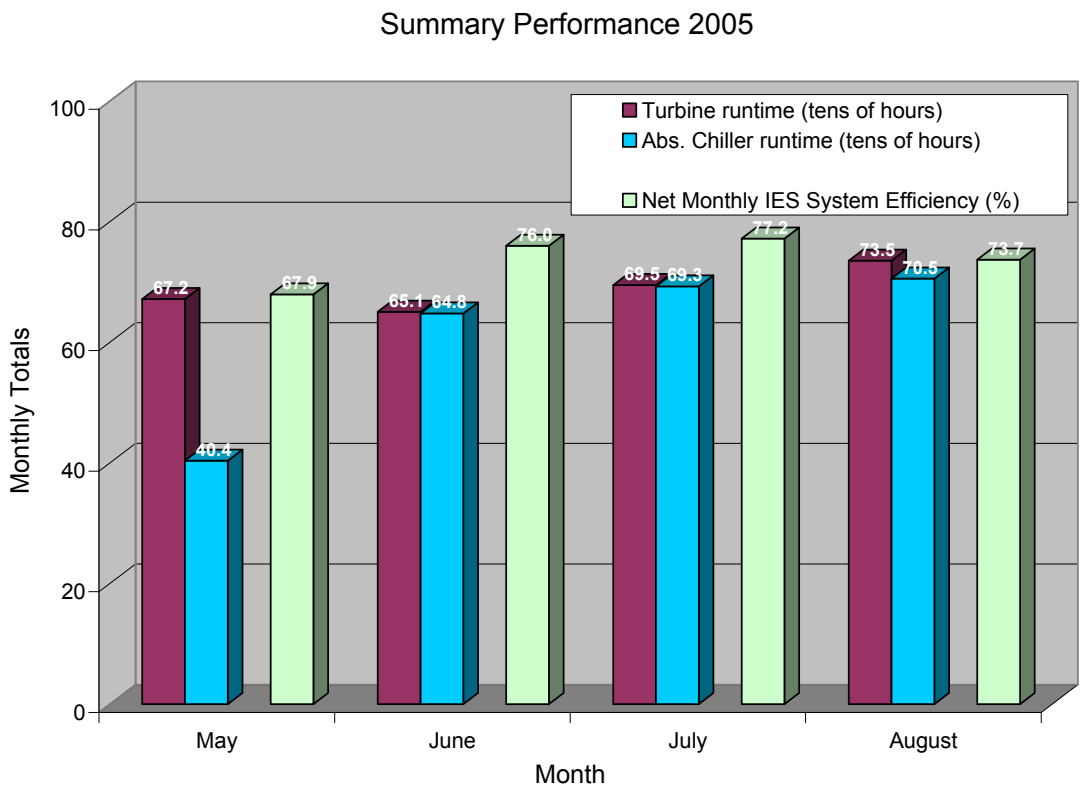
A high-level summary of energy delivery results for the summer months of 2005 is shown in Figure 4-9.



	Summary Performance Data		
Month	Power Generated (kWh)	Steam Generated (lbs.)	Absorption Chiller Output (ton-hours)
May	3,456,023	13,226,844	188,622
June	3,074,551	11,983,409	476,606
July	3,098,944	11,716,781	538,104
August	3,327,250	11,906,622	578,439

