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Mechanical Option
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4/7/11

Peirce Hall, Kenyon College

Senior Thesis Final Report:

Peirce Hall, Kenyon College Building System Improvement Study

Peirce Hall, Kenyon College

Gambier, Ohio

Project Information

Owner - Kenyon College
Architect - Gund Partnership
MEP Engineer - Syska Hennessy Group
Structural Engineer - LeMessurier Consultants, Inc.
Construction Management - The Albert M. Higley Co.
Stories Above Grade - 5
Project Delivery - Design-Bid-Build
Total Cost - $18 million
Size - 66,640 square feet

Architectural

Peirce Hall is one of Kenyon College's most recognizable landmarks with its gothic appeal and stone tower. The 2006-2008 renovation, addition, and expansion project improved and added new signature spaces to the university campus. A combination of the new glass ceiling atrium and restored Great Hall, with its carved rafters, wood paneling, and stained-glass windows capturing scenes from American and British literary classics beautifully exemplifying the building's marvel.

Structural

-Steel gravity system with beam spans up to 43'

-Lateral system composed of moment frames and diagonal HSS braced frames

-Foundation composed of reinforced concrete 1' thick walls, typically 2'x2' and 16"x16" piers, and spread footings

-Typical floor slabs are 7 ½" or 5 ½" thick using 18 GA composite deck with 4 ½" normal weight or 3 ½" light weight concrete

Electrical

-1000kVA, 12.47kV/208V pad mounded transformer

-208Y/120 V, 3 phase, 4 wire service voltage

-400A, 100kW/125kVA, 208/120V natural gas fueled generator for refrigeration building load

-Emergency signage, egress and discharge lighting, and fire alarms are battery powered

Mechanical

-241 ton, 166.3kW scroll type electric water chiller

-Yearlong operational 204-256 ton crossflow cooling tower

-Campus provides 26 psi medium pressure steam supply

-Steam serves (6) air handling units and (4) unit heaters directly

-Steam converter supplies hot water to floor radiant heating system, fin tube radiators, and cabinet unit and unit heaters

Rami Y. Moussa | Mechanical

http://www.engr.psu.edu/ae/thesis/portfolios/2011/rym5018/index.html

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1.0 Executive Summary

The following thesis reports the findings of three studies performed to investigate the possibility of improving building system efficiency in the Peirce Hall dining facility of Kenyon College in Gambier, Ohio. Peirce Hall underwent a major renovation, expansion, and addition project beginning in 2006 and ending in 2008. The intention of the project was to accommodate the increased demand on the facility and replace the outdated building systems with more efficient, economical, reliable, flexible, and maintainable systems. This goal was achieved in many aspects such as the new chiller plant and air distribution system. However, the previously existing campus steam supply is still used to supply heat and power is still purchased from a local provider. These areas showed the greatest potential for significant improvements.

Modifications and additions to the facility's mechanical, lighting, and power systems have been explored to address areas of incompliance and to attempt exceeding requirements of The American Society of Heating Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 90.1 Section G with intent to approach LEED Certified status. Doing so will provide evidence of the facility's performance, and is one way to assure Kenyon College eligibility to apply for various federal funding opportunities.

A depth study was performed to assess the feasibility and effectiveness of using a combined heat and power (CHP) system to supply Peirce Hall with steam and power. Successfully designing an effective CHP plant for the facility would reduce the dependence on campus steam and purchased power. The proposed system uses three Capstone 800kW high-pressure natural gas microturbine packages. The system was observed operating under electrical load and thermal load following scenarios and compared to a modeled interpretation of the existing separate heat and power system, all modeled in Microsoft Excel. Due to a decreased annual utility cost of 9% and a significant reduction in harmful gas emissions, this study determined that Peirce Hall can benefit from a CHP system operated to follow the facility's electric load profile.

To ensure that the microturbine packages specified as the prime mover for the Peirce Hall CHP plant did not create a noise disturbance to the occupants of the facility or surrounding campus, an acoustic breadth study was performed. A variety of scenarios involving different construction material types for the prime mover housing were considered. The goal of this study was to reduce emitted sound levels below 50 A-weighted decibels, the approximate noise level of typical office activities (Egan 13). This was investigated and achieved by using a variety of lightweight concrete masonry unit wall constructions.

The lighting power density values in the Great Hall dining area of Peirce Hall were far above the ASHRAE Standard 90.1 recommended values, as found while performing research for Technical Report I. This again, is a factor that prevents Peirce Hall from LEED certification. To remedy this, 9W Toshiba Dimmable LED PAR20 lamps were specified to replace the existing 40W incandescent candelabra lamps. The LED lamps use much less power and improve illuminance in the dining area to a level closer to the Illuminating Engineering Society of North America recommended level, all while providing a similar warm color temperature. A model was created to calculate and compare illuminance levels of the space under both lighting scenarios in AGi32.

2.0 Intention of Studies

The studies performed in this thesis were intended to investigate possible modifications to the existing building system designs of the sponsored facility that could raise system performance to a level recognized by The United States Green Building Council (USGBC) and United State Department of Energy (DOE) as more sustainable. These groups strongly encourage innovative building system design to reduce energy used by US citizens, harmful gas emissions, dependence on foreign resources, create research opportunities to further building technology, and create or retain employment opportunities. By designing systems with these goals in mind, results beneficial to society are bound to be produced.

When worthy designs are produced and desirable ends are met, these large organizations will often provide compensation to assist in the construction efforts. Compensation such as the Renewable Energy Grants, which receives its funds through The American Recover and Reinvestment Act, can provide significant assistance in constructing a technically advanced system that often have high first costs. This grant in particular funds projects involving CHP, photovoltaic, and fuel cell designs, providing up to $200 per kW of power generated by microturbines and $1,500 per 0.5 kW of power generated by fuel cells. (Database of State Incentives for Renewables & Efficiency) Such grants offer those who are qualified great incentive to go through with constructing their designs. However, in order to prove a system is worthy of compensation many, sometimes painstaking, measures must be taken.

One scale developed by the USGBC to indicate the overall efficiency of a facility's building systems is known as the LEED rating system. As stated by the USGBC, "LEED is an internationally recognized green building certification system." The LEED certification system is a method of rating the strategies and technologies used in buildings that affect energy savings, water efficiency, CO_2 emission reduction, and improving indoor environmental quality. Qualifications for LEED ratings vary between building and construction types like homes, commercial interiors, new construction, and core and shell conditions of existing buildings. (U.S. Green Building Council)

The LEED rating system that applies to the studies of this thesis pertains to the LEED for New Construction and Major Renovations. By achieving different design criteria, each given a weighted point value, one can reach LEED levels of Certified, Silver, Gold, and Platinum. With this title, more often than not comes recognition of a well designed and well performing building. Therefore, the studies performed in this thesis strive to bring system efficiencies of the provided facility to a higher level that will approach LEED Certified worthy credentials.

3.0 Facility Orientation

3.1 Background Information

The Kenyon College campus is located in The Village of Gambier, located in Knox County, Ohio, just 55 miles Northeast of Columbus, Ohio. The Village of Gambier is a historic area with structures dating as far back as the 19th century and holds a very small community. However, this is a community that prides itself on being the hometown of the prestigious Kenyon College, one of the best liberal arts colleges in the country. This pride is clearly symbolized by the central location of the campus in the town shown in Figure 1.

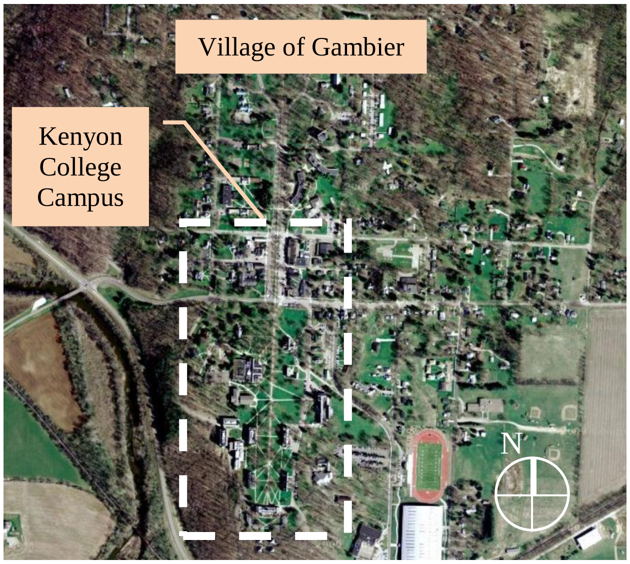


Figure 1: Google Map of the Village of Gambier, Ohio

Peirce Hall, shown in Figure 2 is one of the most recognizable landmarks on the Kenyon College campus. The 66,600 square foot facility is one of the campus's signature buildings and holds well known spaces like the Great Hall shown in Figure 3, a 4,150 square foot dining hall with a 40 foot 8 inch high ceiling. Peirce Hall was originally built in 1929 and added onto in 1964 with the Dempsey Hall to accommodate the growing campus's needs.

Figure 2: Peirce Hall Front Entrance

The building primarily functions as a dining facility for students at the college. Additional spaced include administrative offices, student organization and lounge spaces, a music classroom, and computer lab. In 2006 another modification of Peirce Hall began. An extensive 18 million dollar renovation, addition, and expansion project was conducted to meet the still growing college needs. All of the interior building systems were gutted and redesigned with the exception of about half of the original structure. Additions were also constructed, expanding the building to the South and East. The project team included owner - Kenyon College, architects - Gund Partnership, structural engineers - LeMessurier Consultants, Inc., construction managers - The Albert M. Higley Co., and mechanical, electrical, plumbing, and fire protection engineers - Syska Hennessy Group.

Figure 3: The Great Hall

Since the last modification of Peirce Hall was in the 1960's, many of the building systems of Peirce Hall were quite outdated. The facility still holds walls as much as 80 years old and the facility could not easily be modernized as a result. Prior to 2006, heating was provided by the campus steam system. Steam was delivered to a steam to hot water converter which supplied baseboard and convector units. Means for cooling however were hardly in place. Primary cooling was provided by four air handlers coupled with three air cooled condensing units located away from the building. Three air handlers were located in ceiling plenums and one in a mechanical closet serving the music room. This layout would prove inadequate in providing heating, ventilating, and air conditioning for an expanded building which would have double the conditioned floor space.

The Peirce Hall renovation, addition, and expansion project was intended to make the facility a more useful, comfortable, and better performing building. Of the building systems added during the renovation period, a 3.3 million dollar mechanical system was installed. The design of this system used efficient equipment and intelligent controls to satisfy the intent of the renovation. This system serves as the primary means for heating, cooling, and ventilation and will be the basis for the studies described in the following pages.

3.2 Preliminary Research Summaries

The following sub-sections of section 3.2 summarize the research performed in the academic fall semester of 2010. These studies analyze the design and components of the mechanical building systems of Peirce Hall. Additional information and details pertaining to these studies can be found in the technical report documents.

3.2.1 Technical Report I: Ventilation and Energy Design Evaluation

Technical Report I studied the compliance of the new Peirce Hall mechanical building systems with American Society of Heating, Refrigerating, and Air-Conditioning Engineers Standard 62.1 Section 5 and Standard 90.1 Sections 5 through 10. These standards recommend a minimum level of ventilation to maintain occupant health and minimum equipment performance statistics to ensure minimal energy is used by a system.

The ventilation system designed for the new Peirce Hall uses seven air handlers, supplying a total of 77,100 CFM to spaces. General characteristics of these air handlers can be found in Table 1. The first four units are used for primary ventilation air flow and three additional units are used for make-up air to kitchens, the main servery area, and the loading dock. Ventilation rates determined by ASHRAE Standard 62.1 have been satisfied in almost all areas and in some places greatly over supplied by up to 1146.6%. One air handler has been found to be 14.3% under the required ventilation rate as a result of mainly storage spaces not being ventilated. The most significant reason for discrepancies in required and provided air flows is related to exhaust make-up and occupancy densities in the kitchens, food preparation, and clean-up areas. Further details can be found in Technical Report I, Appendix A Table A.1 and Table A.2.

AHU	System	CFM	Starter	Flow Control	Economizer
1	Kitchen/Servery	8000	Yes	Volume Dampers	Yes
2	Pub/Peirce Hall	11300	Yes	VAV Terminal Units	Yes
3	Tower	6800	VFD	VAV Terminal Units	Yes
4	Dining Hall	30000	VFD	VAV Terminal Units	Yes
5	Catering Make-Up	6850	VFD	Constant	No
6	Servery Make-Up	10500	VFD	Volume Dampers	No
7	Loading Dock	3680	Yes	Volume Dampers	No

Table 1: Air Handler Characteristics

Mechanical building systems comply with ASHRAE Standard 90.1 to an extent. Much of the building envelope requirements have been fulfilled, however the added glass roof over the link between dining area serveries created issues with compliance. Section 5 requires that only 5% of a buildings gross roof area be used as skylight. Since the roof is only pitched at a 15 degree angle from a horizontal plane, it is considered a skylight and the roof covers over 11% of the gross roof area. The over use of glazing on the roof may be able to be argued by the low solar heat gain factor (SHGC) associated with the glass used. The SHGC is less than half the required value. Efficiencies of mechanical system components are all acceptable except for that of the cooling tower. This noncompliance may be able to be attributed to the different testing conditions at which the efficiency was determined. Medium pressure steam is supplied to the building from the campus supply relieving the need for a boiler and limiting the service water heating equipment to only one electric hot water heater. This water heater however, is only capable of energy retention values that satisfy the 1989 version of Standard 90.1 Section 7.

Power distribution is design as efficiently as possible at the service entrance, with the required 2% voltage drop being satisfied. One goal of the renovation of Peirce Hall was to enhance The Great Hall which was already a signature space on the Kenyon College campus. In the design of the lighting system in this dining area and some others, grand chandeliers were hung from the high ceilings. In the Great hall, the previously existing chandeliers were rewired and restored to be used in the new design. These luminaires require large amounts of energy, as they each use thirty 40W incandescent lamps and were a large part of the reason for incompliance with Section 9 lighting power density (LPD) allowances. Approximately half of the spaces in Peirce hall were compliant with required LPD values. Efficiencies of electric motors were designed to comply with the values provided in Section 10 of Standard 90.1.

3.2.2 Technical Report II: Building and Plant Energy Analysis Report

Technical Report II analyzes the components of the Peirce Hall mechanical system that influence and provide service for heating loads, cooling loads, and ventilation rates. In this analysis a Trane Trace 700 load and energy model was created to approximate characteristics of the mechanical system such as heating and cooling capacities, energy consumption of major system components, utility costs, and emission rates. A design load model was provided by Syska Hennessy Group, Inc. which was used as a reference to compare calculated values. This model however, did not contain energy analysis information.

In the created building load model, referred to as the “analysis model,” Peirce Hall is represented by a collection of categorized spaces. Since the facility holds a highly diverse variety of adjacent spaces, each space represents a room of the facility rather than a section of the building. Spaces are categorized by occupancy and use. Each category has its own sensible and latent heat generation value, which has been recommended by the ASHRAE Handbook of Fundamentals. Contributions from lighting and appliances however, have been taken from the construction documents. Exterior environmental conditions of Gambier, Ohio were approximated by using the conditions of Columbus, Ohio which is located 55 miles southwest. The weather conditions considered in the load calculation were the 0.4% cooling conditions which can be found in Table 2.

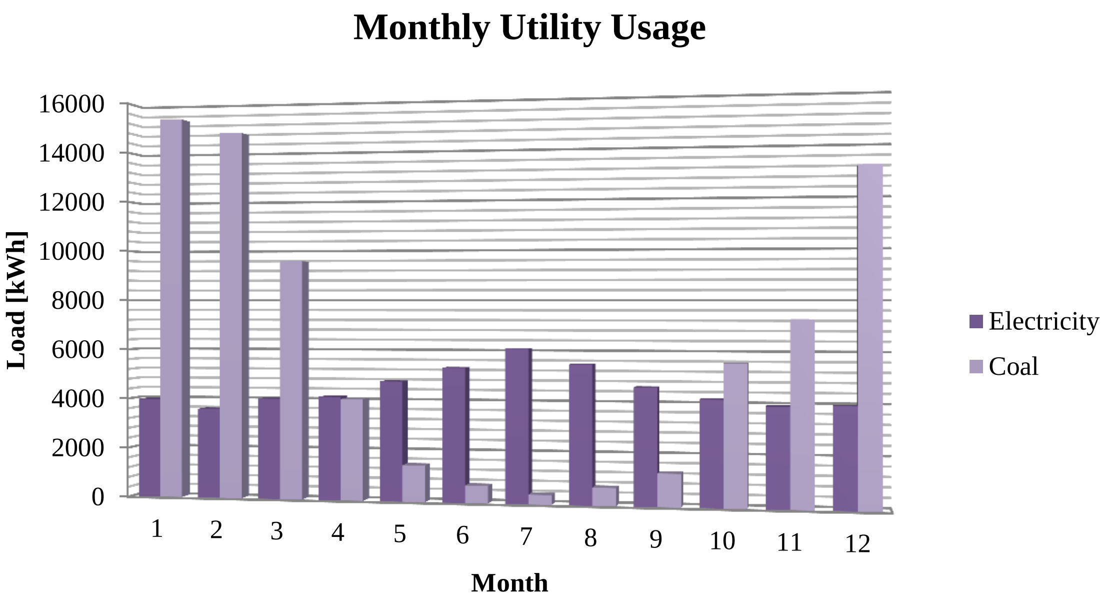
Heating DB	Cooling DB/MCWB		Evaporation WB/MCDB		Dehumidification DP/HR/MCDB		
99.6%	0.4%		0.4%		0.4%		
3.2	91.1	73.8	76.7	86.8	73.6	129.0	81.2

Table 2: Columbus, Ohio Yearly Weather Data

The Peirce Hall mechanical system is composed of 7 air handling units, 1 major fan coil unit and a collection of unit and cabinet unit heaters. Systems were assigned to the same zones as in design documents. However, some zones may have been served by one unit in the original system design and gotten changed at a later point in the design process. Therefore there are some inconsistencies between the design model and analysis model that resulted in larger and smaller supply requirements between the systems. These results can be found in Technical Report II, Table A.2.

Due to the multi-use functionality of Peirce Hall, many spaces required their own occupancy and air flow specification for internal loads to be calculated to reasonable accuracy. Spaces were more individually designed to analyze zone characteristics. A 250 occupant dining hall may have been adjacent to a kitchen, servery, and lobby. The block cooling load was approximated to within 10% of the design model and the heating load within 3.5%.

Information on utilities was not available until a point in time after Technical Report II was written. Therefore instead of actual utility rates, a utility rate template provided in the Trane Trace data base was used. These template cost values greatly underestimated the actual price of utilities that were later provided by the Peirce Hall facility management. With that said the general trend of increases and decreases in seasonal costs proved consistent with analyses performed in later studies. These seasonal cost trends can be observed in Graph 1, where electricity demand is compared to heating energy demand (assumed to be supplied from a campus steam plant with coal fired boilers). Actual energy usage and cost values for Peirce Hall can be found in the combined heat and power depth study of this report.



Graph 1: Technical Report II Monthly Utility Usage

3.2.3 Technical Report III: Mechanical Systems Existing Condition Evaluation

Technical Report III describes detailed features of the new mechanical systems installed in Peirce Hall. A breakdown of design requirements, external influences on the design, major hardware components, system configuration, control logic, operation characteristics, and environmental effects are provided.

