A MODEL-BASED FEASIBILITY STUDY OF COMBINED HEAT AND POWER SYSTEMS FOR USE IN URBAN ENVIRONMENTS

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A MODEL-BASED FEASIBILITY STUDY OF COMBINED HEAT AND POWER SYSTEMS FOR USE IN URBAN ENVIRONMENTS

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

AC	Alternating Current
ATM	Standard Atmosphere
BAU	Business as Usual
CEC	CHP Emissions Calculator
CFM	Cubic Feet per Minute
CHP	Combined Heat and Power
CI	Compression Ignition
COP	Coefficient of Performance
DBA	Decibel
DC	Direct Current
DOE	Department of Energy
EPA	Environmental Protection Agency
EPLUS	EnergyPlus Energy Simulation Software
EQUEST	The Quick Energy Simulation Tool
FT	Feet
GHG	Greenhouse Gas
GW	Gigawatt
HRU	Heat Recovery Unit
HVAC	Heating, Ventilating and Air Conditioning
HZ	Hertz
ISO	International Organization for Standards
KBTU	Thousand British Thermal Units

KW	Kilowatt
KWH	Kilowatt Hour
MMBTU	Million British Thermal Units
NREL	National Renewable Energy Laboratory
PG	Propylene Glycol
PPMV	Parts per Million by Volume
RPM	Revolutions per Minute
SI	Spark Ignition
T&D	Transmission and Distribution
UN	United Nations
W	Watts

SUMMARY

In the United States, about 40% of energy use in 2011 was for electricity generation, but two thirds of the energy used to produce electricity was lost as heat. This wasted energy is an untapped resource which, if utilized correctly, can greatly increase the efficiency of electric power generation. Combined heat and power systems are an energy technology that provides electric and thermal energy at high efficiencies by utilizing excess heat from the process of electricity generation. This technology can offer a decentralized method of energy generation which can provide a more reliable and resilient power supply, can improve U.S. energy security, and can have less of an impact on the environment than certain centralized energy generation systems.

Combined heat and power systems could function particularly well in urban environments. Within the U.S. approximately 80% of the population lives in urban areas, and this number is expected to increase 10% by 2050. The projected increase in population means additional resources for energy generation will be needed. Installation of energy efficient technologies in these urban environments will provide the necessary additional infrastructure, and reduce overall energy consumption.

This work examines the use of a microturbine-based decentralized combined heat and power system and analyzes the technical and environmental feasibility of various system configurations. Energy models are developed for the microturbine-based combined heat and power system in order to analyze the system performance for urban residential and commercial scenarios. Development of the models also enables the identification of the decentralized combined heat and power system environmental

impacts, and the comparison of these to the impacts of a centralized energy system. Within this work the technical and environmental feasibility of the decentralized combined heat and power system is examined for three specific scenarios: an R1 single-family residential building, an R6 6-story residential building and a 2-story office building. The environmental impacts considered are the energy system water consumption, and the total NO_x, SO_2, CO_2, CH_4, and N_2O emissions produced by the system.

This thesis focuses on the use of a decentralized microturbine-based combined heat and power system for energy generation in urban environments. Various combined heat and power system configurations are analyzed within the urban environment in order to understand their technical and environmental feasibility. The combined heat and power system performance is examined, and the energy system water consumption and total emissions produced by the system are compared with the traditional centralized energy generation system in the context of the urban scenario.

CHP systems are an energy efficient technology which could be well-suited for urban environments and which can reduce energy consumption in the U.S. by utilizing waste heat from electricity generation. CHP systems can provide a more reliable and resilient power supply, and improve U.S. energy security. CHP system utilization may also create environmental benefits when compared with the use of certain centralized energy generation technologies.

CHAPTER 1

INTRODUCTION

1.1 Motivation and Background

Energy consumption levels in the United States are among the highest in the world, which is a motivating factor behind the recent domestic interest in energy efficient technologies. The yearly U.S. primary energy consumption has increased steadily since the 1950s (U.S. Energy Information Administration 2012) and the estimated U.S. energy use in 2011 was 97.3 Quadrillion Btu (Lawrence Livermore National Laboratory 2010). According to Figure 1, about 40% of the estimated U.S. energy use in 2011 was for electricity generation. However, two thirds of the energy used to produce electricity was lost as heat. This wasted energy is an untapped resource which, if utilized correctly, can greatly increase the efficiency of electric power generation. The implementation of energy efficient technologies can ultimately reduce the negative economic and environmental impacts of electric power generation in the United States.

Energy efficient technologies have the potential to reduce energy consumption in all regions of the U.S., but these resources could be particularly useful in urban areas. Within the U.S. approximately 80% of the population lives in urban areas, and this number is expected to increase 10% by 2050 (United Nations 2012). The projected increase in population means additional resources for energy generation will be needed. Installation of energy efficient generation technologies in these urban environments will provide the additional infrastructure needed, and reduce overall energy consumption.

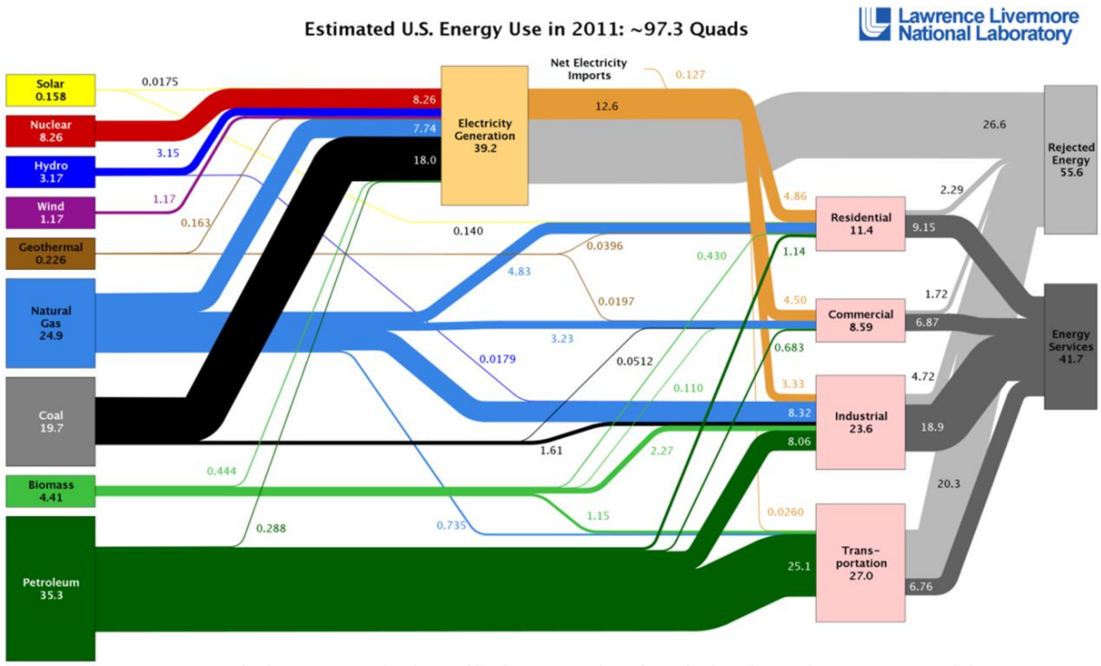


Figure 1: U.S. Total Energy Flow in 2011 (Lawrence Livermore National Laboratory 2010)

An efficient method of energy generation which can be used in urban environments is combined heat and power (CHP). CHP is defined as any number of applied technologies that simultaneously produce two or more forms of energy from a single fuel source (Schultz 2010). CHP systems provide electrical and thermal energy at high efficiencies typically by utilizing excess heat from the process of electricity generation. The CHP systems examined in this paper use microturbines as the prime mover. Within these systems natural gas fuels the microturbines to produce electricity, and excess thermal energy from the microturbines is used for thermal end uses. CHP systems require less fuel than equivalent separate heat and power systems to produce the same amount of energy for the end user, due to capturing and utilizing waste heat. This recovery of energy can provide significant advantages over conventional separate heat and power systems. CHP systems are an energy efficient technology which can reduce energy consumption in the U.S. by utilizing waste energy from electricity generation, and which could be well-suited for installation in urban environments.

CHP systems installed at or near the energy end use are considered a decentralized method of energy generation. Decentralized CHP systems can provide a more reliable and resilient power supply, and improve U.S. energy security. CHP systems help diversify the U.S. energy supply by adding domestically produced and renewable fuels, and improve energy security by reducing the national energy requirements and helping businesses weather energy price volatility and supply disruptions (Shipley, Hampson et al. 2008). CHP systems contribute to energy security and infrastructure reliability as well by supplying energy for critical facilities and facilities vulnerable to supply disruptions. CHP can keep critical facilities running when local or regional grids fail, and protect facilities vulnerable to grid disruptions, such as data centers, from significant financial losses. CHP systems can often operate for long periods of time with minimal time required for maintenance and they provide a low-cost approach to new electricity generation capacity (Gillette 2010). Implementation of decentralized CHP systems can provide energy security, infrastructure reliability, and infrastructure resiliency benefits which can help relieve current and potential future issues in these areas within the U.S.

CHP system utilization can also create environmental benefits when compared with use of certain centralized energy generation technologies. CHP systems capture and use waste heat, so require less fuel than equivalent separate heat and power systems to produce the same amount of energy for the end user. This results in higher efficiency values in the system, and less fuel used overall (Shipley, Hampson et al. 2008). CHP systems also generally have lower levels of greenhouse gas and criteria pollutant emissions than traditional energy generation technologies. Decentralized CHP typically produces low levels of NO_x and CO, and is one of the most cost-effective methods for reducing CO_2 emissions. This reduction of emissions advances the nation's climate change and environmental goals, and provides an improved environmental quality while using clean, domestic energy sources (Shipley, Hampson et al. 2008).

Use of decentralized CHP systems may also provide water consumption benefits. The water-energy nexus describes the relationship between water and energy. Water and energy are interdependent; water cannot be collected and treated without energy, and energy cannot be generated without water. A shift in energy generation technology can impact the related water consumption, and a change in the amount of energy generation necessary to power a building impacts the amount of water consumed to provide that energy. The use of decentralized CHP systems to reduce energy-related water consumption would be beneficial, as the United Nations (UN) predicts that by 2025, 1.8 billion people will be living in countries or regions with absolute water scarcity, and two-thirds of the world's population could be living under water stressed conditions (United Nations 2013).

CHP systems are an energy efficient technology which can be well-suited for urban environments and which can reduce energy consumption in the U.S. by utilizing waste heat from electricity generation. CHP systems can provide a more reliable and resilient power supply, and improve U.S. energy security. CHP system utilization can also create environmental benefits when compared with the use of certain centralized energy generation technologies.

1.2 Research Questions

The concept of CHP has existed for over 100 years, but only recently has technology enabled the development of CHP systems on a micro scale (U.S. Department of Energy 2012). These recent breakthroughs have led to the creation of CHP system models and installations for micro scale applications. In order for the use of CHP systems to become more widespread and mainstream, studies must be performed which analyze the use of these systems in various conditions. This work examines the use of a microturbine-based combined heat and power system in residential and commercial scenarios and analyzes the technical and environmental feasibility of different system configurations. The research presented in this paper provides analysis of micro CHP systems in various applications, and contributes to the development and deployment of CHP systems in the U.S.

This thesis focuses on the use of a decentralized microturbine-based CHP system for energy generation in urban environments. Various CHP system configurations are analyzed within the urban environment for technical and environmental feasibility. The feasibility of the microturbine-based CHP system is compared with the traditional centralized energy generation system in the context of the urban scenario. This leads to the research question:

Is a microturbine-based decentralized CHP system more suitable for urban energy generation than certain centralized energy generation systems?

In order to answer this question, it is necessary to assess the technical and environmental feasibility of the microturbine-based decentralized CHP system for the urban environment. This is done by developing a model for the CHP system. This leads to the following research question:

How should a microturbine-based decentralized CHP system be modeled to understand the system feasibility for urban scenarios and to determine the associated environmental impacts of this type of energy generation?

Developing a model for the microturbine-based decentralized CHP system makes it possible to analyze the system performance for specific urban scenarios. In addition, a model enables the identification of the decentralized CHP system environmental impacts, and the comparison of these to the impacts of a centralized energy system. Within this work the technical and environmental feasibility of the decentralized CHP system is examined for three specific scenarios: an R1 single-family residential building, an R6 6-story residential building and a 2-story office building. The environmental impacts considered are the energy system water consumption, and the total NO_x, SO_2, CO_2, CH_4, and N_2O emissions produced by the energy system.

This work examines the use of a microturbine-based decentralized CHP system in residential and commercial scenarios and analyzes the technical and environmental feasibility of different system configurations. The research presented in this paper provides analysis of micro CHP systems in various applications, and contributes to the development and deployment of micro scale CHP systems in the U.S.

1.3 Approach and Methodology

The research questions posed in this paper were addressed through the development of a model for a microturbine-based decentralized CHP system. The model created and analysis performed demonstrated the feasibility of the microturbine-based

CHP system for various scenarios, and showed the environmental impacts of these systems compared with the use of centralized energy generation technologies. This study specifically focused on water consumption and the total NO_x, SO_2, CO_2, CH_4, and N_2O emissions associated with microturbine-based CHP systems and centralized energy generation. The following details the development of the full CHP system model, and the methodology behind the feasibility study and environmental analysis performed.

A model was created for a microturbine-based decentralized CHP system. Shown in Figure 2 is an overview flowchart for the full CHP system analyzed. As shown in Figure 2, the full CHP system model included several models within it. The models which comprised the full CHP system model were: the Google SketchUp model, the EPlus model, the eQUEST model, the HOMER Energy model, and the CHP system model built in MS Excel. The SketchUp, EPlus, eQUEST and HOMER Energy models were external energy modeling software, while the CHP system model built in MS Excel was developed specifically for this thesis. The models in the top zone in Figure 2 were the building energy models used, the CHP system model in the middle zone took inefficiencies of the CHP system into consideration, and the model in the bottom zone of Figure 2 was the HOMER Energy model, which performed the microturbine sizing and simulated the microturbine.

The full CHP system analyzed was modeled using combinations of several energy models. Two different methods were used to simulate the building energy demand. For Method 1, the building geometry was created in SketchUp, and this was input to the EPlus program with the building location file, weather file, and building specifications. EPlus produced building energy demand data for the building designed. This data was then entered into the CHP system model built in MS Excel. The CHP system model used the building energy demand data and considered CHP system inefficiencies to determine the desired electrical and thermal microturbine output for the full CHP system. The detailed steps which occurred within the CHP system model are shown in Figure 3 and subsequently discussed. The CHP system model built in MS Excel produced data on the desired electrical and thermal microturbine output, which was an input for the HOMER Energy model. The microturbine conditions and microturbine specifications for the building considered were also HOMER Energy inputs. The HOMER Energy model sized the microturbine for each CHP system and simulated the performance of the microturbine. HOMER Energy then gave the optimal size of microturbine, and the amount of electrical and thermal energy it provided.

The second method used to simulate the building energy demand incorporated the eQUEST model instead of the SketchUp and EPlus models. For Method 2, the building geometry and specifications, location file and weather file were input to the eQUEST program. eQUEST produced building energy demand data for the building designed. This data was then used in the CHP system model built in MS Excel. The CHP system model took the building energy demand data and considered CHP system inefficiencies to determine the desired electrical and thermal microturbine output for the full CHP system. This data on desired electrical and thermal microturbine output was then used in the HOMER Energy model with inputs on the microturbine conditions and microturbine specifications for the building considered. Again the HOMER Energy model sized the microturbine for each CHP system and simulated the performance of the microturbine. HOMER Energy then gave the optimal size of microturbine, and the amount of electrical and thermal energy it provided. Methods 1 and 2 in the CHP system analysis used different models to simulate the building energy demand data, but utilized the same models to consider CHP system inefficiencies and to size and simulate the microturbine.

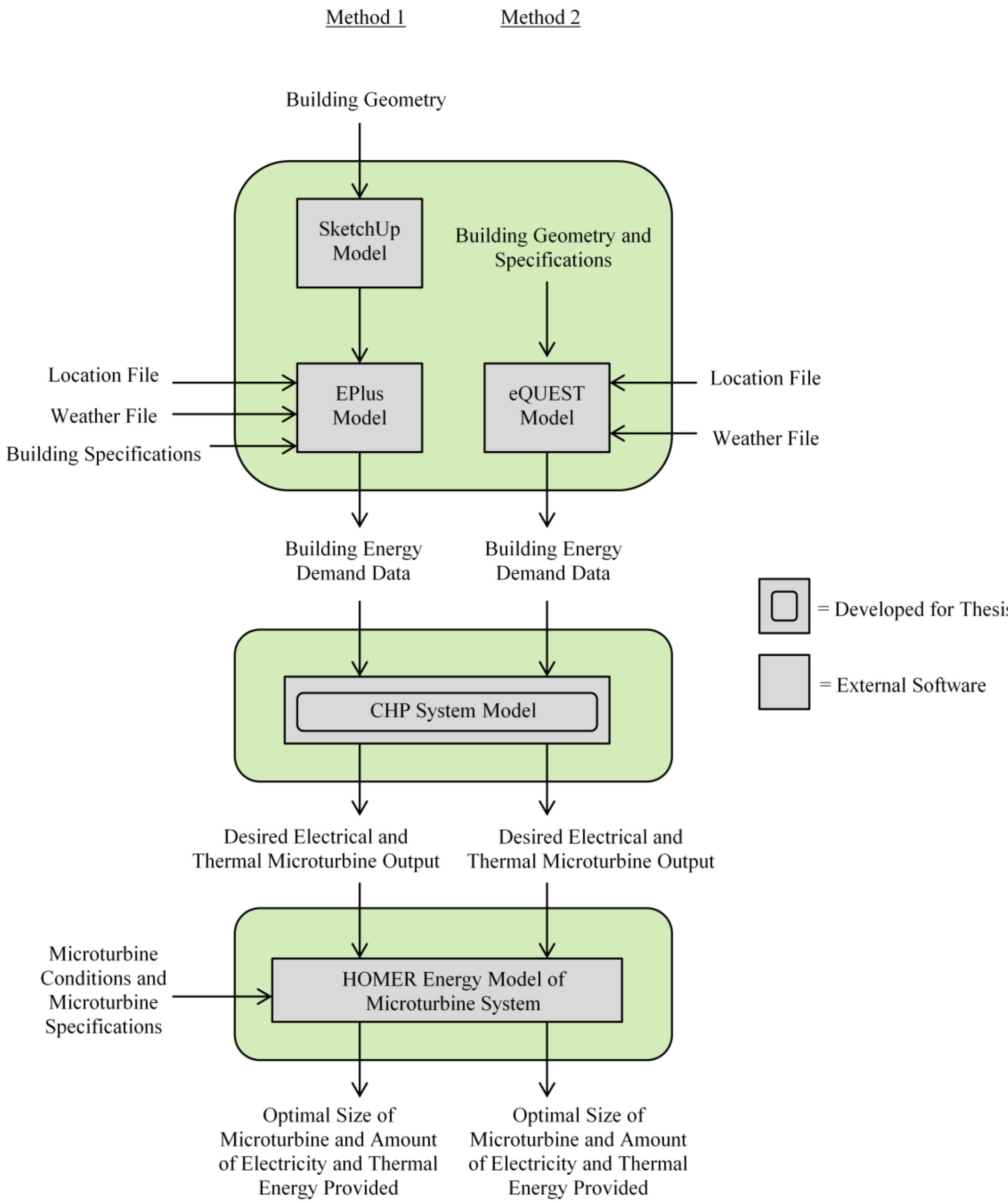


Figure 2: Overview Flowchart for Full CHP System Analyzed

The CHP system model built in MS Excel used building energy demand data and a CHP system configuration to determine desired electrical and thermal microturbine output. Shown in Figure 3 is a flowchart of the processes which occurred within the CHP system model.

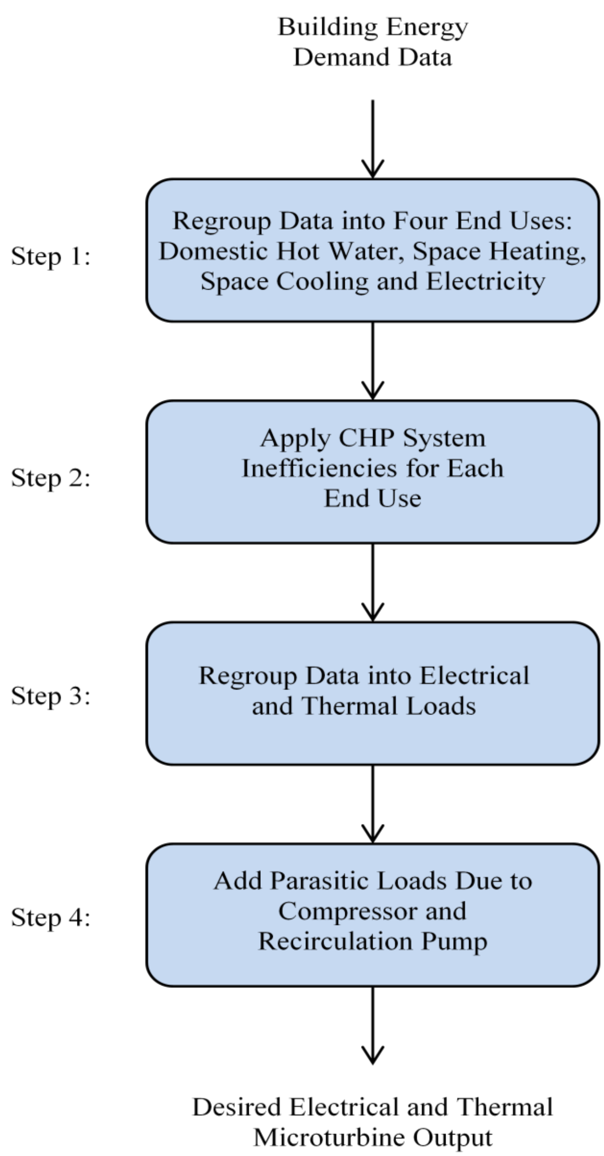


Figure 3: Overview Flowchart for CHP System Model

In Step 1, the building energy demand data was regrouped into the four end uses of the CHP system model: domestic hot water, space heating, space cooling and electricity. In

Step 2, CHP system inefficiencies were applied for each end use identified. In Step 3 the data was regrouped into two categories, electrical and thermal loads. Electricity was considered the electrical load, and domestic hot water, space heating and space cooling were considered the thermal loads. In Step 4, the parasitic loads due to the compressor and recirculation pump were added to the electrical and thermal loads. This gave the desired electrical and thermal microturbine output. Figure 3 shows a flowchart of steps which occurred within the CHP system model built in MS Excel. This model was developed for this thesis, and used within the full CHP system model.

The full CHP system model created demonstrated the feasibility of the microturbine-based CHP system for various scenarios, and showed the environmental impacts of these systems compared with the use of centralized energy generation. The feasibility of the CHP systems for specific scenarios was analyzed based upon the calculated desired electrical and thermal microturbine output and the amount of electrical and thermal energy provided by the microturbine. The environmental impact of these systems was determined based upon the system emissions production and water consumption. The calculated environmental impact of the CHP systems was compared to the emissions production and water consumption of traditional centralized energy generation in order to understand the benefits of decentralized CHP systems.

The full CHP system model was analyzed using both the EPlus and eQUEST building energy demand models for three types of buildings: an R1 single-family residential building, an R6 6-story residential building and a 2-story office building. The definitions of the buildings examined came from the City of Atlanta Office of Planning (City of Atlanta 2013). This office designates zoning in Atlanta, and the buildings considered were assumed to have a location of Atlanta, Georgia. The zoning of each building determined the building geometry and specifications used in the EPlus and eQUEST building energy models.

The background and methodology for the full CHP system models developed are presented in Chapters 2 and 3. Sections 2.1 to 2.5 give information on CHP systems, their applications, potential benefits and barriers to CHP system deployment and previous studies on CHP system models and installations. Sections 2.6, 2.7 and 2.8 provide background on the eQUEST, EPlus and HOMER Energy models, while Section 2.9 provides background on the CHP Emissions Calculator. Section 3.1 discusses the methodology behind the eQUEST and EPlus building energy demand models, and Section 3.2 discusses the methodology behind the HOMER Energy model. Section 3.3 presents the CHP system model built in MS Excel. Within this section, the CHP system components and end use products are discussed and a diagram of the model is shown and examined. Then the system efficiencies and modes of operation for the CHP system model are developed. Once the CHP system model is described, Section 3.4 presents the full CHP system model as it applies to the R1 residential, R6 residential and 2-story office building scenarios. Section 3.5 discusses a methodology to calculate the emissions and water consumption associated with utilization of CHP systems. In this section a methodology is also presented for calculation of emissions and water consumption due to traditional centralized energy systems.

The results for the full CHP system model are presented and discussed in Chapter 4. Section 4.1 details the eQUEST and EPlus model results for the three building scenarios examined, and Section 4.2 presents a validation and comparison of the building energy demand model results. In Section 4.3 the system efficiencies considered in the CHP system model built in MS Excel are discussed. These system efficiency values are then used in the full CHP system model. Section 4.4 presents the results for the full CHP system model using the eQUEST building load data, and Section 4.5 presents the results for the full CHP system model using the EPlus building load data. The full CHP system model using each of these data sets is given for the R1 residential building, the R6 residential building and the 2-story office building. Section 4.6 presents an analysis of the full CHP system model designed for each of the three building scenarios to determine the emissions and water consumption of each system. These results are compared with the emissions and water consumption due to traditional centralized energy systems. The results presented in Section 4.6 are then discussed in Section 4.7. Section 4.8 utilizes the CHP system model results provided in Sections 4.4, 4.5 and 4.6 and scales up these results to present the number of microturbines, emissions production and water consumption which result from using CHP systems to power the R1, R6 and 2-story office buildings in all of Metropolitan Atlanta. Section 4.9 then presents a CHP system sensitivity analysis for the thermostat setpoints used in the simulations, and Section 4.10 provides a CHP system results summary.

The conclusions for the thesis are presented in Chapter 5. Section 5.1 covers a summary of the work completed, and Section 5.2 discusses the research questions posed in Section 1.2, and summarizes the answers provided by the thesis research. Section 5.3 discusses future work.

The research questions posed in this thesis were addressed through the development of a model for a microturbine-based decentralized CHP system. The model created and analysis performed showed the feasibility of the microturbine-based CHP system for various scenarios, and demonstrated the environmental impacts of these systems compared with the use of centralized energy generation technologies.

CHAPTER 2

BACKGROUND AND LITERATURE REVIEW

This chapter presents combined heat and power systems and discusses their technical details and configuration options. For each configuration option discussed several points are examined. Points studied for each configuration option include: a description of the technology option and how it works, its electrical and overall efficiencies, the technology sizes available, the fuels used and emissions for the system, benefits and limitations of the technology, the system's thermal output and how it can be used, and cost of the technology. The research presented in this paper focuses on CHP systems which include microturbines, and microturbines have many similar properties as gas turbines. As a result, microturbines and gas turbines are studied in greater depth than the other configuration options. For microturbines and gas turbines a review of technology performance as a function of turbine conditions is discussed, as well as a more complete discussion of the technology components. Applications for these systems are then examined, followed by the benefits and barriers to CHP system installations.

The relevant literature on CHP system models and installations is then presented, which includes: proposals for and installations of CHP systems, development of CHP system optimization models, and methodologies for calculating CHP system characteristics. Background is then provided on the software used in the analysis of the full CHP system model. The EnergyPlus energy simulation software, eQUEST building energy simulation tool, HOMER energy modeling software and CHP Emissions Calculator are each described, including the program inputs, outputs and capabilities. This chapter presents the background information relevant for understanding the research outlined in this paper. This includes background on CHP systems and their applications, benefits and barriers to CHP system installations, previous studies on CHP systems and background on the software used in the analysis presented in this paper.

2.1 Combined Heat and Power System Description

CHP systems are an energy technology that provides electrical and thermal energy at high efficiencies by utilizing excess heat from the process of electricity generation. CHP is used to either supplement or replace conventional separate heat and power systems. Energy users typically purchase electricity from the local utility and burn fuel for a boiler to produce steam or hot water, but by using CHP systems those energy users can provide both electrical and thermal energy services in one efficient process. Shown in Figure 4 are the efficiency benefits of CHP. CHP systems require less fuel than equivalent separate electrical and thermal energy systems to produce the same amount of energy for the end user by capturing and utilizing waste heat.