Figure 4-9. Energy Delivery Results, Summer 2005

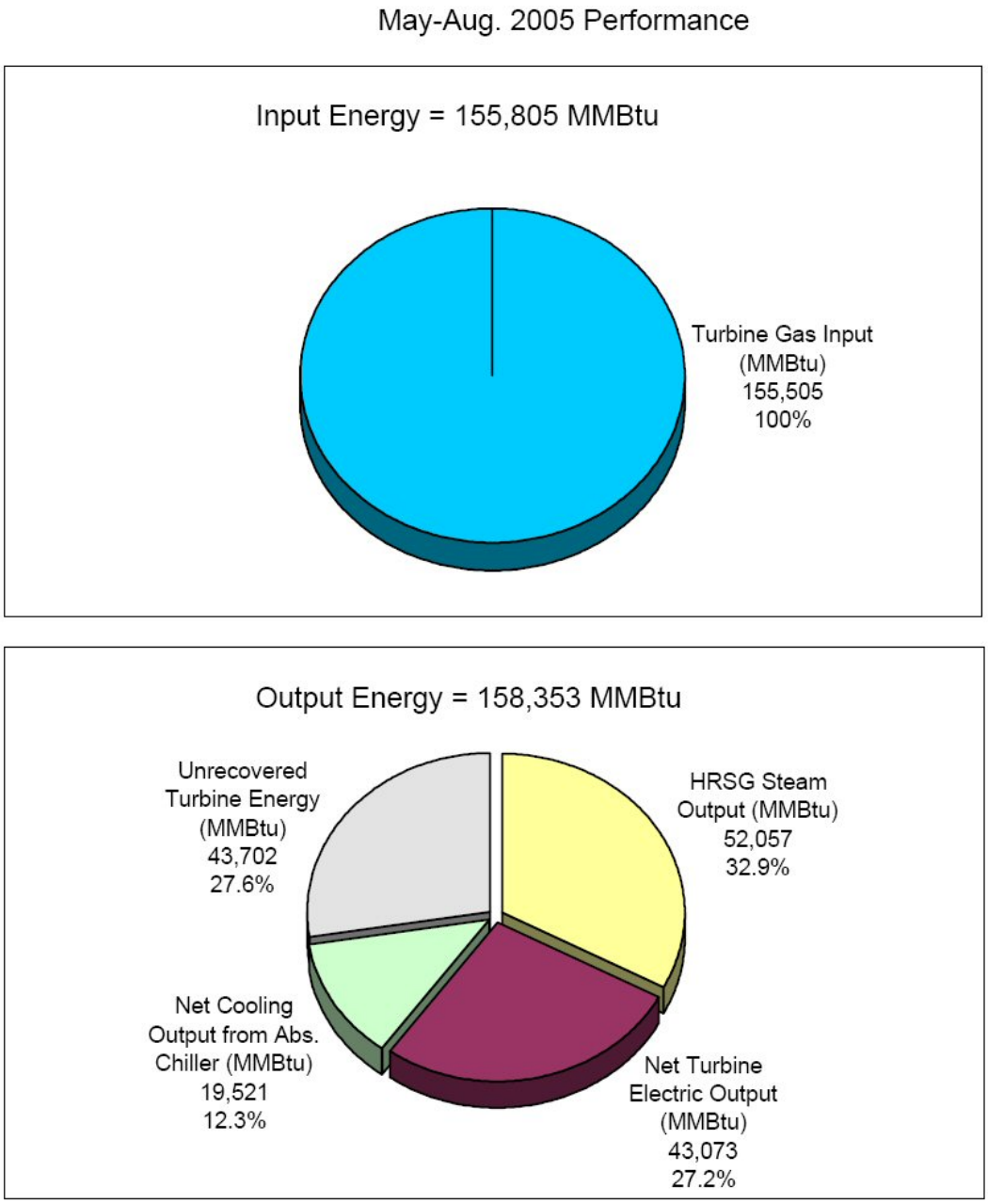
A high-level summary of operational results for the summer months of 2005 is shown in Figure 4-10. The CHP system energy efficiency is based on the LHV of the fuel input.



	Summary Operational Data		
Month	Turbine run hours	Absorption Chiller run hours	Net Monthly IES System Efficiency (%)
May	672	404	67.9
June	651	648	76.0
July	695	693	77.2
August	735	705	73.7

Figure 4-10. Operational Results, Summer 2005

A high-level summary of energy utilization results for the summer months of 2005 is shown in Figure 4-11.



Net IES Efficiency

$$n_{CHP\cdot NET} = \frac{NET\ P_{REAL}(kW) + P_{QNET}(kW)}{P_{FUEL\cdot INPUT}(kW)} \times 100$$

= 73.6%

Figure 4-11. Energy Utilization Results, Summer 2005

4.2.5 Key Results

The field monitoring work successfully measured the performance of the demonstration system at the Ft. Bragg site. In performing this work, the project team identified a number of lessons learned that can help other engineers in the industry. A list of these key outcomes is shown in Table 4-1.