As a part of Kenyon College, the mechanical systems of Peirce Hall did not have many restrictions other than local and international codes. The new system designs, by Syska Hennessy Group, Inc. were driven by the intention to create an efficient, economical, reliable, flexible, and maintainable system. As a part of the Kenyon College campus, Peirce Hall had and still has very few obstructions in the near vicinity to create restrictions on an exterior component. Nevertheless a number of codes and guidelines were followed and considered in the design process. Some highly influential codes included the Ohio Administrative Code, International Building Code 2000 Edition, International Mechanical Code 2000 Edition, ASHRAE Standard 90.1, 2001, and International Fire Code 2000 Edition. Incentives and rebates were not considered, leading most of the design decisions to be based on local yearly weather conditions, existing conditions, and the desires of the owner.

The new HVAC system had to be capable of serving the 33,000 SF additions as well as the 33,000 SF of renovated space. Major systems in the building include the variable primary flow chilled water system, steam system and hot water systems driven by a steam to hot water converter, and the seven air handling unit and fan coil unit ventilation systems. Systems are controlled by a Building Automation System (BAS) and Direct Digital Control (DDC) System.

Environmental effects were measured with a comparison to the LEED 2009 for New Construction and Major Renovations certification checklist. The current systems in Peirce Hall satisfy 27 of the 80 points available in the checklist, not enough to be considered LEED certified.

This could however be remedied with making the facility comply with ASHRAE Standards 62.1 and 90.1.

The control system for the heating, cooling, and ventilation systems is the strongest part of the design. By means of a BACnet building automation system (BAS), facility managers can monitor and control, via a direct digital control (DDC) system, every feature necessary such as differential pressures and valve positions. This makes way for extremely efficient scheduling and operation of the building systems.

Mechanical rooms have been well placed in the facility, allowing for the most practical distribution schemes. Space was used well such as the utilization of the attics for mechanical space and good plenum design. Even though the facility had no centralized chilled water plant prior to the renovation, one was created with successfully. In order to fit the necessary chiller into the designed mechanical room, a scroll type modular chiller with five, three foot wide sections was selected to provide a 241 ton capacity. Maintenance of the systems is reasonably simple, with all access door requirements of ASHRAE Standard 62.1 satisfied and well-designed mechanical room layouts. The condenser water system uses a 720 GPM, cross flow type cooling tower with variable speed fan, located on the South roof of the second floor. Details of these components can be found in Table 3 and Table 4.

Chiller	Total Capacity [tons]	Primary kW/Ton	EER	Evaporator		
				GPM	EWT [F]	LWT [F]
CH-1	241	0.69	17.39	340	60	43

Table 3: Chiller Design Conditions

Cooling Tower	Motor BHP	GPM	EWT [F]	LWT [F]
CT-1	20	720	85	95

Table 4: Cooling Tower Design Conditions

Kenyon College uses centralized steam production and distributes it through the campus. The connection to this steam supply that was used in the previous Peirce Hall mechanical system is utilized in the new design and currently supplies medium pressure (26 PSI) steam. Steam is directly supplied to air handler coils, unit heaters, dishwashers in kitchens, and a steam to hot water converter with general characteristics in Table 5. This converter that was previously installed in Peirce Hall was consolidated and upgraded in the renovation process. Hot water is supplied at 190°F to scattered unit and cabinet unit heaters, convectors, and a radiant floor system.

Steam-to-Hot Water Converter	Shell Side		Tube Side		
	Pressure [PSI]	Min. Cap. [LBS/HR]	GPM [F]	EWT [F]	LWT [F]
HX-1	15	1,071	68.3	160	190

Table 5: Steam to Hot Water Converter Design Conditions

In order to determine whether these system components performed to at a desired level of efficiency, some form of standard was required. The LEED rating system, provided by the USGBC was provided for this purpose. The LEED standard applicable to Peirce Hall is LEED

2009 for New Construction and Major Renovations. After demolishing a portion the original Peirce Hall, the floor area of the addition doubled the square footage of the facility. Since this LEED building category focuses on new construction and projects that involve new equipment and the Peirce Hall renovation, addition, and expansion project included almost complete replacement of the existing building systems, it was determined that this project fell under the "Major Renovation" category. However for the LEED 2009 for New Construction and Major Renovations certification to be applied, the facility must first successfully satisfy the minimum performance qualifications of the LEED 2009 Minimum Program Requirements. An overview of these review of these prerequisites are shown in Table 6 and a summary of points acquired by section of LEED 2009 for New Construction and Major Renovations are shown in Table 7. Detailed analyses of where points were gained and lost can be found in Technical Report III.

Requirement	Status
Must comply with environmental laws.	☑
Must be a complete, permanent building or space.	☑
Must use a reasonable site boundary.	☑
Must comply with minimum floor area requirements.	☑
Must comply with occupancy rates.	☑
Must allow USGBC access to whole building energy and water usage data.	*
Must comply with a minimum building area to site ratio.	☑

* This will be assumed for this study since data could easily be assembled via the BAS monitoring system

Table 6: LEED 2009 Minimum Program Requirement Assessment

Section	Points Acquired
Sustainable Sites	9/29
Water Efficiency	4/10
Energy and Atmosphere	5/35
Materials and Resources	2/14
Indoor Environmental Quality	6/15
Innovation Design	1/6
Regional Priority	0/4
Total	27/80

Table 7: LEED Qualification Checklist Summary

The Energy and Atmosphere section pertains mostly to the facility's mechanical system performance. The studies performed in Technical Report 1 shows that the Peirce Hall mechanical system does not totally comply with each area of 90.1. This dissatisfies the minimum energy performance prerequisite making the optimization of energy performance credits irrelevant. An additional 13 points are required to achieve LEED certification and this area seems to hold the greatest potential for gain.

4.0 Combined Heat and Power Study (Mechanical Depth)

The combined heat and power (CHP) system is a design strategy that involves coupling power generating components with heat recovery components to produce power and heat simultaneously, by making use of energy that would have otherwise been wasted. This section explains and describes the basic concepts behind the workings of CHP systems and the application if this design concept to the Peirce Hall dining facility of Kenyon College.

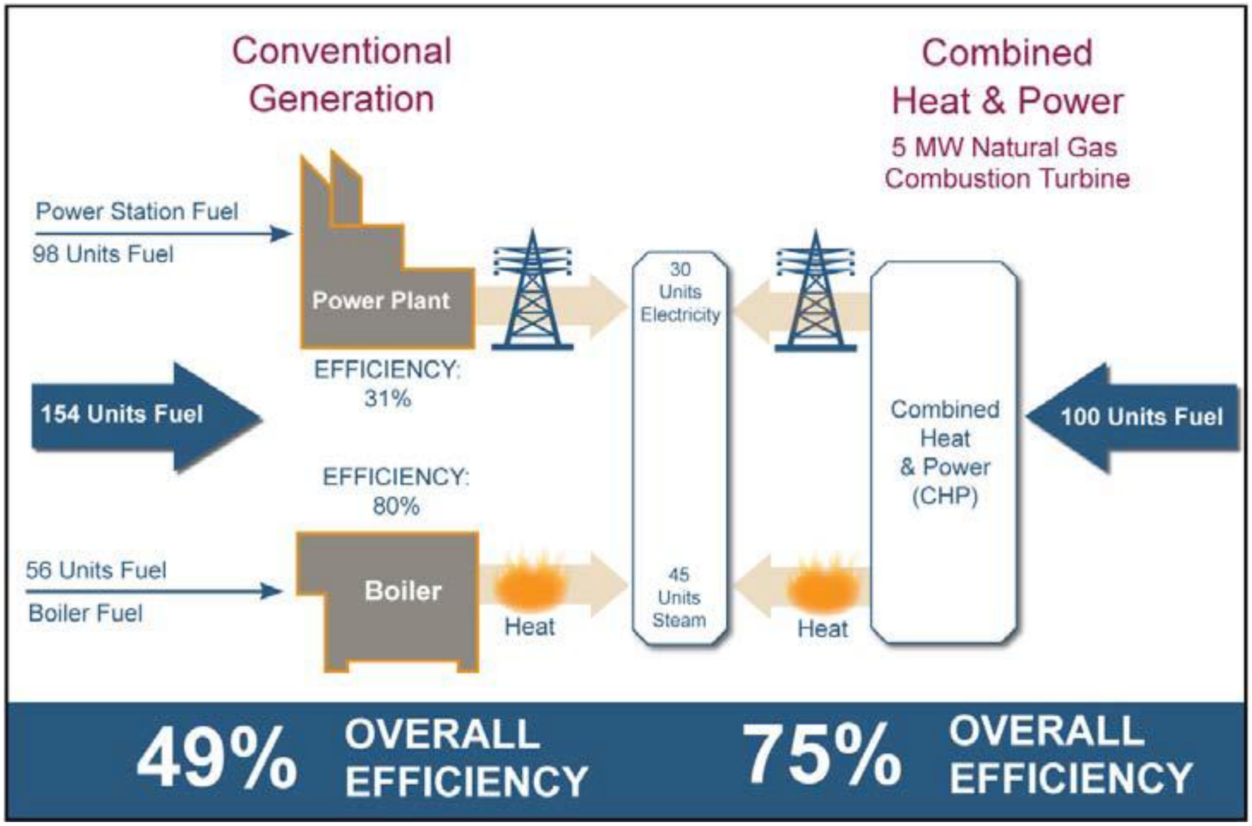
4.1 Basic CHP Concepts

4.1.1 Introduction

The concept of combined heat and power is not new technology, as it has been around for over 100 years. It is used in the United States to reduce annual fuel consumption and carbon dioxide (CO_2) emissions by more than 1.9 Quadrillion British thermal units (Btu) and 248 million metric tons of CO_2 respectively. As stated by the DOE, "Already used by many large industrial, commercial, and institutional facilities, CHP is a proven and effective energy resource, deployable in the near term that can help address current and future US energy needs." CHP designs have been effective in reducing CO_2 and greenhouse gas emissions, increased energy efficiency which often leads to lowering utility costs, providing energy in a variety of environments, and "relieving grid congestion and improving energy security." (Shipley, Hampson and Hedman 3)

CHP is a form of distributed generation (DG) which describes the systems on site location. This allows the end user of the system to benefit from decreased transmission energy losses than a buyer of power from a distant power plant, which has to travel through a dense power grid. Heat, delivered through steam for example, suffers much more significant transmission losses over a shorter distribution distance in comparison to power. This closeness of the utility generating system to a beneficiary facility also allows for waste heat, recovered from the generation process, to be made useful. This heat can be used in a multitude of applications, a decision often dependent on the type of facility which the system is applied. Waste heat can be used to heat water for domestic use, power a boiler to produce hot water or steam for facility heating, re-activate desiccant dehumidification components, or even create additional power such as in cogeneration systems. All of this is possible while using the same amount of fuel that previously would have been used only to generate the same amount of electricity. (U.S. Environmental Protection Agency Combined Heat and Power Partnership 1)

A theoretical comparison of the operation of a CHP versus a separate heat and power (SHP) system, provided in a report on CHP technologies by the U.S. Environmental Protection Agency (EPA), is shown in Figure 4. This figure illustrates excess fuel required by a typical SHP system to generate the same amount of useful resources as a CHP system and the increase in overall efficiency of the CHP system.



Note: Assumes national averages for grid electricity and incorporates electricity transmission losses.

Figure 4: CHP versus SHP Production (U.S. Environmental Protection Agency Combined Heat and Power Partnership 2)

4.1.2 System Mechanics

Every system has a collection of components that allow it to function in a unique way. CHP system are composed of four major components, a prime mover (converts thermal energy to work, also known as a heat engine), generator (converts work to useful electrical energy), heat recovery device (transfers heat from one fluid to another), and interconnections. The primary methods of defining CHP systems are first and foremost by the type of prime mover used, but also by the order in which components of the system are connected and function.

The most common prime movers used in CHP systems today include reciprocating engines, turbines, and fuel cells. Each technology has its own set of advantages and disadvantages, differing in qualities such as power generating efficiency, overall efficiency (considers the ratio of useful power and thermal energy created per unit of fuel), compatible operating fuels, part load operating efficiency, and harmful emissions created. A table summarizing common prime mover statistics provided by the EPA, shown in Appendix A Table A-1, does well to outline the differences in features between the prime movers.

Figure 5: Siemens' W501FD Test Facility in Berlin, Germany (Wolfe and Antos 4)

Figure 6: Capstone C30 Microturbine (Capstone Turbine Corporation)

Each type of the prime mover has sub-types which often operate with vast differences in capacity, yields, or fuel inputs. Turbines for example, come in various forms such as gas turbines, steam turbines, and microturbines. Gas and steam turbine capacities can range from 500kW to 250 MW, where microturbine packages can range from 30kW to 250kW. Turbines can function in a few ways. First turbines can work on a simple cycle producing only power from the input fuel. Secondly turbines can be coupled with a heat recovery device and function in a CHP system. Lastly turbines can operate in a combined cycle configuration where the back pressure cause by steam production causes the turbine to spin, generating electricity hence, the name steam turbine. The microturbine runs in an operation scheme of the second type, but on a much smaller scale. The Siemens' W501G gas turbine, shown in figure 5, is capable of producing 300 MW of power under optimal conditions. This is an exceptionally large capacity, mostly due to the testing environment, but the difference in the scale of this turbine versus the 76" x 30" x 60" Capstone C30, 30kW microturbine in figure 6 is clear.

Reciprocating engines used in CHP applications come in two common forms, the spark ignition (SI) and compression ignition (CI) engines. The difference between the two types are the fuels used in the combustion process and the combustion process itself. Both processes involve the use of controlled combustion series' to spin a shaft; however the ignition process differs with the fuel difference. SI engines, the same type of engine in most compact cars, use large sparks to ignite a compressed fuel-air mixture. CI, or diesel engines, use the heat created by compressing the air in the engine to ignite the fuel, rather than using a spark. Reciprocating engines have been found useful for situation that only need domestic hot water or low pressure steam and have good part load efficiency characteristics.

The final CHP prime mover to be described is the fuel cell. Fuel cells operate on a variety of fuels such as natural gas, methanol, and other hydrocarbon fuels, in a fashion that has potential to be extremely clean and efficient. A fuel cell uses electrochemical process that derives useful energy from the reaction that takes place when hydrogen and oxygen react to form water and release energy. This process requires a catalyst which is one factor that makes these units so expensive. The five catalysts currently in use and development are phosphoric acid (PAFC), proton exchange membrane (PEMFC), molten carbonate (MCFC), solid oxide (SPFC), and alkaline (AFC). The only two types that are currently available for use in CHP systems are the PAFC and MCFC, the first in 200kW and 400 kW modules and the second in 300kW and

1200kW modules. These units are generally used in applications where small heat loads are required.

*Information in the section was found in the U.S. Environmental Protection Agency Combined Heat and Power Partnership *Catalof of CHP Technologies* document.

4.2 Preliminary Design Considerations

During the initial design phase, when a CHP system is being considered, there are two main conditions that must be researched – the system load profiles of the considered facility and the utility spark gap. It is well known that mechanical equipment operates more efficiently when operating at a near constant condition. This is especially true for prime mover operation in CHP applications, because two utilities are being generated simultaneously and designing for large fluctuations in both becomes problematic. Prime movers are specified with a certain maximum capacity power output and a rate at which useful heat can be produced per kW of power generated. The operation of the prime mover can be defined by the facility thermal demand, power demand, or a combination of both. The decided control scheme will determine which utility will either need a supplementary source or need to be sold or wasted during load conditions that stray from the anticipated heat to power demand ratio. Peirce Hall, as a student dining facility, naturally sees great fluctuations in hourly occupancy, which could be a deterrent from using a CHP system. If the selected prime mover has poor part load operating efficiency, a CHP system will most likely not be a beneficial choice.

The spark gap or spark spread in CHP applications is defined by the EPA as “the difference between the cost of fuel for the CHP system to produce power and heat on site and the offset cost of purchased grid power.” This is an important factor to consider when researching the potential cost savings of using a CHP system, because by using CHP, one effectively replaces the cost of grid supplied power with a fraction of the cost of the supplied fuel. A desirable spark gap indicative of potential cost savings from a CHP system is greater than $15 per one million Btu. (Environmental Protection Agency Combined Heat and Power Partnership) The spark gap for utilities of the Peirce Hall facility is equal to $26 based on the average annual natural gas cost and the calculated utility cost per million Btu. Utility cost analyses will be explored more in depth in section 4.3.6.

4.3 Method of Study

4.3.1 Study Overview

The study performed to assess the feasibility and effectiveness of using a CHP system to provide Peirce Hall with power and heat involved an hourly analysis of the performance of a set of prime movers over a year’s duration. Basic load calculation equations were used to calculate hourly building loads in relationship to typical meteorological year (TMY) weather data provided by the U.S. National Renewable Energy Laboratory. Energy requirements of the facility were derived from typical occupancy schedules of restaurant and offices and provided energy requirements. The capability of the selected prime movers to satisfy these loads under thermal load following and electric load following scenarios were then analyzed. The following sections describe the studies performed and the development of the design model that was created in Microsoft Excel.

4.3.2 Existing Facility Energy Use

The Peirce Hall renovation, addition, and expansion project was constructed from 2006-2008. Since the initial start-up of the mechanical systems, detailed energy use of the systems has not been kept. However, some basic information was made available pertaining to the facilities annual energy use, shown in Table 8. Energy loads are represented in millions of Btu (MBtu). There may have been a miscommunication in the initial inquisition period, when it was thought that the natural gas supply characteristics were average monthly rates rather than the annual use.

This issue was resolved by conducting a capacity factor analysis to determine what fraction of the facility's heating capacity was being used in both cases. With the brief calculation shown in Table 9, it is clear that the provided natural gas volume must be an annual value. For if the provided natural gas use value were a monthly rate, the facility usage would be over three times its capability. Natural gas was considered to have a heat content of 1,030 Btu per cubic foot, as defined by the Encyclopedia of Earth. (Cleveland) Since these values represent the total energy necessary to satisfy the building loads rather than the load on the mechanical system, these values were used directly to calculate necessary outputs of the prime mover(s). Thus, efficiencies of the existing system components, such as the steam to hot water converter, were largely neglected.

Average Monthly Electricity Demand Characteristics			
Power [kW]	56.4		
Energy [kWh]	349,626	MBtu Equivalent:	1,193
Cost [$]	21,482		
Average Monthly Cooling Demand Characteristics			
Load [ton]	144	Btu/h Equivalent:	1,728,000
Chiller COP	5.1		
Input Power [Btu/h]	338,824		
Input Energy [MBtu]	247		
Annual Natural Gas Demand Characteristics			
Volume [mcf]	9,568	MBtu Equivalent:	9,865
Cost [$]	96,084		

Table 8: Facility Energy Consumption Rates

Capacity Factor Calculation		
Assumed Time Frame	Annual	Monthly
Approximate Peirce Hall Combined System Capacity [MBtu/h]	4.274	
Annual Capacity [Mbtu]	37,440	
Annual Demand [Mbtu]	9,865	118,380
Capacity Factor	26%	316%

Table 9: Annual versus Monthly Heating Capacity Factor Comparison

Before any other value was taken to be accurate, each was checked for proportionate value and relation to typical facility energy use of similar occupancies. Table 10 shows the distribution of energy to each of the systems in Peirce Hall. The power system is broken down into two sections, displaying the energy used by the electrically driven scroll type chiller in the cooling category and all other sources such as lighting and plug loads are referred to as the constant load. The percentages calculated in the energy model conducted in Technical Report II do not match the values provided by Kenyon College, however the order of significance remains consistent. The power system still has the greatest demand and the cooling demand is the least. The heating energy demand remains smaller than the constant load, but still much larger than the cooling load. These results seem plausible, relative to the climate and use of the facility.