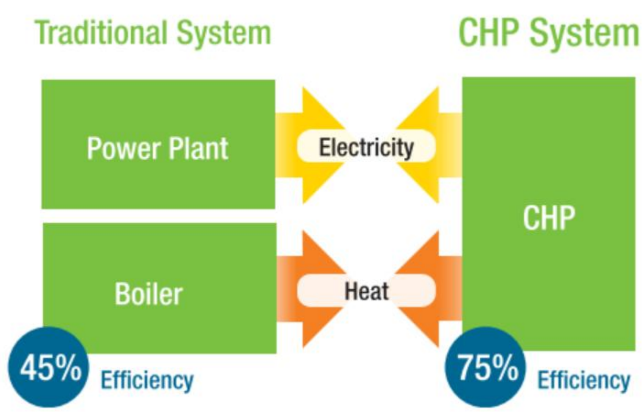


Figure 4: Efficiency Benefits of CHP Systems (U.S. Department of Energy 2012)

All CHP system applications involve the recovery of thermal energy that would be otherwise wasted to produce additional electricity or thermal energy (U.S. Department of

Energy 2012). This recovery of energy can provide significant environmental and energy efficiency advantages over conventional separate heat and power systems. CHP systems often operate at 65 to 75% efficiency, while a traditional system operates at a national average of 45% efficiency. CHP systems can have applications in a range of settings, but this work focuses on CHP systems used in decentralized, on-site energy generation.

2.2 CHP System Configuration Options

CHP is defined as any number of applied technologies that simultaneously produce two or more forms of energy from a single fuel source (Schultz 2010), and this broad definition results in many configuration options for CHP systems. CHP systems are typically identified based upon their prime movers or technology types, which include reciprocating engines, combustion or gas turbines, steam turbines, microturbines and fuel cells. These prime movers can operate using a range of fuels, including natural gas, coal, oil and alternative fuels (Shipley, Hampson et al. 2008). CHP systems are also classified based upon the order in which energy flows through the components of the system. In a topping cycle, fuel is used to power a prime mover then the excess thermal energy from the process is used for heating, cooling and dehumidification applications. The alternative to a topping cycle is a bottoming cycle, in which fuel is used to drive thermal processes, and the excess thermal energy is used to produce power (Schultz 2010). Four of the prime movers most common in CHP systems: reciprocating engines, gas turbines, microturbines and fuel cells are all used in topping cycles, while steam turbines are typically used in bottoming cycles.

2.2.1 Reciprocating Engines

Reciprocating engines are the most common technology for power generation, and are often used for both small portable generators and larger industrial applications (Shipley, Hampson et al. 2008). Reciprocating engines are readily available, cost-effective, are reliable and have a fast start-up capability, but also can produce relatively high emissions levels (Energy and Environmental Analysis Inc 2008d). While reciprocating engines are a well-established CHP technology, they present both benefits and limitations for the development of future CHP systems and installations.

Two basic types of reciprocating engines exist: spark ignition (SI) and compression ignition (CI). These engines both create mechanical energy in order to produce electricity, but achieve the result different ways. SI engines use a spark plug to ignite a fuel-air mixture in the cylinder, while CI engines compress the air in the cylinder to a high pressure, and this raises the temperature in the cylinder to the auto-ignition temperature of the fuel injected into the cylinder (Energy and Environmental Analysis Inc 2008d). Shown in Figure 5 are the main features of an SI and CI, or diesel engine. The CI engine uses a fuel injector, while the SI engine uses a spark plug to ignite the fuel-air mixture in the cylinder and produce mechanical energy. SI and CI engines operate using different fuels. When used in power generation applications, SI engines usually run on natural gas, but can also be configured to run on propane, gasoline, landfill gas or biogas (Shipley, Hampson et al. 2008). CI engines usually run on diesel fuel but can also be set up to run in a dual-fuel configuration that burns mostly natural gas with small amounts of diesel fuel (Energy and Environmental Analysis Inc 2008d).

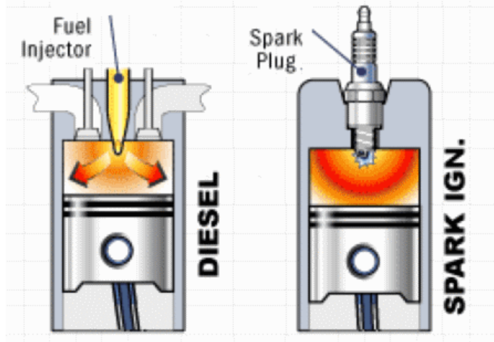


Figure 5: Main Features of Diesel and Spark Ignition Engines (King Abdullah University of Science and Technology 2013)

When used in CHP applications, reciprocating engines produce electricity and usable waste heat. The engines are available in sizes from 10 kW to over 5 MW, and electrical efficiencies range from about 25 to 45% (Onovwiona and Ugursal 2006). These efficiencies tend to increase with the size of the engine. A reciprocating engine has four sources of usable waste heat: exhaust gas, engine jacket cooling water, lube oil cooling water, and turbocharger cooling. This recovered heat is usually in the form of hot water or low pressure steam, so a CHP system with a reciprocating engine works well in a setting which requires these thermal outputs (Schultz 2010). The hot water and low pressure steam produced by reciprocating engine CHP systems can be utilized for low temperature process needs, such as space heating, space cooling or refrigeration, domestic hot water heating, or to power absorption chillers (Energy and Environmental Analysis Inc 2008d). Overall CHP efficiencies of 65 to 80% are typical with natural gas engine systems, and reciprocating engine performance degrades as the ambient temperature or site elevation increases. Reciprocating engines are generally rated at the International Organization for Standards (ISO) condition of 77ºF and 0.987 standard atmospheres (atm), but engine efficiency and power are reduced by about 4% per 1,000 feet of altitude above 1,000 feet, and by about 1% for every 10ºF above 77ºF (Energy and Environmental Analysis Inc 2008d).

The main environmental concern surrounding reciprocating engines are the exhaust emissions, with the primary pollutants being: NO_x, CO and VOCs. NO_x emissions are a critical consideration for reciprocating engines, and vary based upon the type of fuel used in the engine. A diesel engine run on heavy oil produces 900 - 1800 parts per million by volume (ppmv) NO_x, while a SI engine run on natural gas with a lean burn produces 45 - 150 ppmv NO_x (Onovwiona and Ugursal 2006). SI engines are able to run much cleaner than diesel engines, so SI engines are generally used over CI within CHP applications. In fact, SI engines fueled by natural gas or other gaseous fuels comprise 84% of the installed reciprocating engine CHP capacity (Energy and Environmental Analysis Inc 2008d).

Reciprocating engines have many benefits when used for CHP applications. They have a fast start-up capability, which makes them good for emergency power or peak power applications, and they have high efficiency in part-load operation, which makes them good for electrical load-following applications. In addition, they are readily available and reliable power generators, as long as they are provided the proper maintenance, and are a relatively cost-effective technology for the CHP application. The typical installed cost of natural gas, SI engine CHP systems range from about $1,100/kW to $2,200/kW, depending on the size of the engine, where cost per kW decreases as size increases (Energy and Environmental Analysis Inc 2008d). Reciprocating engines are a useful prime mover for CHP, but have both advantages and disadvantages within this application.

2.2.2 Fuel Cells

Fuel cells are a technology which use an electrochemical process to convert the chemical energy of hydrogen into water and electricity (Shipley, Hampson et al. 2008). The reactants, usually hydrogen and oxygen gas, are fed into the fuel cell reactor and the reaction which takes place produces electricity with water as a by-product. This overall reaction is exothermic, so the released heat can be harnessed for useful applications. The hydrogen used for fuel typically comes from a hydrocarbon fuel, for example natural gas, while the oxygen necessary for the energy-producing reaction comes from ambient air (Energy and Environmental Analysis Inc 2008a). Shown in Figure 6 are the key system components for a fuel cell. Hydrogen and oxygen gas enter the fuel cell reactor, and this reaction produces electricity, water and waste heat. The electricity produced travels to a power conditioner or inverter which converts the DC electricity into AC or regulated DC, and the waste heat produced is utilized by some heating installation.

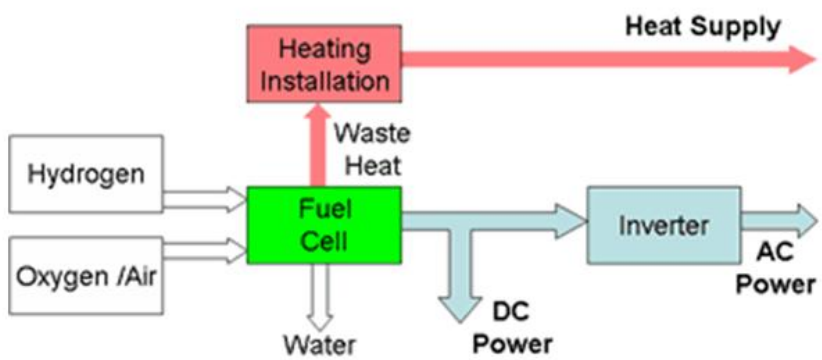


Figure 6: Fuel Cell Key System Components for CHP Applications (Woodbank 2005)

A fuel cell typically consists of three parts: the fuel cell stack that generates DC electricity, the fuel processor which converts the natural gas into hydrogen fuel, and the power conditioner. In most cases, heat recovered from fuel cell CHP systems is appropriate for low temperature process needs, domestic water heating and space heating (Energy and Environmental Analysis Inc 2008a).

The size and environmental impact of fuel cells make this technology ideal for CHP applications. Fuel cells are available in a variety of sizes: 200 to 1200 kW for commercial and industrial CHP applications, 3 to 10 kW for residential and commercial CHP applications, and 0.5 to 5 kW for back-up and portable power system applications. Fuel cells are constructed by combining individual cells which generate 100 W to 2 kW per cell, so virtually any system size is possible (Energy and Environmental Analysis Inc 2008a). The efficiencies of fuel cells range from 25 to 55%, depending on the type of fuel cell. The highest efficiency type is a solid oxide fuel cell, which averages 50% electrical efficiency. These high electrical efficiencies contribute to high overall efficiencies; fuel cells usually run at overall efficiencies of 65 to 85% (Energy and Environmental Analysis Inc 2008a). Fuel cells are designed for ISO conditions of 77ºF and 0.987 atm, and both the fuel cell output and efficiency performance degrade as ambient temperature or site elevation increase (Onovwiona and Ugursal 2006). In addition, since the fuel reacts electrochemically in the cells and is not combusted, this technology produces virtually no air pollution (Onovwiona and Ugursal 2006). The emissions which are produced are: < 2 ppmv CO, < 1 ppmv NO_x, and negligible SO_x (Energy and Environmental Analysis Inc 2008a).

Fuel cells have many characteristics which make them useful in CHP systems. Fuel cells are quiet and acceptable for indoor installation, as during normal operation they produce sound at a conversational level, 60 decibels (dBA) at 30 feet (Energy and Environmental Analysis Inc 2008a). Fuel cell systems may be installed in an indoor or outdoor setting. Fuel cells are modular and can be installed in small commercial or residential scenarios, and their electrical output is high quality, meeting critical power requirements without interruption. The primary fuel source for fuel cells is hydrogen, which comes from natural gas, coal gas, methanol, or other fuels containing hydrocarbons, but fuel cell systems can also be designed to operate on a variety of alternative fuels, including: liquefied petroleum gas, sour gas, biogas, industrial waste gases, and manufactured gases (Energy and Environmental Analysis Inc 2008a).

The significant limitation to use of fuel cells in CHP systems is expense. The cost of an installed system varies based upon: scope of the CHP system equipment, geographical area, competitive market conditions, special site requirements, labor rates, and whether the system is a new or retrofit application. The expense of the installed system also varies based upon the type of fuel cell used, but total plant cost ranges from about $5000/kW to $9000/kW. The CHP fuel cell systems also require expensive maintenance; these systems have few moving parts but stacks can have issues with seals and electrical shorting, and a stack rebuild is recommended every 5 to 7 years (Energy and Environmental Analysis Inc 2008a). Fuel cells are well-suited to CHP systems, but their comparatively high costs limit the number of installations of this CHP prime mover.

2.2.3 Steam Turbines

Steam turbines are one of the oldest and most versatile prime movers used to generate electricity. When steam turbines are used in CHP applications, they work with a boiler and generate electricity as a by-product of heat generation. Shown in Figure 7 are the primary components of a steam turbine system for CHP applications. Within this system a boiler burns fuel to produce steam, then that steam powers the steam turbine which produces electricity through a generator. The low pressure steam which exits the turbine is exhausted to a condenser which delivers the steam to its end use. The condensate from the condenser is returned to the pump, to be sent to the boiler and travel back through the cycle (Energy and Environmental Analysis Inc 2008e). This thermodynamic cycle on which steam turbines operate is the Rankine cycle.

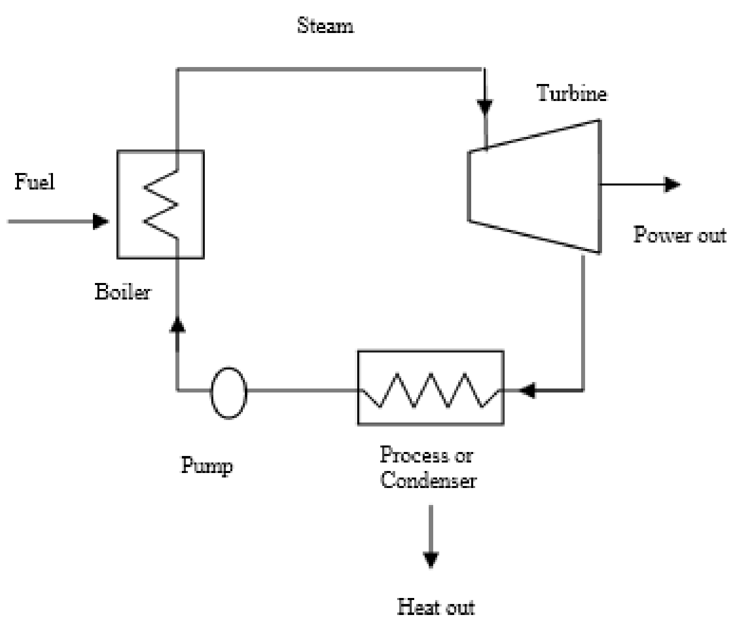


Figure 7: Steam Turbine Key System Components for CHP Applications (Energy and Environmental Analysis Inc 2008e)

The steam turbine system is useful for CHP applications due to the low pressure steam from the condenser which is available for use directly in a thermal process, or for use in building heating or cooling, used to provide domestic hot water, or used to provide chilled water (Energy and Environmental Analysis Inc 2008e).

Steam turbine-based CHP systems are costly, but have many benefits when compared with other prime movers. The fuel for a steam turbine CHP system is simply burned to create steam in a boiler, so a wide variety of fuels can be used to power steam turbines, including: natural gas, solid waste, coal, wood, wood waste, and agricultural by-products (Shipley, Hampson et al. 2008). A steam turbine-based CHP system has many interrelated subsystems which must often be custom designed. Installed cost for a steam turbine CHP plant includes costs for: the boiler, fuel handling, the storage and preparation system, stack gas cleanup and pollution controls, the steam turbine generator and field construction and plant engineering. The cost of the actual steam turbine is a fraction of the total cost for the system. Due to the complexity of the steam turbine-based CHP system, the costs are usually $2,000 to $3,000/kW or above (Energy and Environmental Analysis Inc 2008e). Since the costs of the systems necessary for steam turbines to operate within CHP systems are relatively high when compared with other prime mover options, they are typically installed in medium and large-scale industrial and institutional applications where the systems are most cost-effective. The expense of the systems is reduced even further when inexpensive or free waste fuels are available. Steam turbines are common in paper mills, an industrial setting with excess waste fuels, as well as in chemical plants and in the food industry (Energy and Environmental Analysis Inc 2008e).

Steam turbines have many benefits and several shortcomings when used for CHP applications. Steam turbines are commercially available in sizes from 50 kW to over 250 MW (Shipley, Hampson et al. 2008) and are very reliable. Steam turbines also have long lives; there are steam turbines which have been in service for over 50 years. The electrical efficiency of steam turbine power plants varies from 10 to 36%, depending upon the size and specifics of the system, and total CHP system efficiency is usually about 80% (Energy and Environmental Analysis Inc 2008e). Large steam turbines have long start up and shut down times, often several hours. The systems must be warmed up and cooled down slowly in order to minimize the differential expansion between parts within the technology. Emissions associated with steam turbine-based CHP systems are dependent upon the fuel used for the boiler, as well as the environmental conditions of the boiler. Typical emissions ranges for a boiler fueled by wood are: NO_x - 0.22 to 0.49 lbs/Million British thermal units (MMBtu), CO - 0.6 lbs/MMBtu and PM - 0.33 to 0.56 lbs/MMBtu. Typical emissions ranges for a boiler fueled by natural gas are: NO_x - 0.03 to 0.1 lbs/MMBtu and CO - 0.08 lbs/MMBtu (Energy and Environmental Analysis Inc 2008e). Steam turbines work well as CHP prime movers in medium and large-scale industrial and institutional applications, but are not the most cost-effective or efficient option outside these scenarios.

2.2.4 Gas Turbines

The gas turbine is a well-established power generation technology which operates on the thermodynamic cycle, the Brayton cycle. This system is composed of a compressor, a combustor and a turbine. The compressor takes air at atmospheric pressure and increases its pressure for entry into the combustor then the combustor combines this air with fuel and burns it. Next the hot exhaust gases are sent into the turbine, where the energy is converted into mechanical work (Schultz 2010). Shown in Figure 8 are the primary components of a simple-cycle gas turbine. The gas turbine system used for CHP applications produces electricity as a product of the turbine mechanical work, and produces gas turbine exhaust which can be 800ºF to 1,100ºF, depending on the type of turbine. These high exhaust temperatures allow the thermal energy to be used for direct industrial applications, used for heating or cooling of the building, used to provide domestic hot water, or used to provide chilled water. In addition, the high quality heat from the gas turbine exhaust allows the thermal energy to be used to provide electricity using a steam turbine along with the gas turbine in a combined cycle process (Energy and Environmental Analysis Inc 2008b). In a combined cycle, the gas turbine exhaust is used to power a steam turbine, and that steam turbine produces electricity which supplements the electricity produced by the gas turbine. In this configuration only electricity is produced for end use. As of 2008, most of the U.S. CHP installations which included gas turbines were large combined cycle systems (Shipley, Hampson et al. 2008).

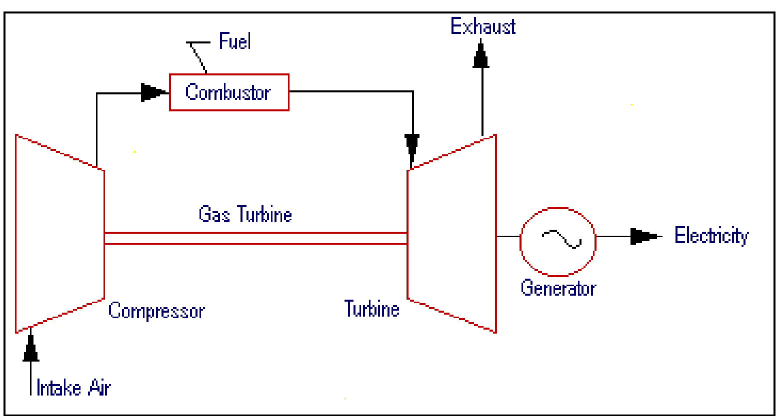


Figure 8: Gas Turbine Key System Components for CHP Applications (Renewable Energy Institute)

Gas turbines are efficient, cost-effective, and can run on a variety of fuels. Gas turbines are commercially available in sizes of several hundred kW to over 200 MW (Shipley, Hampson et al. 2008), and typically have electrical efficiencies of 20 to 40%, with overall system efficiencies of 65 to 80% (Energy and Environmental Analysis Inc 2008b). Gas turbines can operate using natural gas, petroleum fuels, synthetic gas, biogas or landfill gas, or can use a combination of these fuels (Shipley, Hampson et al. 2008). Typical emissions for a gas turbine are NO_x emissions below 25 ppmv and CO emissions in the 10 to 50 ppmv range. A gas turbine CHP system has many parts, the basic components are: the gas turbine, gearbox, electric generator, inlet and exhaust ducting, inlet air filtration, lubrication and cooling systems, standard starting system and exhaust silencing. The total cost of these components varies based upon the size of the gas turbine, but ranges from $900/kW to about $1,500/kW, with a typical cost of about $1,000/kW (Energy and Environmental Analysis Inc 2008b).

Gas turbines are used as the prime mover in a range of CHP system applications. A significant amount of gas turbine based U.S. CHP capacity is located at industrial or institutional facilities, where many of these systems are combined cycle. Some simple cycle gas turbine-based systems operate in applications such as: oil recovery, chemicals, paper production, food processing and universities. Simple cycle CHP applications are most common in smaller installations, typically in systems with turbines less than 40 MW (Energy and Environmental Analysis Inc 2008b).

One limitation to the use of gas turbines in CHP systems is the relation between gas turbine percent load and the efficiency of the system. Gas turbines reduce power output by reducing combustion temperature, so the gas turbine efficiency at part load operation can be much lower than at full capacity operation. Gas turbines do not follow load well, and become inefficient at low percent loads. Shown in Figure 9 is a typical part load performance curve for a gas turbine (Energy and Environmental Analysis Inc 2008b). The performance curve shows a significant decrease in electrical efficiency of the gas turbine as the percent load decreases, with very low efficiencies at loads below 50%. Emissions are also generally increased at part load conditions, especially at half load and below (Energy and Environmental Analysis Inc 2008b).

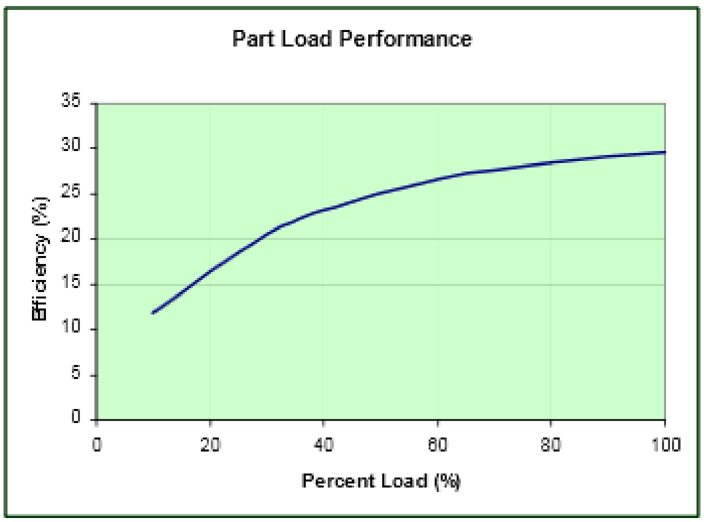


Figure 9: Part Load Performance for Typical Gas Turbine (Energy and Environmental Analysis Inc 2008b)

Gas turbines are designed for ISO conditions of 59ºF and an altitude of sea level, and changes in these ambient conditions impact the power output and efficiency of the gas turbine. As inlet air temperature for the gas turbine increases, both the power output and efficiency of the technology decrease. This is due to the corresponding decrease in inlet air density. A gas turbine can also produce more than its ISO-rated power at cool temperatures due to the increase in inlet air density (Energy and Environmental Analysis

Inc 2008b). Figure 10 shows the impact of ambient temperature on the power output and efficiency of a gas turbine. Changes in altitude also impact the power output and efficiency of the gas turbine. The density of air decreases as altitude increases, and so the percent of full load of the technology decreases. Figure 11 shows the impact of altitude on the gas turbine percent load (Energy and Environmental Analysis Inc 2008b).

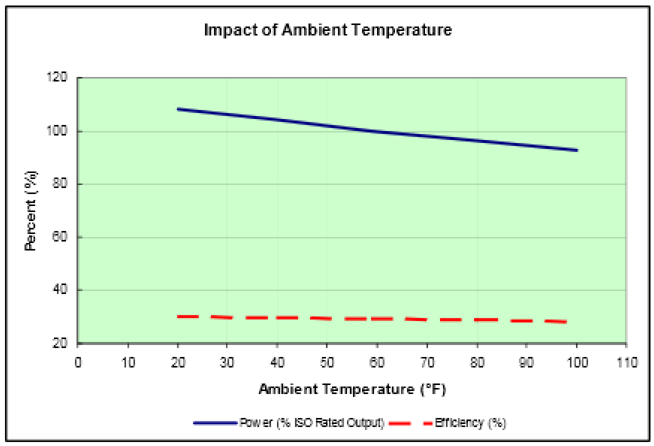


Figure 10: Impact of Ambient Temperature on Gas Turbine Power Output and Efficiency (Energy and Environmental Analysis Inc 2008b)

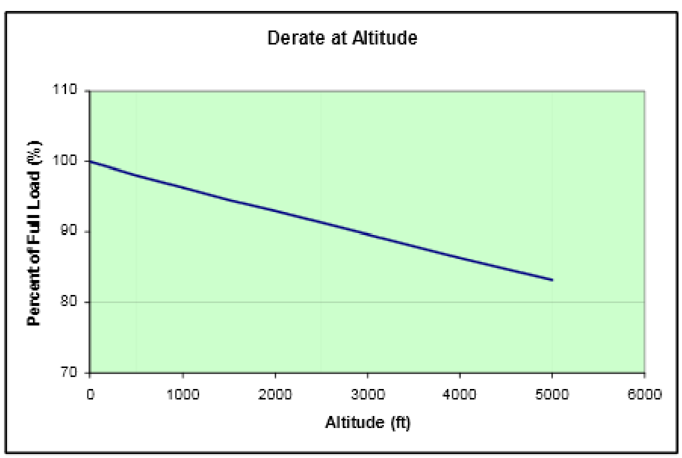


Figure 11: Impact of Altitude on Gas Turbine Percent Load (Energy and Environmental Analysis Inc 2008b)

When used in the right applications gas turbines are efficient and cost-effective, and their flexibility within installation configurations will continue to make this prime mover a favorable choice for CHP systems.

2.2.5 Microturbines

Microturbines are a relatively new technology which operate on the same principles as gas turbines but are smaller and thus more versatile for a variety of applications (Schultz 2010). Microturbines have few moving parts, and the technology has evolved from the turbochargers used in automotive applications and auxiliary power units for airplanes and tanks (Shipley, Hampson et al. 2008). Microturbines have the benefits of compact size, relatively light weight, low noise, low emissions and a quick start when compared with other prime movers (Onovwiona and Ugursal 2006). The first commercial microturbines only became available about 15 years ago, but this technology is well-suited for CHP applications.

Microturbines operate on the same thermodynamic cycle as larger gas turbines, the Brayton cycle. The basic components of a microturbine are: the compressor, generator, turbine and recuperator. Microturbines are designed in both one-shaft and two-shaft models. In a single-shaft model the compressor, turbine and generator are all mounted on one shaft. Shown in Figure 12 is a single-shaft microturbine-based CHP system (Energy and Environmental Analysis Inc 2008c). Within a microturbine, ambient air enters at the air intake and is compressed in the compressor. Fuel is burned in the combustor to raise the temperature of the compressed air, and the high pressure hot gases expand through the turbine to produce mechanical power for the generator. The recuperator recovers thermal energy from the hot gases to heat the compressed air before it enters the combustor. This reduces the amount of fuel consumed, thus increasing the efficiency of the system (Gillette 2010). The generator produces high-frequency electrical output, and this travels through a rectifier and an inverter to be converted into end use electricity.

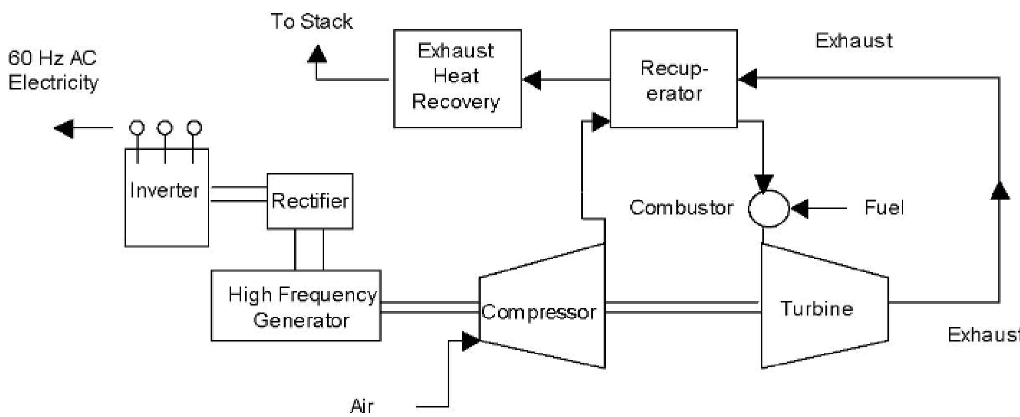


Figure 12: Single-Shaft Microturbine-Based CHP System (Energy and Environmental Analysis Inc 2008c)

Figure 13 shows a cutaway view of a 65 kW commercially available microturbine from Capstone Corporation. The basic components of the microturbine are shown, including the compressor, combustor, turbine, recuperator and generator.