Table 4-1. Key Outcomes of the Field Performance Monitoring Task

Key Outcome	Remarks
1. Cleaning of turbine blades should be done according to the turbine manufacturers' recommendations.	Careful monitoring of blade condition will keep the turbine operating at or near the desired performance.
2. Parasitic energy consumed by the induced draft (ID) fan at the Ft. Bragg site was not a serious issue (in terms of energy efficiency). (In the Ft. Bragg IES system, the ID fan was used to guarantee proper exhaust flow thru the absorption chiller.)	Measured field data over a complete cooling season showed that the ID fan was not a major contributor to parasitic energy required to operate the system.
3. Seasonal variations in energy efficiency are to be expected, due to varying thermal loads and equipment operating characteristics.	The measured performance at the Ft. Bragg site was very good, and met the expectations defined at the beginning of the project. Monthly energy efficiencies of up to 80% (based on LHV) were measured at the site.
4. System-level performance can be measured and design intent verified with the proper amount of field instrumentation.	Steady-state performance can be measured quite adequately using standard control system quality instrumentation. More in-depth investigations will likely require more elaborate instrumentation and data collection equipment. Careful attention to sensor calibration is also a key ingredient to success.
5. Equipment-level performance can also be measured, and design intent verified with the proper amount of field instrumentation.	The field data verified that each item of major equipment in the Ft. Bragg IES system was able to meet or exceed its design performance specifications. (Note: Detailed results of the performance monitoring work are contained in separate performance reports that were published earlier in this project.)

Section 5. Conclusions

Under this project, the industry team developed packaging and related technologies for large (1-5 MW) integrated energy systems, and demonstrated the technologies in a field site installation. Applying these technologies broadly can help to achieve the energy efficiency and other goals for DOE's efforts in integrated energy systems in the commercial buildings sector. The conclusions reached in this project are described in the following sections.

5.1 Development of IES Reference Designs

Our work in the development of CAD-based modular reference designs for large IES systems produced the following key conclusions:

- This concept can help to reduce the complexity and installed cost of large IES systems. Our analysis showed that the use of reference design data could save up to 8% of a project's engineering costs (through reductions in up-front project feasibility analysis, detailed design, and preparation of construction documents).
- Interconnection with building HVAC systems is a key project design task. Application use of well-known engineering design practices (through resources provided in an earlier project report) can provide a good result.
- Interconnection with local electric utility is also a key project design task. While this has been a barrier to some IES projects in the past, recent standards work is helping to eliminate this problem (these resources are also provided in an earlier project report).

5.2 Development of Exhaust-Driven Absorption Cooling Technology

Our work in the development of exhaust-driven absorption cooling technology for large IES systems produced the following key conclusions:

- Exhaust-driven absorption cooling technology can be utilized to provide simpler IES system designs, especially if implemented as a chiller-heater (by avoiding the use of a HRSG in applications where steam is not required).
- This technology does not require special training for plant operators or service personnel. This type of equipment is very similar to the more common steam-driven or gas-fired absorption chiller technology.
- The exhaust-driven chiller installed at the field demonstration site provided very good performance and met the design specifications. However, a small amount of regular maintenance is required in order to keep the unit operating at peak performance.

5.3 Development of On-line Control Optimization Technology

Our work in the development of a supervisory control system with on-line control optimization capability produced the following key conclusions:

- A simulation analysis showed that on-line control optimization could deliver an annual energy cost savings of approximately 6%, as compared with a user-defined "smart" operating strategy.
- Experience from the Ft. Bragg site showed that enterprise-level operating objectives can sometimes override plant-level control optimization. While this is not a frequent occurrence, it is to be expected occasionally.
- On-line control optimization capability can help to identify periods when it is not economical to operate the IES system due to high fuel prices or low thermal loads. Without optimization, these decisions may not otherwise be obvious to plant operators or energy managers.

5.4 IES Plant Operations

Installation and field monitoring work at the Ft. Bragg site produced the following key conclusions:

- Commissioning is a very important part of an IES installation project. Extra effort during this phase of a project will pay off in the long run.
- Additional instrumentation (beyond that required for control purposes) is a valuable part of an IES project. This provides more information to plant operators and energy managers, about equipment and system operating performance.

5.5 IES System Measured Performance

Field performance monitoring work at the Ft. Bragg site produced the following key conclusions:

- With the proper amount of field instrumentation, system-level and equipment-level performance can be measured and design intent verified. Our site measurements showed that the design intent was met at the Ft. Bragg site.
- Based on measured performance at the Ft. Bragg site, monthly energy efficiencies of up to 80% (based on the lower heating value, LHV of the fuel input) are possible with IES technology. However, seasonal variations in energy efficiency are to be expected, due to varying thermal loads and equipment operating characteristics.