Overall Annual Energy Distribution			
Source	Load [MBtu]	Percentage	As Modeled
Heating	9,865	41%	20%
Power	14,315	59%	80%
Constant	11,348	47%	73%
Cooling	2,968	12%	7%

Table 10: Overall Energy Distribution Over Major Building Systems

The last check to ensure the data received was usable and relevant was to compare the total energy used by the facility per square foot, also known as the building energy utilization index (EUI), to the typical EUI of facilities with similar occupancy characteristics. The EUI is measured in thousands of Btu per square foot of the facility's conditioned floor space per year. Considering the sum of the heating and power loads shown in Table 10 as the total building energy use and dividing it by Peirce Hall's 66,640 square feet of conditioned floor space, the EUI computes to 363 thousand Btu per square foot per year. This is 77% greater than the recommended 205 thousand Btu per square foot per year for food service facilities, by the U.S. Energy Information Administration (EIA). (Capehart, Turner and Kennedy) Although this may seem like a large difference, the values are of the same order of magnitude and the value presented by the EIA is a comparative range.

4.3.3 Modeling of Energy Demands

The energy demands described in the previous section validated and summarized annual energy use of Peirce Hall. In order to apply the characteristics of a prime mover to supply these demands, the demands must be broken down into hourly values. The hourly energy demanded by the "constant" portion of the facility's power system was derived first.

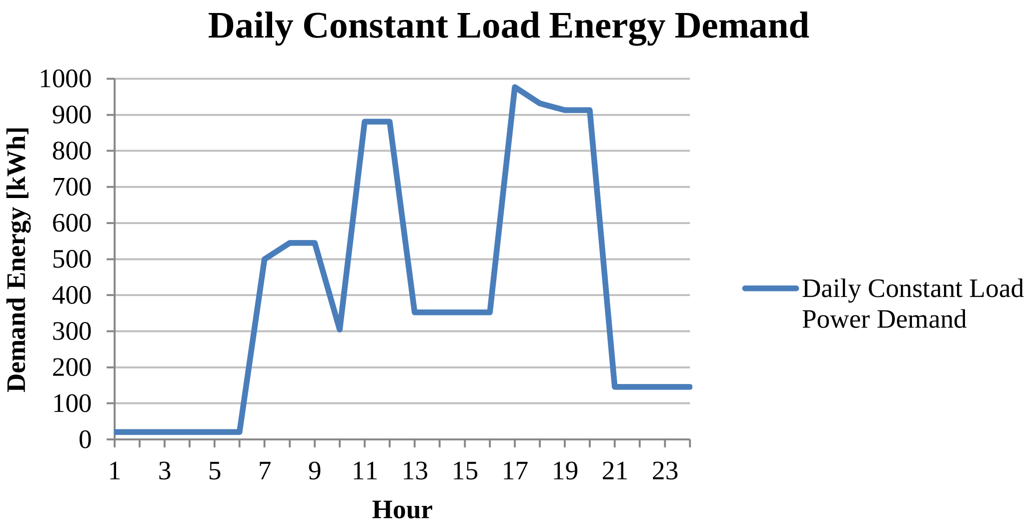
To derive the hourly value of energy demanded by the constant portion of the power system of Peirce Hall as accurately as possible, the demand value was considered to be a factor of the hourly occupancy. Peirce Hall was considered to contain two occupancy types, dining and office space. Table 11 shows area composition of the total facility's floor space. Therefore, typical weekly population schedules for restaurant and office facilities were referred to from the Trane Trace program. The restaurant template was used for the dining space, however was modified to account for Peirce Hall dining hours that were defined on the facility website and dining hall higher occupancy rates on weekends. Peirce Hall is the only dining hall on the

Kenyon College campus so it was assumed that occupancies would reach high capacity percentages. A 2% load was considered to be constant for emergency and standby lighting. The typical week's hourly demand, in terms of percent of the maximum demand load, is shown in Appendix B Table B-1. The combined demand load fraction was determined by weighting the weekly occupancy templates in terms of the area of the facility that the particular occupancy covered.

Percent of Floor Area per Occupancy Type	
Dining	93.7%
Office	6.3%

Table 11: Floor Area Composition of Peirce Hall by Occupancy

The hourly demand fractions for the year were then used to derive the maximum demand load. By entering incremental base load values into an equation that multiplied that load by the demand fraction for each hour, and then summed those energy values, the modeled annual sum could be compared to the actual annual energy demand. The resulting difference between the modeled and actual annual energy requirement was much less than 1% with a maximum demand load of 1024 kWh. The typical weekday schedule is shown in Graph 2.



Graph 2: Daily Constant Load Energy Demand

The hourly cooling and heating demand energy were derived from a combination of known energy requirements and simple load calculations. The load calculation equations used are a variation of the following equation: (Capehart, Turner and Kennedy)

$$HL = \frac{(UA)_b (T_b - T_{amb})}{\eta}$$

(Eq-1)

In this equation, HL refers to the heating load which is calculated by multiplying the constant $(UA)_b$ by the difference between a temperature T_b, below which heating is considered necessary (65°F as recommended), and the ambient temperature, all divided by the operating efficiency of the heat source. The constant $(UA)_b$ is the ratio of energy created by the intended heating process and degree days of the facility's location. However as previously stated, the known annual heating value is the heating energy required to satisfy the demand load. Hence the $(UA)_b$ and efficiency factors have been replaced with the constant C_h as shown below, where HL represents the annual heating energy and $\Sigma(T_b - T_{amb})$ represents the annual temperature deviation from 65°F.

$$C_h = \frac{HL}{\sum(T_b - T_{amb})} \qquad \text{(Eq-2)}$$

The resulting equation below can then be used to calculate the energy required for heating at a specific hour when the ambient temperature drops below 65°F.

$$HL = C_h(T_b - T_{amb}) \qquad \text{(Eq-3)}$$

A similar equation is used for cooling demand energy. However in the case of cooling, the annual cooling demand energy replaces HL in the Eq-2, T_{amb} is subtracted from T_b, and the equivalent Eq-3 is conditional applied to hours when the ambient temperature is above 65°F. Details on the calculations pertaining to the heating and cooling load calculation model load constants (C_h and C_c) can be found in Appendix B Table B-2.

All of the load calculations explained to this point are displayed in Appendix B Tables B-3 through 6 under the "Demand Loads" columns.

4.3.4 Prime Mover Selection

In selecting a prime mover for the Peirce Hall CHP system, specific design criteria had to be met. The campus steam plant is currently supplied natural gas to fuel the steam boilers. It was assumed that this fuel source could additionally feed a natural gas fueled prime mover. The traditional design strategy of CHP systems begins with satisfying the heating load and purchasing power from to satisfy the required energy demand of the power systems. However one priority of CHP system was to make Peirce Hall as independent as possible from outside energy sources. The providing power company, Ohio Power Company, a branch of the American Electric Power Company, uses coal to fuel their power plant. By switching to a natural gas fueled power source, a significant amount of CO_2 emissions can be prevented. In addition, due the presence of such a large spark gap, a more electric load following system

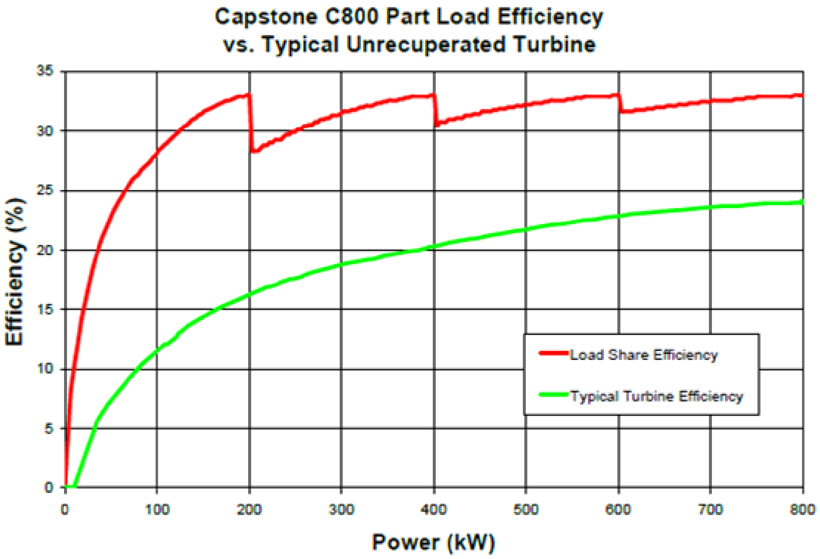
Figure 7: Capstone C800 Power Package
(Capstone Turbine Corporation)

approach was taken.

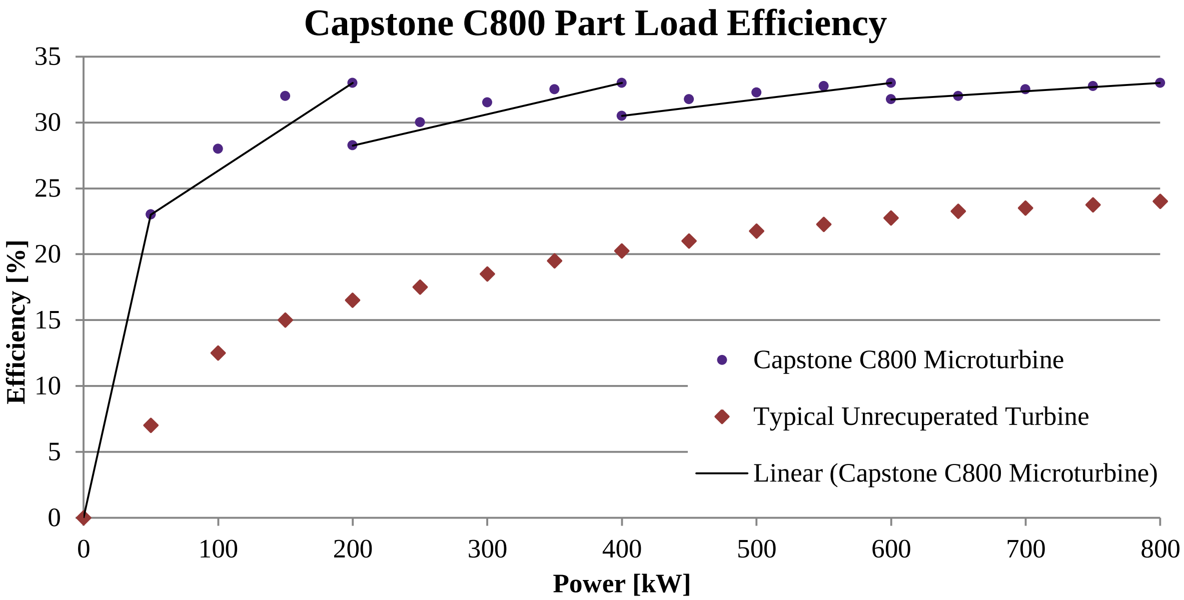
The selected prime mover was the Capstone C800 800 kW Power Package high-pressure natural gas microturbine. The C800 Power Package combines 4 of the Capstone C200 200kW Power Packages in a modular form with excellent part load operation efficiency. Capstone also produces module packages with capacities of 400kW, 600kW and 1MW, each with a different number of C200 units contained in the housing the housing shown in Figure 7. Each package has future modification capacities of up to a 1MW capacity unit. This is thought to be ideal for Peirce Hall as it has shown a history of expansion and addition projects.

Three of these C800 power packages were modeled in parallel connection to serve Peirce Hall's calculated maximum power demand of 1950 kW. These three units provided an 18% safety factor and due to the modular nature of the units. Part load electric efficiency of the C800 unit, as provided in the Capstone product specification sheet is shown in Graph 3 peaking at 33%. Graph 4 shows the linear simplified data as used in the Microsoft Excel model. These graphs display the advantageous part load performance characteristics of microturbine systems. Excellent part load efficiencies are required by a system to be used in Peirce Hall, due to the highly fluctuating demand loads as seen in Graph 2 from the previous section.

Heat recovery rates of the C800 are not directly stated, since to apply the unit to a CHP system an additional internal heat recovery device must be installed. This heat recovery device is provided by Capstone Turbine Corporation as stated in the Revico Wastewater Treatment Plant case study. (Capstone Turbine Corportation) The heat recovery efficiency was assumed to be 80% of the exhaust energy as, specified for the Capstone C65 in its product specification sheet. Therefore, the heat recovery rate was assumed to be approximately 5,400 Btu/h per kW of energy produced and overall peak efficiency of the package to be 85%. Additional assets of the Capstone C800 are its very fast startup time, and low noise emissions.



Graph 3: Capstone C800 Part Load Efficiency versus Typical Unrecuperated Turbine



Graph 4: Modeled Capstone C800 Part Load Efficiency versus Typical Unrecuperated Turbine

*Specification sheets for Capstone microturbine C65 and C800 models available in Appendix C.

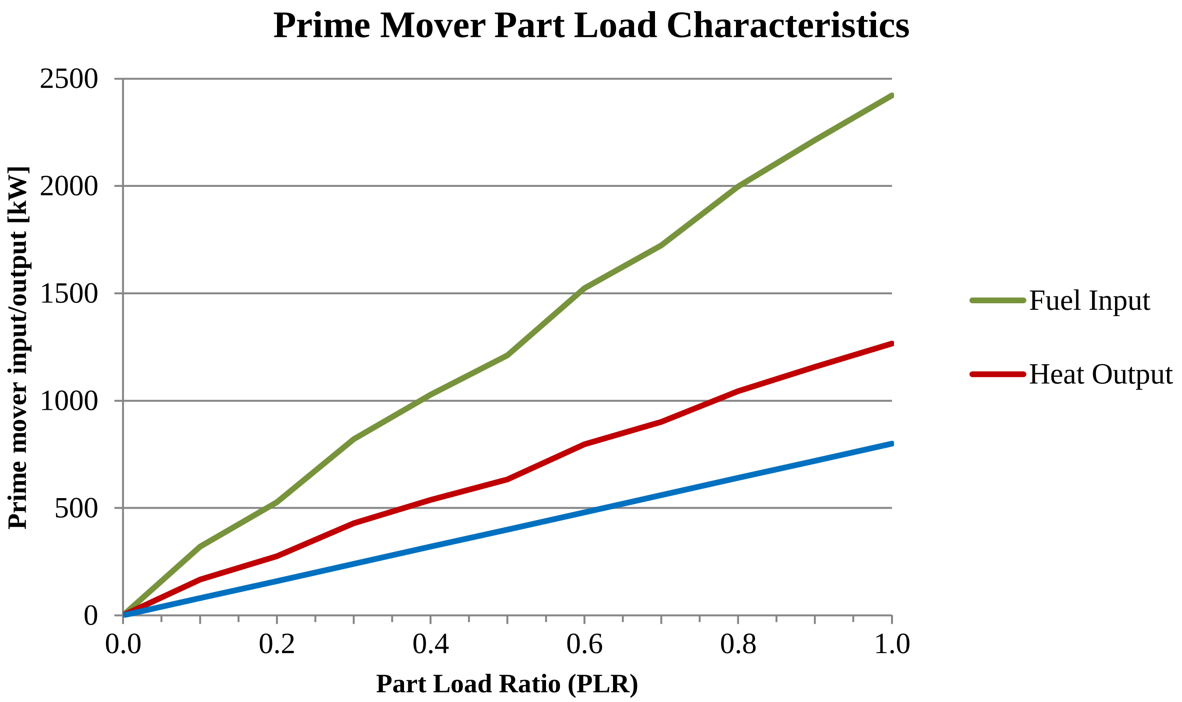
4.3.5 Modeling CHP System Performance

The designed CHP system was modeled in Microsoft Excel to calculate outputs of the three Capstone C800 microturbine packages. To simplify modeling, the packages were designed to run in sequence without any over lapping, i.e. when the demand load reached a greater value than the maximum capacity of the currently operating package(s) the next package would startup. The partial operating efficiency of the prime mover at varying loads is shown in Graph 4, however Graph 5 shows the relation of input to output power. From the observation that the part load ratio characteristics are very close to linear, the conclusion was to treat them as such in the model. The resulting simplified prime mover characteristics are shown in Graph 6.

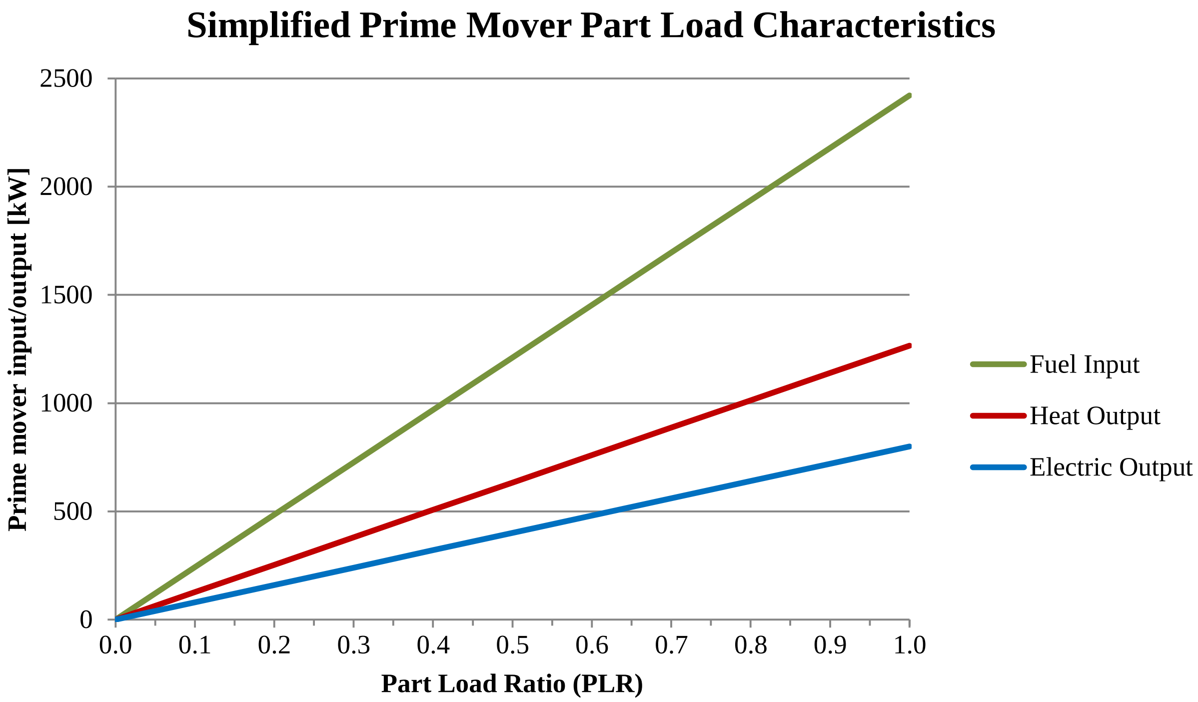
The results of the modeling study are shown in Appendix Tables B-4 through B-7. These tables show system operation on two days of the year under the two operating scenarios tested. One operation scenario satisfies all electric demand loads. In the electric load following scenario the thermal output of the leading operating package was determined by the following equation: (where Q_{CHP} represents the thermal output, Q_{max} is the maximum thermal output of the prime mover, and PLR represents the part load ratio)

$$Q_{CHP} = Q_{max} \cdot PLR \tag{Eq-4}$$

The part load ratio in the electric load following case is equal to P_{CHP}/P_{max}, where is P_{CHP} is the hourly electrical output of the prime mover and P_{max} is the maximum electrical output of the prime mover. Q_{CHP} can also be replaced with F_{CHP} (the fuel used by the system) and Q_{max} with



Graph 5: Prime Mover Part Load Characteristics



Graph 6: Simplified Prime Mover Part Load Characteristics

F_{max} (the maximum fuel input) to calculate the fuel use of the leading package. If more than one prime mover is active, the result from Eq-4 is added to the value obtained by multiplying the number of active packages by the maximum heat production capacity or fuel input depending on what quantity desired.