Microturbines are designed in both one-shaft and two-shaft models, and there are distinct benefits to each type. In a single-shaft model, the expansion turbine turns the compressor and also turns the generator. This single moving part of the one-shaft design reduces the potential need for maintenance and increases overall reliability (Onovwiona and Ugursal 2006).

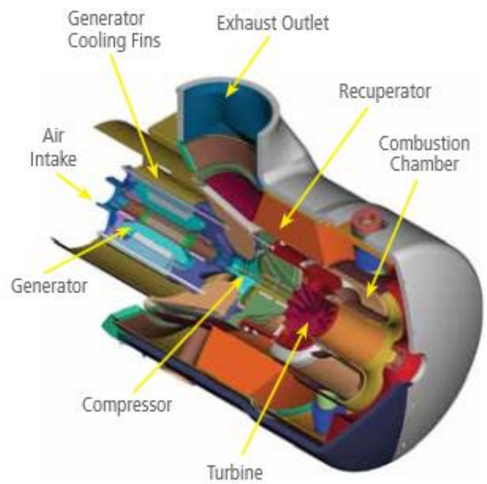


Figure 13: Cutaway View of Capstone 65 kW Microturbine (Capstone 2010)

In a two-shaft model the turbine on the first shaft directly drives the compressor, while a power turbine on the second shaft drives a gearbox and generator. The two-shaft design does not require power electronics to convert the high frequency alternating current (AC) into usable electricity as does the one-shaft design (Onovwiona and Ugursal 2006), although it does have a greater number of moving parts than the one-shaft design. Single-shaft microturbines generally operate at speeds over 60,000 revolutions per minute (rpm) and generate high frequency AC electrical power. This power is then rectified to direct current (DC), and inverted to 60 Hertz (Hz) 400 V to 480 V three-phase AC for consumer end use (Energy and Environmental Analysis Inc 2008c).

Microturbines are commercially available in sizes from 30 kW to 300 kW, and systems are scalable up to 10 MW (Shipley, Hampson et al. 2008). Microturbines have electrical efficiencies of 20 to 30%, with overall system efficiencies of 60 to 80% (Onovwiona and Ugursal 2006). These systems are usually designed to operate on natural gas as their primary fuel, but can also operate using: gasoline, kerosene, liquefied petroleum gas, biogas, sour gases, industrial waste gases, manufactured gases and diesel fuel (Energy and Environmental Analysis Inc 2008c). Microturbines have a design life between 40,000 and 80,000 hours depending upon the type of system and its application. Installed costs for microturbines can vary significantly depending upon the scope of the plant equipment, special site requirements, emissions control requirements, prevailing labor rates, geographical area, competitive market conditions and whether the system is a new or retrofit application. A microturbine-based CHP system capital cost averages $1,500/kW to $3,000/kW when equipment, labor, engineering and project management costs are all taken into account (Energy and Environmental Analysis Inc 2008c). Typical microturbine maintenance costs range from $0.010/kW to $0.025/kW, and vary depending upon the service contract and the size of the microturbine. Maintenance costs also benefit from economies of scale, to a small degree (Energy and Environmental Analysis Inc 2008c).

Microturbines have many benefits when used for CHP applications. They are compact and lightweight systems, and can operate continuously for long periods of time with minimal outage time for maintenance (Gillette 2010). Microturbines are also highly reliable, and work well for distributed generation applications due to their ability to be used in parallel to serve larger loads (Energy and Environmental Analysis Inc 2008c). Microturbines produce low levels of emissions; shown in Table 1 are the typical emissions for several microturbines. Microturbines typically have overall NO_x emissions below 10 ppmv and CO emissions below 50 ppmv. These values are lower than the emissions for a similar gas turbine, and for microturbines 65 kW and above, the emissions levels drop to about 5 ppmv for NO_x and 5 to 10 ppmv CO.

Table 1: Emissions for Microturbine Systems (Energy and Environmental Analysis Inc 2008c)

Emissions Characteristics*	System 1	System 2	System 3
Nominal Electricity Capacity (kW)	28	65	250
Electrical Efficiency, HHV	23%	25%	29%
NO_x, ppmv	9	4	5
NO_x, lb/MWh[13]	0.54	0.22	0.29
CO, ppmv	40	9	5
CO, lb/MWh	1.46	0.30	0.14
THC, ppmv	9	5	5
THC, lb/MWh	0.19	0.09	0.10
CO_2, (lb/MWh)	1,736	1,597	1,377

A significant difference between microturbines and larger gas turbines is the common use of recuperators in microturbines. A recuperator is an air-to-air heat exchanger which recovers thermal energy from the turbine exhaust gas, which is typically around 1200ºF, to preheat the air going into the combustor, which is typically around 300ºF. This reduces the amount of fuel needed to heat the air to the required turbine inlet temperature, and fuel savings of 30 to 40% is common by preheating using a recuperator (Onovwiona and Ugursal 2006). Recuperators also decrease the temperature of the microturbine exhaust, reducing the effectiveness of the microturbine in CHP applications. Microturbines with or without recuperators may be used within microturbine-based CHP systems, but in each case the waste heat from the microturbine is used for a variety of applications, including: for space heating and potable water heating, to drive absorption chillers or desiccant dehumidification equipment, and to supply thermal energy for process heating or other building uses (Energy and Environmental Analysis Inc 2008c).

Microturbines require bearings to support the internal shafts, and two types are typically used, oil-lubricated bearings or air bearings. Oil-lubricated bearings are mechanical and offer benefits in terms of life, operating temperature and lubricant flow. These are a well-established technology but require an oil pump, oil filtering system and liquid cooling which add to the microturbine cost and can increase maintenance requirements. Air bearings allow the turbine to spin on a thin layer of air, so that friction is low and rpm is high. In this system no oil or additional equipment is necessary, and there are no maintenance or reliability concerns. There is some uncertainty regarding the durability of air bearings under numerous and repeated starts due to the metal on metal friction which occurs during the startup, shutdown and load changes, but little data exists regarding these potential issues (Energy and Environmental Analysis Inc 2008c). Shown in Figure 14 is the patented air bearing used by Capstone Corporation in their microturbines. Use of these air bearings and air-cooling systems eliminates the need for cooling water and lubrication systems in microturbines (Shipley, Hampson et al. 2008).

Figure 14: Capstone Patented Air Bearing (Capstone 2010)

Microturbines show the same relations between temperature, efficiency and power as in gas turbines. When a microturbine is run at part load, the output is reduced by a combination of mass flow reduction and turbine inlet temperature reduction. When these conditions are changed, both the power output and efficiency of the microturbine are decreased. Figure 15 shows a typical part load performance curve for a 30 kW microturbine. The performance curve shows a significant decrease in overall efficiency of the microturbine as the percent load decreases, with very low efficiencies at loads below about 50% (Energy and Environmental Analysis Inc 2008c).

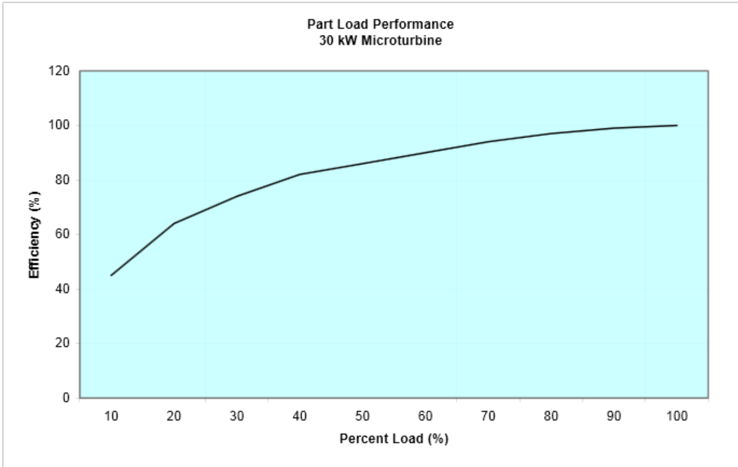


Figure 15: Part Load Performance for Typical 30 kW Microturbine (Energy and Environmental Analysis Inc 2008c)

The power output and efficiency of a microturbine are also impacted by the ambient conditions of the environment. Microturbines are designed for ISO conditions of 59ºF and an altitude of sea level, and changes in these ambient conditions impact microturbine performance. As ambient air temperature increases, both the power output and efficiency of the technology decrease. Figure 16 shows the impact of ambient temperature on the power output and efficiency of a 30 kW microturbine, and Figure 17 shows the impact of temperature on the power output and efficiency of a 70 kW microturbine (Energy and Environmental Analysis Inc 2008c).

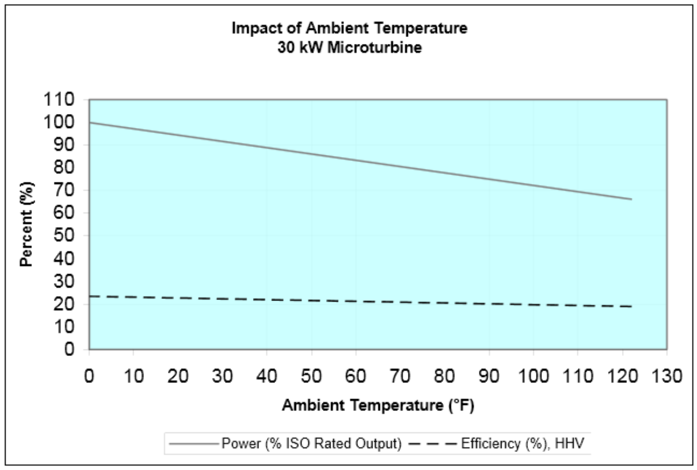


Figure 16: Impact of Ambient Temperature on 30 kW Microturbine Power Output and Efficiency (Energy and Environmental Analysis Inc 2008c)

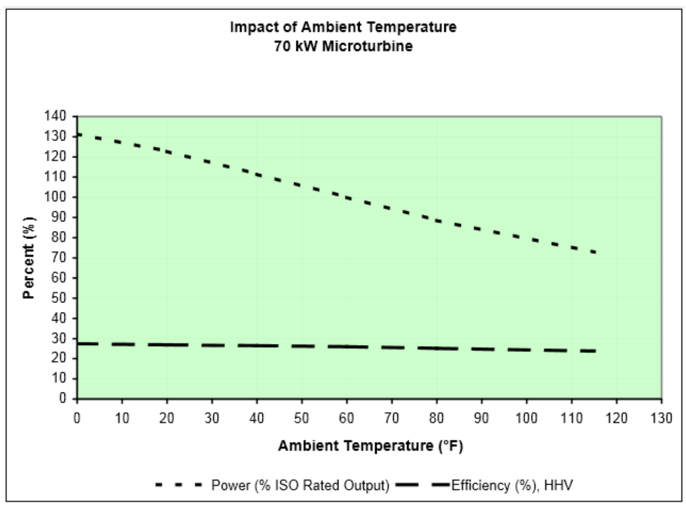


Figure 17: Impact of Ambient Temperature on 70 kW Microturbine Power Output and Efficiency (Energy and Environmental Analysis Inc 2008c)

Changes in altitude also impact the power output and efficiency of the microturbine. The density of air decreases with increasing altitude, and so the percent of full load of the technology decreases. Shown in Figure 18 is the impact of altitude on the microturbine percent load (Energy and Environmental Analysis Inc 2008c).

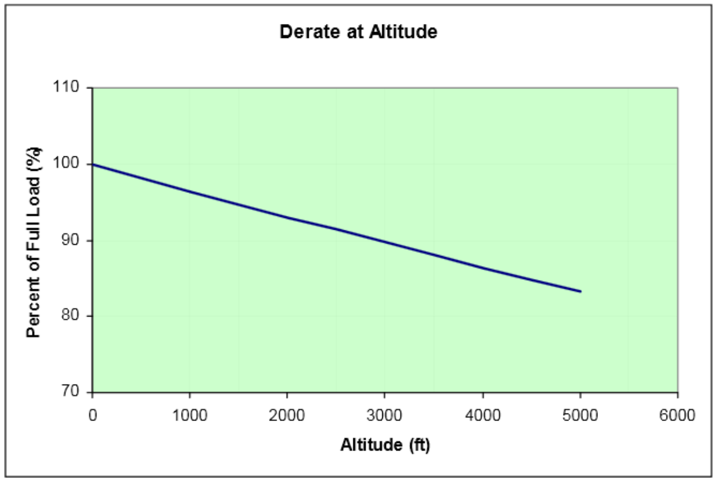


Figure 18: Impact of Altitude on Microturbine Percent Load (Energy and Environmental Analysis Inc 2008c)

The relationships between temperature, power output and efficiency can be used to improve overall microturbine performance. Within a microturbine, the power produced by a turbine and consumed by a compressor is proportional to the absolute temperature of the gas moving through these devices. Thus, the highest efficiency and specific power values are obtained by operating the turbine at the highest practical temperature and operating the compressor with the lowest practical inlet airflow temperature. In addition, as technology advances allow higher turbine inlet temperatures, the pressure ratio also increases, which contributes to higher efficiency and specific power (Energy and Environmental Analysis Inc 2008c). Overall the improvement process for microturbines is toward a combination of higher temperatures and pressures, and the drive toward higher temperatures and pressures is balanced by the need to use relatively inexpensive materials for the turbine which can withstand these conditions.

Microturbines are a technology well-suited for CHP applications. They are compact and have few moving parts, and are cost-effective, reliable and have a fast start-up capability. Although a fairly new technology when compared with other prime movers for CHP applications, microturbines are becoming more mainstream and affordable, and will contribute to the development and volume of installations of CHP systems.

2.3 Applications of CHP

CHP systems can be used in a wide variety of distributed generation applications, including commercial buildings, small and large industrial facilities, institutional facilities and campuses, district energy systems and single-family and multi-family residences. CHP currently represents about 8% of U.S. generating capacity, with an installed capacity of 82 gigawatts (GW). Existing CHP capacity in the U.S. is used for industrial, commercial and institutional applications. Shown in Figure 19 is the existing CHP capacity in the U.S. (U.S. Department of Energy 2012). 87% of existing U.S. CHP capacity is in industrial applications, with 13% in commercial and institutional applications.

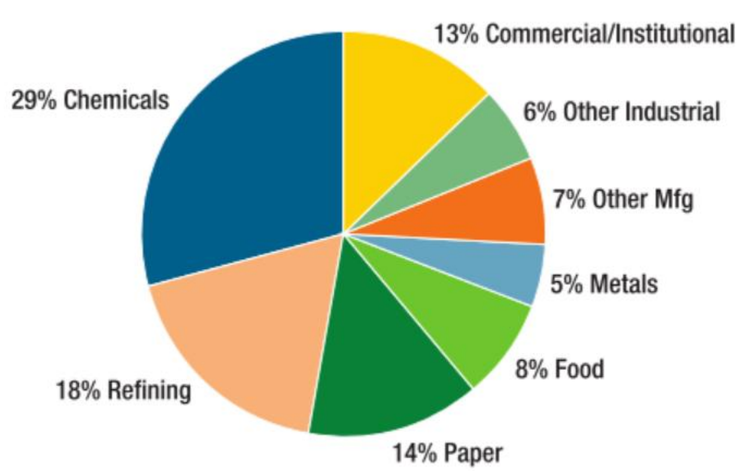


Figure 19: Existing CHP Capacity in the U.S. (U.S. Department of Energy 2012)

The industrial applications where CHP is currently used are: chemicals, paper, refining, food processing, and metals manufacturing, while CHP is used in commercial and institutional applications by providing electricity and thermal energy to schools, hospitals, hotels, nursing homes, university campuses, office buildings and apartment complexes (U.S. Department of Energy 2012).

CHP systems can be used anywhere in the U.S., but they are particularly well-suited for specific conditions and scenarios. CHP systems require a continuous thermal demand in order to operate efficiently, and the systems run most efficiently when the thermal demand is present close to 24 hours a day. The thermal demand can be for any application, including building heating or cooling, domestic hot water, domestic chilled water or desiccant dehumidification (Shipley, Hampson et al. 2008).

Commercial and institutional target customers for decentralized CHP systems include financial services, data processing, telecommunications, the hospitality industry and healthcare facilities (Farret 2006). Data centers require large amounts of thermal energy for cooling, so CHP can greatly reduce energy consumption in this application. The hospitality industry, such as hotels, casinos and resorts can also be a good application for CHP due to their thermal requirements. These facilities typically have on-site laundry, showers and other thermally intensive needs which require a constant supply of thermal energy (Gillette 2010). Industries such as financial services, telecommunications and healthcare benefit from the continuous supply of reliable, high-quality power provided by CHP systems. Reliable power in a healthcare facility protects patients and private information, while reliable power in financial services, telecommunications and other similar industries protects the companies against significant financial losses which result from grid disruptions (Shipley, Hampson et al. 2008).

Industrial applications particularly well-suited for CHP systems include resource recovery operations, petrochemical and petroleum refining, landfill operations, food processing and wastewater treatment operations. Large petrochemical and petroleum refining industries have high thermal demands so are a logical application for CHP, and food processing facilities have substantial losses associated with power outages, so high-quality, reliable power is vital (Shipley, Hampson et al. 2008). Wastewater treatment plants are also a fitting application for CHP systems. Treatment plants often produce waste gas as a by-product of the treatment process, and a prime mover can run on this gas to produce the electrical power needed at the treatment plant, while the heat produced can be applied to the digesters at the plant so they run at optimum efficiency (Gillette 2010). Similarly, landfill operations and resource recovery operations at oil and gas production fields, coal mines and wellheads also produce waste gas as a by-product. Locations for resource recovery operations are often remote from the grid, so the ability to use the waste gas from these operations to power a CHP system on site is particularly useful (Farret 2006).

CHP systems offer many benefits over separate heat and power for a wide variety of users and applications, including industrial manufacturers, commercial buildings, institutions and residential buildings. CHP systems are particularly well-suited for facilities with a constant thermal demand, but provide benefits in a wide variety of applications. 87% of existing CHP capacity in the U.S. is for industrial applications, while only 13% is for commercial and institutional applications. By developing and understanding CHP systems for underutilized applications, the number of CHP systems in the U.S. will continue to grow and CHP system users and the nation will experience its benefits.

2.4 Potential Benefits and Barriers to CHP System Deployment

There are many benefits to the implementation of CHP systems, but there are also potential barriers to CHP system deployment. CHP systems have environmental, local energy, economic, energy security, and infrastructure resiliency benefits. However, barriers to CHP installation include: a lack of education and awareness regarding the technology, uncertainties regarding costs of electricity and natural gas, uncertainties regarding the position of the electric utilities, and installation issues. Understanding these potential benefits and limitations helps continue to improve the technology and the way it is used, and this contributes to the reliability, resiliency and efficiency of the U.S. energy supply.

CHP systems can provide local energy benefits which are not provided by traditional centralized energy systems. CHP systems can operate 24 hours a day in any climate or location in the U.S., where many other energy technologies cannot (Shipley, Hampson et al. 2008). CHP is also a near-term solution; the technology needed to install these systems is available and cost-effective, and is not just a potential future option. CHP systems can provide power to remote applications where traditional power lines are not available, such as construction sites and offshore facilities (Farret 2006). In these remote cases the systems can often operate using nontraditional fuels considered waste or by-products, which have little to no cost associated with them (Shipley, Hampson et al.

2008). Decentralized CHP systems have local energy benefits not produced by traditional centralized energy systems, which can make CHP the optimal energy system available for an application.

CHP systems can create excellent environmental benefits when compared with traditional energy generation technology in the U.S. CHP systems capture and utilize waste heat, so require less fuel than equivalent separate electrical and thermal energy systems to produce the same amount of energy for the end user. This results in higher efficiency values in the system, and less fuel used overall (Shipley, Hampson et al. 2008). CHP systems also often have superior levels of greenhouse gas and criteria pollutant emissions compared with traditional energy generation technologies. Decentralized CHP typically produces low levels of NO_x and CO, and is one of the most cost-effective methods of reducing CO_2 emissions. This reduction of emissions advances the nation's climate change and environmental goals, and provides an improved environmental quality while using clean, domestic energy sources (Shipley, Hampson et al. 2008).

As the U.S. energy infrastructure ages and the availability of fuel resources becomes an issue, infrastructure resiliency and energy security have developed as important concerns in the U.S. CHP systems provide many benefits in these areas. When properly integrated, CHP can increase grid capacity, improve grid stability, and prevent power outages. This is accomplished through: load reduction, planning for grid congestion, reducing costly transmission and distribution infrastructure upgrade investments and deferring construction of generation and transmission and distribution equipment (Shipley, Hampson et al. 2008). Additional electrical capacity reduces strain on the electric grid, and by limiting congestion and offsetting transmission losses the resiliency of the energy infrastructure is improved. U.S. energy demand increases each year, but investment in energy infrastructure has not grown at the same rate as the energy demand. As a result, the current electricity and natural gas transmission and distribution systems are near capacity, especially in urban areas. Investment in distributed energy generation will help relieve the congestion in these areas, allowing the current transmission and distribution systems to continue to satisfy energy delivery needs while putting off or avoiding costly investments in energy infrastructure (Shipley, Hampson et al. 2008).

CHP systems can provide significant energy security and infrastructure reliability benefits. These systems help diversify the U.S. energy supply by adding domestically produced and renewable fuels, and improve energy security by reducing the national energy requirements and helping businesses weather energy price volatility and supply disruptions (Shipley, Hampson et al. 2008). CHP systems contribute to energy security and infrastructure reliability as well by supplying energy for critical facilities and facilities vulnerable to grid disruptions. CHP can keep critical facilities running when local or regional grids fail, and protect facilities vulnerable to grid disruptions, such as data centers, from significant financial losses. CHP systems can often operate for long periods of time with minimal time required for maintenance and they provide a low-cost approach to new electricity generation capacity (Gillette 2010). Implementation of CHP systems can provide many energy security and infrastructure reliability benefits which can help relieve current and potential future issues in these areas within the U.S.

CHP systems provide economic benefits for their continuing development and installation. Implementation of CHP creates reduced energy costs for the user as a result of decreased fuel use and project economics, and building and installing a CHP system creates U.S. jobs (Farrar and Punwani 2003). CHP system implementation in U.S. businesses can grow the economy by lowering energy costs for businesses, making them more competitive (U.S. Department of Energy 2012). In addition, some industrial plants must meet very low emissions limits, so when these restrictions are imposed CHP systems can be used to meet the emissions limits without the need to add expensive exhaust after-treatment equipment (Gillette 2010). The enhancement of power grid security which results from addition of CHP systems to the electric grid also has an economic impact; the CHP systems lessen the need for new transmission and distribution infrastructure, providing an economic benefit for the electric utilities and the energy consumer (U.S. Department of Energy 2012).

Installation of CHP systems creates many economic benefits, but market development is also impacted by the energy market conditions and related state and federal policies. CHP development in the near future will be powered by three important issues: the changing outlook for natural gas supply and price, state policymaker support for CHP, and changing market conditions for power and industrial sectors. The economics of CHP have improved as a result of the changing outlook in the long-term supply and price of natural gas in North America. The natural gas recovered from shale formations has created a large new domestic supply of the fuel, and this has led to a significant drop in natural gas prices. These continuing moderate and less volatile gas prices will be a strong incentive for CHP market development. Increasing state policymaker support for CHP is another important issue which will contribute to the development of the technology. Policymakers are increasingly recognizing the benefits of CHP, and beginning to adapt policies which encourage its implementation. CHP market development will also be impacted by the changing market conditions for the industrial and power sectors. Coal-fired power plants in the U.S. are aging, and prices for coal are slowly rising. In addition, the U.S. Environmental Protection Agency (EPA) recently finalized air regulations for the power sector which will require investments in pollution control technology at fossil-fired power plants which currently lack these controls (U.S. Department of Energy 2012). Traditional centralized energy generation systems are aging and becoming more expensive to operate, while policymakers are recognizing CHP as a beneficial alternative, and these systems are becoming more cost-effective. Current CHP systems can create significant benefits, and recent developments suggest increased CHP implementation in the future.

Many benefits exist for the implementation of CHP systems, but important potential barriers for their development must be addressed. Limitations to CHP development include: installation issues, a lack of education and awareness regarding the technology, uncertainties regarding costs of electricity and natural gas, and uncertainties regarding the position of the electric utilities. Electric utilities policies, attitudes and actions can have a significant impact on a CHP project's economics. Many facilities that install CHP remain connected to the grid for supplemental power, and utility tariff structures and standby rates along with a complex interconnection process can delay CHP projects or create added expenses. The structure of most electric utilities also directly links sales and revenue, which is a disincentive for utilities to encourage distributed generation such as CHP. Uncertainties regarding the position of the electric utilities are compounded with uncertainties regarding the costs of electricity and natural gas. CHP systems require a significant capital investment, and projects often provide a return on investment over the course of a long project lifetime. Volatile electricity and natural gas prices can make this a risky investment; slight changes in these prices can make a profitable CHP investment an unprofitable one, and the uncertainties surrounding this can make it unattractive to many potential investors (Shipley, Hampson et al. 2008).

Installation issues and a lack of education and awareness regarding CHP systems are also potential barriers for the development and implementation of CHP. The current CHP supply infrastructure is limited, as CHP is not presently a large market in the U.S. The size and focus of industry sales and service infrastructure is also limited, although this would most likely grow as demand for related products and services grows (U.S. Department of Energy 2012). Local permitting and siting issues can also cause problems for the development of CHP projects. CHP systems must comply with zoning, environmental, health and safety requirements at the site, and many local agencies have no experience with CHP projects or the technologies involved. This unfamiliarity can lead to a longer and more complex installation process, potentially increasing the cost of the project (U.S. Department of Energy 2012).

A lack of education and awareness regarding CHP systems can also create limitations for CHP development. Most business owners know little about CHP or its benefits compared with traditional options, and are sensitive to investment risks of CHP systems. These risks involve unknowns regarding environmental policy, utility and power market regulation and future economic conditions. This lack of information often results in reverting to the status quo of traditional centralized energy generation systems, and little to no development for CHP systems (U.S. Department of Energy 2012).

Potential barriers for the development of CHP include: installation issues, a lack of education and awareness regarding the technology, uncertainties regarding costs of electricity and natural gas, and uncertainties regarding the position of the electric utilities, and it is vital to address these issues in order for CHP systems to be more frequently implemented. There are many benefits to the deployment of CHP systems, but there are also potential barriers to its implementation, and understanding these will help to contribute to the reliability, efficiency and resiliency of the U.S. energy system.

2.5 Previous Studies: CHP System Models and Installations

The concept of CHP has existed for over 100 years, but only recently has technology enabled the development of CHP systems on a micro scale (U.S. Department of Energy 2012). These recent breakthroughs have led to an increased availability of relevant literature on CHP system models and installations. This section presents the pertinent CHP system installations and experimental models. The previous studies presented reveal a lack of literature on generalized CHP system models for specific building types. The research presented in this paper seeks to fill this space, contributing to the development and deployment of CHP systems in the U.S.

The most prevalent CHP system literature covers proposals for and installations of CHP systems. Some of these systems are developed and tested in the laboratory, but many of them are installed and studied on site. Two publications from Wagner, et al. examine the installation and operation of a microturbine-based CHP system at the Ritz-Carlton in San Francisco, California (Wagner, Sweetser et al. 2009), (Wagner and Rosfjord 2007). The objective of this project was to install, operate and monitor a CHP system, and the project took place under collaboration between the DOE, the Gas Technology Institute and Oak Ridge National Laboratory. The CHP system installed consisted of 4 60 kW microturbines, a double-effect absorption chiller, two fuel gas boosters and control hardware and software. The system produced electricity and hot or chilled water, and was capable of providing up to 227 kW of electricity and 142 refrigeration tons of chilled water at a 59ºF ambient temperature. The CHP system installed was monitored for one year, and data collected during this time was used to characterize the technical and economic performance of the system under normal operating conditions. Data collected included the power output for the microturbine and the entering and leaving temperatures for the thermal equipment. This data was used to calculate component and system efficiencies over the course of the year, energy delivered and overall energy savings from the CHP system. The studies from Wagner, et al. found that the hotel utilized all electrical energy produced by the CHP system, while the system provided an excess of thermal energy (Wagner and Rosfjord 2007), (Wagner, Sweetser et al. 2009). The publications also discussed the difficulties of installing a microturbine-based CHP system in an urban environment, and ways to overcome these challenges.