The second operation scenario tested with the Capstone C800 microturbine packages satisfied all thermal load demands. In this scenario a similar concept to Eq-4 was applied however, the heat input was considered the independent variable. The PLR was defined by Q_{CHP}/Q_{max} and multiplied by either P_{max} or F_{max} to calculate the power produced or fuel input.

Other quantities were calculated in this study from the values found with the above method in order to observe the distribution of energy to the demanding systems and where demanded energy was coming from. From this, it was found that there were times when the CHP system generated more of a utility than needed and times when not enough of a utility were generated. When additional steam was required in the electric load following scenario, the campus steam system was assumed to be available and connected to the facility in parallel. When additional electricity was required in the thermal load following scenario, a parallel connection to the current grid supplier was assumed to make power available. A summary of the findings from this study can be found in Appendix B Tables B-8 through B-10.

4.3.6 Utility Cost Analysis

The financial assessment of this study was based purely on utility costs. As such, detailed information on gas pricing and electrical costs was necessary. The natural gas provider of the Peirce Hall facility was unknown; therefore the average monthly costs of natural gas per thousand cubic feet in Ohio were used. The natural gas rates from 2009 were used, found in the Natural Gas Monthly January 2011 Report, provided by the EIA. (U.S. Energy Information Administration) These rates can be found in Appendix C Table C-1. To calculate the total annual cost of gas, the monthly sums of gas used by the CHP system as well as gas used by the campus steam system to produce the supplementary steam used by Peirce Hall, were multiplied by the average monthly costs.

The power currently provided to Peirce Hall if from the Ohio Power Company, a branch of the American Electric Power Company (AEP). Since the factors that determine the cost of energy provided by AEP are numerous, a monthly cost estimator which can be found on the AEP website was used to calculate monthly energy costs. This estimator took into account factors such as total monthly kWh usage, maximum kWh and peak kW demands from which ratchet charges were based, and applied distribution, generation, and other various company standard charges. The cost estimator used applied rates that applied to the current contract type used by Peirce Hall. However, the resulting average monthly bill came to be quite a bit larger than the price provided by Kenyon College. The value calculated by the estimator was the value considered so that it could be properly compared to the thermal load following scenario energy price.

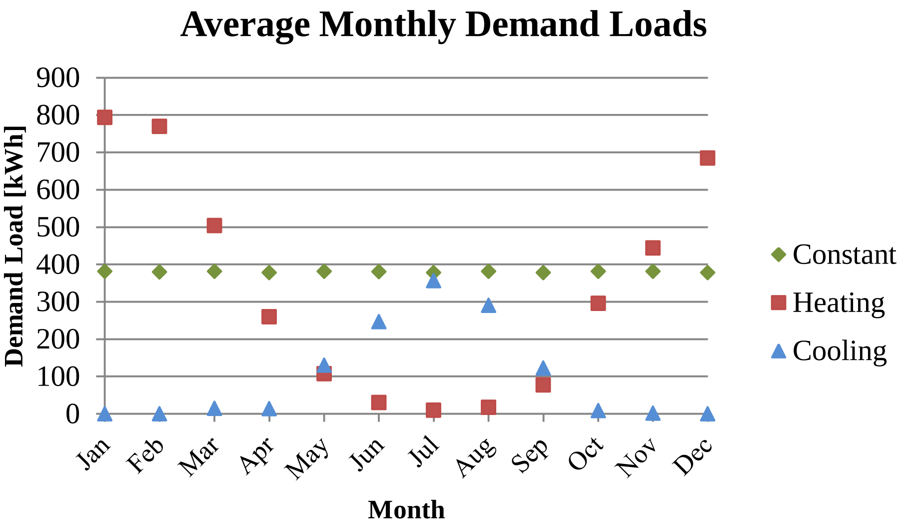
A summary of the costs for utilities and the spark gap calculation can be found in Appendix B Table B-7 through B-10.

4.4 Discussion of Study Results

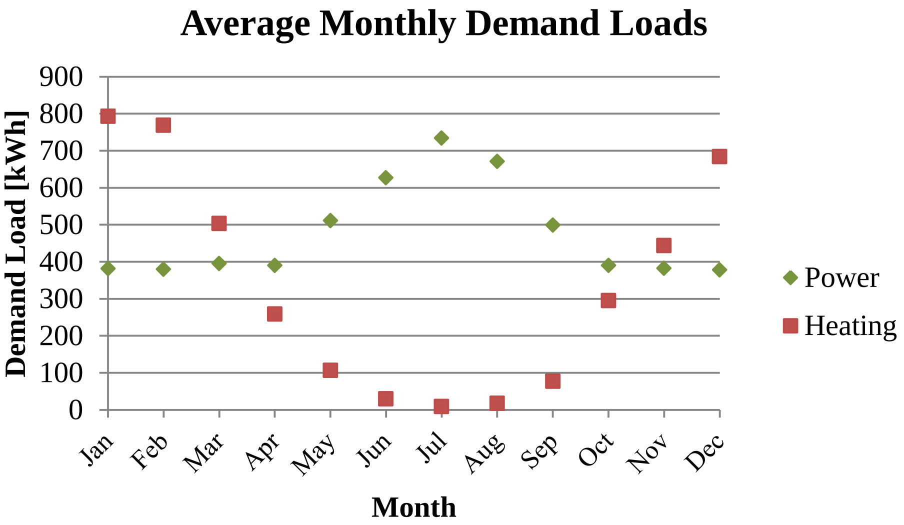
The purpose of designing the previously discussed combined heat and power plant for the Peirce Hall dining facility at Kenyon College was to assess the feasibility and effectiveness of using such a system. To accomplish this, a Microsoft Excel model was created to represent the hourly operation of three Capstone C800 800 kW Power Package microturbine prime movers over the course of one year. With this model, both energy and cost analyses were able to be conducted.

4.4.1 Energy Analysis Results

The energy analysis conducted in this study shows the high effectiveness of the electric load following control scenario and the ineffectiveness of the thermal load following control scenario. One clear indication of this is the thermal load following system's inability to provide any of the energy demanded by the cooling system during summer operation. This is countered by the thermal energy wasted by the electric load following system which could have otherwise been recovered during winter operation. However with the prime mover electrical generation efficiency fluctuating around 30%, the performance is still nearly as efficient as the 31% efficiency rating of power plants. (U.S. Environmental Protection Agency Combined Heat and Power Partnership) Graphs 7 shows the large fluctuation in monthly heating and cooling demand where Graph 8 summarizes the system demand load profiles. The area that is not shared under each curve in Graph 8 is energy that is essentially lost.

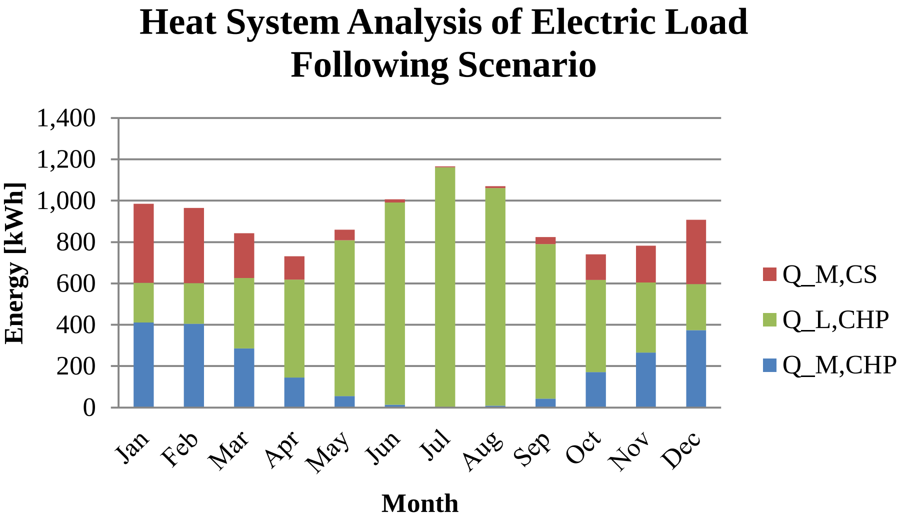


Graph 7: Average Monthly Demand Loads by Sub-System



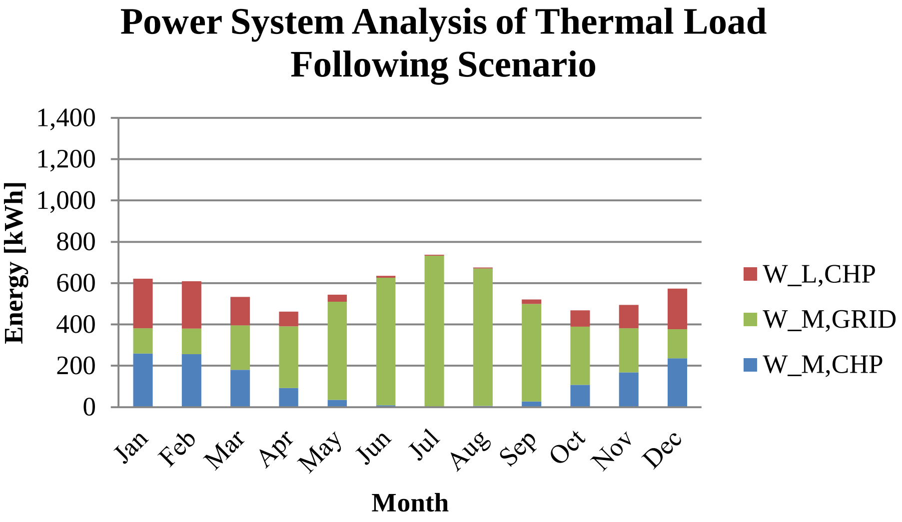
Graph 8: Average Monthly Demand Load by System

Graph 9 shows the energy distribution patterns of the heating system in the electric load following scenario. This graph shows a clear resemblance of the energy demand load profile shown in Graph 8, as the rate at which heat and power are produced by the prime mover (the heat to power ratio) is a constant value. The green area of the graph is heat energy that is being lost and is quite significant however can be used with additional system modifications. This option will be further discussed in section 4.5.



Graph 9: Heat System Analysis of Electric Load Following Scenario

Graph 10 is a similar comparison, showing the energy distribution patterns of the power generated by the prime mover, in the thermal load following scenario. The unusable energy (in red) is not very significant compared to the unusable energy in Graph 9 (in green). The important factor to consider here is that the energy represented by green in Graph 10 is purchased energy, adding a more significant quantity to the annual utility cost than additional natural gas for steam from the campus supply.



Graph 10: Power System Analysis of Thermal Load Following Scenario

4.4.2 Utility Cost Analysis

A critical factor in defining the feasibility of the discussed CHP system is the annual utility cost for operation. Table 12 was developed with the costs derived from the previous study for annual utility costs of natural gas (fuel) and power. This cost comparison shows that the electric load following CHP system truly takes advantage of the spark gap and avoids cost increasing factors like the ratchet charges of the power distributer. The electric load following CHP system decreases the annual utility cost 9% for a total savings of approximately $48,000. Due to this significant decrease in annual utility cost, this study has determined that Peirce Hall can benefit from a combined heat and power system operated to follow the facilities electric load profile.

Annual Cost Comparison by Operation Scenario						
System	Fuel	Δ from SHP	Power	Δ from SHP	Total	Δ from SHP
SHP	$99,395		$416,570		$515,965	
CHP (Electric)	$468,129	371%	$0	-100%	$468,129	-9%
CHP (Thermal)	$190,066	91%	$378,097	-9%	$568,163	10%

Table 12: Annual Cost Comparison by Operation Scenario

4.4.3 Harmful Gas Emissions Analysis

The greater efficiency of CHP systems over SHP systems can be highly advantageous in terms of lowering the cost of utility, but also in terms of harmful and greenhouse gas emissions. By burning less fuel in a CHP system to do the same work as an SHP system, exhaust gas emissions are greatly reduced. By entering the system data of the electric load following CHP system into a "CHP Emissions Calculator" provided by the DOE, Table 13 was generated. (U.S. Department of Energy Combined Heat and Power Partnership)

Annual Emissions Analysis	CHP System	Displaced Electricity Production	Displaced Thermal Production	Emissions/Fuel Reduction	Percent Reduction
NOx (tons/year)	0.77	9.34	1.29	9.86	93%
SO2 (tons/year)	0.01	28.15	0.01	28.14	100%
CO2 (tons/year)	2,530	3,942	1,500	2,913	54%
Carbon (metric tons/year)	625	975	371	720	54%
Fuel Consumption (MBtu/year)	43,352	38,426	25,714	20,788	32%
Number of Cars Removed				481	

Table 13: Harmful Exhaust Gas Emission Reduction of CHP system

The emission calculator used to generate Table 13 compares the input system to the "anticipated" separate heat and power system. This comparison shows a significant decrease in each gas emission discussed with the prescribed microturbine CHP system, using approximately 43,300 MBtu of natural gas per year. This shows yet another reason enforcing the feasibility of a CHP system benefiting Peirce Hall.

4.5 Room for Improvement

The CHP system designed for Peirce Hall has shown a large potential to benefit the facility. However, there are some areas of the system that could be modified to increase the effectiveness of this design. Now focusing on the electric load following CHP system, the biggest issue preventing the system from certain success is the large waste of recovered heat energy. One remedy for this and a common reason for the use of CHP systems on college campuses is upscale the system and connect it to another building on campus with a somewhat opposite load demand schedule. This effectively switches the destination of the heat to the facility that needs it.

In times when heating is not needed at all, such as summer operation, a common practice is to supply the heat to an absorption chiller. The absorption chiller will then produce cooling energy, thus reducing the wasted heat and electrical demand from the grid. However, this may not be a very cost effective solution for Peirce Hall, as they just installed a new scroll type chiller in the 2006-2008 renovation, addition, and expansion project.

Through creative design modifications, the qualities that may be keeping the current CHP plant design from its full potential can be used to its advantage.

5.0 CHP System Acoustic Study (Breadth No. 1)

5.1 CHP System Acoustic Characteristics

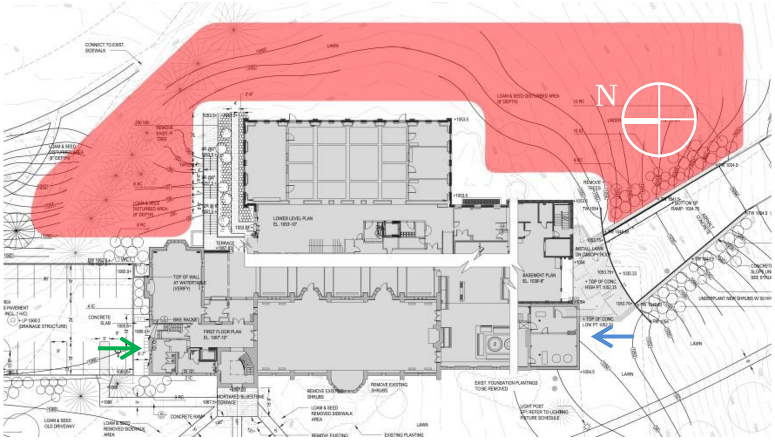


Figure 8: Peirce Hall Surrounding Site

The CHP system specified for Peirce Hall in section 4.0 involved three Capstone C800 800 kW microturbine power packages. As with most power generators, there is a significant potential for a large amount noise emissions. As there is no space in the Peirce Hall facility to fit the large microturbine packages, they much be located outside if they are to be installed. Determining the location and housing of the units has been considered critical in not disturbing the historic campus and the other facility surroundings. The possible locations for these units are shown as the red area in Figure 8. The green arrow represents the steam entrance point and the blue arrow represents the power enetrance to the facility. The ideal position for the microturbines would be as close to the steam entrance as possible due to the more significant transmission energy loss of steam in comparison to electricity.

As shown in the specification sheet for the Capstone C800 units, available in Appendix C, the typical sound pressure level (SPL) at 5 meters (m) from a single unit running at full capacity is 65 A-weighted decibels (dBA). This information is useful in getting a general idea of the unit's characteristics, but information pertaining to the distribution of the SPL over a frequency spectrum is necessary to ensure the prevention of high or low frequency noise disturbances. The goal of this study is to reduce the SPL of the operating units to 50 dBA, the approximate noise of office activity, before it reaches the exterior wall of the facility. (Egan 13)

Detailed sound emission tests have not been taken by Capstone Turbine Corporation for the C800 model; however they did provide the sound emission report of the smaller C30 unit upon request. The test results for a C30 unit, showed an average of 65 dBA at 10m with a peak at 1.6 and 3.15 kilo Hertz (kHz). Performing the calculation shown in Table B-11 using equations Eq-5 through Eq- 7 showed an SPL of the C30 at 5m of 71 dBA. Since the SPL of the C800 at 5m is less than that of the C30, the C30 data was used with the confidence.

$$L = 10\, log \frac{I}{I_0}$$

L = sound intensity level (dB)
I = sound intensity (W/m^2)
I_0 = reverence sound intensity, 10^{-12} (W/m^2)

(Eq-5)

$$I = \frac{W}{4\pi d^2}$$

I = sound intensity (W/m^2)
W = sound power (W)
d = distance from sound source (ft or m)

(Eq-6)

$$\frac{I_1}{I_2} = \left(\frac{d_2}{d_1}\right)^2$$

I = sound intensity (W/m^2)
d = distance from sound source (ft or m)

(Eq-7)

Capstone C30 SPL Calculation		
Distance	10	m
L	65	dBA
I	3.16E-06	W/m^2
W	0.004	W
Distance	5	m
I	1.26E-05	W/m^2
L	71	dBA

Table 14: Calculation of SPL loss of Capstone C30 from 5 to 10 Meters

In the Capstone C30 acoustic tests, SPL measurements of the unit were taken from five angles around a 5m radius from the operating unit. This data is shown in appendix B Table B-11.

5.2 Acoustic Treatment Solution

After analyzing the prime mover acoustic characteristics a way to contain a portion of the emitted noise was needed. Common building materials with high transmission loss performance at 1.6 kHz and 3.15 kHz are high-mass materials. The considered wall construction material was light weight concrete masonry units (CMU). Three variations of the CMU wall were considered, Type A - the standard 8” x 8” x 16” 3-cell block with no enter grout at 28 lbs/block, Type B - with center grout and #5 rebar reinforcement, and Type C - with center grout, #5 rebar reinforcement, and two coats of oil based paint on each side. The sound transmission classes (STC) of the three construction types were 45, 48, and 55 respectively.

For the sake of calculation, the prime movers’ containing structure was considered to be a sealed box and the only sound considered to be directed toward the Peirce Hall facility was that of one wall. The condition under which the calculation was base was one where all prime movers were operating at full capacity and the sound in the structure formed a diffuse field. As such, the following equation (Eq-8) was used to calculate the SPL created by the prime movers at the surface of Peirce Hall’s exterior wall at a specified distance. (Long 355)

$$L_r = \bar{L}_S - \Delta L_{TL} + 10\,log\left(\frac{S_W Q}{16\pi z^2}\right)$$

L_r = sound pressure level at a point in the receiving area (dB)
$\bar{L}_S$= diffuse sound pressure level in the source room (dB)
ΔL_{TL} = transmission loss (dB)
S_W = area of the transmitting surface (ft^2 or m^2)
z = distance from the surface of the source to the receiver (m or ft)
Q = directivity of the wall (usually 2)

(Eq-8)

The dimension of each microturbine package is 8' x 30' x 12'. By assuming a 52' x 46' structure, the units have an approximately 8' between each for maintenance considerations. The roof is assumed to sloped in one direction to direct as much noise away from Peirce Hall as possible and the resulting end wall heights are about 14' and 37'. Locating the prime movers on the North side of the building does not seem plausible as there is limited space and residential areas are very nearby. Therefore location of study will be on the South side of the Peirce Hall, near to the loading dock of the facility. The side wall of the prime mover housing structure will face Peirce Hall, and the intake and exhaust vents of the structure will be located away from the facility as not to direct additional noise toward it. These criteria define the value of S_W and allow for the series of calculations shown below in Table 15 through 17. Appendix B Table B-11 shows the calculation of the average SPL of three Capstone C800 packages at 1m, used for the value of $\bar{L}_S$.

Type A		
$L_{BAR,S}$	87	dBA
ΔL_{TL}	45	dB
S_W	1173	ft^2
Q	2	
z	20	ft
L_R	33	dBA

Table 15: SPL at Peirce Hall Exterior with Construction A

Type B		
$L_{BAR,S}$	87	dBA
ΔL_{TL}	48	dB
S_W	1173	ft^2
Q	2	
z	20	ft
L_R	30	dBA

Table 16: SPL at Peirce Hall Exterior with Construction B

Type C		
$L_{BAR,S}$	87	dBA
ΔL_{TL}	55	dB
S_W	1173	ft^2
Q	2	
z	20	ft
L_R	23	dBA

Table 17: SPL at Peirce Hall Exterior with Construction C

By performing this study, it is clear that locating three Capstone C800 microturbine packages in a CMU structure as close as 20 ft from Peirce Hall will not produce a SPL greater than 50 dBA. Figure 9 shows the selected region (in red) to place the CHP plant with a 20' setback from Peirce Hall. The purple region represents the approximate size of the prime mover housing and the desired orientation with the roof pointing away from the loading dock shown to the West.

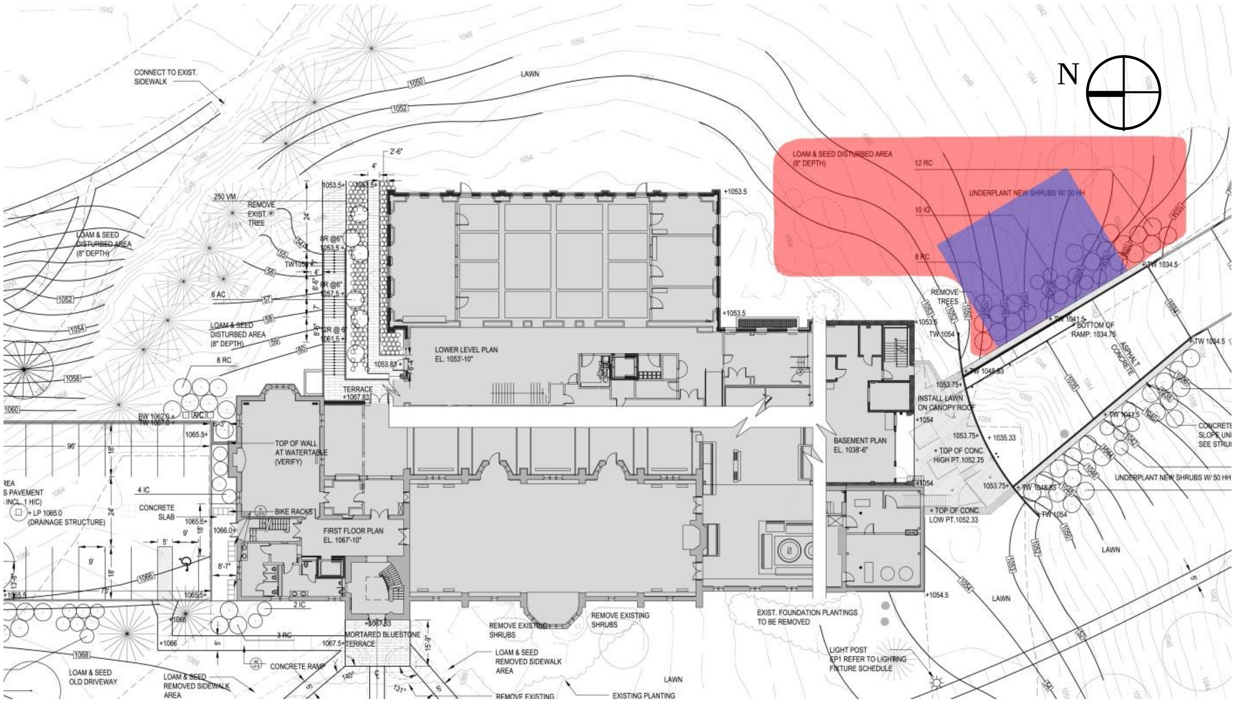


Figure 9: Selected CHP Plant Location with Approximate Size of Prime Mover Housing

6.0 Lighting Study (Breadth No. 2)

6.1 Existing Lighting Design of the Great Hall

The Piece Hall dining facility is one of the signature buildings on the Kenyon College campus, and as such holds some very well known spaces. The Great Hall is one such space with an open 40' tall ceiling that exposes the intricate wood roof structure. Grand chandeliers hanged from the ceiling to light this space prior to the 2006 renovation, expansion, and addition project. The decision was made rewired and restored these chandelier luminaires. Each luminaire holds thirty 40W incandescent lamps, drawing a total of 1200W. With 10 of these luminaires lighting the 4,140 square foot dining hall, this equates to a 2.9 W/ft^2 lighting power density (LPD). For any hope of meeting the 1.4 W/ft^2 expectations of the ASHRAE Standard 90.1 LPD recommendation, these luminaries have to be modified.

To prepare for a design modification, an AGi32 model of the existing facility was prepared. The 40W incandescent lamps were represented by 35W candelabra lamps due to inability to find an .ies modeling file for a 40W. Using the 11th edition IESNA Lighting Handbook to define lamp lumen depreciation, dirt depreciation, and ballast factor power loss, a template for these lamps was made. (Illuminating Engineering Society of North America) Dimensions of the luminaires were not available, hence the approximate dimensions of about 2' long arms were used with 5 lamps evenly distributed in a circle at each end. The hanged height of the luminaires was 14'. The result of this model calculation showed an average illuminance of 7.72 foot candles (Fc) at 2.5', which was estimated to be the height of the eating surface in the dining hall. Figure 10 through 12 show the results of this existing lighting design model.

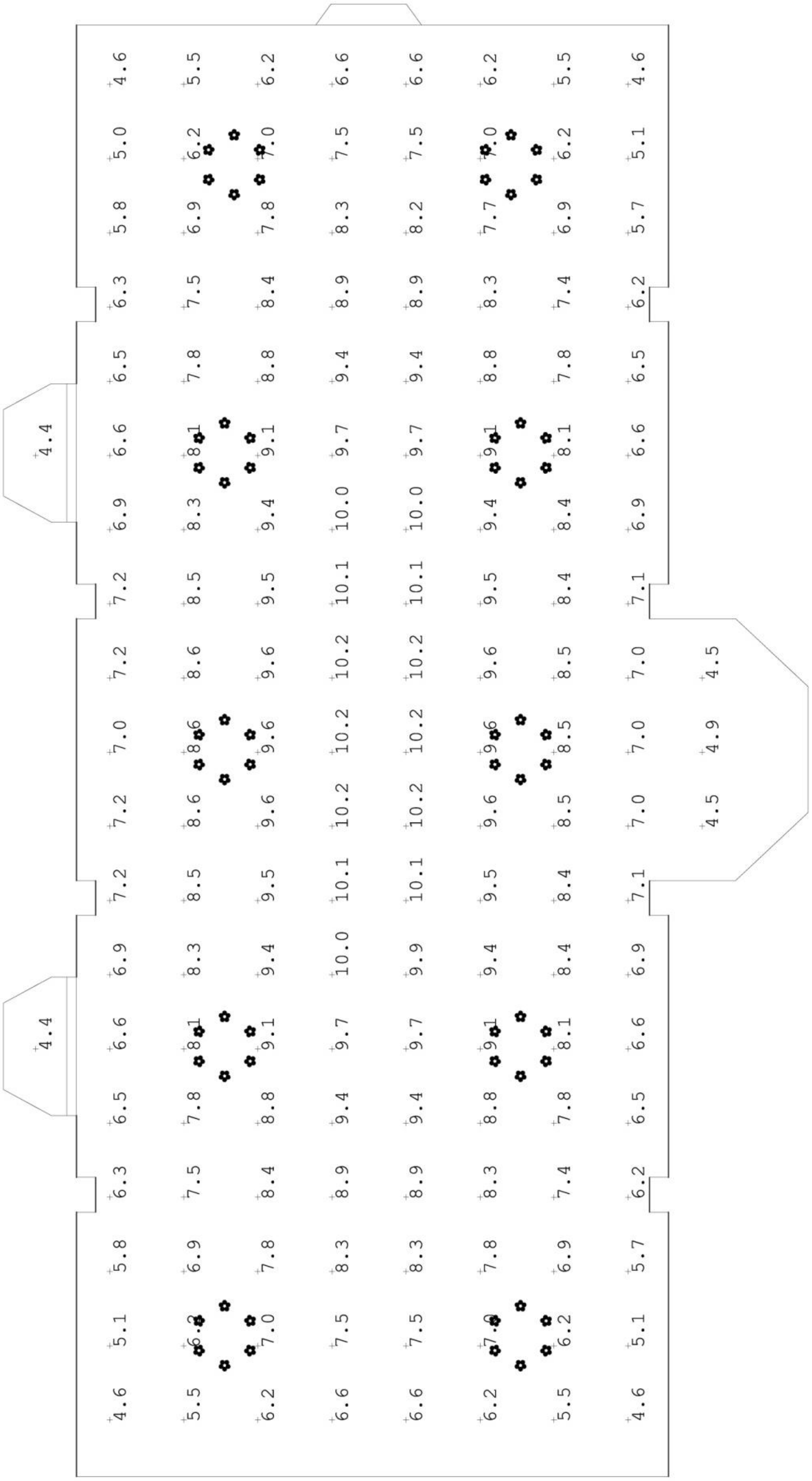


Figure 10: Great Hall Existing Lighting Design Model Illuminance Levels

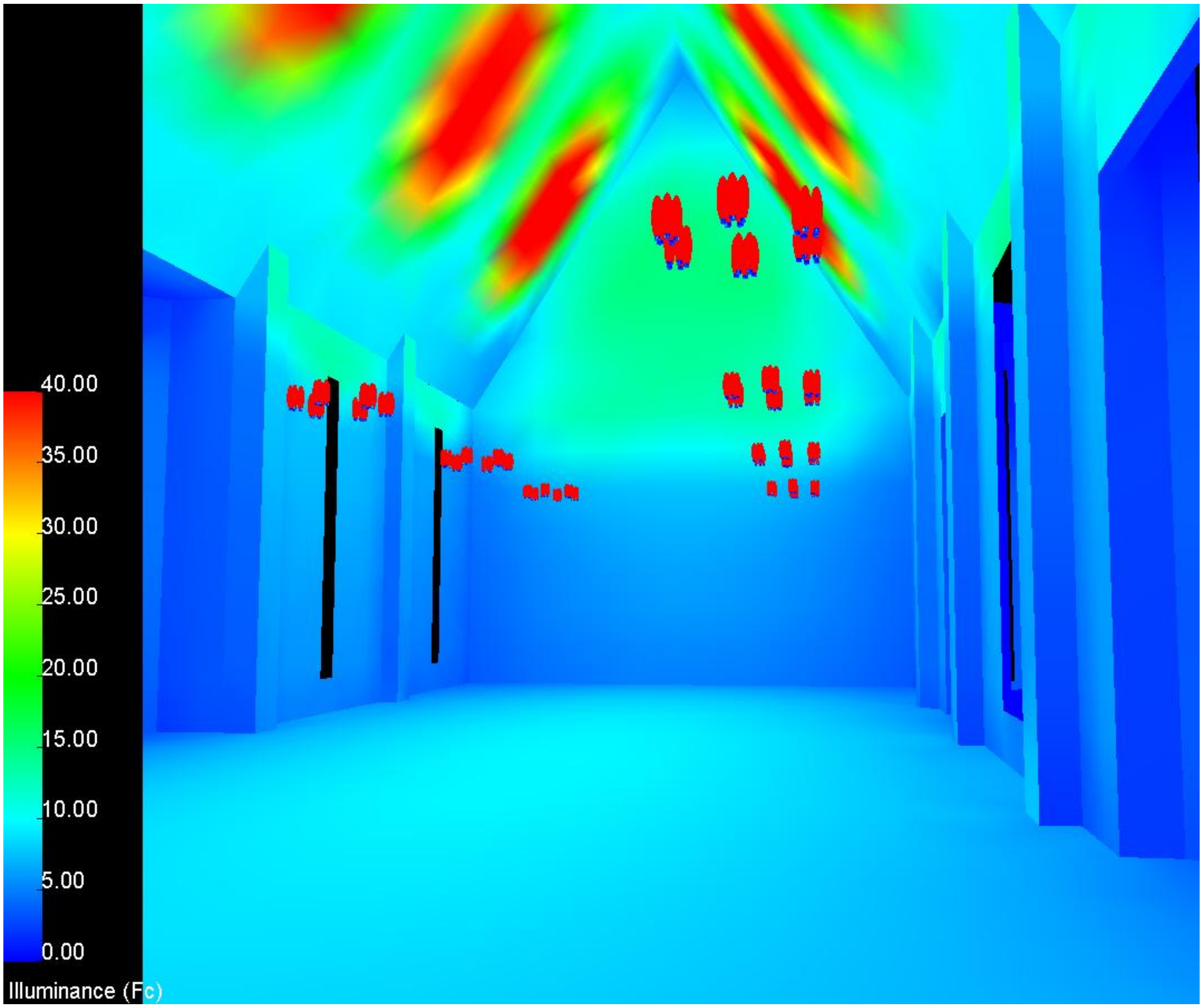


Figure 11: Great Hall Existing Lighting Design Model Perspective Rendering

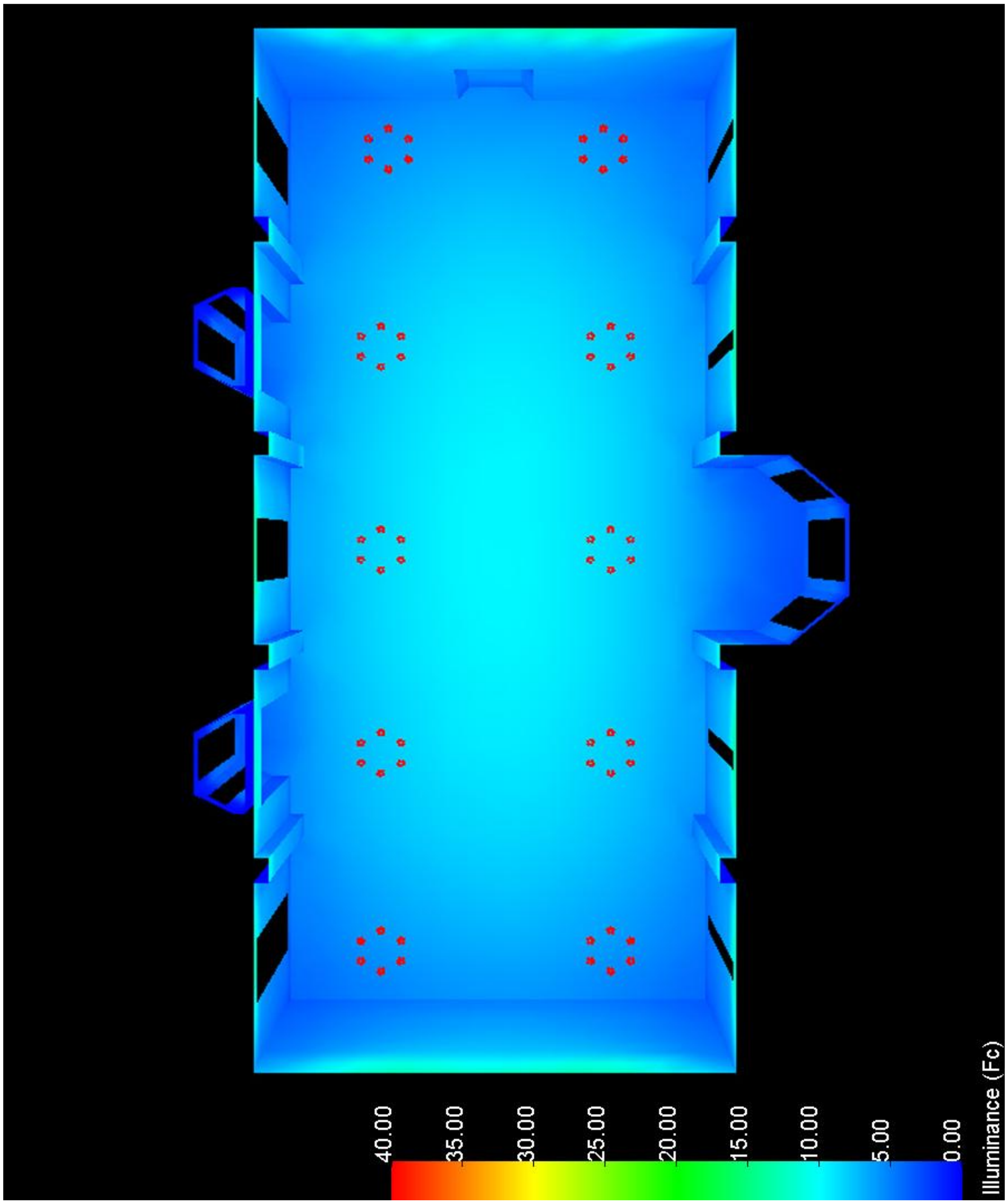


Figure 12: Great Hall Existing Lighting Design Model Floor Illuminance Rendering

6.2 Modified Lighting Design of the Great Hall

To reduce the power use of the lighting system in the Great Hall, LED lamps were used to replace the existing incandescent lamps. 9W Toshiba Dimmable LED PAR20 lamps were specified to reduce the power use by over 75%. The resulting LPD achieved was 0.7 W/ft^2, half of the LPD expected by ASHRAE Standard 90.1. One problem with a lot of LED lamps is the color temperature is very cool, which in the case of replacing an incandescent will not create the same effect in a space. The Toshiba PAR 20 lamp has a specified 3000 Kelvin (k) color temperature, close enough to the 2900k incandescent color temperature range as not to create a dramatic difference. Specification information can be found in Appendix C for the Toshiba LED PAR 20 lamps.

In addition to a more desired LPD, the average calculated illuminance value for the space was 9.85 Fc. This is much closer to the recommended 10 Fc by IESNA than the existing lighting system. (Illuminating Engineering Society of North America) These results are depicted in Figure 13 through 15.