Two additional studies on CHP system installations were performed by the Greenhouse Gas Technology Center Southern Research Institute under a cooperative agreement with the U.S. EPA (U.S. EPA and Greenhouse Gas Technology Center Southern Research Institute 2003a), (U.S. EPA and Greenhouse Gas Technology Center Southern Research Institute 2003b). These studies were completed as part of the U.S. EPA Environmental Technology Verification Program, which facilitates the deployment and installation of environmental technologies through performance verification and education. These reports verified the performance of two CHP systems with microturbines as the prime movers. The first system developed was tested in a 57,000 ft^2 supermarket. This CHP system consisted of a Capstone 60 kW microturbine and a heat exchanger. The heat exchanger was connected to the store's air handling unit, which provided space heating, space cooling and dehumidification in the building. The second system was tested in a 60,000 ft^2 skilled nursing facility which provided care for approximately 120 residents. This CHP system consisted of an Ingersoll-Rand PowerWorks System, which included a 70 kW microturbine, and a heat exchanger. The heat exchanger was connected to the existing building equipment to provide domestic hot water and space heating. The two CHP system installations were each monitored for several weeks to collect performance data. The data collected verified the heat and power production performance of the systems, their power quality performance and their emissions performance. The studies showed that both the installed systems met performance expectations.

Although much of the CHP system literature details installations, many publications simply present proposals for CHP system designs. Gerstmann and Zogg each produced reports from private project teams working under U.S. DOE awards to propose CHP system installations (Gerstmann 2006), (Zogg 2006). The two reports each presented a project to develop and commercialize a micro CHP system for residential applications that provided electrical power, heating and cooling for the home. The CHP system proposed by Gerstmann's team supplied energy for a large single-family home. This system included a 4.7 kW generator driven by a reciprocating engine, where the engine supplied a thermal output of 12.5 kW. The CHP system also included a thermal storage unit, which was heated by the engine and which supplied hot water for domestic hot water use, space heating and dehumidification processes (Gerstmann 2006). The CHP system proposed by Zogg's team also supplied energy for a single-family home, but used a different system configuration. This system included a prime mover based on a free-piston Stirling engine power system with a generation capacity of 1.5 kW, where the excess heat from the prime mover provided space heating (Zogg 2006). The reports produced by both Zogg and Gerstmann's teams detailed the assessment of market requirements for micro CHP systems, preliminary system designs, detailed system designs, manufacturing cost estimates and commercialization plans.

The objective of the reports produced by Gerstmann and Zogg somewhat resembled the objective of the work presented in this paper, but the CHP system configurations chosen in these reports were vastly different from the microturbine-based system configurations studied in this paper, and so the system models developed were very different. It was notable that the reports produced by Gerstmann and Zogg outlined a CHP system configuration for a generalized single-family home. Most CHP system literature covers proposals for and installations of CHP systems for specific sites.

An additional proposal for a CHP system design was presented by Velumani et al. (Velumani, Enrique Guzmán et al. 2010). The hybrid CHP system analyzed included a 200 kW solid oxide fuel cell, a 30 kW microturbine and a single-effect absorption chiller. The model created was based upon experimental models, and the system used natural gas as its fuel. Excess heat from the fuel cell and microturbine powered the absorption chiller, which was used to provide air conditioning. The theoretical CHP system presented was designed to supply power to a commercial-scale building. Velumani et al.

performed a technical and economic analysis of the CHP system presented, and found that the installation costs for the designed system were very high compared with other commercially available CHP systems (Velumani, Enrique Guzmán et al. 2010). It was again notable that this study outlined a CHP system configuration for a generalized building, but the CHP system configuration analyzed was very different from the microturbine-based CHP systems studied in this paper.

Rocha, Andreos et al. and Petrov, Rizy et al. studied more traditional CHP system models which included microturbines as the prime movers (Rocha, Andreos et al. 2012), (Petrov, Rizy et al. 2005). Both of these studies focused on CHP systems which were developed and tested in the laboratory. Rocha, Andreos et al. examined two CHP systems; the first system tested used a prime mover of a 30 kW microturbine, while the second used a prime mover of a 26 kW natural gas powered internal combustion engine coupled to an electric generator. Both of the CHP systems examined also included an absorption chiller for producing chilled water and a heat recovery boiler to produce hot water. Experimental data was collected for the inlet and outlet temperatures and inlet and outlet flow rates for heat transfer medium and gases for each piece of equipment in each CHP system. This data was collected and used to draw conclusions regarding the energy production of the systems and their efficiencies (Rocha, Andreos et al. 2012).

Petrov, Rizy et al. also examined two CHP systems; the first system tested included a microturbine, a heat recovery unit and an indirect-fired desiccant dehumidification unit, and the second system tested included a microturbine, a heat recovery unit and a single-effect absorption chiller. The testing performed focused on the dynamic response of the systems for scenarios of cold start-up and power-dispatch. Data was collected for the inlet and outlet temperatures and inlet and outlet flow rates for heat transfer medium and gases for each piece of equipment used in the system. The data collected provided information on transition times and time constants for reaching steady-state operation of the CHP system. The studies performed by Rocha, Andreos et al. and Petrov, Rizy et al. both focused on CHP systems built and tested in the laboratory. The data collected by Rocha, Andreos et al. was used to understand CHP system efficiencies in order to reduce thermal energy losses, while the data collected by Petrov, Rizy et al. was used to understand the dynamic response of the CHP systems designed. Both studies produced valuable information on the experimental CHP systems developed, but the work also focused only on the systems analyzed and did not attempt to generalize the CHP systems designed for any modeling purposes.

While much of the CHP system literature examines specific installations, other publications center on the optimization of CHP system models. Ameli, Agnew et al. and Karki, Manohar et al. both discussed the use of decentralized energy system optimization models to analyze the economic and environmental performance of the system studied (Ameli, Agnew et al. 2007), (Karki, Manohar et al. 2007). Ameli, Agnew et al. presented the development of IDEAS, a comprehensive software package for designing, optimizing and monitoring distributed energy systems based on microturbines, fuel cells and IC engines. The study discussed the desired capabilities of the software, and the types of simulations which would be included in the software package. In order to demonstrate the IDEAS software concepts, a case study of a microturbine-based CHP system was detailed. The IDEAS software concept incorporated electrical and thermal system simulation, and economic models (Ameli, Agnew et al. 2007). The study performed by

Ameli, Agnew et al. details the requirements of developing IDEAS, but to date the software is incomplete, and the need for CHP system models which accurately predict performance data exists.

Karki, Manohar et al. studied and assessed the environmental, technical and economic benefits from using decentralized energy systems (Karki, Manohar et al. 2007). This work utilized a HOMER optimization model to quantify the energy and emissions savings achieved by using CHP systems with various prime movers. The study then presented an economic analysis comparing CHP and separate heat and power systems using net present cost and average cost of electricity. A case study of a commercial facility in New York was examined to validate the model. The model identified the least cost distributed generation system for satisfying the electrical and thermal load, and HOMER determined the optimal size and configuration of the distributed generation technologies. The HOMER analysis performed for the case study found the optimal system configuration was a 500 kW reciprocating engine and a 350 kW microturbine (Karki, Manohar et al. 2007). The study completed by Karki, Manohar et al. achieved similar objectives as that of the work presented in this paper, but the model presented by Karki, Manohar et al. utilized only the HOMER optimization model, which does not take into consideration the inefficiencies of the CHP system components other than the prime mover. The work presented in this thesis utilizes HOMER for identifying the optimal microturbine size for each scenario examined, but also develops the rest of the CHP system model and examines the performance of the full system. In addition, the work presented in this paper develops energy load models for three specific types of buildings.

CHP system optimization models were also designed and presented by Wang, Zhai et al. and Sanaye and Ardali (Wang, Zhai et al. 2011), (Sanaye and Ardali 2009). Wang, Zhai et al. developed a genetic algorithm optimization model of a CHP system which included the objective function, decision variables, constraint conditions and solution method. The model objective function was the cost of the system, and the initial parameters for the optimization model were technical, economic and environmental considerations. The optimization model developed was applied to the case study of a hotel, and the analysis performed showed relationships between the optimal cooling ratio, the absorption chiller's coefficient of performance (COP), the power generation unit efficiency, and the optimal capacity for the power generation unit (Wang, Zhai et al. 2011).

Sanaye and Ardali presented an optimization model of a CHP system which used an objective function of annual profit (Sanaye and Ardali 2009). Within this work annual profit took into consideration parameters such as: cost of conventional electricity and heat generation, costs of electricity and heat generation using a CHP system, and costs of buying and selling electricity to and from the grid. The CHP system studied used microturbines as the prime mover, and the microturbines were considered to be able to operate in partial load. Scenarios where electricity could and could not be sold back to the grid were each analyzed. The CHP model developed used an energy-economic analysis to select the appropriate type and number of microturbines for a building with specific electricity and heat load curves. This was achieved through system modeling and thermodynamic analysis, an estimation of energy cost in all flow lines, and a maximization of the annual profit objective function. The developed model of the CHP system was applied to the case study of a commercial building. This work identified the most profitable combination of microturbines for the scenario examined (Sanaye and Ardali 2009). The studies completed by Wang, Zhai et al. and Sanaye and Ardali each created an optimization model of a CHP system where the objective function was an economic consideration. The objective of optimizing a CHP system for specific scenarios was similar to the objective of the work presented in this thesis, but the work presented in this thesis did not size CHP systems based upon economic factors, and the methodology utilized by Wang, Zhai et al. and Sanaye and Ardali were each different than the methodology used in this paper.

A technical-economic approach to selecting the optimum power and number of microturbines for a CHP system was presented in a publication from Meybodi and Behnia (Meybodi and Behnia 2012). This approach was applied to small scale CHP systems for three modes of operation: one-way connection mode, two-way connection mode and heat demand following mode. Electricity purchases from the grid were allowed in all three modes of operation examined, while selling excess electricity back to the grid was only possible in the two-way connection mode and heat demand following mode of operation. The economic approach used for the analysis was based upon a net present worth method, and the economics of a possible carbon tax were also considered in the analysis (Meybodi and Behnia 2012). The approach developed was applied to the case study of an athletic center in Australia. It was again notable that this study had a similar objective as the work presented in this thesis, but the study focused on sizing the CHP systems based upon economic factors, where this thesis sized the systems based upon technical considerations.

A study completed by Chamra presented a methodology for calculating performance characteristics of small-scale CHP system components (Chamra 2008a). The study considered two CHP system configurations; the first system included an internal combustion engine, a heat exchanger, an absorption chiller and a boiler, and the second system included a diesel engine, a heat exchanger, an absorption chiller and a boiler. Thermodynamic cycles were used to model each individual CHP system component, then the individual component models were linked together to evaluate the performance of each of the full CHP systems. The CHP system models developed were applied to the case study of a commercial building for validation of the model. The CHP system models developed produced data on total monthly fuel consumption, system efficiencies and CHP system energy savings (Chamra 2008a). The thermodynamic CHP system component modeling used in this study was similar to the methodology for CHP system component modeling used in the thesis, but the CHP systems analyzed utilized different prime movers. In addition, Chamra's study used only one energy load data set in the model developed, while this thesis presents energy models for three different types of buildings, and these three energy load data sets are each used in the CHP system model.

Moné, Chau et al. investigated the economic feasibility of using a CHP system with a commercially available gas turbine as the prime mover, where the system included a commercially available single, double or triple effect absorption chiller to recover waste energy (Moné, Chau et al. 2001). The CHP system designed produced electricity, building heating and building cooling. Moné, Chau et al. examined the potential savings and payback of the CHP system with each type of absorption chiller, and found that the amount of heating and cooling available from rejected heat was significant, where the actual amount available to the absorption system was a function of the mass flow rate of the exhaust gas, the temperature of the gas, and the turbine size. The publication from Moné, Chau et al. discussed the potential financial savings from installing each type of CHP system examined, due to the avoided electrical costs and the avoided costs for thermal energy. The configuration of the CHP systems studied by Moné, Chau et al. were interesting and related to the CHP system configuration studied in this thesis, but the focus on economic feasibility of the system was not a focus of the thesis.

Although most of the CHP system literature available covers CHP system models and installations, the characterization of CHP system emissions is also a relevant topic. Canova, Chicco et al. examined the emissions from natural gas-fueled CHP systems, where the system prime movers were microturbines or internal combustion engines (Canova, Chicco et al. 2008). The emission factor model was used to characterize the emissions from natural-gas fired microturbines and internal combustion engines then the emission balance approach was used to characterize the local and global environmental impacts of using these systems. The criteria air pollutants produced by CHP systems, CO and NO_x, were analyzed in detail, as well as the CO_2 produced by the systems. The emission characterization developed was performed for two prime movers on the market, a microturbine and an internal combustion engine. Canova, Chicco et al. found that the microturbine had lower NO_x emissions than the IC engine, but when the microturbine operated at partial load the CO emissions increased dramatically. CHP system emissions were characterized for the CHP system models developed in this thesis, but Canova, Chicco et al. employed a different methodology than that used in the thesis.

Recent developments in CHP system technology have led to an increased availability of relevant literature on micro CHP system models and installations. This section presented the significant CHP system installations and experimental models. The previous studies presented reveal a lack of literature on generalized CHP system models for specific building types. The research presented in this thesis includes generalized CHP system models for three types of buildings, contributing to the development and deployment of CHP systems in the U.S.

2.6 eQUEST Building Energy Simulation Tool

The Quick Energy Simulation Tool (eQUEST) is a building energy use simulation program which allows the user to perform detailed analysis of building designs and technologies. This software was developed by James J. Hirsch & Associates in collaboration with Lawrence Berkeley National Laboratory, with the work performed mostly under funding from the United States Department of Energy (DOE) (Hirsch 2012). eQUEST uses a building creation wizard, an energy efficiency measure wizard, and a graphical results display module along with a simulation engine in order to produce building models. Inputs to these models include: a building's architectural features, its heating, ventilating, and air-conditioning (HVAC) equipment, the building's weather location, the building's footprint and orientation, its construction materials and U-values for those materials, and the building's occupancy schedule. Once a building model is complete, the simulation results can be viewed through a number of graphical formats. Overall estimated building energy use data is available on a monthly or annual basis, and detailed performance of individual building components may also be examined. The simulation provides data on the monthly electric and gas consumption of the building modeled, and these building consumption measurements are broken down based upon energy end use. The simulation also provides 2-D and 3-D views of the designed building.

The building energy simulation function of eQUEST, the ease of use of the program, and the reliability of its results made it an excellent source for realistic building load data. The ability of the program to simulate various regions of the country and to provide relatively generic load data for a particular type of building also made it a useful tool. The building simulations performed were completed using eQUEST version 3.64.

2.7 EnergyPlus Energy Simulation Software

EnergyPlus (EPlus) is an energy analysis and thermal load simulation program developed by the U.S. DOE. EPlus is used by engineers, architects and researchers to model energy use in buildings. EPlus models heating, cooling, lighting, ventilation, water use and other energy flows in buildings (U.S. Department of Energy 2013b). In order to create a building model using EPlus, the building is first modeled in a 3-D drawing interface. The 3-D building file is then imported into EPlus, and building features are input into the EPlus model. EPlus model inputs include: building materials and construction, building occupancy, building lighting and electric loads, HVAC system composition, thermostat setpoints, and building schedules. Once the building model is complete, a weather file is selected for the location of the building, and the model is simulated. EPlus includes many options for viewing results, and produces excel files of the selected output data. Output options for EPlus models include: time-based building energy consumption, building energy metering and time-based building component and zone energy consumption.

EPlus completes a rigorous thermodynamic analysis of each building simulated, and the level of detail necessary for the model inputs and the analysis performed results in highly reliable and accurate building load data. The accuracy of the data produced by this software makes EPlus an excellent tool for simulating building load data. The building simulations performed were completed in EnergyPlus version 8.0.0. The 3-D building files were created in Google SketchUp, and the Legacy OpenStudio Plug-in for SketchUp was used for the 3-D building models. EnergyPlus and the Legacy OpenStudio Plug-in for SketchUp are both available for download through the U.S. DOE, and Google SketchUp is also available for download online.

2.8 HOMER Energy Modeling Software

HOMER is an energy modeling software used to design and analyze distributed generation systems. This computer model simplifies the task of designing distributed generation systems, both on and off the grid, and allows the user to utilize a variety of technology options in the model. HOMER includes optimization and sensitivity analysis algorithms which help the user evaluate the economic and technical feasibility of the technology options, and which account for variations in technology costs and resource availability. HOMER was originally designed at the National Renewable Energy Laboratory (NREL), but is now licensed to HOMER Energy (Lilienthal 2009).

HOMER is used to design and analyze distributed generation systems, and the program provides many technology component options, including: photovoltaic panels, wind turbines, microturbines, generators and batteries. The program allows the user to identify loads for the system, such as electrical and thermal loads, and allows the user to specify whether or not the system is connected to the grid. The user sets up the framework for the system to be modeled, then enters specifications regarding the system equipment, the loads served by the system, the fuel used for the system components and the economics of the project. HOMER uses these inputs to simulate different system configurations and generate results which are viewed as a list of feasible configurations. HOMER also provides plots and tables which assist the user in evaluating the various system configurations possible.

The function of HOMER as a distributed generation design and analysis tool made it valuable for the study of CHP systems in urban environments. The ability of the software to simulate a microturbine then test various sizes of that microturbine relative to electrical and thermal loads provided important information on the design of the CHP systems for various scenarios. HOMER Legacy version 2.68 was used for the microturbine system design and analysis performed.

2.9 CHP Emissions Calculator

The CHP Emissions Calculator (CEC) is a tool used to estimate the net emissions produced by a CHP system. The CEC performs calculations to determine the anticipated carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), carbon dioxide equivalent (CO_2e), sulfur dioxide (SO_2) and nitrogen oxide (NO_x) emissions from a CHP system. The CEC then compares these emissions levels to those of a separate heat and power system. The CEC was originally developed by the Distributed Energy Program at the

U.S. DOE and by Oak Ridge National Laboratory. Subsequent enhancements have been supported by the U.S. Environmental Protection Agency (EPA) CHP Partnership (U.S. Environmental Protection Agency 2013).

The CEC is a MS Excel spreadsheet which calculates net emissions based upon inputs from the user. The spreadsheet inputs include: the type of CHP prime mover used, the system electric generating capacity, the number of hours per year the CHP system operates, the fuel used, the thermal outputs provided by the system, and the prime mover efficiency. In addition, the spreadsheet requires inputs which describe: the CHP system thermal equipment, the displaced electric system, and the displaced thermal system. Data on the displaced energy systems allows the CEC to calculate the difference in net emissions between the CHP system and a separate heat and power system. The CEC provides an annual emissions analysis which details the net emissions from the CHP system, and the net emissions from a separate heat and power system of comparable size.

The function of the CEC as a CHP system emissions analysis tool made it valuable for the study of CHP system environmental impacts. The analysis of the CHP system accompanied by the analysis of the comparable separate heat and power system was particularly useful, and the extent of detail required as inputs for the CHP systems produced well-developed results. The CEC available on the U.S. EPA Combined Heat and Power Partnership website, last updated August 29, 2012 was used for the emissions analysis performed (U.S. Environmental Protection Agency 2013).

CHAPTER 3

METHODOLOGY

This chapter presents the methodology behind the development of the full CHP system model. As shown in Figure 2 in Chapter 1, the full CHP system model includes several models within it. The models which comprise the full CHP system model are: the SketchUp model, the EPlus model, the eQUEST model, the HOMER Energy model, and the CHP system model built in MS Excel. The development of the eQUEST energy demand models for the R1, R6 and 2-story office buildings are first presented, followed by the development of the SketchUp and EPlus energy demand models for the same buildings. The creation of the microturbine system HOMER Energy model is then outlined and the configuration of this model and its inputs and outputs are discussed.

The development of the CHP system model built in MS Excel is then presented. First the CHP system components and end use products are discussed and a diagram of the model is shown and examined. Next the system efficiencies and modes of operation for the CHP system model are developed. Once the CHP system model is described, the development of the full CHP system model is presented as it applies to the R1, R6 and 2-story office building scenarios. The energy flow through the full CHP system model is detailed, as well as the way the inputs and outputs from each of the SketchUp, EPlus, eQUEST, HOMER Energy and CHP system models are connected. The final sections in this chapter present a methodology to calculate the emissions and water use associated with utilization of CHP systems. The methodology developed is applied to the CHP system models for the R1, R6 and 2-story office building scenarios. A methodology is also presented for calculation of emissions and water use due to traditional centralized energy systems.

3.1 Development of Building Energy Demand Models

3.1.1 eQUEST Model

Energy demand models were created for the R1 single-family residential building, the R6 6-story residential building and the 2-story office building using the eQUEST building energy simulation tool. The model for each of these buildings was designed using the Building Creation Wizard function within eQUEST. For each building model, inputs were added in the Building Creation Wizard then the building performance was simulated to produce energy consumption data for the building. Inputs to the building models included: architectural features, HVAC equipment, construction materials and U-values for those materials, the occupancy schedule, and the building's footprint, orientation and weather location. This section presents the inputs used for the three eQUEST models generated.

In order to create the eQUEST model for the R1 single-family residential building, model details were entered into the Building Creation Wizard. The building type was a multifamily low-rise, and the assumed location was Atlanta, Georgia. The home was two stories above grade and none below grade, with a total of 3,000 ft^2. The heating equipment was a furnace, and the cooling equipment was DX coils. The building footprint shape was a rectangle, with dimensions of 50 feet by 30 feet, and an orientation facing north. The building had 1,500 ft^2 per floor, with a floor-to-ceiling height of 8 feet. The house had a pitched roof with no attic, where the roof had a 25º pitch and a 2 inch overhang. The building had a standard wooden frame, with a shingle roof and insulation of R-1.3 and R-19 used in the walls. The house had 15% windows on all sides, where the windows were double-pane. The exterior finish of the building was wood, with a concrete ground floor and carpeted interior floors. The house had a steel front door on the north side, a sliding glass door on the south side and an additional steel door on the east side.

The building was assumed to operate on a typical use schedule of being unoccupied in the daytime, where Monday to Friday the building was unoccupied from 7 am to 5 pm, unoccupied on Saturday from 11 am to 4 pm, and Sunday from 1 pm to 4 pm. The maximum occupancy value was assumed to be 624 ft^2 per person. The interior end uses were: interior (ambient) lighting, cooking equipment, miscellaneous equipment, and self-contained refrigeration. The exterior end use was domestic hot water. The interior lighting was assumed to require 0.5 W/ft^2, the cooking equipment was assumed to require 1.13 W/ft^2, the refrigeration equipment was assumed to require 0.18 W/ft^2, and the miscellaneous equipment was assumed to require 0.3 W/ft^2. The HVAC system was a packaged single zone DX with a furnace, where the furnace was operated using natural gas. The seasonal thermostat setpoints were: occupied/unoccupied cool - 78ºF, occupied/unoccupied heat - 68ºF. The system had a minimum design flow of 0.5 cubic feet per minute (cfm)/ft^2, and it was assumed that 20 gallons of domestic hot water was used per person per day. The R1 residential building model assumptions for eQUEST are summarized in Table 2.

Table 2: Inputs for R1, R6 and Office Building eQUEST Energy Demand Models

Building Model Inputs	R1 Building	R6 Building	Office Building
Building Type	Multifamily low-rise	Multifamily mid-rise	2-Story office building
Location	Atlanta, GA	Atlanta, GA	Atlanta, GA
Number of Floors	2	6	2
Building Area	3,000 ft^2	46,000 ft^2	15,100 ft^2
Building Dimensions	50 ft by 30 ft	90 ft by 85 ft	86.9 ft by 86.9 ft
Orientation	Facing north	Facing north	Facing north
Heating Equipment	Furnace	Furnace	Furnace
Cooling Equipment	DX Coils	DX Coils	DX Coils
Floor-to-Ceiling Height	8 ft	8 ft	9 ft
Window Area	15% of wall area	15% of wall area	40% of wall area
Number of Doors	3	4	2
Thermostat Setpoints (Occupied Building)	Cool: 78ºF, Heat: 68ºF	Cool: 78ºF, Heat: 68ºF	Cool: 76ºF, Heat: 70ºF
Water Use	20 gallons/person/day	20 gallons/person/day	1 gallon/person/day

The eQUEST model created for the R6 6-story residential building had many similar inputs as the model created for the R1 building, but also some different inputs. The building type was a multifamily mid-rise with interior entries, and the assumed location was Atlanta, Georgia. The building area was about 46,000 ft^2, with 6 floors above grade and none below grade. The heating equipment was a furnace, and the cooling equipment was DX coils. The building footprint shape was a rectangle, with dimensions of 90 feet by 85 feet, and an orientation facing north. The zoning pattern was perimeter/core, where the perimeter zone depth was 25 feet. The building had 7,650 ft^2 per floor, with a floor-to-ceiling height of 8 feet. The building had a standard wooden frame, with insulation of R-1.3 and R-19 used in the walls, and R-38 insulation used in the roof. The building had a concrete ground floor and carpeted interior floors, along with a revolving glass door on the north side, steel side doors on the east and west sides, and a glass door on the south side. The building had 15% windows on all sides, where the windows were all double-pane.

The R6 building was assumed to operate on a typical use schedule of being unoccupied in the daytime, where Monday to Friday the building was unoccupied from 7 am to 5 pm, and on Saturday and Sunday it was unoccupied from 9 am to 4 pm. The building was composed of different area types, and each of these had different maximum occupancy values. The multifamily dwelling units made up 71% of the building area, and had a maximum occupancy of 624 ft^2 per person. The corridors made up 16% of the building area, and had a maximum occupancy of 1,000 ft^2 per person. Storage areas made up 7% of the building area and had a maximum occupancy of 500 ft^2 per person, and laundry areas made up 6% of the building area and had a maximum occupancy of 200 ft^2 per person. The corridors, storage and laundry areas were in the core of the building, while the residential units were in the perimeter of the building.

There were six residential units per floor, and within each unit the interior end uses were: interior (ambient) lighting, cooking equipment, miscellaneous equipment, and self-contained refrigeration. The exterior end use was domestic hot water. Laundry facilities were within each unit, and in these areas the lighting was assumed to require 1.28 W/ft^2. The residential areas had assumed lighting loads of 0.5 W/ft^2, the corridors had assumed lighting loads of 0.57 W/ft^2 and the storage areas had assumed lighting loads of 1.19 W/ft^2. The cooking equipment required 2.5 W/ft^2, the refrigeration equipment required 0.45 W/ft^2, and the miscellaneous equipment required 0.3 W/ft^2 in the residential areas and 0.15 W/ft^2 in the laundry areas. The HVAC system was a packaged single zone DX with a furnace. The seasonal thermostat setpoints were: occupied/unoccupied cool - 78ºF, occupied/unoccupied heat - 68ºF. The system had a minimum design flow of 0.5 cfm/ft^2, and it was assumed that 20 gallons of domestic hot water was used per person per day. The R6 residential building model assumptions for eQUEST are summarized in Table 2.

The eQUEST model of the 2-story office building had similar inputs to the residential models created, but was utilized for a different building use. The building type was a 2-story office building, and the assumed location was Atlanta, Georgia. The building area was 15,100 ft^2, with two floors above grade and none below grade. The heating equipment was a furnace, and the cooling equipment was DX coils. The building footprint shape was a square, with each side 86.9 feet long, and an orientation facing north. As in the R6 building, the zoning pattern was perimeter/core, where the perimeter zone depth was 15 feet. The building had 7,552 ft^2 per floor, with a floor-to-ceiling height of 9 feet. Insulation of R-2 and R-19 were used in the walls, the building had a concrete ground floor with carpeted interior floors, and the building had ceilings of lay-in acoustic tile. The office building had a glass door on the north side, and a steel door on the east side. The building had 40% windows on all sides, where the windows were double-pane.

The 2-story office building was assumed to operate on normal business hours, where the building was occupied from 8 am to 5 pm Monday to Friday, and unoccupied on Saturday and Sunday. The building was composed of different area types, and each of these had different maximum occupancy values. The offices made up 70% of the building area, and had a maximum occupancy of 225 ft^2 per person. The corridors made up 10% of the building area, and had a maximum occupancy of 150 ft^2 per person. The office lobby made up 5% of the building area and had a maximum occupancy of 150 ft^2 per person, the restrooms made up 5% of the building area and had a maximum occupancy of 52.5 ft^2 per person, and the conference room made up 4% of the building area and had a maximum occupancy of 22.5 ft^2 per person. In addition, the mechanical/electrical room made up 4% of the building area and had a maximum occupancy of 450 ft^2 per person, and the copy room made up 2% of the building area and had a maximum occupancy of 187.5 ft^2 per person. The lobby and mechanical/electrical room were both on the first floor of the building, and the offices were mostly on the perimeter of the building, while the corridors, restrooms, mechanical/electrical room, and copy room were all in the core of the building.

Each area in the building had different lighting and plug load values. These are shown in Table 3. The lighting load values ranged from 0.6 to 1.6 W/ft^2 depending upon the area type, and the plug loads ranged from 0.2 to 3 W/ft^2. During unoccupied building hours, some equipment was assumed to run at a percentage of the occupied building load. Plug loads were assumed to run at 20% of occupied load during unoccupied hours in the offices, mechanical/electrical room and the copy room, and plug loads were 0% everywhere else. Lighting was assumed to run at 10% of occupied load during unoccupied hours in the lobby and corridors, and was off everywhere else. The HVAC system was a packaged single zone DX with a furnace. The seasonal thermostat setpoints were: occupied cool - 76ºF, occupied heat - 70ºF, and unoccupied cool - 82ºF, unoccupied heat - 64ºF. The system had a minimum design flow of 0.5 cfm/ft^2, and it was assumed that 1 gallon of domestic hot water was used per person per day. The office building model assumptions for eQUEST are summarized in Table 2.

Table 3: Lighting and Plug Loads by Area Type for eQUEST Office Building Model

Area Type	Lighting Loads (W/ft^2)	Plug Loads (W/ft^2)
Office	1.3	1.5
Corridor	0.6	0.2
Lobby (office reception/waiting)	1.1	0.5
Restrooms	0.6	0.2
Conference Room	1.6	1
Mechanical/Electrical Room	0.7	0.2
Copy Room	1.5	3

Once all inputs were added to each of the building models, the Building Creation Wizard was closed and the building performance was simulated. This simulation produced a report on the monthly energy consumption by end use for the R1 residential building, the R6 residential building and the 2-story office building. These results are presented in Chapter 4.

3.1.2 EPlus Model

Energy demand models were created for the R1 single-family residential building, the R6 6-story residential building and the 2-story office building using the EnergyPlus energy simulation software. For each building model, a 3-D drawing of the building was created in Google SketchUp, and the building thermal zones were identified. The SketchUp building file was then imported into EPlus, and the IDF editor in EPlus was used to add building model inputs. Inputs to the building model included: building materials and construction, HVAC equipment, the building occupancy schedule and load schedules, a domestic hot water loop, the run period for the simulation and the building internal loads. A weather file for the building location was then selected from the EPlus launch screen, and the building simulation was run to produce energy consumption data for the building. This section presents the inputs used for the three EPlus models generated.

In order to create the EPlus model for the R1 single-family residential building, a 3-D drawing of the building was first completed in SketchUp. The building consisted of two thermal zones, Floor 1 and Floor 2, where the building was two stories above grade and none below grade, with a total of 3,000 ft^2. Each floor was 1,500 ft^2 and the building footprint shape was a rectangle, with dimensions of 50 feet by 30 feet and an orientation facing north. The floor-to-ceiling height was 8 feet, and the house had a pitched roof with no attic, where the roof had a 25º pitch and a 2 inch overhang. The house had 15% windows on all sides, where the window sill height was 3 feet, and the window height was 4.25 feet. The house had a steel front door on the north side, a glass door on the south side and an additional steel door on the east side, where all doors were 6.7 feet tall and 3 feet wide.

Once the R1 building SketchUp model was complete, the 3-D drawing of the building was imported into EPlus, and the IDF editor in EPlus was used to add building model inputs. The model was set to do zone and system sizing calculations, the location was set to Atlanta, Georgia, USA and design day data was input for 18 design days. The run period was set as one full year, and schedules were added for the occupancy load, the cooking load, the refrigeration load, the lighting load and the miscellaneous equipment load. These schedules are shown in Appendix B. Schedules were also added for the hot water set point temperature, the ambient water temperature, and the hot water end use temperature and flow. The building had a standard wooden frame, with a shingle roof and insulation of R-19 used in the walls. The exterior finish of the building was wood, with a concrete ground floor and double-pane windows.

The R1 building was assumed to have people load, lighting load, and electric equipment loads. The people load operated on the occupancy schedule and had a load of 624 ft^2 per person. The lighting load operated on the lighting schedule and had a load of 0.5 W/ft^2. The R1 building had three electric equipment loads: cooking, refrigeration and miscellaneous electrical equipment. The cooking load operated on the cooking schedule and had a load of 1.13 W/ft^2, the refrigeration load operated on the refrigeration schedule and had a load of 0.18 W/ft^2, and the miscellaneous electrical equipment load operated on the miscellaneous electrical schedule and had a load of 0.3 W/ft^2. All loads for the R1 building applied to all zones of the building.

The building domestic hot water supply was provided by a water heater and a domestic hot water loop. The hot water loop was autosized by the EPlus model, and the water heater was sized based upon the specification of 20 gallons of water/person/day needed for the R1 building. This specification was entered into EPlus as the necessary hot water storage capacity/person, which was 2.67 ft^3 per person. The domestic hot water loop set point temperature followed the hot water set point temperature schedule. EPlus default settings were used for all other inputs for the hot water loop and the water heater.

The HVAC system for the R1 building consisted of packaged terminal air conditioners. Each zone had its own packaged unit which supplied space heating and space cooling, and each unit operated using a constant setpoint thermostat. The thermostat had a heating setpoint of 68ºF, and a cooling setpoint of 78ºF. The outdoor air flow rate was 0.5 cfm/ft^2, and the packaged unit heating coil operated using natural gas. The zone cooling design supply air temperature was 55ºF, and the zone heating design supply air temperature was 120ºF. The coils for the HVAC packaged units were automatically sized by EPlus. A weather file for Atlanta, Georgia was input to EPlus from the launch screen, and the building simulation was run to produce monthly end use energy consumption data. The R1 residential building model assumptions for EPlus are summarized in Table 4.

The EPlus model created for the R6 6-story residential building included a different construction than that of the R1 building, but had many similar building model inputs. The SketchUp model of the R6 building consisted of 41 thermal zones, where the building had six stories above grade and none below grade. The building had an area of about 46,000 ft^2, where the building footprint shape was a rectangle, with dimensions of 85 feet by 90 feet and an orientation facing north. The zoning pattern was perimeter/core, where the perimeter zone depth was 25 feet. The residential areas were on the perimeter of the building, and the corridor areas were in the core of the building. The first floor had 5 residential units and a lobby area, and each other floor in the building had 6 residential units and a corridor area. The building had 7,650 ft^2 per floor, with a floor-to-ceiling height of 8 feet. The building had a flat roof and 15% windows on all sides, where the window sill height was 3 feet, and the window height was 4.25 feet.

The building had a glass door on the north side, steel doors on the east and west sides, and a glass door on the south side. The glass doors on the north and south sides of the building were 7 feet tall and 6 feet wide, while the steel doors on the east and west sides of the building were 6.7 feet tall and 3 feet wide.

Table 4: Inputs for R1, R6 and Office Building EPlus Energy Demand Models

Building Model Inputs	R1 Building	R6 Building	Office Building
Location	Atlanta, GA	Atlanta, GA	Atlanta, GA
Number of Floors	2	6	2
Building Area	3,000 ft^2	46,000 ft^2	15,100 ft^2
Building Dimensions	50 ft by 30 ft	90 ft by 85 ft	86.9 ft by 86.9 ft
Orientation	Facing north	Facing north	Facing north
Number of Thermal Zones	2	41	11
HVAC Equipment	Packaged terminal air conditioners	Packaged terminal air conditioners	Packaged terminal air conditioners
Floor-to-Ceiling Height	8 ft	8 ft	9 ft
Window Area	15% of wall area	15% of wall area	40% of wall area
Number of Doors	3	4	2
Thermostat Setpoints (Occupied Building)	Cool: 78ºF, Heat: 68ºF	Cool: 78ºF, Heat: 68ºF	Cool: 76ºF, Heat: 70ºF
Hot Water Storage Capacity	2.67 ft^3/person	2.67 ft^3/person	0.1337 ft^3/person

Once the R6 building SketchUp model was complete, the 3-D drawing of the building was imported into EPlus, and the IDF editor in EPlus was used to add building model inputs. The model was set to do zone and system sizing calculations, the location of the building was set to Atlanta, Georgia, USA and design day data was input for 18 design days. The run period was set as one full year, and schedules were added for the occupancy load, the cooking load, the refrigeration load, the lighting load and the miscellaneous equipment load, as in the case of the R1 model created in EPlus. These schedules are shown in Appendix B. Schedules were also added for the hot water set point temperature, the ambient water temperature, and the hot water end use temperature and flow. The building had a standard wooden frame, with a concrete ground floor and R-19 insulation used in the walls. All windows in the building were double-pane.

The R6 building was assumed to have people loads, lighting loads, and electric equipment loads. The people loads operated on the occupancy schedule, and the building had a load of 1000 ft^2 per person for the corridor zones and a load of 624 ft^2 per person for the residential zones. The lighting loads operated on the lighting schedule and the building had a load of 0.5 W/ft^2 for the residential zones, and a load of 0.57 W/ft^2 for the corridor zones. The R6 building had three electric equipment loads: cooking, refrigeration and miscellaneous electrical equipment. All three of these loads applied only to the residential zones in the building. The cooking load operated on the cooking schedule and had a load of 2.5 W/ft^2, the refrigeration load operated on the refrigeration schedule and had a load of 0.45 W/ft^2, and the miscellaneous electrical equipment load operated on the miscellaneous electrical schedule and had a load of 0.3 W/ft^2.

The building domestic hot water supply was provided by a water heater and a domestic hot water loop, as in the case of the R1 building. The hot water loop was autosized by the EPlus model, and the water heater was sized based upon the specification of 20 gallons of water/person/day needed for the R6 building. This specification was entered into EPlus as the necessary hot water storage capacity/person, which was 2.67 ft^3 per person. The domestic hot water loop set point temperature followed the hot water set point temperature schedule. EPlus default settings were used for all other inputs for the hot water loop and the water heater.

The HVAC system for the R6 building consisted of packaged terminal air conditioners. Each zone had its own packaged unit which supplied space heating and space cooling, and each unit operated using a constant setpoint thermostat. The thermostat had a heating setpoint of 68ºF, and a cooling setpoint of 78ºF. The outdoor air flow rate was 0.5 cfm/ft^2, and the packaged unit heating coil operated using natural gas. The zone cooling design supply air temperature was 55ºF, and the zone heating design supply air temperature was 120ºF. The coils for the HVAC packaged units were automatically sized by EPlus. A weather file for Atlanta, Georgia was input to EPlus from the launch screen, and the building simulation was run to produce monthly end use energy consumption data. The R6 residential building model assumptions for EPlus are summarized in Table 4.

The EPlus model created for the 2-story office building had similar inputs as the residential models created, but the building was utilized for a different use. The SketchUp model of the office building consisted of 11 thermal zones, where the building had two stories above grade and none below grade. The building had an area of about 15,100 ft^2, where the building footprint was a square, with dimensions of 86.9 feet by 86.9 feet and an orientation facing north. The zoning pattern was perimeter/core, where the perimeter zone depth was 15 feet. The offices were mostly on the perimeter of the building, and the restrooms, conference room, copy room and mechanical and electrical room were all in the core of the building. The corridor separated the offices on the perimeter of the building from the zones in the core of the building. The building lobby, copy room, mechanical and electrical room, and some offices were on the first floor, while the remainder of the offices, the restrooms, and the conference room were on the second floor of the building. The office building had a floor-to-ceiling height of 9 feet, with a flat roof and 40% windows on all sides. The window sill height was 3 feet, and the window height was 5.22 feet. The building had a glass door on the north side and a steel door on the east side. Each of these doors was 7 feet tall and 6 feet wide.

Once the office building model was complete, the 3-D drawing of the building was imported into EPlus, and the IDF editor in EPlus was used to add building model inputs. As in the case of the other two models created in EPlus, the model was set to perform zone and system sizing calculations, the location of the building was set to Atlanta, Georgia, USA and design day data was input for 18 design days. The run period was set as one full year, and schedules were added for the occupancy load, the lighting load and the electrical equipment load. The schedules for the loads all followed the main schedule for the building. Schedules were also added for the hot water set point temperature, the ambient water temperature, and the hot water end use temperature and flow. The building opened at 8 am and closed at 5 pm during the weekdays, and was closed on the weekends. The office building occupancy was at 90% of capacity while the building was open, and was at 0% while the building was closed. The office building lights were at 90% of capacity while the building was open, and were at 10% of capacity in the corridor and lobby while the building was closed, and at 0% in all other areas. The office building electrical equipment was at 90% of capacity while the building was open, and was at 20% of capacity in the offices, copy room and mechanical and electrical room while the building was closed. The electrical equipment in all other areas was off when the building was closed. The building had a concrete ground floor, insulation of R-19 in the walls and lay-in acoustic tile in the ceilings. All windows in the building were double-pane.

The office building was assumed to have people loads, lighting loads, and electric equipment loads. The people loads operated on the occupancy schedule, the lighting loads operated on the lighting schedule, and the electrical equipment loads operated on the schedule for the electrical equipment. The people, lighting and electrical loads for each thermal zone are shown in Table 5.

The office building domestic hot water supply was provided by a water heater and a domestic hot water loop. The hot water loop was autosized by the EPlus model, and the water heater was sized based upon the specification of 1 gallon of water/person/day needed for the building. This specification was entered into EPlus as the necessary hot water storage capacity/person, which was 0.1337 ft^3 per person. The domestic hot water loop set point temperature followed the hot water set point temperature schedule. EPlus default settings were used for all other inputs for the hot water loop and the water heater.

The HVAC system for the office building consisted of packaged terminal air conditioners. Each zone had its own packaged unit which supplied space heating and space cooling, and each unit operated using a constant setpoint thermostat. The thermostat had a heating setpoint of 70ºF, and a cooling setpoint of 76ºF. The outdoor air flow rate was 0.5 cfm/ft^2, and the packaged unit heating coil operated using natural gas. The zone cooling design supply air temperature was 55ºF, and the zone heating design supply air temperature was 120ºF. The coils for the HVAC packaged units were automatically sized by EPlus. A weather file for Atlanta, Georgia was input to EPlus from the launch screen, and the building simulation was run to produce monthly end use energy consumption data. The 2-story office building model assumptions for EPlus are summarized in Table 4.

Table 5: People, Lighting and Plug Loads by Area Type for EPlus Office Building Model

Area Type	People Loads (ft^2/person)	Lighting Loads (W/ft^2)	Plug Loads (W/ft^2)
Office	225	1.3	1.5
Corridor	150	0.6	0.2
Lobby (office reception/waiting)	150	1.1	0.5
Restrooms	52.5	0.6	0.2
Conference Room	22.5	1.6	1
Mechanical/Electrical Room	450	0.7	0.2
Copy Room	187.5	1.5	3

Energy demand models were created for the R1 residential building, the R6 residential building and the 2-story office building using the EPlus energy simulation software. The models developed produced reports on the monthly end use energy consumption for each of the buildings. These results are presented in Chapter 4.

3.2 Development of Microturbine System HOMER Energy Model

A HOMER energy model of a microturbine system was developed for use in the CHP system model. Within the HOMER energy model it was assumed that a microturbine provided AC electricity and thermal energy. The electric and thermal loads of a building were simulated, and it was assumed that the microturbine met all of the energy needs for the building. Inputs regarding the system component characteristics were required for the model. Monthly data on desired electrical and thermal microturbine output was entered into the model, as were the capital, replacement and operations and maintenance costs of the microturbines considered. The capital cost for a microturbine was assumed to be $1500/kW, and the replacement cost for a microturbine was assumed to be $1500/kW. The operations and maintenance cost for the microturbine was considered to be $0.01/hr. The minimum load ratio for the microturbine was entered as 100%, so the system always ran at 100% capacity. The microturbine was considered to have a lifetime of 80,000 operating hours, and the cost of grid electricity was assumed to be very high, as the microturbine provided all electrical and thermal energy for the building. The microturbine was assumed to run constantly, and in the scenarios where reasonable, only commercially available microturbine sizes were considered.

The HOMER energy model developed simulated a microturbine system and the electrical and thermal energy loads it met. The model provided information on the optimal size of microturbine for a given scenario, and generated time-based data on the electrical and thermal energy provided by a microturbine system. In addition, the HOMER energy model compared the data on energy provided by the microturbine system and the data on energy loads to determine how effectively the microturbine operated, and whether or not it produced the correct amount of energy for the application.

3.3 Development of CHP System Analyzed

3.3.1 System Components and End Use Products

The CHP system model developed was created for commercial, institutional or residential applications and utilized a microturbine as the system prime mover. The CHP system was a topping cycle, where fuel is used to power the microturbine then excess thermal energy from the process is used for thermal applications. The system was designed to operate using natural gas, and to be able to produce electricity, domestic hot water, chilled air and hot air as end use products.

The CHP system model was designed by consulting reports on previously installed CHP systems. Two Environmental Technology Verification Reports from the Greenhouse Gas Technology Center Southern Research Institute in collaboration with the U.S. EPA were examined (U.S. EPA and Greenhouse Gas Technology Center Southern Research Institute 2003b), (U.S. EPA and Greenhouse Gas Technology Center Southern Research Institute 2003a), along with a report produced by Dr. Louay Chamra at the Micro CHP and Biofuel Center at Mississippi State University (Chamra 2008a). Each of these reports analyzed a CHP system within a specific application and discussed the power and emissions performance of the system. Part of the framework of the CHP model designed was based upon the configuration of the electricity generation component of the CHP system. The report from Dr. Chamra was also consulted for a portion of the thermal system in the CHP model designed. Two articles on CHP system performance were reviewed for relevant equipment descriptions and operational data. CHP system component information from an article in *Applied Thermal Engineering* was used to define the equipment in the CHP model designed (Rocha, Andreos et al. 2012). Data on operational conditions and system equipment from an article in *ASHRAE Transactions* was used to help more thoroughly understand the thermal system properties of the CHP system model developed (Petrov, Rizy et al. 2005). These reports, in conjunction with the background and literature review compiled for CHP systems, led to the development and design of the CHP system model presented.

Shown in Figure 20 is a diagram of the CHP system model. The end use products for the model are electricity, domestic hot water, hot air and chilled air. The system is composed of a microturbine with an onboard air compressor, an electrical transformer, a heat recovery unit, an absorption chiller, a set of chilled water coils, and two sets of heating coils. The microturbine unit operates on natural gas and consists of a compressor, recuperator, combustor, turbine and a generator.

The CHP system converts natural gas into electricity and thermal energy, and this process involves many intermediate steps. First, low pressure ambient air enters at the air intake and is compressed in the compressor. Natural gas is burned in the combustor to raise the temperature of the compressed air, and the high pressure hot gases expand through the turbine to produce mechanical power for the generator. The recuperator recovers thermal energy from the hot gases to heat the compressed air before it enters the combustor. This reduces the amount of fuel consumed, thus increasing the efficiency of the system. The generator produces high-frequency electrical output, and this travels through an electrical transformer to be converted into end use electricity. The process involving the compressor, combustor, turbine, recuperator and generator all occurs within the microturbine, while the electrical transformer is a separate unit. The microturbine and electrical transformer produce electricity, but the CHP system also involves a thermal energy component.

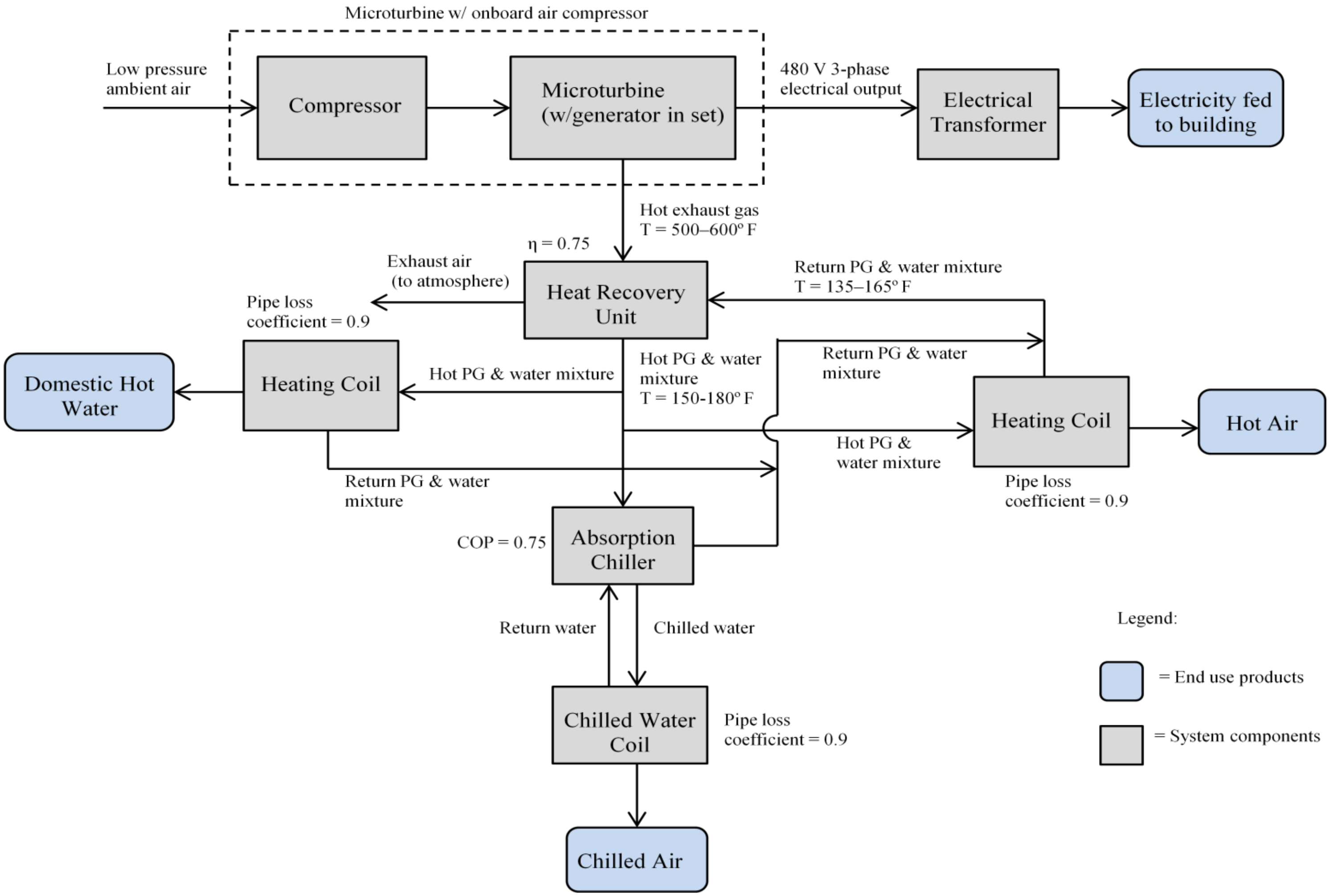


Figure 20: Diagram of CHP System Model

The microturbine produces both high-frequency electrical output and waste heat in the form of hot exhaust gases. This waste heat powers the thermal section of the CHP system. The hot exhaust gases from the microturbine, which are typically 500 to 600ºF, enter a heat recovery unit (HRU), which is an aluminum fin and tube heat exchanger. A mixture of propylene glycol (PG) in water is used as the heat-transfer medium to recover energy from the microturbine exhaust gas stream. The HRU produces a hot PG and water mixture typically at temperatures of 150 to 180ºF. The cooled gases from the microturbine exit the HRU and are exhausted to the atmosphere. The hot PG and water mixture from the HRU travels to sets of heating coils and an absorption chiller. This mixture travels through heating coils to produce domestic hot water and hot air for building heating. The PG and water mixture used for the domestic hot water and hot air end uses is returned to the heat recovery unit once it travels through the coils. The hot PG and water mixture which goes to the absorption chiller is used to produce chilled water. The absorption chiller uses a condensation and evaporation process to utilize the hot PG and water mixture to generate chilled water, typically at 44ºF. This chilled water travels through chilled water coils to produce chilled air for building cooling. The hot PG and water mixture which powers the absorption chiller is returned to the HRU once it travels through the coils and this return mixture enters the HRU typically at 135 to 165ºF. The CHP system model developed demonstrates a feasible design for an installed system. This system utilizes low-cost natural gas as its fuel and produces electricity, domestic hot water, and building heating and cooling. The benefits of this system make it an interesting model to analyze for feasibility in various scenarios.

3.3.2 System Modes and Efficiencies

The CHP system model developed was assumed to have two modes of operation, summer mode and winter mode. In summer mode, the system produced electricity, domestic hot water and chilled air for building cooling. In winter mode, the system produced electricity, domestic hot water and hot air for building heating. Shown in Figure 21 is a diagram of the CHP system model with the summer mode active components highlighted, and shown in Figure 22 is a diagram of the CHP system model with the winter mode active components highlighted. In summer mode the hot PG and water mixture is not sent to the sets of heating coils for building heating, while in winter mode the hot PG and water mixture is not sent to the absorption chiller for building cooling.

The CHP system model utilizes different system components based upon the mode in which it is operating, and thus has different efficiencies for its different modes of operation. Efficiency values were calculated for the CHP system model paths between the thermal output of the microturbine and the energy available for each thermal end use. These values were determined by finding the composite efficiency value for each end use, taking the efficiency of each component in the path between the microturbine and the end use into consideration. In order to perform these calculations, the efficiency value for each component was determined. The HRU used in the model was assumed to have an average efficiency of 0.75, the absorption chiller used in the model was assumed to have an average coefficient of performance (COP) of 0.75, and a pipe loss coefficient of 0.9 was considered for each end use product.