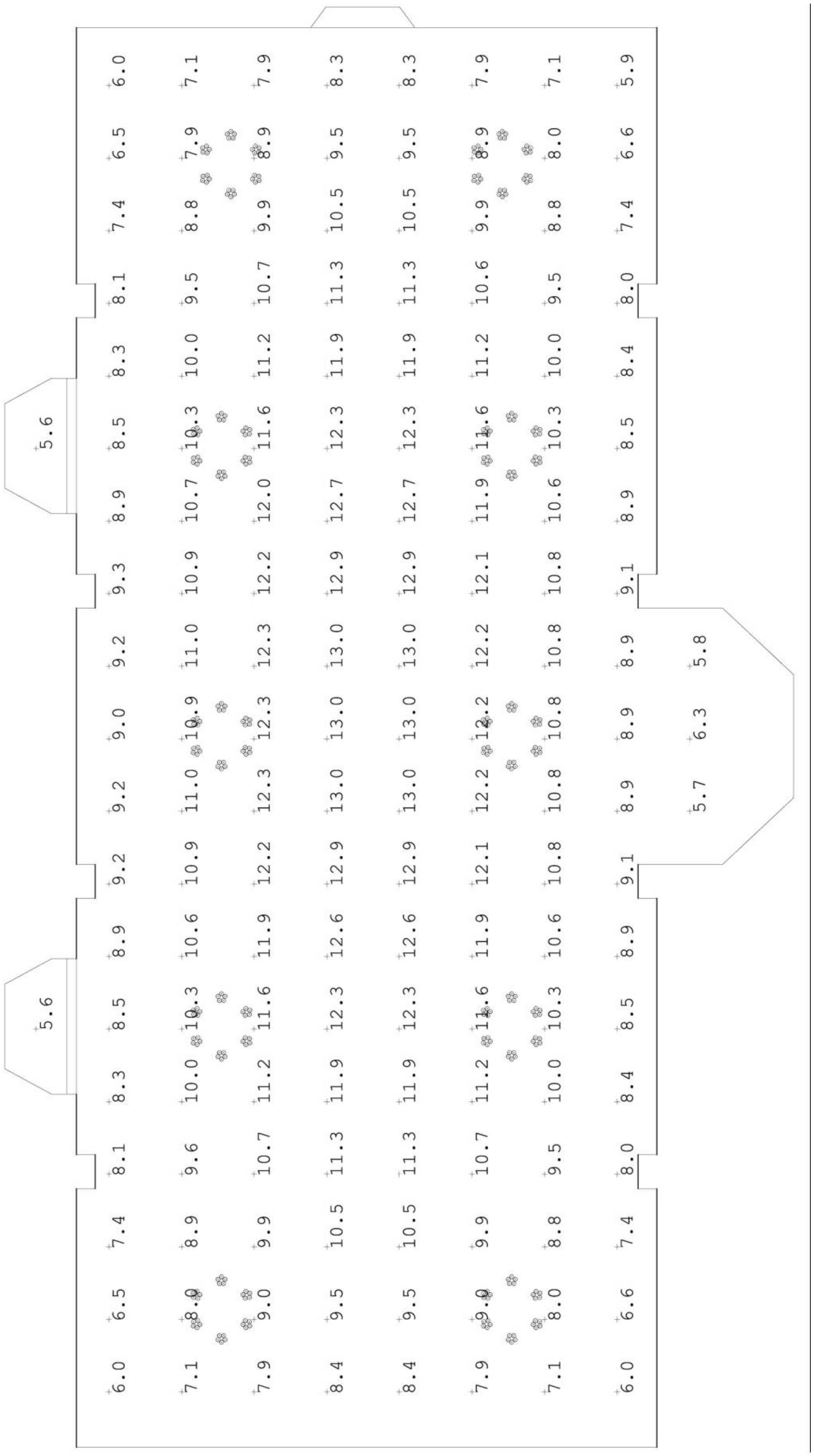


Figure 13: Great Hall Modified Lighting Design Model Illuminance Levels

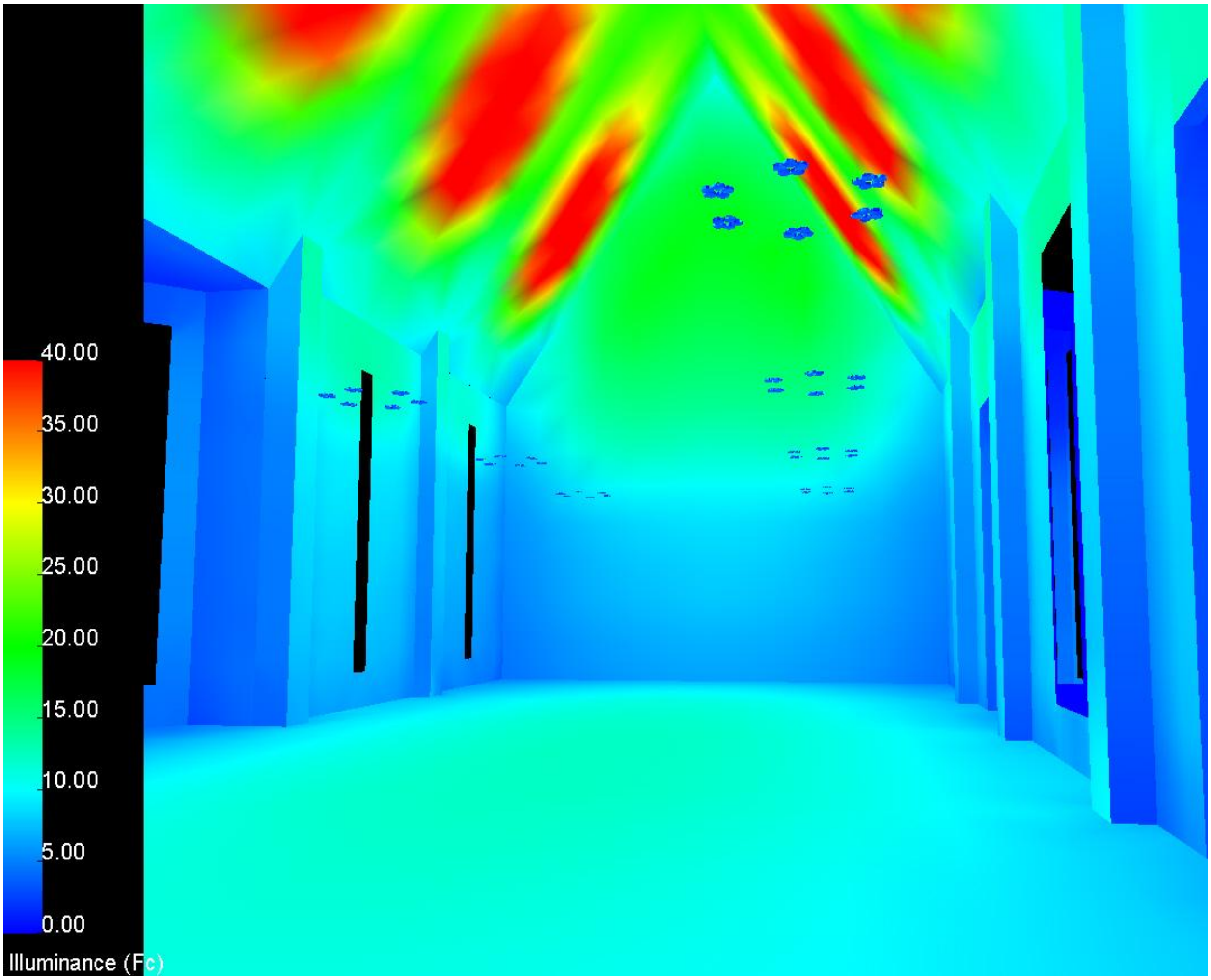


Figure 14: Great Hall Modified Lighting Design Model Perspective Rendering

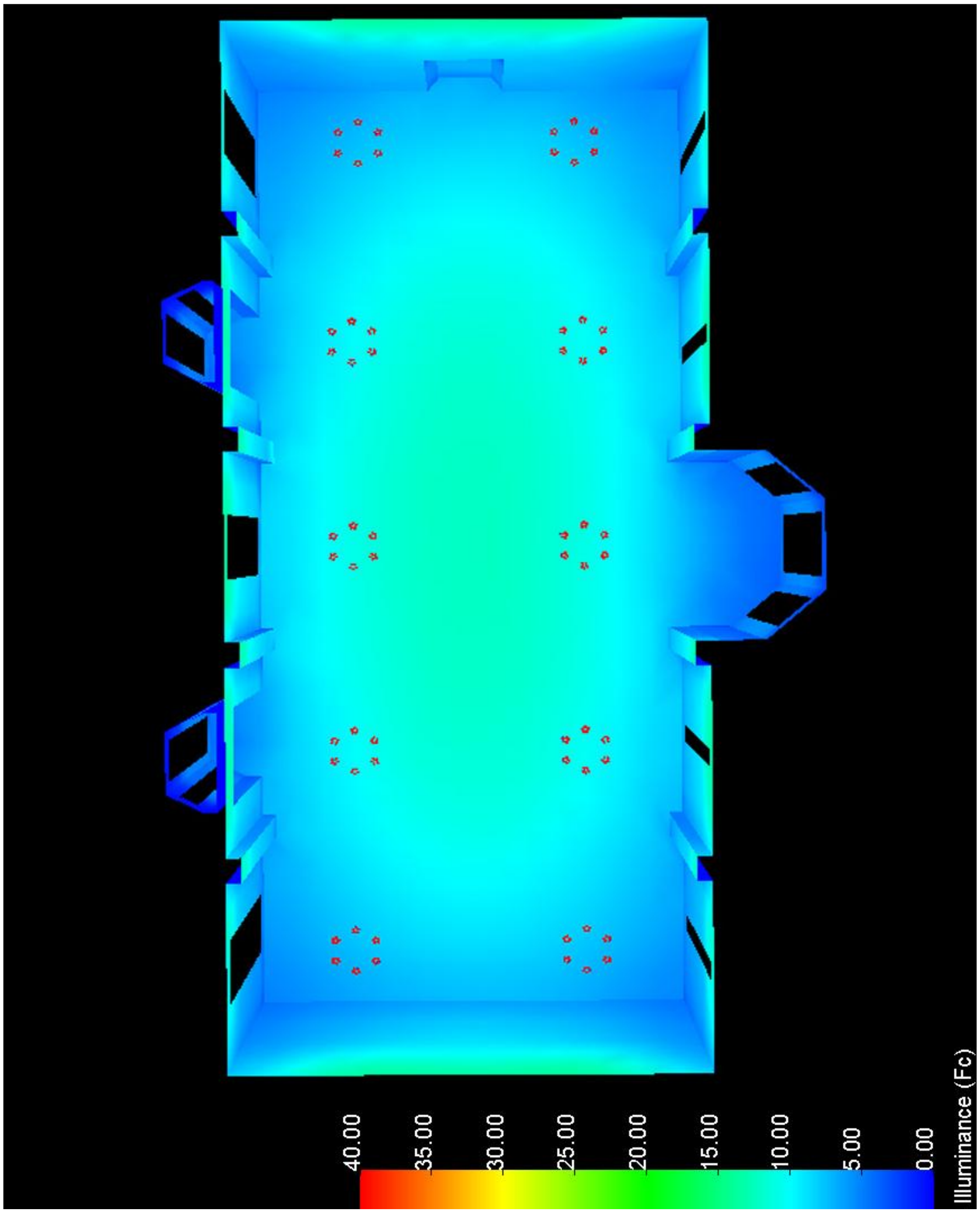


Figure 15: Great Hall Modified Lighting Design Model Floor Illuminance Rendering

7.0 Meeting Study Intentions

The studies performed in this thesis were intended to investigate possible modifications to the existing building system designs of the sponsored facility that could raise system performance to a level recognized by the USGBC and DOE as more sustainable. This was attempted by designing a CHP plant and replacing existing incandescent lamps with hi efficiency LED lamps. As previously shown, the modifications explored in these studies have the potential to significantly reduce energy use of Peirce Hall.

In order to qualify for LEED Certification, an additional 13 points were shown to be required. The “Optimize Energy Performance” category of the LEED for New Construction and Major Renovations holds 19 potential points, none of which were previously attained due to failure to meet minimum prerequisites. Approximately 32% less fuel is used by Peirce Hall than the conventional SHP system with the specified CHP system as estimated by the EPA provided CHP Emissions Calculator. The Optimize Energy Performance category of LEED offers the full 19 points for a 44% reduction in energy use and 13 points exactly for a 32% reduction in energy use. This is just enough points to bring Peirce Hall to the point of LEED Certification. Now to be eligible to receive these points various prerequisites must first be met, including meeting ASHRAE Standard 90.1 Section G.

Section G describes a method for determining overall compliance with Standard 90.1, which is analyzed in Technical Report I. From the studies done in this technical report, the goal of satisfying ASHRAE Standard 90.1 does not seem out of the question. Therefore, by installing the specified CHP system, lighting system, and without extensive additional modification, this study determines that LEED Certification and a more efficient running Peirce Hall is feasible.

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Appendix A: Table of Typical Prime Mover Characteristics

Technology	Steam Turbine	Recip. Engine	Gas Turbine	Microturbine	Fuel Cell
Power efficiency (HHV)	15-38%	22-40%	22-36%	18-27%	30-63%
Overall efficiency (HHV)	80%	70-80%	70-75%	65-75%	55-80%
Effective electrical efficiency	75%	70-80%	50-70%	50-70%	55-80%
Typical capacity (MWe)	0.5-250	0.01-5	0.5-250	0.03-0.25	0.005-2
Typical power to heat ratio	0.1-0.3	0.5-1	0.5-2	0.4-0.7	1-2
Part-load	ok	ok	poor	ok	good
CHP Installed costs (\$/kW$_e$)	430-1,100	1,100-2,200	970-1,300 (5-40 MW)	2,400-3,000	5,000-6,500
O&M costs (\$/kWh$_e$)	<0.005	0.009-0.022	0.004-0.011	0.012-0.025	0.032-0.038
Availability	near 100%	92-97%	90-98%	90-98%	>95%
Hours to overhauls	>50,000	25,000-50,000	25,000-50,000	20,000-40,000	32,000-64,000
Start-up time	1 hr - 1 day	10 sec	10 min - 1 hr	60 sec	3 hrs - 2 days
Fuel pressure (psig)	n/a	1-45	100-500 (compressor)	50-80 (compressor)	0.5-45
Fuels	all	natural gas, biogas, propane, landfill gas	natural gas, biogas, propane, oil	natural gas, biogas, propane, oil	hydrogen, natural, gas, propane, methanol
Noise	high	high	moderate	moderate	low
Uses for thermal output	LP-HP steam	hot water, LP steam	heat, hot water, LP-HP steam	heat, hot water, LP steam	hot water, LP-HP steam
Power Density (kW/m2)	>100	35-50	20-500	5-70	5-20
NOx (lb/MMBtu) (not including SCR)	Gas 0.1-.2 Wood 0.2-.5 Coal 0.3-1.2	0.013 rich burn 3-way cat. 0.17 lean burn	0.036-0.05	0.015-0.036	0.0025-.0040
lb/MWhTotalOutput (not including SCR)	Gas 0.4-0.8 Wood 0.9-1.4 Coal 1.2-5.0	0.06 rich burn 3-way cat. 0.8 lean burn	0.17-0.25	0.08-0.20	0.011-0.016

Figure A-1: "Summary Table of Typical Cost and Performance Characteristics by CHP Technology" (U.S. Environmental Protection Agency Combined Heat and Power Partnership)

Appendix B: Calculation and Model Material

Table B-1: Typical Weeks Hourly Demand Percent by Occupancy

Hour	Dining	Office	Combined	Hour	Dining	Office	Combined
Monday-Friday				Saturday (continued)			
1:00	0.02	0.02	0.020	13:00	0.85	0.02	0.798
2:00	0.02	0.02	0.020	14:00	0.3	0.02	0.282
3:00	0.02	0.02	0.020	15:00	0.3	0.02	0.282
4:00	0.02	0.02	0.020	16:00	0.3	0.02	0.282
5:00	0.02	0.02	0.020	17:00	0.95	0.02	0.891
6:00	0.02	0.02	0.020	18:00	0.95	0.02	0.891
7:00	0.5	0.3	0.487	19:00	0.95	0.02	0.891
8:00	0.5	1	0.532	20:00	0.95	0.02	0.891
9:00	0.5	1	0.532	21:00	0.25	0.02	0.236
10:00	0.25	1	0.297	22:00	0.25	0.02	0.236
11:00	0.85	1	0.859	23:00	0.25	0.02	0.236
12:00	0.85	1	0.859	24:00	0.25	0.02	0.236
13:00	0.3	1	0.344	Sunday			
14:00	0.3	1	0.344	1:00	0.02	0.02	0.020
15:00	0.3	1	0.344	2:00	0.02	0.02	0.020
16:00	0.3	1	0.344	3:00	0.02	0.02	0.020
17:00	0.95	1	0.953	4:00	0.02	0.02	0.020
18:00	0.95	0.3	0.909	5:00	0.02	0.02	0.020
19:00	0.95	0.02	0.891	6:00	0.02	0.02	0.020
20:00	0.95	0.02	0.891	7:00	0.02	0.02	0.020
21:00	0.15	0.02	0.142	8:00	0.02	0.02	0.020
22:00	0.15	0.02	0.142	9:00	0.02	0.02	0.020
23:00	0.15	0.02	0.142	10:00	0.7	0.02	0.657
24:00	0.15	0.02	0.142	11:00	0.7	0.02	0.657
Sat				12:00	0.7	0.02	0.657
1:00	0.02	0.02	0.020	13:00	0.7	0.02	0.657
2:00	0.02	0.02	0.020	14:00	0.15	0.02	0.142
3:00	0.02	0.02	0.020	15:00	0.15	0.02	0.142
4:00	0.02	0.02	0.020	16:00	0.15	0.02	0.142
5:00	0.02	0.02	0.020	17:00	0.8	0.02	0.751
6:00	0.02	0.02	0.020	18:00	0.8	0.02	0.751
7:00	0.02	0.02	0.020	19:00	0.8	0.02	0.751
8:00	0.5	0.02	0.470	20:00	0.8	0.02	0.751
9:00	0.5	0.02	0.470	21:00	0.15	0.02	0.142
10:00	0.25	0.02	0.236	22:00	0.15	0.02	0.142
11:00	0.85	0.02	0.798	23:00	0.15	0.02	0.142
12:00	0.85	0.02	0.798	24:00	0.15	0.02	0.142

Total Temperature Deviation from 65 [°F]	
Cooling	Heating
21,759	136,446
Total Energy Demand [Btu]	
Cooling	Heating
2.968E+09	9.865E+09
Model Load Constants	
C_c [Btu/°F]	C_h [Btu/°F]
136403.7035	72299.41

Table B-2: Model Load Constant Calculations

Legend for the Following Tables:

T_{amb}: Outdoor Ambient Dry Bulb Temperature
W_D: Electrical Energy Demand
Q_D: Heating Energy Demand
C_D: Cooling Energy Demand
P_{CHP}: Maximum Electrical Output from CHP System
Q_{CHP}: Maximum Heat Output from CHP System
F_{CHP}: Fuel Used by CHP System
$W_{M,CHP}$: Electrical Demand Load Met By CHP System
$C_{M,CHP}$: Electrical Cooling Demand Load Met By CHP System
$P_{M,GRID}$: Electrical Demand met by Grid
$Q_{M,CHP}$: Heating Demand Load Met By CHP System
$Q_{M,CS}$: Heating Demand Load Met By Campus Steam System
$W_{L,CHP}$: Unused Electricity Generated by CHP Prime Mover
$Q_{L,CHP}$: Unused Heat Generated by CHP Prime Mover

Annual Conditions			**Demand Loads**			**CHP Capacities**			**Combined Heat and Power System Performance**							**CHP Hourly Grid Power Demand**	
Date	Hour	T_{amb} [F]	W_D [kWh]	C_D [kWh]	Q_D [MBtu]	P_{CHP} [kWh]	Q_{CHP} [MBtu]	F_{CHP} [mcf]	$W_{M,CHP}$ [kWh]	$C_{M,CHP}$ [kWh]	$P_{M,GRID}$ [kWh]	$Q_{M,CHP}$ [MBtu]	$Q_{M,CS}$ [MBtu]	$W_{L,CHP}$ [kWh]	$Q_{L,CHP}$ [MBtu]	On-Peak [kWh]	Off-Peak [kWh]
1/1	1	26.06	20.49	0.000	2.815	20.49	0.11	0.21	20.49	0.00	0.00	0.11	2.70	0.00	0.00	0.00	0.00
1/1	2	26.96	20.49	0.000	2.750	20.49	0.11	0.21	20.49	0.00	0.00	0.11	2.64	0.00	0.00	0.00	0.00
1/1	3	26.06	20.49	0.000	2.815	20.49	0.11	0.21	20.49	0.00	0.00	0.11	2.70	0.00	0.00	0.00	0.00
1/1	4	24.98	20.49	0.000	2.893	20.49	0.11	0.21	20.49	0.00	0.00	0.11	2.78	0.00	0.00	0.00	0.00
1/1	5	24.98	20.49	0.000	2.893	20.49	0.11	0.21	20.49	0.00	0.00	0.11	2.78	0.00	0.00	0.00	0.00
1/1	6	24.08	20.49	0.000	2.958	20.49	0.11	0.21	20.49	0.00	0.00	0.11	2.85	0.00	0.00	0.00	0.00
1/1	7	24.08	499.40	0.000	2.958	499.40	2.70	5.00	499.40	0.00	0.00	2.70	0.26	0.00	0.00	0.00	0.00
1/1	8	23	544.59	0.000	3.037	544.59	2.94	5.45	544.59	0.00	0.00	2.94	0.10	0.00	0.00	0.00	0.00
1/1	9	26.06	544.59	0.000	2.815	544.59	2.94	5.45	544.59	0.00	0.00	2.82	0.00	0.00	0.13	0.00	0.00
1/1	10	35.06	304.57	0.000	2.165	304.57	1.64	3.05	304.57	0.00	0.00	1.64	0.52	0.00	0.00	0.00	0.00
1/1	11	44.06	880.62	0.000	1.514	880.62	4.76	8.82	880.62	0.00	0.00	1.51	0.00	0.00	3.24	0.00	0.00
1/1	12	48.02	880.62	0.000	1.228	880.62	4.76	8.82	880.62	0.00	0.00	1.23	0.00	0.00	3.53	0.00	0.00
1/1	13	50	352.58	0.000	1.084	352.58	1.90	3.53	352.58	0.00	0.00	1.08	0.00	0.00	0.82	0.00	0.00
1/1	14	51.98	352.58	0.000	0.941	352.58	1.90	3.53	352.58	0.00	0.00	0.94	0.00	0.00	0.96	0.00	0.00
1/1	15	53.06	352.58	0.000	0.863	352.58	1.90	3.53	352.58	0.00	0.00	0.86	0.00	0.00	1.04	0.00	0.00
1/1	16	51.98	352.58	0.000	0.941	352.58	1.90	3.53	352.58	0.00	0.00	0.94	0.00	0.00	0.96	0.00	0.00
1/1	17	50	976.63	0.000	1.084	976.63	5.27	9.78	976.63	0.00	0.00	1.08	0.00	0.00	4.19	0.00	0.00
1/1	18	48.02	931.44	0.000	1.228	931.44	5.03	9.33	931.44	0.00	0.00	1.23	0.00	0.00	3.80	0.00	0.00
1/1	19	48.02	913.37	0.000	1.228	913.37	4.93	9.15	913.37	0.00	0.00	1.23	0.00	0.00	3.70	0.00	0.00
1/1	20	50	913.37	0.000	1.084	913.37	4.93	9.15	913.37	0.00	0.00	1.08	0.00	0.00	3.85	0.00	0.00
1/1	21	48.92	145.30	0.000	1.163	145.30	0.78	1.46	145.30	0.00	0.00	0.78	0.38	0.00	0.00	0.00	0.00
1/1	22	48.02	145.30	0.000	1.228	145.30	0.78	1.46	145.30	0.00	0.00	0.78	0.44	0.00	0.00	0.00	0.00
1/1	23	48.92	145.30	0.000	1.163	145.30	0.78	1.46	145.30	0.00	0.00	0.78	0.38	0.00	0.00	0.00	0.00
1/1	24	48.2	145.30	0.000	1.215	145.30	0.78	1.46	145.30	0.00	0.00	0.78	0.43	0.00	0.00	0.00	0.00

Table B-3: Electric Load Following CHP Analysis for January 1st

Annual Conditions			**Demand Loads**			**CHP Capacities**			**Combined Heat and Power System Performance**							**CHP Hourly Grid Power Demand**	
Date	Hour	T_{amb} [F]	W_D [kWh]	C_D [kWh]	Q_D [MBtu]	P_{CHP} [kWh]	Q_{CHP} [MBtu]	F_{CHP} [mcf]	$W_{M,CHP}$ [kWh]	$C_{M,CHP}$ [kWh]	$P_{M,GRID}$ [kWh]	$Q_{M,CHP}$ [MBtu]	$Q_{M,CS}$ [MBtu]	$W_{L,CHP}$ [kWh]	$Q_{L,CHP}$ [MBtu]	On-Peak [kWh]	Off-Peak [kWh]
7/1	1	59	20.49	0.000	0.434	20.49	0.11	0.21	20.49	0.00	0.00	0.11	0.32	0.00	0.00	0.00	0.00
7/1	2	58.28	20.49	0.000	0.486	20.49	0.11	0.21	20.49	0.00	0.00	0.11	0.38	0.00	0.00	0.00	0.00
7/1	3	57.74	20.49	0.000	0.525	20.49	0.11	0.21	20.49	0.00	0.00	0.11	0.41	0.00	0.00	0.00	0.00
7/1	4	57.02	20.49	0.000	0.577	20.49	0.11	0.21	20.49	0.00	0.00	0.11	0.47	0.00	0.00	0.00	0.00
7/1	5	55.94	20.49	0.000	0.655	20.49	0.11	0.21	20.49	0.00	0.00	0.11	0.54	0.00	0.00	0.00	0.00
7/1	6	57.92	20.49	0.000	0.512	20.49	0.11	0.21	20.49	0.00	0.00	0.11	0.40	0.00	0.00	0.00	0.00
7/1	7	64.94	20.49	0.000	0.004	20.49	0.11	0.21	20.49	0.00	0.00	0.00	0.00	0.00	0.11	0.00	0.00
7/1	8	69.98	20.49	199.089	0.000	219.58	1.19	2.20	20.49	199.09	0.00	0.00	0.00	0.00	1.19	0.00	0.00
7/1	9	75.02	20.49	400.576	0.000	421.07	2.27	4.22	20.49	400.58	0.00	0.00	0.00	0.00	2.27	0.00	0.00
7/1	10	77	673.35	479.732	0.000	1153.08	6.23	11.55	673.35	479.73	0.00	0.00	0.00	0.00	6.23	0.00	0.00
7/1	11	78.08	673.35	522.908	0.000	1196.25	6.46	11.98	673.35	522.91	0.00	0.00	0.00	0.00	6.46	0.00	0.00
7/1	12	80.06	673.35	602.063	0.000	1275.41	6.89	12.77	673.35	602.06	0.00	0.00	0.00	0.00	6.89	0.00	0.00
7/1	13	80.96	673.35	638.043	0.000	1311.39	7.08	13.13	673.35	638.04	0.00	0.00	0.00	0.00	7.08	0.00	0.00
7/1	14	82.04	145.30	681.219	0.000	826.52	4.46	8.28	145.30	681.22	0.00	0.00	0.00	0.00	4.46	0.00	0.00
7/1	15	82.94	145.30	717.199	0.000	862.50	4.66	8.64	145.30	717.20	0.00	0.00	0.00	0.00	4.66	0.00	0.00
7/1	16	84.02	145.30	760.375	0.000	905.68	4.89	9.07	145.30	760.37	0.00	0.00	0.00	0.00	4.89	0.00	0.00
7/1	17	84.02	769.35	760.375	0.000	1529.73	8.26	15.32	769.35	760.37	0.00	0.00	0.00	0.00	8.26	0.00	0.00
7/1	18	82.04	769.35	681.219	0.000	1450.57	7.83	14.53	769.35	681.22	0.00	0.00	0.00	0.00	7.83	0.00	0.00
7/1	19	80.06	769.35	602.063	0.000	1371.42	7.41	13.73	769.35	602.06	0.00	0.00	0.00	0.00	7.41	0.00	0.00
7/1	20	80.06	769.35	602.063	0.000	1371.42	7.41	13.73	769.35	602.06	0.00	0.00	0.00	0.00	7.41	0.00	0.00
7/1	21	75.92	145.30	436.556	0.000	581.86	3.14	5.83	145.30	436.56	0.00	0.00	0.00	0.00	3.14	0.00	0.00
7/1	22	75.02	145.30	400.576	0.000	545.88	2.95	5.47	145.30	400.58	0.00	0.00	0.00	0.00	2.95	0.00	0.00
7/1	23	73.04	145.30	321.420	0.000	466.72	2.52	4.67	145.30	321.42	0.00	0.00	0.00	0.00	2.52	0.00	0.00
7/1	24	71.96	145.30	278.244	0.000	423.55	2.29	4.24	145.30	278.24	0.00	0.00	0.00	0.00	2.29	0.00	0.00

Table B-4: Electric Load Following CHP Analysis for July 1st

Annual Conditions			**Demand Loads**			**CHP Capacities**			**Combined Heat and Power System Performance**							**CHP Hourly Grid Power Demand**	
Date	Hour	T_{amb} [F]	W_D [kWh]	C_D [kWh]	Q_D [MBtu]	P_{CHP} [kWh]	Q_{CHP} [MBtu]	F_{CHP} [mcf]	$W_{M,CHP}$ [kWh]	$C_{M,CHP}$ [kWh]	$P_{M,GRID}$ [kWh]	$Q_{M,CHP}$ [MBtu]	$Q_{M,CS}$ [MBtu]	$W_{L,CHP}$ [kWh]	$Q_{L,CHP}$ [MBtu]	On-Peak [kWh]	Off-Peak [kWh]
1/1	1	26.06	20.493	0.000	2.815	521.366	2.815	5.222	20.493	0.000	0.000	2.815	0.000	500.874	0.000	0.000	0.000
1/1	2	26.96	20.493	0.000	2.750	509.316	2.750	5.101	20.493	0.000	0.000	2.750	0.000	488.824	0.000	0.000	0.000
1/1	3	26.06	20.493	0.000	2.815	521.366	2.815	5.222	20.493	0.000	0.000	2.815	0.000	500.874	0.000	0.000	0.000
1/1	4	24.98	20.493	0.000	2.893	535.827	2.893	5.366	20.493	0.000	0.000	2.893	0.000	515.334	0.000	0.000	0.000
1/1	5	24.98	20.493	0.000	2.893	535.827	2.893	5.366	20.493	0.000	0.000	2.893	0.000	515.334	0.000	0.000	0.000
1/1	6	24.08	20.493	0.000	2.958	547.877	2.958	5.487	20.493	0.000	0.000	2.958	0.000	527.384	0.000	0.000	0.000
1/1	7	24.08	499.405	0.000	2.958	547.877	2.958	5.487	499.405	0.000	0.000	2.958	0.000	48.472	0.000	0.000	0.000
1/1	8	23	544.591	0.000	3.037	562.337	3.037	5.632	544.591	0.000	0.000	3.037	0.000	17.746	0.000	0.000	0.000
1/1	9	26.06	544.591	0.000	2.815	521.366	2.815	5.222	521.366	0.000	23.224	2.815	0.000	0.000	0.000	23.224	0.000
1/1	10	35.06	304.571	0.000	2.165	400.866	2.165	4.015	304.571	0.000	0.000	2.165	0.000	96.294	0.000	0.000	0.000
1/1	11	44.06	880.618	0.000	1.514	280.365	1.514	2.808	280.365	0.000	600.253	1.514	0.000	0.000	0.000	600.253	0.000
1/1	12	48.02	880.618	0.000	1.228	227.345	1.228	2.277	227.345	0.000	653.274	1.228	0.000	0.000	0.000	653.274	0.000
1/1	13	50	352.575	0.000	1.084	200.835	1.084	2.011	200.835	0.000	151.741	1.084	0.000	0.000	0.000	151.741	0.000
1/1	14	51.98	352.575	0.000	0.941	174.324	0.941	1.746	174.324	0.000	178.251	0.941	0.000	0.000	0.000	178.251	0.000
1/1	15	53.06	352.575	0.000	0.863	159.864	0.863	1.601	159.864	0.000	192.711	0.863	0.000	0.000	0.000	192.711	0.000
1/1	16	51.98	352.575	0.000	0.941	174.324	0.941	1.746	174.324	0.000	178.251	0.941	0.000	0.000	0.000	178.251	0.000
1/1	17	50	976.626	0.000	1.084	200.835	1.084	2.011	200.835	0.000	775.792	1.084	0.000	0.000	0.000	775.792	0.000
1/1	18	48.02	931.440	0.000	1.228	227.345	1.228	2.277	227.345	0.000	704.095	1.228	0.000	0.000	0.000	704.095	0.000
1/1	19	48.02	913.365	0.000	1.228	227.345	1.228	2.277	227.345	0.000	686.021	1.228	0.000	0.000	0.000	686.021	0.000
1/1	20	50	913.365	0.000	1.084	200.835	1.084	2.011	200.835	0.000	712.531	1.084	0.000	0.000	0.000	712.531	0.000
1/1	21	48.92	145.303	0.000	1.163	215.295	1.163	2.156	145.303	0.000	0.000	1.163	0.000	69.992	0.000	0.000	0.000
1/1	22	48.02	145.303	0.000	1.228	227.345	1.228	2.277	145.303	0.000	0.000	1.228	0.000	82.042	0.000	0.000	0.000
1/1	23	48.92	145.303	0.000	1.163	215.295	1.163	2.156	145.303	0.000	0.000	1.163	0.000	69.992	0.000	0.000	0.000
1/1	24	48.2	145.303	0.000	1.215	224.935	1.215	2.253	145.303	0.000	0.000	1.215	0.000	79.632	0.000	0.000	0.000

Table B-5: Thermal Load Following CHP Analysis for January 1st

Annual Conditions			Demand Loads			CHP Capacities			Combined Heat and Power System Performance							CHP Hourly Grid Power Demand	
Date	Hour	T_{amb} [F]	W_D [kWh]	C_D [kWh]	Q_D [MBtu]	P_{CHP} [kWh]	Q_{CHP} [MBtu]	F_{CHP} [mcf]	$W_{M,CHP}$ [kWh]	$C_{M,CHP}$ [kWh]	$P_{M,GRID}$ [kWh]	$Q_{M,CHP}$ [MBtu]	$Q_{M,CS}$ [MBtu]	$W_{L,CHP}$ [kWh]	$Q_{L,CHP}$ [MBtu]	On-Peak [kWh]	Off-Peak [kWh]
7/1	1	59	20.493	0.000	0.434	80.334	0.434	0.805	20.493	0.000	0.000	0.434	0.000	59.841	0.000	0.000	0.000
7/1	2	58.28	20.493	0.000	0.486	89.974	0.486	0.901	20.493	0.000	0.000	0.486	0.000	69.481	0.000	0.000	0.000
7/1	3	57.74	20.493	0.000	0.525	97.204	0.525	0.974	20.493	0.000	0.000	0.525	0.000	76.711	0.000	0.000	0.000
7/1	4	57.02	20.493	0.000	0.577	106.844	0.577	1.070	20.493	0.000	0.000	0.577	0.000	86.351	0.000	0.000	0.000
7/1	5	55.94	20.493	0.000	0.655	121.304	0.655	1.215	20.493	0.000	0.000	0.655	0.000	100.811	0.000	0.000	0.000
7/1	6	57.92	20.493	0.000	0.512	94.794	0.512	0.949	20.493	0.000	0.000	0.512	0.000	74.301	0.000	0.000	0.000
7/1	7	64.94	20.493	0.000	0.004	0.803	0.004	0.008	0.803	0.000	19.689	0.004	0.000	0.000	0.000	19.689	0.000
7/1	8	69.98	20.493	199.089	0.000	0.000	0.000	0.000	0.000	0.000	219.581	0.000	0.000	0.000	0.000	219.581	0.000
7/1	9	75.02	20.493	400.576	0.000	0.000	0.000	0.000	0.000	0.000	421.069	0.000	0.000	0.000	0.000	421.069	0.000
7/1	10	77	673.346	479.732	0.000	0.000	0.000	0.000	0.000	0.000	1,153.078	0.000	0.000	0.000	0.000	1,153.078	0.000
7/1	11	78.08	673.346	522.908	0.000	0.000	0.000	0.000	0.000	0.000	1,196.253	0.000	0.000	0.000	0.000	1,196.253	0.000
7/1	12	80.06	673.346	602.063	0.000	0.000	0.000	0.000	0.000	0.000	1,275.409	0.000	0.000	0.000	0.000	1,275.409	0.000
7/1	13	80.96	673.346	638.043	0.000	0.000	0.000	0.000	0.000	0.000	1,311.389	0.000	0.000	0.000	0.000	1,311.389	0.000
7/1	14	82.04	145.303	681.219	0.000	0.000	0.000	0.000	0.000	0.000	826.522	0.000	0.000	0.000	0.000	826.522	0.000
7/1	15	82.94	145.303	717.199	0.000	0.000	0.000	0.000	0.000	0.000	862.502	0.000	0.000	0.000	0.000	862.502	0.000
7/1	16	84.02	145.303	760.375	0.000	0.000	0.000	0.000	0.000	0.000	905.677	0.000	0.000	0.000	0.000	905.677	0.000
7/1	17	84.02	769.354	760.375	0.000	0.000	0.000	0.000	0.000	0.000	1,529.728	0.000	0.000	0.000	0.000	1,529.728	0.000
7/1	18	82.04	769.354	681.219	0.000	0.000	0.000	0.000	0.000	0.000	1,450.573	0.000	0.000	0.000	0.000	1,450.573	0.000
7/1	19	80.06	769.354	602.063	0.000	0.000	0.000	0.000	0.000	0.000	1,371.417	0.000	0.000	0.000	0.000	1,371.417	0.000
7/1	20	80.06	769.354	602.063	0.000	0.000	0.000	0.000	0.000	0.000	1,371.417	0.000	0.000	0.000	0.000	1,371.417	0.000
7/1	21	75.92	145.303	436.556	0.000	0.000	0.000	0.000	0.000	0.000	581.859	0.000	0.000	0.000	0.000	0.000	581.859
7/1	22	75.02	145.303	400.576	0.000	0.000	0.000	0.000	0.000	0.000	545.879	0.000	0.000	0.000	0.000	0.000	545.879
7/1	23	73.04	145.303	321.420	0.000	0.000	0.000	0.000	0.000	0.000	466.723	0.000	0.000	0.000	0.000	0.000	466.723
7/1	24	71.96	145.303	278.244	0.000	0.000	0.000	0.000	0.000	0.000	423.547	0.000	0.000	0.000	0.000	0.000	423.547