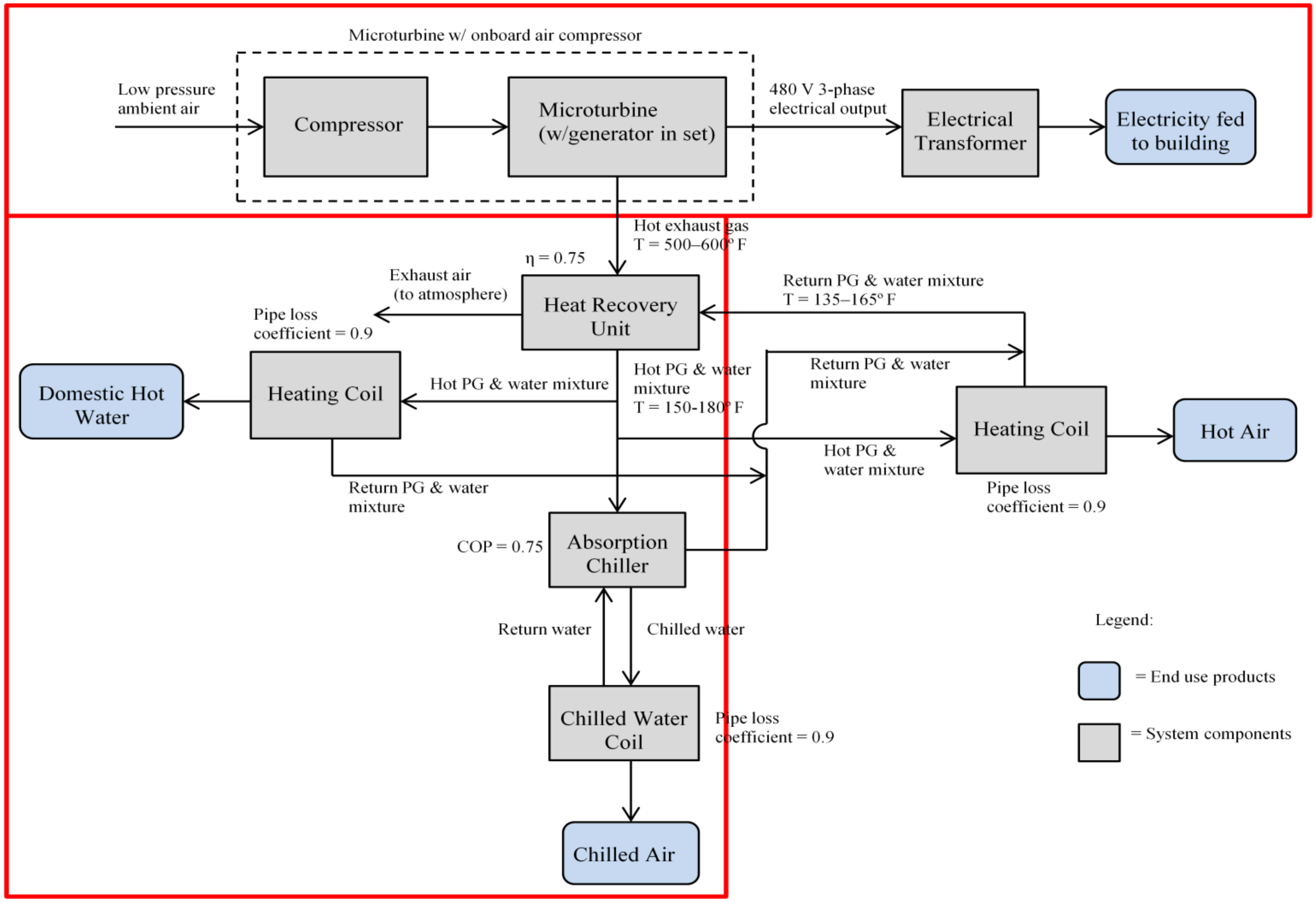


Figure 21: Diagram of CHP System Model - Summer Mode

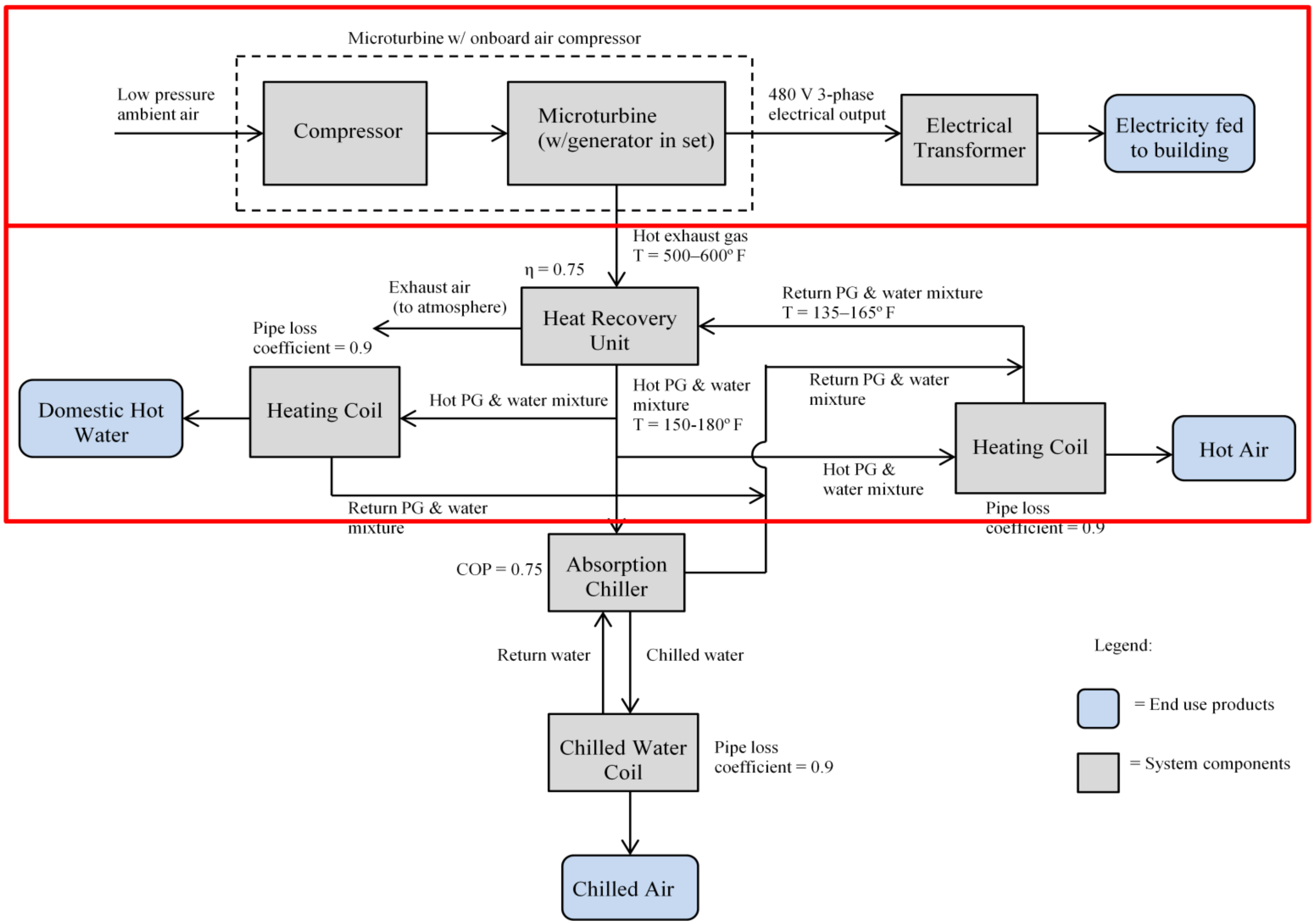


Figure 22: Diagram of CHP System Model - Winter Mode

The HRU efficiency of 0.75 was assumed based upon an article in *Applied Thermal Engineering* and work from Dr. Louay Chamra at the Micro CHP and Biofuel Center at Mississippi State University (Meybodi and Behnia 2012), (Chamra 2008b). The single-effect absorption chiller COP of 0.75 and the pipe loss coefficient of 0.9 were also assumed based upon work from Dr. Louay Chamra (Chamra 2008b). The pipe loss coefficient of 0.9 used in Chamra's paper was for an office space powered, heated and cooled by a micro-CHP system located in Meridian, MS. This office space consisted of a floor area of 4300 ft^2 and an average ceiling height of 9 feet. Thus, the pipe loss coefficient of 0.9 was estimated to apply for a building of this size, and in the southeastern part of the U.S. The composite efficiency value for each of the thermal end uses was calculated by multiplying the efficiency or COP values of each component in the path between the microturbine and the end use. The composite efficiency values for domestic hot water and space heating were calculated by multiplying the efficiency value of the HRU by the pipe loss coefficient, and the composite efficiency value for space cooling was calculated by multiplying the efficiency value of the HRU by the COP value of the absorption chiller and the pipe loss coefficient. The CHP system model path for electricity was assumed to have negligible energy loss between the electrical output of the microturbine and the electricity available for end use, so no efficiency value was calculated.

3.4 Models of CHP System Analyzed for Scenarios

The CHP system model developed was applied to three scenarios: an R1 residential building, an R6 residential building and a 2-story office building. Figure 23 shows a process flowchart for the full CHP system analyzed. The building energy demand models created in eQUEST and EPlus provided the electrical and thermal energy building load for each scenario. Figure 23 defines Method 1 as the analytical process followed for the EPlus building energy demand data, and defines Method 2 as the analytical process followed for the eQUEST building energy demand data. The building load data was then used in the CHP system model to find the desired electrical and thermal microturbine output, taking system inefficiencies into consideration. These desired electrical and thermal microturbine output values were compared with the output produced by a commercially available microturbine, and a microturbine was sized for each application. The development of the CHP system model for each scenario generated time-based data on the electrical and thermal energy provided by a CHP system, and the electrical and thermal energy consumed by the building. The CHP system model for each of these scenarios was then further analyzed to determine feasibility and impacts of the system.

The full CHP system model analyzed for each scenario began with the building energy demand models created in eQUEST and EPlus. eQUEST and EPlus each had inputs of building geometry, building specifications, location files, and weather files, as seen in Figure 23. These models then produced monthly building electric and gas consumption data listed by end use. Energy conversions were performed on the regrouped monthly data, and this gave information on the building electrical and thermal energy demand in kilowatt hours (kWh).

The data on the building electrical and thermal energy demand was then used in the CHP system model developed in MS Excel. Shown in Figure 24 is a flowchart of the analytical process which occurred within the CHP system model. The data on the monthly building end use energy demand was first regrouped into the four end uses of the CHP system model: domestic hot water, space heating, space cooling and electricity. This part of the CHP system analysis is shown in Step 1 in Figure 24.

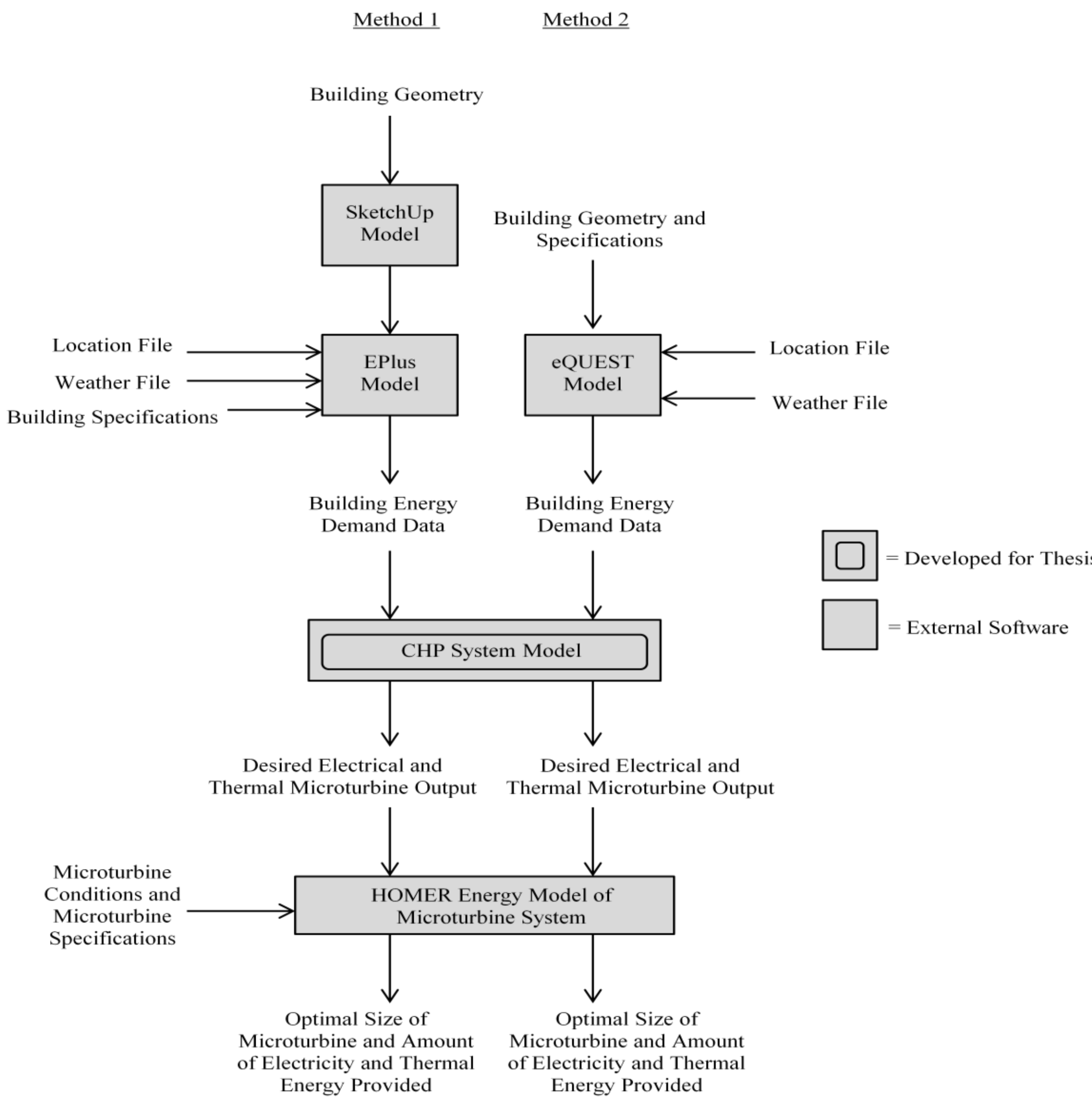


Figure 23: Process Flowchart for Full CHP System Analyzed

These regrouped monthly demand values corresponded to the end use energy needed for the building, but inefficiencies existed in the CHP system model between the end use energy and the energy which exited the microturbine. In order to analyze the CHP system model for each scenario, this electrical and thermal energy which exited the microturbine needed to be calculated. The data on the building energy load for each end use was divided by the composite inefficiency for that thermal end use. This gave the microturbine energy output needed to power the building. This part of the CHP system analysis is shown in Step 2 in Figure 24.

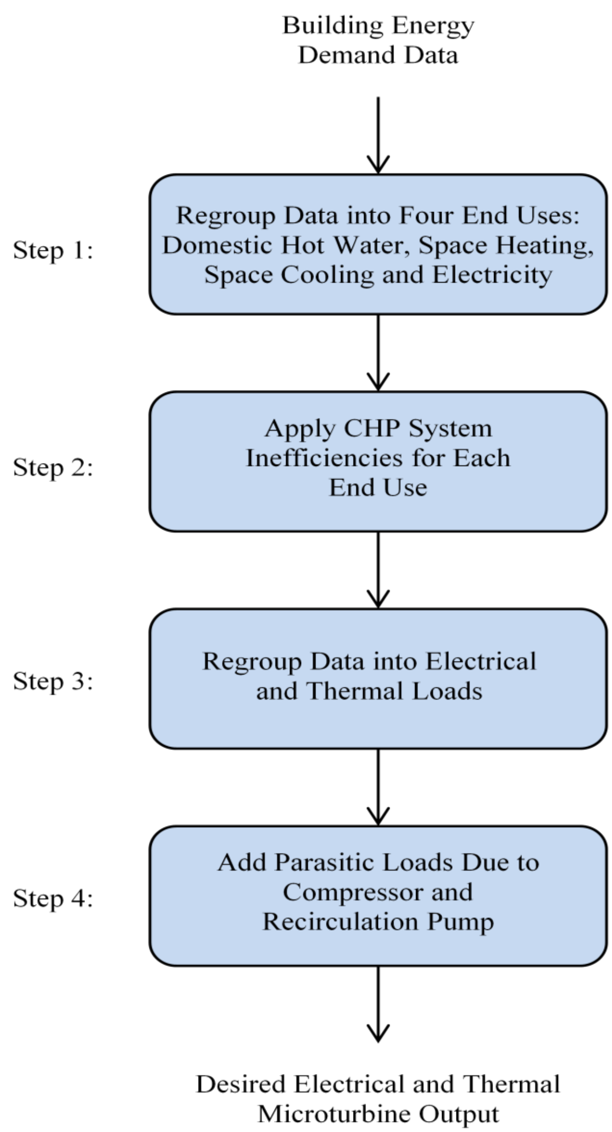


Figure 24: Process Flowchart for CHP System Model

The microturbine energy output calculated was called the 'desired microturbine output'. Desired microturbine output values were determined for the end uses of space cooling, space heating and domestic hot water for each month. The desired microturbine output values for the electric energy load were the same as the electric energy needed to power the building, as it was assumed there were negligible system inefficiencies between the electric output of the microturbine and electricity end use.

Once the desired microturbine output values were calculated for each end use, the data was regrouped into electrical and thermal energy loads. This part of the CHP system analysis is shown in Step 3 in Figure 24. The building thermal energy load was considered the energy needs for space cooling, space heating and domestic hot water, and the building electrical energy load was considered the electricity needed to power the building. Next the parasitic loads due to the compressor in the microturbine and the recirculation pump in the heat recovery unit were added to the desired microturbine output values. This is shown in Figure 24 in Step 4. The pump required about 1 kW of thermal energy to operate and was assumed to always be running. This meant the recirculation pump required 720 kWh / month, so this additional thermal energy requirement was added to the overall desired thermal microturbine output. The compressor required about 2 kW of electricity to operate and was also assumed to always be running. This meant the compressor required 1440 kWh / month, so this additional electrical energy requirement was added to the overall desired electrical microturbine output. The desired microturbine output values for the end uses of space cooling, space heating and domestic hot water were added to the parasitic load due to the HRU recirculation pump to find the monthly total thermal energy needed to be produced by the microturbine. The desired microturbine output value for the end use of electricity was added to the parasitic load due to the compressor to find the monthly total electrical energy needed to be produced by the microturbine. These monthly total desired microturbine output values were then used to identify the optimal microturbine for each scenario.

The data on the monthly total desired microturbine output for electrical and thermal energy was entered into the HOMER energy model of the microturbine along with inputs on the system component characteristics for each scenario. This is shown in Figure 23. Within each scenario, the microturbine was assumed to run constantly and at full capacity. For the R6 residential building and 2-story office building scenarios, only commercially available microturbine sizes were considered for the model. The R1 residential building scenario was handled differently as the energy load for this building was much smaller than the smallest commercially available microturbine.

Theoretical microturbine sizes were considered for the R1 residential scenario, as the smallest commercially available microturbine provided significantly more energy than was needed by a single R1 building. The smallest theoretical microturbine which completely powered the R1 building was then scaled up so the microturbine was a commercially available size. The relation between microturbine sizes and the energy they provide scales linearly, so the theoretical microturbine size was multiplied by a scaling factor to achieve a commercially available microturbine size, while the electrical and thermal energy loads for the building were also multiplied by that scaling factor. The results represented a commercially available microturbine which could provide the electrical and thermal energy for a calculated number of R1 buildings.

The HOMER energy models were developed to simulate a microturbine and the electrical and thermal loads they met within each application studied. The models produced provided information on the optimal size of microturbine for each scenario, and generated time-based data on the electrical and thermal energy provided by a CHP system, and the electrical and thermal energy consumed by the building. This final output is shown at the bottom of Figure 23. This data was compared to determine the effectiveness of the microturbine in meeting or exceeding the energy demands of the building. This data also provided information on the amount of excess energy produced by the microturbine, and was utilized to draw additional conclusions regarding the feasibility and impacts of the systems designed.

3.5 CHP System Environmental Calculations

3.5.1 CHP System Emissions

An emissions characterization was performed for the CHP systems designed for the R1 single-family residential building, the R6 6-story residential building and the 2-story office building using the CHP Emissions Calculator (CEC). For each emissions characterization inputs were added to the CEC, then the system emissions performance was calculated. The net emissions for each CHP system analyzed were compared with the net emissions due to a separate heat and power system of similar size. Inputs to the CEC included: the type of prime mover used in the CHP system, the fuel used, the CHP system thermal equipment, and the displaced electric and thermal system. This section presents the inputs used for each of the three emissions characterizations completed.

In order to complete the CHP emissions characterization for the R1, R6 and 2-story office building, details on the CHP systems designed for each building and the types of electrical and thermal energy systems they displaced were entered into the CEC. Shown in Table 6 is a summary of the assumptions used to calculate the net emissions for the CHP systems in the R1, R6 and 2-story office buildings.

Table 6: Inputs for R1, R6 and Office Building Emissions Characterizations

CEC Input Category	Inputs for R1, R6 and 2-Story Office Building
Type of System	Microturbine
CHP System Operation Schedule	8760 hrs/yr
CHP System Thermal Output Provided	Heating and cooling
Type of Fuel	Natural gas
Electric Efficiency	23%
Type of Absorption Chiller Used	Typical single-effect
Absorption Chiller COP	0.7
Type of Cooling System Displaced	Average new rooftop unit
Type of Heating System Displaced	Existing gas boiler
Efficiency of Displaced Thermal System	80%
Generation Profile for Displaced Electricity	eGRID 2012 Average Fossil
Subregion for eGRID Data	Georgia
Electric Grid Region for T&D Losses	Eastern Interconnect

The inputs regarding the configuration of the CHP system were the same for all the buildings examined. The CHP systems for the R1, R6 and 2-story office buildings all used a microturbine as the prime mover, and ran 8,760 hours per year. Each of the CHP systems considered provided both space heating and space cooling, but not simultaneously. The system fuel was natural gas, and the default CO_2 emissions rate for natural gas was used in the calculation, which was 116.9 lb CO_2/MMBtu. The electric efficiency for the microturbines was 23%, and the default NO_x emissions rate for microturbines was assumed, which was 0.042 lb NO_x/MMBtu. Each of the CHP systems analyzed included a typical single-effect absorption chiller with a COP of 0.7. The displaced cooling system was assumed to be an average new rooftop unit, and the displaced heating system was assumed to be an existing gas boiler with an efficiency of 80%. The default CO_2 emissions rate for natural gas was assumed for the existing gas boiler, which was 116.9 lb CO_2/MMBtu. The default NO_x emissions rate for the gas boiler was 0.1 lb NO_x/MMBtu. The generation profile for the displaced electricity due to the use of the CHP system came from the eGRID 2012 Average Fossil Data, and the sub region for this data was specified as Georgia. In order to consider transmission and distribution (T&D) losses, the electric grid region was assumed to be the Eastern Interconnect.

Once all inputs were added to the CEC model of the CHP systems designed for the R1, R6 and 2-story office buildings, the inputs window was closed and the results were generated. The analysis produced a summary of the annual emissions of the CHP systems designed for the R1 residential building, the R6 residential building and the 2-story office building. The analysis also produced a summary of the annual emissions of a separate heat and power system of comparable size for each CHP system studied. The emissions characterization for the CHP systems and their similar separate heat and power systems are presented in Chapter 4.

3.5.2 CHP System Water Use

Water consumption values were calculated for the CHP systems designed for the set of R1 single-family residential buildings, the R6 6-story residential building and the 2-story office building. These values were compared to the calculated water consumption of centralized energy generation systems for the set of R1 residential buildings, the R6 residential building and the 2-story office building. In order to perform the water consumption calculations, specific values were assumed for the amount of energy generated by the energy system, the consumptive water use for energy production for each type of fuel used, and the Georgia generation mix for electric utilities. This section presents the inputs used for each of the water consumption calculations completed, and outlines the methodology behind these calculations.

The water consumption calculation for the CHP systems designed for the set of R1 residential buildings, the R6 residential building and the 2-story office building required several inputs. The first of these inputs was the energy produced by the microturbine. Shown in Table 7 is the electrical and thermal energy generated by the microturbine in each building scenario. For the R6 building scenario the CHP system included a 60 kW microturbine, while for the 2-story office building scenario the CHP system included a 30 kW microturbine. For the R1 building scenario the CHP system required a theoretical microturbine size, so in order for the system to be commercially feasible the CHP system was scaled up to include a set of R1 buildings. The scaled up system consisted of a 30 kW microturbine which powered 6 R1 buildings completely, and provided the thermal energy for an additional 5 R1 buildings. This scenario of the R1 building set is shown in Figure 25.

Table 7: Water Consumption Calculation Inputs - Electrical and Thermal Energy Generated by Microturbines

Building Type	Energy Type	Energy Generated
R1 Residential	Electrical - from 30 kW Microturbine	262,800 kWh/year
R1 Residential	Thermal - from 30 kW Microturbine	452,509 kWh/year
R1 Residential	Electricity for 5 Additional R1 Buildings	175,930 kWh/year
R6 Residential	Electrical - from 60 kW Microturbine	525,600 kWh/year
R6 Residential	Thermal - from 60 kW Microturbine	905,018 kWh/year
2-Story Office	Electrical - from 30 kW Microturbine	262,800 kWh/year
2-Story Office	Thermal - from 30 kW Microturbine	452,509 kWh/year

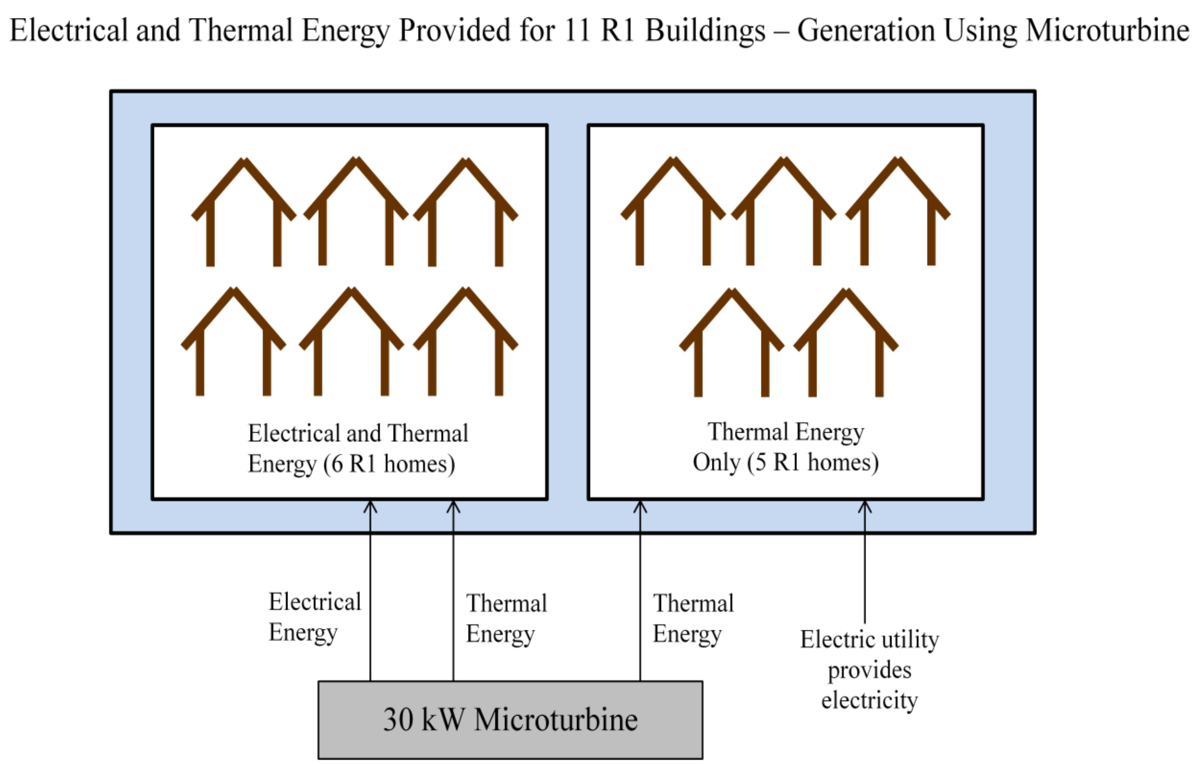


Figure 25: 30 kW Microturbine-Based CHP System for Set of R1 Buildings

The electrical and thermal energy produced by the 30 kW microturbine powered 6 R1 buildings completely and provided the thermal energy for another 5 R1 buildings, but the electricity for the other 5 R1 buildings was provided by the electric utility.

The first two rows of Table 7 show the amounts of electrical and thermal energy generated by a 30 kW microturbine in a year. This was the energy provided by the 30 kW microturbine for the R1 building set. Electricity for the additional 5 R1 buildings was supplied by the electric utility, and the amount of energy generated for this purpose is shown in the third row of Table 7. The fourth and fifth rows of Table 7 show the electrical and thermal energy generated by a 60 kW microturbine in a year, which was the energy provided by the 60 kW microturbine for the R6 building. The sixth and seventh rows of Table 7 show the electrical and thermal energy generated by a 30 kW microturbine in a year, which was the energy provided by the 30 kW microturbine for the office building. In order to find the water consumption for each of the CHP systems designed, the amount of electrical energy generated by the microturbine was multiplied by the consumptive water use for energy production for the fuel used in the system. The CHP systems all used microturbines which operated using natural gas with no cooling, so the consumptive water use for energy production of natural gas with no cooling was utilized. This gave the amount of water consumed each year due to use of the CHP systems designed. The water consumption for the CHP systems for the R1 building set, the R6 building and the 2-story office building are presented in Chapter 4.

Once the water consumption due to the designed CHP systems was calculated, the water consumption was determined for separate heat and power systems for the R1 building set, the R6 building and the 2-story office building scenarios. These calculations required a greater number of inputs than the water calculations for the CHP systems. Energy consumption for the R1 building, R6 building and 2-story office building was calculated in the eQUEST and EPlus programs, so this data was used to find the amount of energy produced for the buildings each year. The values for the electrical energy consumed by the buildings were divided by 0.93 to account for 7% transmission and distribution losses between the centralized electric power plant and the building. The values for the thermal energy consumed by the building did not include any losses, since the thermal energy was generated on site. The electrical and thermal energy building consumption data from eQUEST and EPlus, including the transmission and distribution losses, is shown in Tables 8 and 9.

Table 8: Water Consumption Calculation Inputs - Electrical and Thermal Energy Consumed by Buildings - EPlus Model Data

Building Type	Energy Type	Energy Consumed
R1 Residential	Electrical	35,186 kWh/year
R1 Residential	Thermal	1,961 kWh/year
R6 Residential	Electrical	456,373 kWh/year
R6 Residential	Thermal	11,019 kWh/year
2-Story Office	Electrical	166,716 kWh/year
2-Story Office	Thermal	16,094 kWh/year

The calculation of the water consumption for the separate heat and power systems for the R1 building set, the R6 building and the 2-story office building scenarios also required the consumptive water use for energy production for the fuels considered, and the Georgia energy generation mix for electric utilities.

Table 9: Water Consumption Calculation Inputs - Electrical and Thermal Energy Consumed by Buildings - eQUEST Model Data

Building Type	Energy Type	Energy Consumed
R1 Residential	Electrical	34,860 kWh/year
R1 Residential	Thermal	1,738 kWh/year
R6 Residential	Electrical	548,925 kWh/year
R6 Residential	Thermal	11,480 kWh/year
2-Story Office	Electrical	172,559 kWh/year
2-Story Office	Thermal	16,468 kWh/year

Shown in Table 10 is the Georgia energy generation mix for electric utilities in 2012. This data came from the U.S. EIA Electricity Data Browser (U.S. Energy Information Administration 2013).

Table 10: Georgia Generation Mix for Electric Utilities (U.S. Energy Information Administration 2013)

Fuel Type	Percent
Coal	40%
Natural Gas	25%
Nuclear	34%
Conventional Hydroelectric	1%
Total	100%

Shown in Table 11 is the consumptive water use for energy production for the fuels used in Georgia electricity generation. Table 11 lists the water consumption per kWh for each fuel considered, and breaks down the water consumption by the extraction, processing, transport and plant phases of the fuel production. The data in Table 11 for the conventional hydroelectric energy was from a report produced by the National

Renewable Energy Laboratory (Torcellini 2003), and all other data was from an article in *Annual Review of Energy and the Environment* (Gleick 1994).

Table 11: Consumptive Water Use for Energy Production (Gleick 1994), (Torcellini 2003)

Fuel Type	Extraction ($L\ H_2O/kWh$)	Processing ($L\ H_2O/kWh$)	Transport ($L\ H_2O/kWh$)	Plant/Cooling ($L\ H_2O/kWh$)	Total ($L\ H_2O/kWh$)
Coal	0.01	0.01	0.14	2.60	2.77
Natural Gas (no cooling)	0.00	0.02	0.01	0.00	0.03
Natural Gas (cooling)	0.00	0.02	0.01	1.10	1.13
Nuclear	0.07	0.18	0.00	3.20	3.45
Conventional Hydroelectric	0.00	0.00	0.00	179.50	179.50

The average water consumption per kWh for the Georgia generation mix considered was calculated using a weighted average. The percent of the total generation for each fuel was multiplied by the total water consumption per kWh for that fuel, and each of these calculated values were added together. This gave an average water consumption per kWh for Georgia electricity from electric utilities. The value calculated was multiplied by the electrical energy consumed by each building. This gave the amount of water consumed per year due to electricity generation by a centralized electricity generation system. The amount of water consumed per year due to electricity generation was added to the amount of water consumed per year due to thermal energy generation. The water consumed per year due to thermal energy generation was calculated by multiplying the amount of thermal energy consumed by each building by the consumptive water use for natural gas with no cooling. This process produced the total water consumption for a centralized energy generation system for the R1building, the R6 building and the 2-story office building. The calculation of the total water consumption for the centralized energy generation system for each scenario was performed using both the eQUEST and EPlus data, and each data set produced slightly different results. The total water consumption for a centralized energy generation system for the R1, R6 and 2-story office building scenarios are presented in Chapter 4.

Since the water consumption calculations for the CHP system in the R1 scenario were performed for a set of R1 buildings, the same number of buildings was considered for the water consumption calculations for the centralized energy generation system. This set was composed of 11 R1 buildings, which received electrical and thermal energy from a centralized energy generation system. Shown in Figure 26 is a diagram of the set of R1 buildings considered for the water consumption calculations for the centralized energy generation system. The water consumption calculations for the R1 building set were performed the same way as for the other building scenarios, the water consumption for one R1 building was simply multiplied by 11 so it was comparable to the data for the R1 building set using a CHP system.

After the initial water consumption calculations were performed for the CHP systems designed for the R1 single-family residential building, the R6 6-story residential building and the 2-story office building, and for the centralized energy generation systems for the R1, R6 and 2-story office buildings, assumptions were changed in the calculations. First, the same calculations were performed where the transmission and distribution losses for centralized electricity were assumed to be zero. Next, the same calculations were performed, but the electricity generation due to conventional hydroelectric energy was omitted. The results for these calculations with different assumptions are presented in Chapter 4.

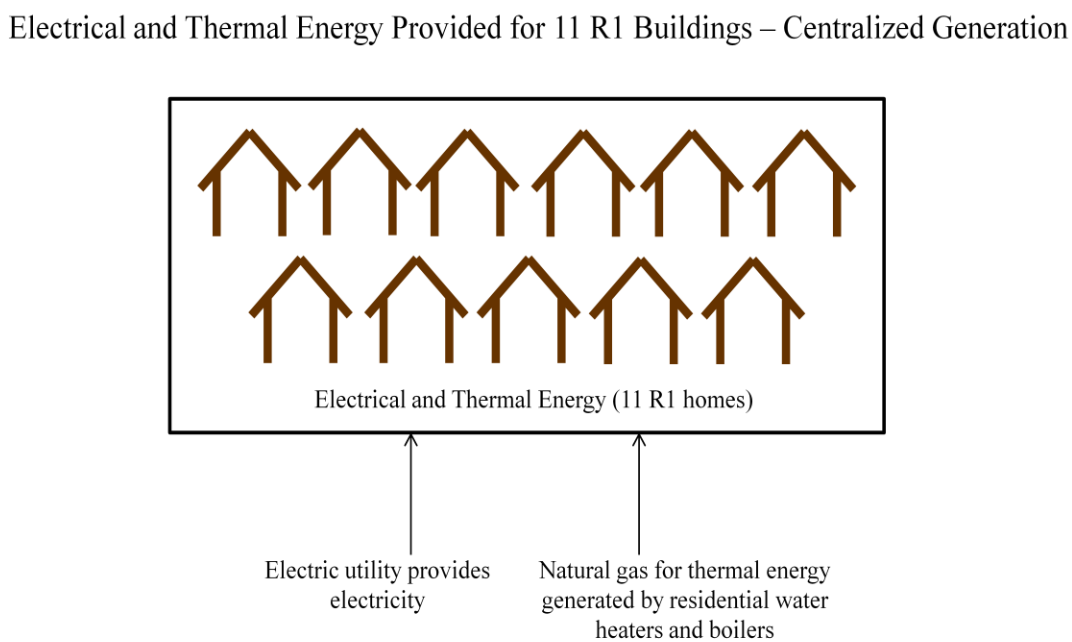


Figure 26: Centralized Energy Generation System for Set of R1 Buildings

Water consumption values were calculated for the CHP systems designed for the set of R1 residential buildings, the R6 residential building and the 2-story office building. These values were compared to the calculated water consumption of centralized energy generation systems for the set of R1 buildings, the R6 building and the 2-story office building. The values calculated are presented in Chapter 4.

CHAPTER 4

RESULTS AND DISCUSSION

This chapter presents and discusses the results produced by the building energy demand models, the HOMER Energy model, and the CHP system model built in MS Excel. The results for each of these models are then tied together to present the full CHP system model results for the R1 residential building, the R6 residential building and the 2-story office building. First the eQUEST and EPlus model results are given for the three building scenarios examined. Views are shown of the building models created, and the building energy consumption data by end use is presented. A validation and comparison of the building energy demand model results is then presented. Next the system efficiencies considered in the CHP system model built in MS Excel are discussed. These system efficiency values are then used in the full CHP system model.

The results for the full CHP system model using the eQUEST building load data are presented, followed by the results for the full CHP system model using the EPlus building load data. The full CHP system model using each of these data sets is given for the R1 residential building, the R6 residential building and the 2-story office building. The preliminary calculations performed for the full CHP system model are discussed then the results for the desired electrical and thermal microturbine output and the optimal microturbine size for each scenario are presented. These results are given for the full CHP system model using each of the building load data sets simulated.

The full CHP system model designed for each of the three building scenarios are analyzed to determine the emissions production and water consumption of each system. These results are compared with the emissions production and water consumption due to traditional centralized energy systems. The CHP system environmental results are then discussed, and the CHP system model results are scaled up to all of Metropolitan Atlanta. This chapter provides information on the full CHP system models designed for the R1 residential building, the R6 residential building and the 2-story office building using two different sets of building load data. The results detailed contribute to the understanding of CHP system functions in a range of scenarios, and this can lead to the deployment of CHP systems in a greater number of environments and applications.

4.1 Building Energy Demand Model Results

4.1.1 eQUEST Model

An energy demand model was created for the R1 single-family residential building, the R6 6-story residential building and the 2-story office building using the eQUEST building energy simulation tool. The Building Creation Wizard function within eQUEST was used to design the models for each of these buildings then the building performance was simulated to produce energy consumption data by end use for each of the buildings modeled. Shown in Figure 27 is the 3 dimensional view of the R1 residential building model created in eQUEST. Figure 28 shows the same view of the R6 residential building model created in eQUEST, and Figure 29 shows the 3-D view of the 2-story office building model designed in eQUEST. The 3-D view of the R6 building shows the bottom two levels of the building and the top level of the building, as the intermediate levels of the building are identical to the ones shown.

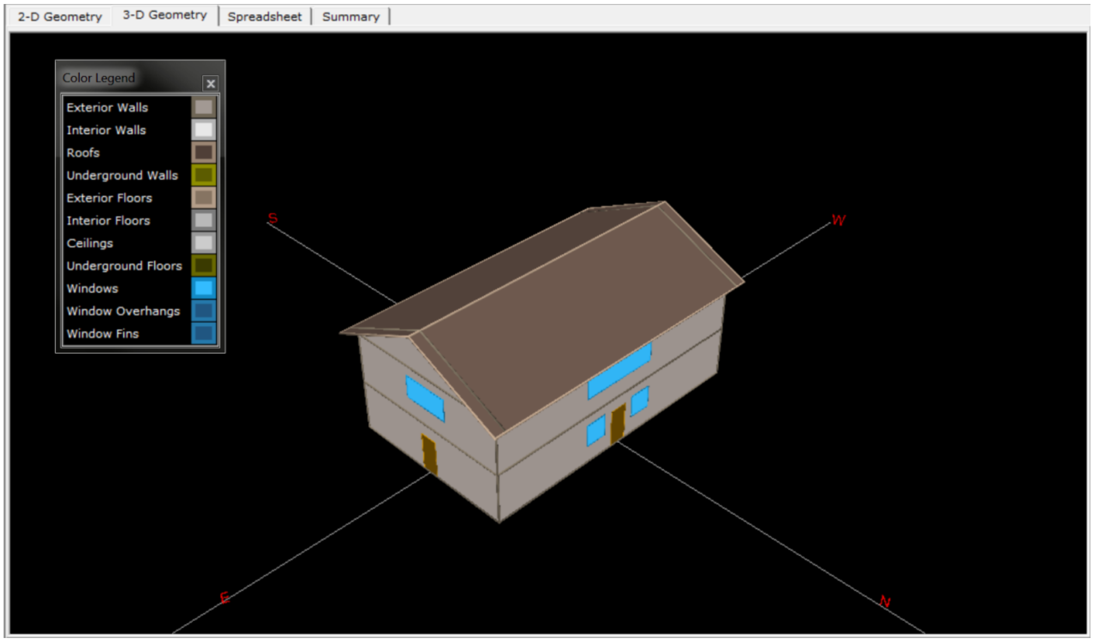


Figure 27: 3-D View of R1 Residential Building Model Created in eQUEST

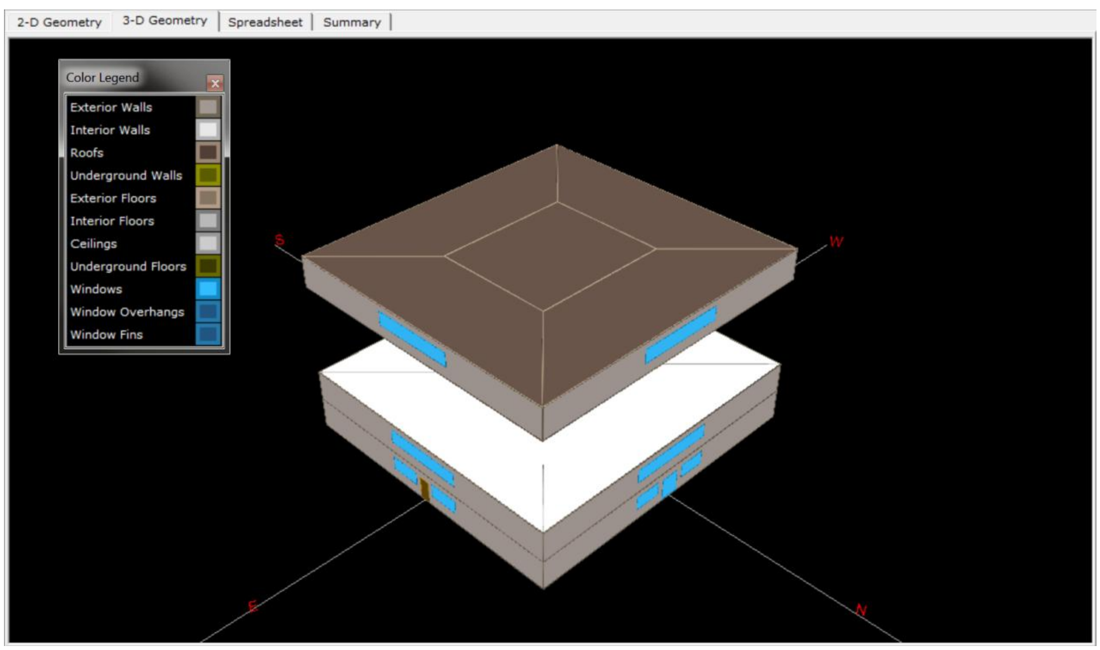


Figure 28: 3-D View of R6 Residential Building Model Created in eQUEST

A building performance simulation was run for each of the eQUEST building models, and this produced monthly energy consumption data by end use. The results for the building energy simulations are shown in Appendix A.

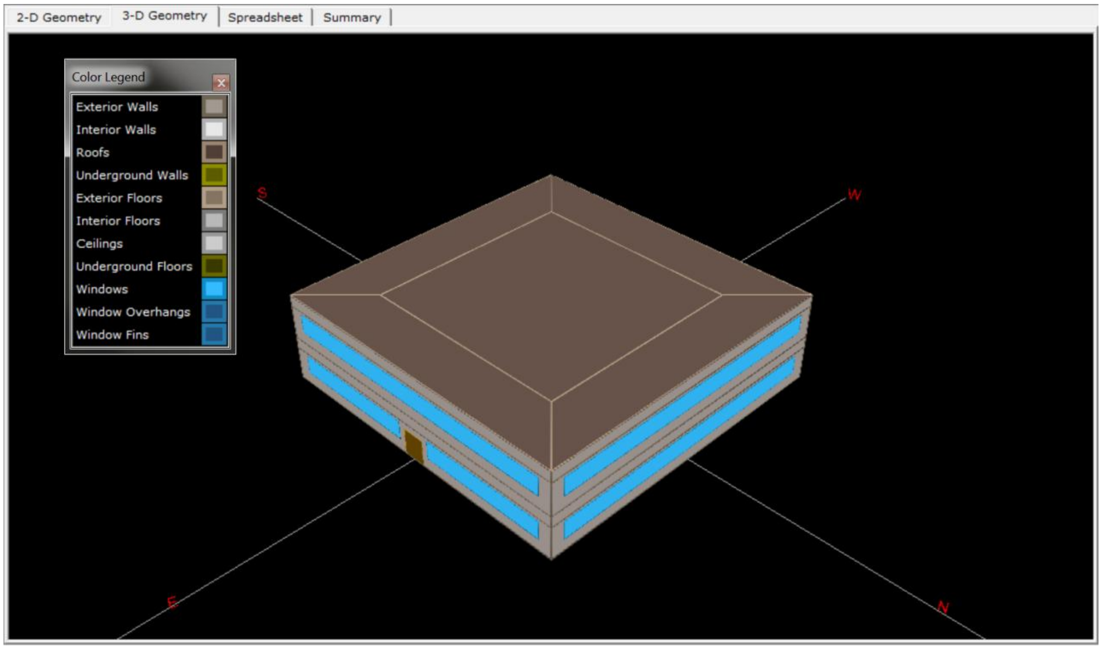


Figure 29: 3-D View of Two Story Office Building Model Created in eQUEST

Table 67 shows the R1 building monthly energy consumption by end use, Table 68 shows the R6 building monthly energy consumption by end use, and Table 69 shows the office building monthly energy consumption by end use. The data produced by the eQUEST building models was used as input for the CHP system models developed for each building type.

4.1.2 EPlus Model

Energy demand models were also created for the R1 single-family residential building, the R6 6-story residential building and the 2-story office building using the EPlus energy simulation software. For each building model, a 3-D drawing of the building was created in Google SketchUp then this model was imported into EPlus. Additional building model inputs were then added to the EPlus model, a weather file was selected for the building location, and the building performance was simulated to produce energy consumption data by end use for each of the buildings modeled. Shown in Figure

30 is a 3 dimensional view of the R1 residential building model created in SketchUp. Figure 31 shows the same view of the R6 residential model created in SketchUp, and Figure 32 shows the office building model designed in SketchUp. Each of these figures also shows the list of thermal zones designated for the building.

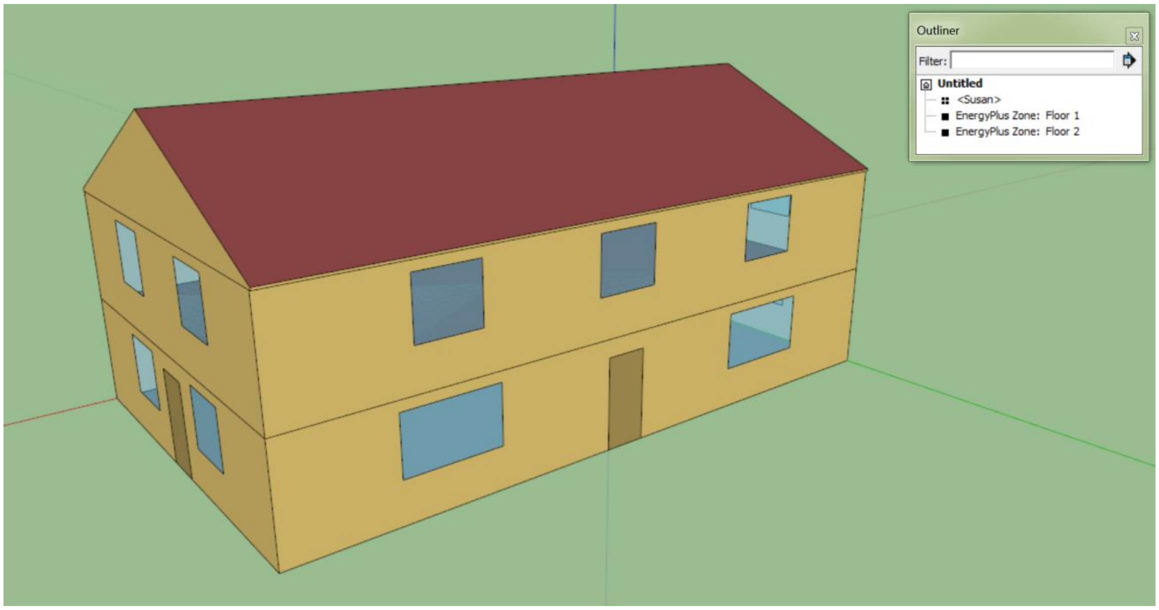


Figure 30: 3-D View of R1 Residential Building Model Created in SketchUp

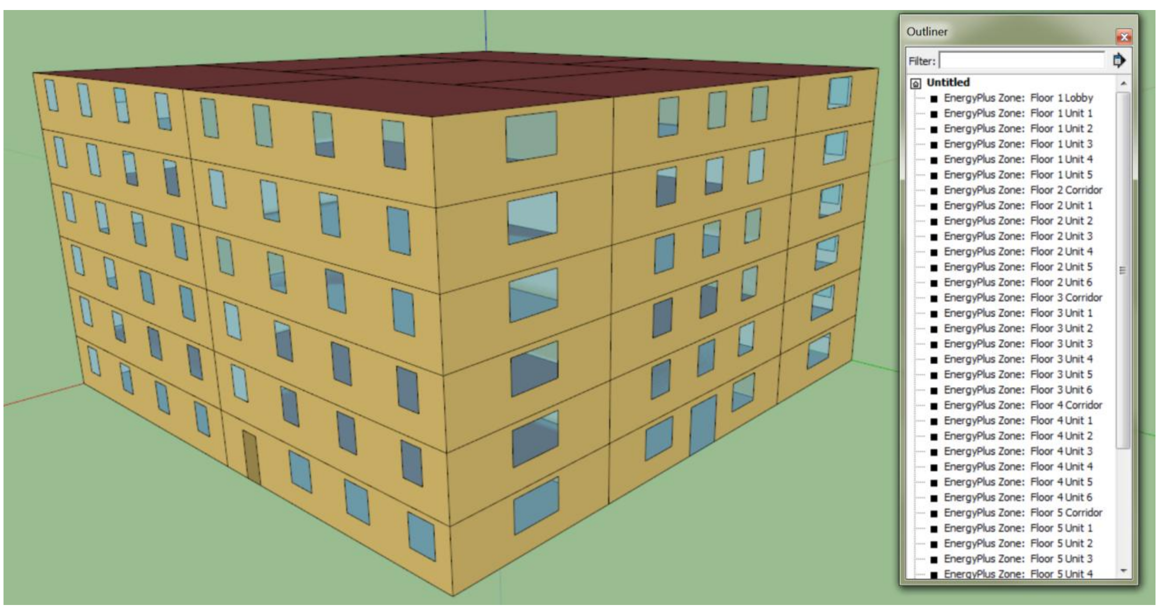


Figure 31: 3-D View of R6 Residential Building Model Created in SketchUp

Once the SketchUp building models were imported into EPlus and the additional inputs for the EPlus models were complete, a building performance simulation was run for each of the EPlus models. These building performance simulations produced monthly energy consumption data by end use for each building.

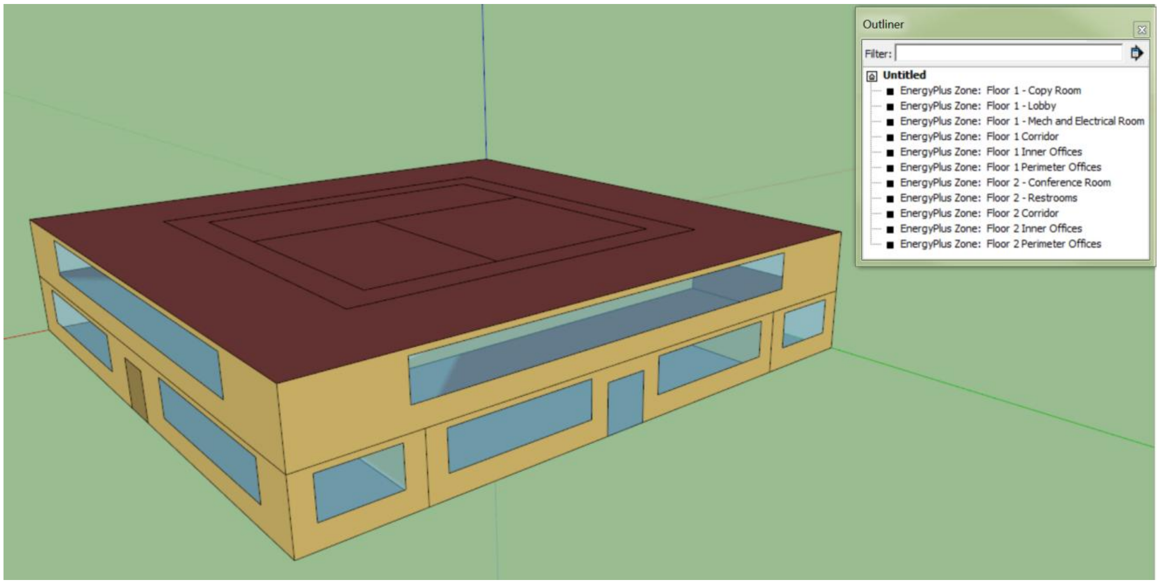


Figure 32: 3-D View of Two Story Office Building Model Created in SketchUp

The results for the building energy simulations are shown in Appendix B. Table 79 shows the R1 building monthly energy consumption by end use, Table 80 shows the R6 building monthly energy consumption by end use, and Table 81 shows the office building monthly energy consumption by end use. The data produced by the EPlus building models was used as input for the CHP system models developed for each building type.

4.2 Validation and Comparison of Building Energy Demand Model Results

4.2.1 R1 Residential Building

The energy consumption data produced by the eQUEST and EPlus building models were compared to each other and to external data for validation purposes. Shown in Table 12 is a comparison of the end use energy consumption data for the eQUEST and EPlus models produced for the R1 building. As shown in the table, the end uses of hot water, interior equipment, interior lights and space heat all had similar energy consumption values for the two models. The energy consumption for space cooling in the two models were slightly different, as were the energy consumption values for the vent. fans and the pumps and auxiliary equipment.

Table 12: Comparison of eQUEST and EPlus Model Results for R1 Building

End Use	eQUEST Energy Consumption (kWh/year)	EPlus Energy Consumption (kWh/year)
Space Cool	6000	8427
Hot Water	3920	4067
Vent. Fans	3010	197
Pumps & Aux.	230	0
Interior/Misc. Equip.	14970	15206
Interior Lights	4290	4825
Space Heat	1738	1961
Total	34158	34684

The differences in energy consumption for the vent. fans was likely a result of the programs modeling the fans different ways. In addition, eQUEST considered pumps and auxiliary equipment as its own end use category, while EPlus did not. EPlus also modeled the energy consumption for the pumps and auxiliary equipment, but likely grouped this energy consumption into the miscellaneous equipment category. The differences in energy consumption for the space cooling end use was also likely a result of differences in the way the programs modeled the heating and cooling of the building. The EPlus model overall seemed to estimate the heating and cooling for the building to be slightly higher than the estimates of the eQUEST model. However, the results for both models were within the same order of magnitude, which indicated that the models designed successfully simulated the R1 building using the same building geometry and specifications in each simulation.

The site energy use intensity values for the eQUEST and EPlus models were calculated to validate the simulations. The calculated site energy use intensity values were compared with the average site energy use intensity value for similar buildings in the DOE Buildings Performance Database. The site energy use intensity values were calculated for the EPlus and eQUEST models by converting the total building energy consumption for the year into units of kBtu, then dividing this value by the area of the building. The calculated site energy use intensity values for these models are shown in Table 13. The average site energy use intensity value for similar buildings in the DOE Buildings Performance Database was determined by entering building classification, information, location and detail filters into the program. The DOE Buildings Performance Database is a database of existing buildings in the U.S., categorized by building specifications (U.S. Department of Energy 2013a). By entering details about a specific type of building, the number of buildings within the database which have those specifications and the average site energy use intensity for that set of buildings appears.

The specifications for the R1 building were entered into the DOE Buildings Performance Database, and the average site energy use intensity for the set of buildings which met those specifications is shown in Table 13.

Table 13: Comparison of Site Energy Use Intensities for R1 Building (U.S. Department of Energy 2013a)

R1 Residential Building	eQUEST Energy Demand Model	EPlus Energy Demand Model	DOE Buildings Performance Database
Site Energy Use Intensity ($kBtu/ft^2/year$)	39	39	34

The site energy use intensity values for the eQUEST and EPlus models were close to the average site energy use intensity value for similar buildings in the DOE Buildings Performance Database. 33,107 buildings in the database had a similar building type, geometry and location as the R1 building used in the simulations, so this set of buildings was used to calculate the average site energy use intensity.