Table B-6: Thermal Load Following CHP Analysis for July 1st

Cost per Million Btu		Spark Gap
Power	Fuel	
$36	$10	$26

Table B-7: Spark Gap Calculation

Separate Heat and Power System					
$W_{M,GRID}$ [kWh]	$C_{M,GRID}$ [kWh]	$Q_{M,CS}$ [MBtu]	Total Fuel Cost [$]	Total Utility Cost [$]	Total Cost of Energy [$]
3,325,896	869,871	9,865	$99,395	$416,570	$515,965

Table B-8: Summary of Separate Heat and Power Performance Values

Electric Load Following CHP System									
$W_{M,CHP}$ [kWh]	$C_{M,CHP}$ [kWh]	$P_{M,GRID}$ [kWh]	$Q_{M,CHP}$ [MBtu]	$Q_{M,CS}$ [MBtu]	$W_{L,CHP}$ [kWh]	$Q_{L,CHP}$ [MBtu]	Total Fuel Cost [$]	Total Utility Cost [$]	Total Cost of Energy [$]
3,325,896	869,871	0.00	5,399	4,466	0.00	17,258	$468,129	$0	$468,129

Table B-9: Summary of Electric Load Following Combined Heat and Power System Performance Values

Thermal Load Following CHP System									
$W_{M,CHP}$ [kWh]	$C_{M,CHP}$ [kWh]	$P_{M,GRID}$ [kWh]	$Q_{M,CHP}$ [MBtu]	$Q_{M,CS}$ [MBtu]	$W_{L,CHP}$ [kWh]	$Q_{L,CHP}$ [MBtu]	Total Fuel Cost [$]	Total Utility Cost [$]	Total Cost of Energy [$]
999,839	0	3,195,928	9,865	0.00	827,039	0.00	$190,066	$378,097	$568,163

Table B-10: Summary of Thermal Load Following Combined Heat and Power System Performance Values

Capstone Test Information at 5 m						Calculated Data at 1m		
Frequency [kHz]	0.1	1.6	3.15	16	Overall A Weighted	SPL at 1m	Per 3 units	Average SPL (L_{BAR})
Front	40.25	58.86	68.32	52.66	71.5	79	84	87
Front Left	40.54	53.31	69.16	50.32	71.14	85	90	
Left	44.68	56.88	62.51	44.49	68.23	82	87	
Back Left	40.83	53.52	65.9	46.38	69.06	83	88	
Back	42.51	51.56	66	41.06	68.8	83	88	

Table B-11: Average Acoustic Sound Pressure Level for Three Capstone C800 Packages Calculation Data

Appendix C: Resources

2009 Ohio Average Natural Gas Cost per mcf for Commercial Consumers	
Month	Price [$]
January	11.47
February	11.49
March	11.02
April	10.16
May	10.01
June	10.44
July	10.19
August	9.56
September	9.33
October	9.08
November	9.36
December	9.04

Table C-1 2009 Ohio Average Monthly Cost of Natural Gas per Thousand Cubic Feet for Commercial Customers

C65 & C65-ICHP MicroTurbine Natural Gas

Achieve ultra-low emissions and reliable electrical/thermal generation from natural gas.

- Ultra-low emissions
- One moving part: Minimal maintenance and downtime
- Patented air bearing: No lubricating oil or coolant
- 5 and 9 year Factory Protection Plans available
- Remote monitoring and diagnostic capabilities
- Integrated utility synchronization and protection(1)
- Small, modular design allows for easy, low-cost installation
- Reliable: Tens of millions of run hours and counting

C65 MicroTurbine

Electrical Performance(2)

Electrical Power Output	65kW
Voltage	400–480 VAC
Electrical Service	3-Phase, 4 wire
Frequency	50/60 Hz, grid connect operation
	10–60 Hz, stand alone operation
Maximum Output Current	100A, grid connect operation
	127A, stand alone operation(3)
Electrical Efficiency LHV	29%

C65-ICHP MicroTurbine

Fuel/Engine Characteristics(2)

Natural Gas HHV	30.7–47.5 MJ/m^3 (825–1,275 BTU/scf)
Inlet Pressure(4)	517–552 kPa gauge (75–80 psig)
Fuel Flow HHV	888 MJ/hr (842,000 BTU/hr)
Net Heat Rate LHV	12.4 MJ/kWh (11,800 BTU/kWh)

Exhaust Characteristics(2)

	C65
NOx Emissions at 15% O_2(5)	< 9 ppmvd (18 mg/m^3)
NOx / Electrical Output(5)	0.16 g/bhp-hr (0.46 lb/MWhe)
Exhaust Gas Flow	0.49 kg/s (1.08 lbm/s)
Exhaust Gas Temperature	309°C (588°F)

Reliable power when and where you need it. Clean and simple.

C65-ICHP Heat Recovery(6)

Integrated Heat Recovery Module Type	Copper Core	Stainless Steel Core
Hot Water Heat Recovery	120 kW (408,000 BTU/hr)	74 kW (251,000 BTU/hr)
Total System Efficiency LHV	82%	62%

Dimensions & Weight(7)

	C65	C65-ICHP
Width x Depth(8) x Height(9)	0.76 x 1.9 x 1.9 m (30 x 77 x 76 in)	0.76 x 2.2 x 2.4 m (30 x 87 x 93 in)
Weight - Grid Connect Model	758 kg (1,671 lb)	1000 kg (2,200 lb)
Weight - Dual Mode Model	1121 kg (2,471 lb)	1364 kg (3,000 lb)

Minimum Clearance Requirements(10)

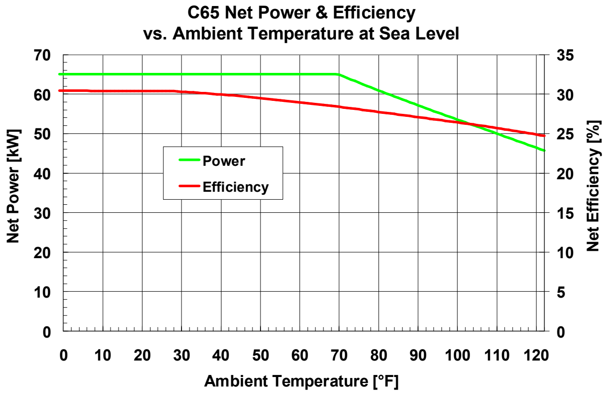
	C65	C65-ICHP
Vertical Clearance	0.61 m (24 in)	0.61 m (24 in)
Horizontal Clearance		
Left & Right	0.76 m (30 in)	0.76 m (30 in)
Front(11)	1.7 m (65 in)	1.7 m (65 in)
Rear	0.91 m (36 in)	0.76 m (30 in)

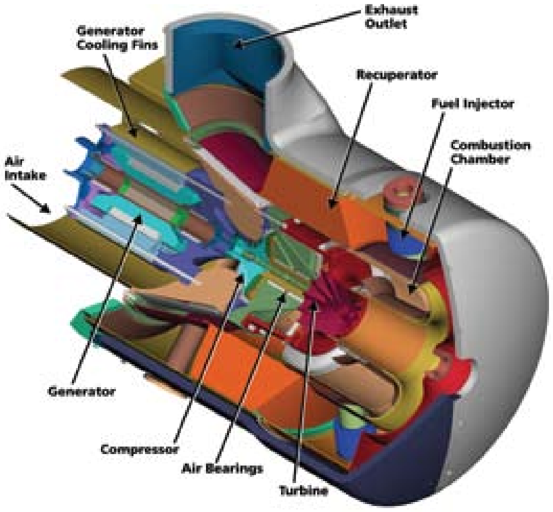
Sound Levels

	C65	C65-ICHP
Acoustic Emissions at Full Load Power(12)		
Nominal at 10 m (33 ft)	70 dBA	65 dBA

Certifications

- Certified to UL 2200 and UL 1741 for natural gas operation (UL files AU2687, E209370)
- Complies with IEEE 1547 and meets statewide utility interconnection requirements for California Rule 21 and the New York State Public Service Commission
- Materials Equipment Acceptance (MEA) approval for New York City
- Models available with optional equipment for CE Marking





(1) Some utilities may require additional equipment for grid interconnectivity
(2) Nominal full power performance at ISO conditions: 59˚F, 14.696 psia, 60% RH
(3) With linear load
(4) Inlet pressure for standard natural gas at 39.4 MJ/Nm³ (1,000 BUT/scf) (HHV)
(5) Exhaust emissions for standard natural gas at 39.4 MJ/Nm³ (1,000 BTU/scf) (HHV)
(6) Heat recovery for water inlet temperature of 38°C (100°F) and flow rate of 2.5 l/s (40 GPM)
(7) Approximate dimensions and weights
(8) Depth includes 10 inch extension for the heat recovery module rain hood on ICHP versions
(9) Height dimensions are to the roof line. Exhaust outlet extends at least 7 inches above the roof line
(10) Clearance requirements may increase due to local code considerations
(11) Dual Mode MicroTurbine configuration for Battery Removal clearance
(12) The optional acoustic inlet hood kit can reduce acoustic emissions at the front of the MicroTurbine by up to 5 dBA

Specifications are not warranted and are subject to change without notice.

21211 Nordhoff Street • Chatsworth • CA • 91311 • 866.422.7786 • 818.734.5300 • www.capstoneturbine.com

P0410 C65 & C65-ICHP Data Sheet CAP139 | Capstone P/N 331035D

C800 800kW Power Package
High-pressure Natural Gas

World's largest air-bearing microturbine produces 800kW of clean, green and reliable power.

- High electrical efficiency over a very wide operating range
- Low maintenance air bearings require no lube oil or coolant
- Ultra-low emissions
- High availability – part load redundancy
- Proven technology with tens of millions of operating hours
- Integrated utility synchronization and protection with a modular design
- 5 and 9 year Factory Protection Plans available
- Remote monitoring and diagnostic capabilities
- Upgradable to 1MW with field installation of Capstone 200kW power module
- Internal fuel gas compressor available for low fuel pressure Natural Gas applications

C800 800kW Power Package

Electrical Performance(1)

Electrical Power Output	800kW
Voltage	400 – 480 VAC
Electrical Service	3-Phase, 4 wire
Frequency	50/60 Hz, grid connect operation
	10 – 60 Hz, stand alone operation
Maximum Output Current	1,160A RMS @ 400V, grid connect operation
	960A RMS @ 480V, grid connect operation
	1,240A RMS, stand alone operation(2)
Electrical Efficiency LHV	33%

Fuel/Engine Characteristics(1)

Natural Gas HHV	30.7 – 47.5 MJ/m^3 (825 – 1,275 BTU/scf)
Inlet Pressure(3)	517 – 552 kPa gauge (75 – 80 psig)
Fuel Flow HHV	9,600 MJ/hr (9,120,000 BTU/hr)
Net Heat Rate LHV	10.9 MJ/kWh (10,300 BTU/kWh)

Exhaust Characteristics(1)	Standard	CARB Version
NOx Emissions @ 15% O_2(4)	< 9 ppmvd (18 mg/m^3)	< 4 ppmvd (8 mg/m^3)
NOx / Electrical Output(4)	0.14 g/bhp-hr (0.4 lb/MWhe)	0.05 g/bhp-hr (0.14 lb/MWhe)
Exhaust Gas Flow	5.3 kg/s (11.7 lbm/s)	5.3 kg/s (11.7 lbm/s)
Exhaust Gas Temperature	280°C (535°F)	280°C (535°F)
Exhaust Energy	5,680 MJ/hr (5,400,000 BTU/hr)	5,680 MJ/hr (5,400,000 BTU/hr)

Reliable power when and where you need it. Clean and simple.

Dimensions & Weight(5)

Width x Depth x Height	2.4 x 9.1 x 2.9 m (96 x 360 x 114 in)
Weight - Grid Connect Model	12084 kg (32,000 lbs)
Weight - Dual Mode Model	17917 kg (39,500 lbs)

Minimum Clearance Requirements(6)

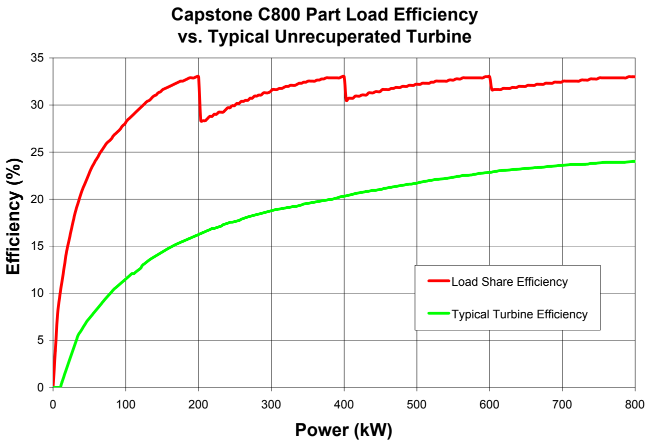
Vertical Clearance	0.6 m (24 in)
Horizontal Clearance	
Left & Right	1.5 m (60 in)
Front	1.5 m (60 in)
Rear	1.8 m (72 in)

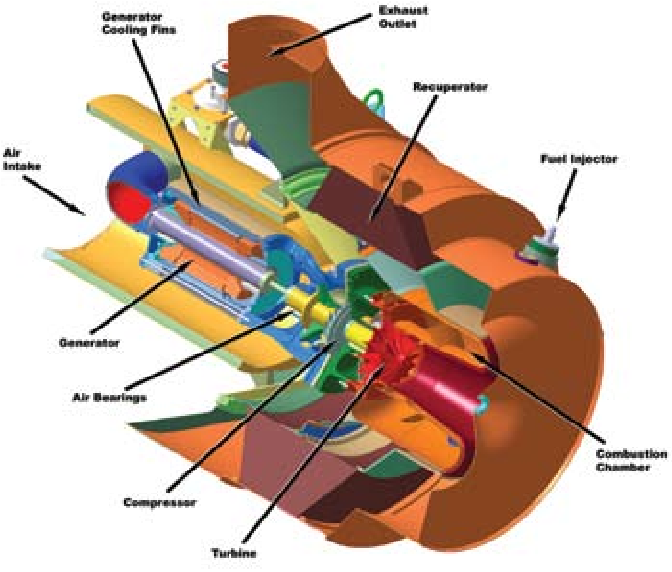
Sound Levels

Acoustic Emissions at Full Load Power	
Nominal at 10 m (33 ft)	65 dBA

Planned Certifications

- UL 2200 and UL 1741 for natural gas operation under existing UL files(7)
- Will comply with IEEE 1547 and will meet statewide utility interconnection requirements for California Rule 21 and the New York State Public Service Commission
- Models will be available with optional equipment for CE marking





C200 Engine

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(1) Nominal full power performance at ISO conditions: 59˚F, 14.696 psia, 60% RH
(2) With linear load
(3) Inlet pressure for standard natural gas at 39.4 MJ/Nm^3 (1,000 BTU/scf) (HHV)
(4) Emissions for standard natural gas at 39.4 MJ/Nm^3 (1,000 BTU/scf) (HHV)
(5) Approximate dimensions and weights
(6) Clearance requirements may increase due to local code considerations
(7) All models are planned to be UL Listed or available with optional equipment for CE marking

Specifications are not warranted and are subject to change without notice.

P0410 C800 800kW Power Package HP Natural Gas Data Sheet CAP158 | Capstone P/N 331053C

TOSHIBA

E-CORE™ | Dimmable LED PAR20 400 Series

Project:	Toshiba Lamp:
Type:	Notes:

Ordering Information

Ordering Code	Input Voltage (VAC)	Lamp Shape	Base Type	Wattage (W)	CCT [1]	Beam Angle	Initial Lumens (lm)[2]	Lamp Efficacy (lm/W)	Rated Life (hrs)[3]	CBCP (cd)	CRI	Power Factor	Equivalency[4]	Lamp Weight lb (g)
9P20/827SP8	120	PAR20	E26	8.6	2700K	8°	380	44.2	40,000	6600	80	>0.70	60W Halogen	0.38 (172)
9P20/827NFL25	120	PAR20	E26	9.0	2700K	25°	390	43.3	40,000	1600	80	>0.70	55W Halogen	0.41 (186)
9P20/830SP8	120	PAR20	E26	8.6	3000K	8°	385	44.8	40,000	6700	81	>0.70	60W Halogen	0.38 (172)
9P20/830NFL25	120	PAR20	E26	9.0	3000K	25°	400	44.4	40,000	1600	80	>0.70	55W Halogen	0.41 (186)

1. CCT Range complies to ANSI C78.377-2008.
2. Thermally stable typical lumens (± 10%)
3. Rated life is based on 70% lumen maintenance, and engineering testing and probability analysis.
4. Equivalency based on the Energy Star® Integral LED Lamp Center Beam Intensity Benchmark Tool.

Note: All information consistent with IESNA LM-80-08 results and IESNA LM-79-08 testing completed by a qualified third party facility.
Note: All lamps meet Energy Star® Integral LED Lamp requirements, and will be submitted for testing.
Note: 5 Year Warranty based on 24 hr/day usage.

5 FIVE YEAR WARRANTY

lighting facts

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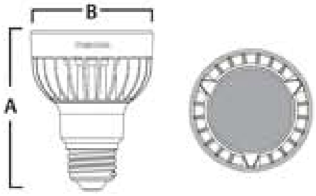
Dimensions

E-Core Model	MOL (A)	Diameter (B)
PAR20	3.26" (82.7 mm)	2.48" (63 mm)

Note: Lamp shape conforms to ANSI C78.21-2003.
Note: Designed to comply with RoHS Directive 2002/95/EC.



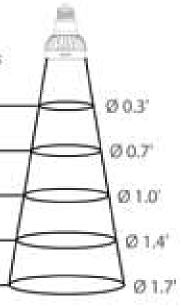
Illuminance Cone Diagrams

9P20/830SP8

Wattage 8.6 CBCP (cd) 6700

Lumens 385 Beam Angle 8°

Distance feet	Footcandles
2'	1675
4'	419
6'	186
8'	105
10'	67

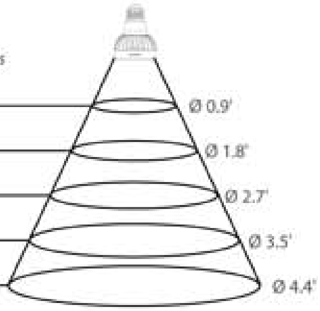


9P20/830NFL25

Wattage 9.0 CBCP (cd) 1600

Lumens 400 Beam Angle 25°

Distance feet	Footcandles
2'	400
4'	100
6'	44
8'	25
10'	16



Energy Savings

	20W Halogen	35W Halogen	55W Halogen	60W Halogen
9P20/830SP8	$50.16	$116.16	$204.16	$226.16*
9P20/830NFL25	$48.40	$114.40	$202.40*	$224.40

*Actual Equivalent Replacement, based on the Energy Star® Integral LED Lamp Center Beam Intensity Benchmark Tool.
Note: Energy Savings based on using one bulb for 40,000 hr rated life at 11¢/kWh. Does not include maintenance and replacement lamp savings.

Ordering Guide

9	P20 /	827	SP8
Wattage 8.6/9.0 Watts = 9	**Lamp Type** PAR20 = P20	**CRI + CCT** 80 CRI + 2700K = 827 80 CRI + 3000K = 830	**Beam Angle** Spot 8° = SP8 Narrow Flood 25° = NFL25


lighting facts

Light Output (Lumens)	390
Watts	9
Lumens per Watt (Efficacy)	43
Color Accuracy	80
Light Color	2700 (Warm White)

Available for all color temperatures