4.2.2 R6 Residential Building

As in the case of the R1 building, the energy consumption data produced by the eQUEST and EPlus models for the R6 residential building were compared to each other and to external data for validation purposes. Shown in Table 14 is a comparison of the end use energy consumption data for the eQUEST and EPlus models produced for the R6 building. For this building scenario, the end uses of hot water, interior equipment, interior lights and space heat all had similar energy consumption values for the two models. The energy consumption for space cooling in the two models were different, as were the energy consumption values for the vent. fans and the pumps and auxiliary equipment.

Table 14: Comparison of eQUEST and EPlus Model Results for R6 Building

End Use	eQUEST Energy Consumption (kWh/year)	EPlus Energy Consumption (kWh/year)
Space Cool	78770	42940
Hot Water	59840	59888
Vent. Fans	48010	4798
Pumps & Aux.	1830	0
Interior/Misc. Equip.	261440	243101
Interior Lights	60610	73700
Space Heat	11480	11019
Total	521980	435446

The differences in energy consumption for the vent. fans and the pumps and auxiliary equipment were likely results of the same issues as occurred in the R1 building models. Again, the energy consumption for the vent. fans were likely different due to the programs modeling the fans different ways, and the energy consumption for the pumps and auxiliary equipment were likely different since EPlus did not use this end use category, and probably grouped this energy consumption into a different end use category. The differences in energy consumption for the space cooling end use was again likely a result of differences in the way the programs modeled the heating and cooling of the building, although in this case the difference was significant. The eQUEST model overall seemed to estimate the heating and cooling for the building to be higher than the estimates of the EPlus model, which was the reverse of the trend in the R1 building model. However, again the results for both models were within the same order of magnitude, which indicated that the models successfully simulated the R6 building using the same building geometry and specifications in each simulation.

The site energy use intensity values for the eQUEST and EPlus models were calculated to validate the simulations. These values were compared with the average site energy use intensity value for similar buildings in the DOE Buildings Performance Database. Shown in Table 15 are the calculated site energy use intensity values for the eQUEST and EPlus models. The average site energy use intensity value for similar buildings in the DOE Buildings Performance Database was again determined by entering building specification filters into the program. The details for the R6 building were entered into the DOE Buildings Performance Database, and the average site energy use intensity for the set of buildings which met those specifications is shown in Table 15.

Table 15: Comparison of Site Energy Use Intensities for R6 Building (U.S. Department of Energy 2013a)

R6 Residential Building	eQUEST Energy Demand Model	EPlus Energy Demand Model	DOE Buildings Performance Database
Site Energy Use Intensity (kBtu/ft^2/year)	39	32	34

The site energy use intensity values for the eQUEST and EPlus models were close to the average site energy use intensity value for similar buildings in the DOE Buildings Performance Database. 32,973 buildings in the database had a similar building type, geometry and location as the R6 building used in the simulations, so this set of buildings was used to calculate the average site energy use intensity.

4.2.3 Two Story Office Building

The energy consumption data produced by the eQUEST and EPlus models for the 2-story office building were compared to each other and to external data for validation purposes. Shown in Table 16 is a comparison of the end use energy consumption data for the eQUEST and EPlus models produced for the 2-story office building. For this building scenario, the end uses of hot water, interior equipment, interior lights and space heat all had similar energy consumption values for the two models. The energy consumption for space cooling in the two models were different, as were the energy consumption values for the vent. fans and the pumps and auxiliary equipment.

Table 16: Comparison of eQUEST and EPlus Model Results for 2-Story Office Building

End Use	eQUEST Energy Consumption (kWh/year)	EPlus Energy Consumption (kWh/year)
Space Cool	39070	53976
Hot Water	4690	4769
Vent. Fans	17860	1288
Pumps & Aux.	1210	0
Interior/Misc. Equip.	56070	57751
Interior Lights	41580	37263
Space Heat	16468	16094
Total	176948	171140

The differences in energy consumption for the vent. fans and the pumps and auxiliary equipment were likely results of the same issues as occurred in the R1 and R6 building models. The energy consumption for the vent. fans were likely different due to the programs modeling the fans different ways, and the energy consumption for the pumps and auxiliary equipment were likely different since EPlus did not use this end use category, and probably grouped this energy consumption into a different end use category. The differences in energy consumption for the space cooling end use was likely a result of the differences in the way the programs modeled the heating and cooling of the building. In this case the EPlus model seemed to estimate the cooling for the building to be higher than the estimates of the eQUEST model, but the eQUEST model estimated a slightly higher space heating load than the EPlus model. Overall, the results for both models were on the same order of magnitude, which indicated that the models successfully simulated the 2-story office building using the same building geometry and specifications in each simulation.

The site energy use intensity values for the eQUEST and EPlus models were calculated to validate the simulations. These values were compared with the average site energy use intensity value for similar buildings in the DOE Buildings Performance Database. Shown in Table 17 are the calculated site energy use intensity values for the eQUEST and EPlus models. The average site energy use intensity value for similar buildings in the DOE Buildings Performance Database was again determined by entering building specification filters into the program. The details for the 2-story office building were entered into the DOE Buildings Performance Database, and the average site energy use intensity for the set of buildings which met those specifications is shown in Table 17.

The site energy use intensity values for the eQUEST and EPlus models were not close to the average site energy use intensity value for similar buildings in the DOE Buildings Performance Database. The set of office buildings in the DOE Buildings Performance Database had an average site energy use intensity of 118 kBtu/ft^2/year, while the eQUEST model had a site energy use intensity of 40 kBtu/ft^2/year, and the

EPlus model had a site energy use intensity of 39 kBtu/ft^2/year. This significant difference in site energy use intensity values is likely due to different internal loads in the office buildings studied. In addition, only 357 buildings in the database had a similar building type, geometry and location as the 2-story office building used in the simulations, which was a much smaller set of buildings used to calculate the average site energy use intensity than in the other two scenarios. The similarities between the site energy use intensity values for the eQUEST and EPlus models also indicates that the same building internal loads were used for these two simulations, but that the buildings considered in the DOE Buildings Performance Database had different internal loads, or other different building specifications.

Table 17: Comparison of Site Energy Use Intensities for 2-Story Office Building (U.S. Department of Energy 2013a)

2-Story Office Building	eQUEST Energy Demand Model	EPlus Energy Demand Model	DOE Buildings Performance Database
Site Energy Use Intensity (kBtu/ft^2/year)	40	39	118

4.3 System Efficiencies

The CHP system model was assumed to have two modes of operation, summer mode and winter mode. The system produced electricity, domestic hot water and chilled air for building cooling in summer mode, while in winter mode the system produced electricity, domestic hot water and hot air for building heating. The CHP system model used different system components based upon its mode of operation, and thus had different efficiencies for its different modes of operation. Efficiencies were calculated for each of the CHP system model paths between the thermal output of the microturbine and the energy available for each thermal end use. These composite efficiencies were calculated by taking the efficiency of each component in the path between the microturbine and the end use into consideration. In order to perform these calculations, the efficiency value for each component was needed. The HRU used in the model was assumed to have an average efficiency of 0.75, the absorption chiller used in the model was assumed to have an average COP of 0.75, and a pipe loss coefficient of 0.9 was considered for each end use product.

The composite efficiency value for each of the thermal end uses was calculated by multiplying the efficiency values of each component in the path between the microturbine and the end use. The composite efficiency values for domestic hot water and space heating were calculated by multiplying the efficiency value of the HRU by the pipe loss coefficient, and the composite efficiency value for space cooling was calculated by multiplying the efficiency value of the HRU by the COP of the absorption chiller and the pipe loss coefficient. This gave an efficiency of 68% for the domestic hot water end use, an efficiency of 51% for the chilled air end use, and an efficiency of 68% for the hot air end use. Average electrical efficiency for a microturbine is 23%, so this value was assumed for the electrical component of the CHP system model. Shown in Figure 33 is a diagram of the CHP system model with the summer mode active components highlighted and the efficiencies labeled for each active end use. Shown in Figure 34 is a diagram of the CHP system model with the winter mode active components highlighted, and the efficiencies defined for each active end use. The efficiencies calculated were later used to determine the desired electrical and thermal microturbine output for each building scenario examined.

4.4 CHP System Model Results - Using eQUEST Building Load Data

The CHP system model developed was applied to three scenarios: an R1 single-family residential building, an R6 6-story residential building and a 2-story office building. The building energy demand model created in eQUEST provided the electrical and thermal energy building load for each scenario. The building load data was used in the CHP system model to find the desired electrical and thermal microturbine output, taking system inefficiencies into consideration. These desired microturbine output values were compared with the output produced by a commercially available microturbine, and a microturbine was sized for each application. The development of the CHP system model for each scenario generated time-based data on the electrical and thermal energy provided by a CHP system, and the electrical and thermal energy consumed by the building.

4.4.1 Preliminary Calculations

Development of the CHP system model for each scenario began with the building energy demand model created in eQUEST. eQUEST produced monthly electric and gas consumption data listed by end use, and this data needed to be regrouped into the four end uses of the CHP system model: domestic hot water, space heating, space cooling and electricity.

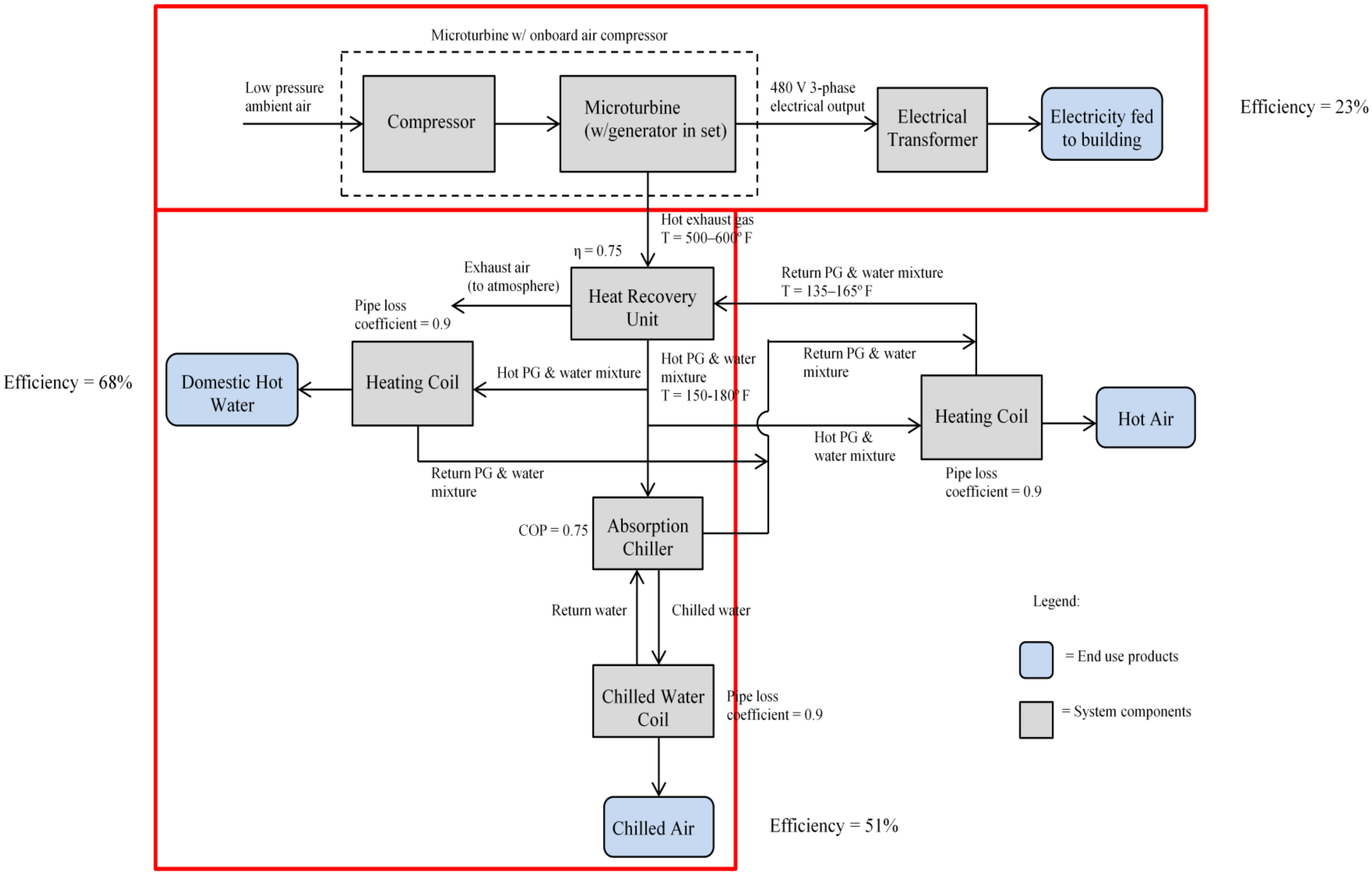


Figure 33: Diagram of CHP System Model with Efficiencies - Summer Mode

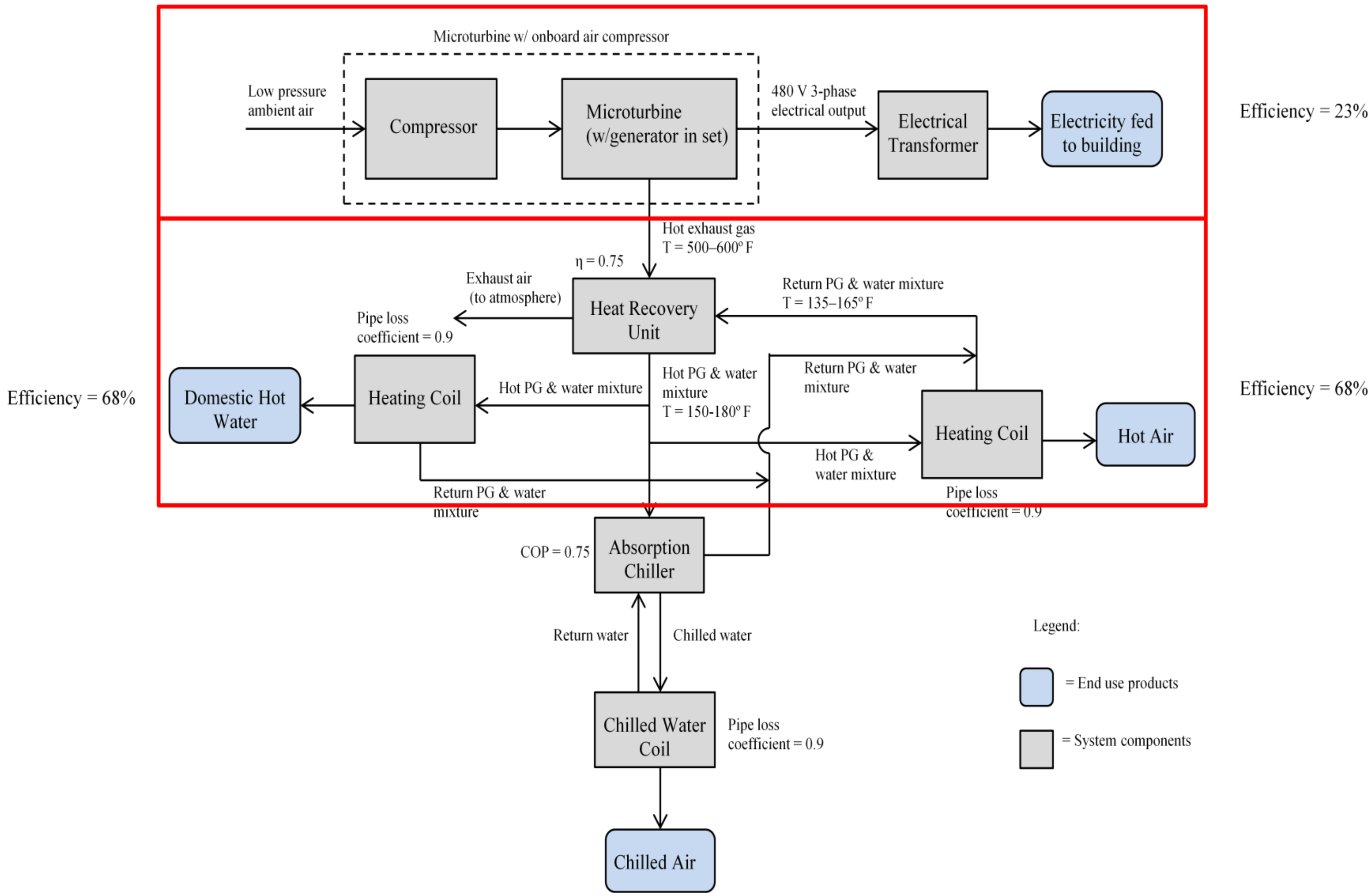


Figure 34: Diagram of CHP System Model with Efficiencies - Winter Mode

The building energy consumption data listed in Appendix A in Tables 67, 68 and 69 was converted into units of kWh for ease of calculation. The resulting values are listed in Appendix A in Tables 70, 71 and 72. Table 70 shows the R1 residential building load data in kWh, Table 71 shows the R6 residential building load data in kWh, and Table 72 shows the office building load data in kWh. The monthly data from Tables 70, 71 and 72 was then regrouped into the four end uses of the CHP system model: domestic hot water, space heating, space cooling and electricity. The end uses of space cooling, space heating and hot water were all considered part of the thermal energy load, while the electricity end use was the electrical energy load. The space cooling, space heating and hot water end uses listed in Tables 70, 71 and 72 were each considered their own end use for the CHP system model, and the end uses of area lights, miscellaneous equipment, pumps, auxiliary, and vent fans were all grouped into the electricity end use. The monthly data from Tables 70, 71 and 72 was regrouped into the end uses of the CHP system model: electricity, domestic hot water, space heating and space cooling.

Once the building consumption data was regrouped into the end uses of the CHP system model, the inefficiencies of the CHP system were considered in the analysis. The efficiency for each end use of the CHP system had been previously calculated; the efficiency for domestic hot water was 0.68, the efficiency for space cooling was 0.51, and the efficiency for space heating was 0.68. It was assumed there was negligible energy loss between the electrical output of the microturbine and the electricity available for end use, so this efficiency was considered 1. The efficiency values for each end use were used to calculate the energy which exited the microturbine. The efficiency value for each end use reflected the energy loss between the energy which exited the microturbine and the energy available for end use, so the data on the building energy load for each end use was divided by the composite inefficiency for that thermal end use. This gave the microturbine energy output which corresponded to the energy needed to power the building for that end use. This microturbine energy output was called the 'desired microturbine output'. Desired microturbine output values were calculated for the end uses of space cooling, space heating and domestic hot water for each month. The desired microturbine output values for the electric energy load were the same as the electric energy needed to power the building, as the efficiency was assumed to be 1 in this case.

Once the desired microturbine output values were calculated for each end use, the parasitic loads due to the compressor in the microturbine and the recirculation pump in the HRU were added to the desired microturbine output values. The pump required about 1 kW of thermal energy to operate and was considered to always be running. This meant the recirculation pump required 720 kWh/month, so this additional thermal energy requirement was added to the overall desired thermal microturbine output for each month. The compressor required about 2 kW of electricity to operate and was also assumed to always be running. This meant the compressor required 1440 kWh/month, so this additional electricity requirement was added to the overall desired electrical microturbine output for each month. The desired microturbine output values for the end uses of space cooling, space heating and domestic hot water were added to the parasitic load due to the HRU recirculation pump to find the monthly total thermal energy needed to be produced by the microturbine. The desired microturbine output value for electricity was added to the parasitic load due to the compressor to find the monthly total electricity needed to be produced by the microturbine.

Shown in Appendix A in Tables 73, 74 and 75 are the electrical and thermal energy loads with inefficiencies for the R1 residential building, the R6 residential building and the 2-story office building. The column of tables on the left side of the page shows the thermal energy loads, and the column of tables on the right side of the page shows the electric energy loads. Each small table in the set shows the electric or thermal energy load for a specific month. The 'End Output Needed' row gives the data on the building energy load for each end use, and the 'Composite Inefficiencies' row gives the efficiency value for each end use. The 'MT Output' row gives 'End Output Needed' for that end use divided by the corresponding efficiency value. The desired microturbine output values were summed for the electric and thermal energy loads, and the parasitic loads due to the compressor and the recirculation pump added to this total. The total given in each month table represents the total electric or thermal energy needed to be produced by the microturbine for that month, and is referred to as 'desired electric microturbine output' and 'desired thermal microturbine output' in the results.

Once the desired total electric and thermal energy microturbine output for each month was found, these numbers were compared with the output produced by a commercially available microturbine, and a microturbine was sized for each application. The development of the CHP system model for each scenario generated time-based data on the electrical and thermal energy provided by a CHP system, and the electrical and thermal energy consumed by the building.

4.4.2 R1 Residential Building Results

A CHP system model was developed for the R1 single-family residential building using the time-based data on desired electric and thermal microturbine output. This monthly data is shown in Table 18 for the R1 residential building, where the desired electric and thermal microturbine output values were calculated using the eQUEST building load data. The data on the desired electric and thermal microturbine output was then entered into the HOMER energy model of the microturbine, along with inputs on the system component characteristics.

Table 18: Desired Electric and Thermal Microturbine Output for R1 Building - Calculations using eQUEST Building Load Data

Month	Electrical Energy (kWh)	Thermal Energy (kWh)
January	3450.00	2317.43
February	3190.00	2291.65
March	3310.00	1804.20
April	3280.00	2165.29
May	3320.00	2605.82
June	3220.00	2863.21
July	3360.00	3144.69
August	3280.00	2942.22
September	3270.00	2685.43
October	3360.00	2205.23
November	3330.00	1750.81
December	3410.00	2097.96

The microturbine was assumed to run constantly and at full capacity. The HOMER energy model simulated a microturbine system and the electric and thermal energy loads it met. The model provided information on the optimal size of microturbine, and generated time-based data on the electric and thermal energy provided by a microturbine system.

The HOMER model for the R1 residential building showed that a 6 kW microturbine was the smallest theoretical size which would completely meet the desired electric and thermal microturbine output. The microturbine was assumed to run constantly and at full capacity, so the microturbine produced the same amounts of electric and thermal energy each month. The electric and thermal energy provided by the 6 kW microturbine is shown in Table 19.

Table 19: Electric and Thermal Energy Provided by 6 kW Microturbine for R1 Building - Calculations using eQUEST Building Load Data

Month	Electrical Energy (kWh)	Thermal Energy (kWh)
January	4320	7500
February	4320	7500
March	4320	7500
April	4320	7500
May	4320	7500
June	4320	7500
July	4320	7500
August	4320	7500
September	4320	7500
October	4320	7500
November	4320	7500
December	4320	7500

The microturbine was sized to the R1 building so that the building was completely powered by the microturbine; as a result the microturbine produced excess energy throughout the year.

Figure 35 shows the desired electrical and thermal microturbine output for the R1 building with the electrical and thermal energy provided by the 6 kW microturbine. In each month the electrical energy provided by the 6 kW microturbine was slightly greater than the desired electrical microturbine output needed to power the building. The thermal energy provided by the 6 kW microturbine was much greater than the desired thermal microturbine output. These differences in microturbine energy production and building energy consumption are also shown in Table 20. The table shows the microturbine energy production and building energy consumption for both electric and thermal energy, and the resulting excess electric and thermal energy. For the scenario of the R1 residential building powered by a 6 kW microturbine, all building energy demands were met, with about 23.6% excess electricity and about 67.7% excess thermal energy.

Table 20: Excess Electric and Thermal Energy for 6 kW Microturbine in R1 Building - Calculations Using eQUEST Building Load Data

	Electrical Energy (kWh/year)	Thermal Energy (kWh/year)
Microturbine Energy Production	52,560	90,498
Building Energy Consumption	40,150	29,200
Excess Energy	12,410	61,298

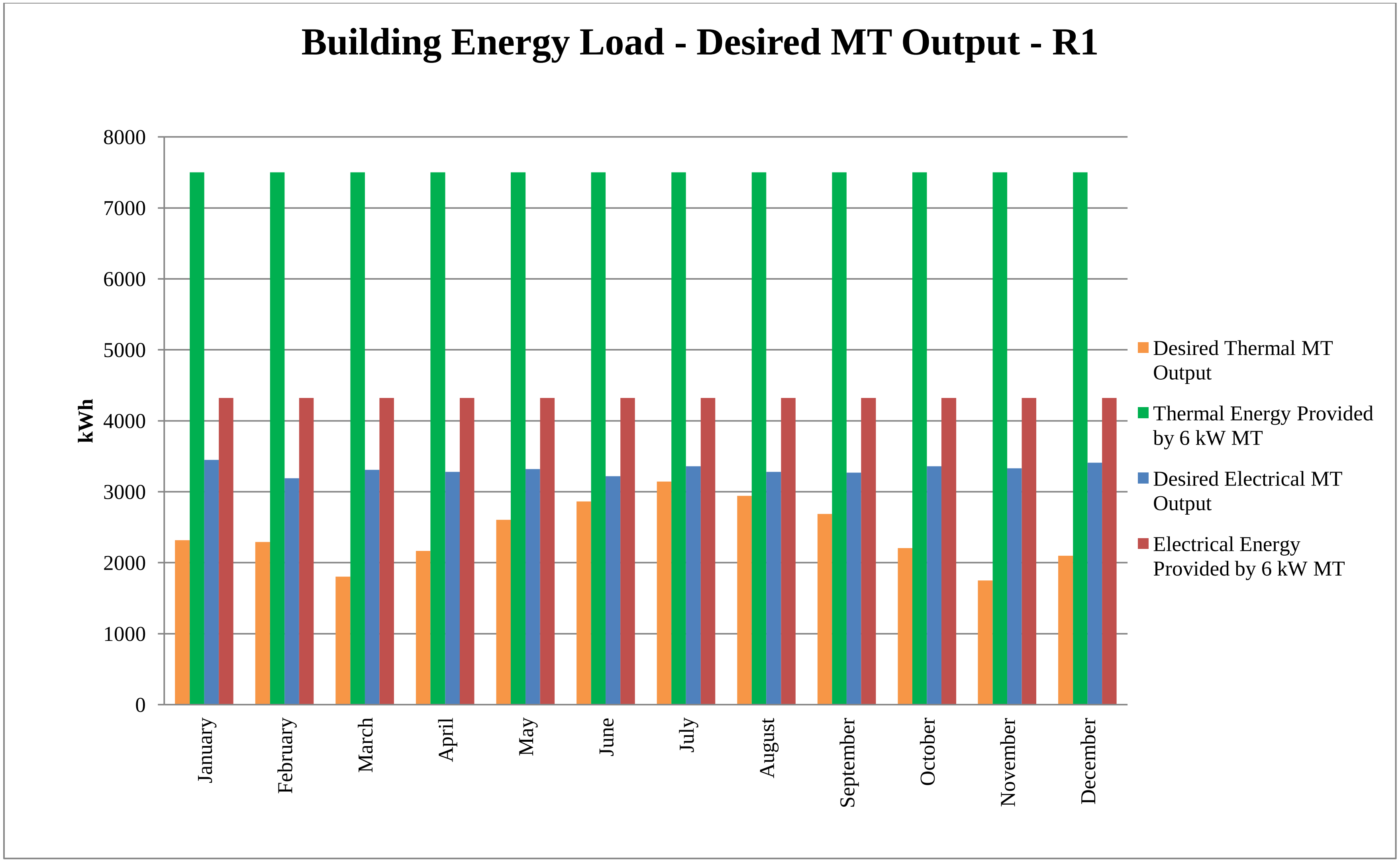


Figure 35: Desired Microturbine Output and Energy Provided by Microturbine - R1 Building - Calculations Using eQUEST Data

A 6 kW microturbine was the smallest theoretical size which completely met the desired electric and thermal microturbine output for a R1 residential building, but microturbines are not currently commercially available at this size. In order for the CHP system design for the R1 building to be feasible, the theoretical 6 kW microturbine was scaled up to a commercially available size. The relation between microturbine sizes and the energy they provide scales linearly, so the theoretical microturbine size was multiplied by a scaling factor to achieve a commercially available size, while the electrical and thermal loads for the building were also multiplied by that scaling factor. The smallest commercially available microturbine size was considered 30 kW, so the theoretical microturbine system and its electrical and thermal loads were multiplied by a scaling factor of 5. This scaling process is shown in Figure 36. The 6 kW microturbine powered one R1 building completely with 23.6% excess electricity and 67.7% excess thermal energy, so was able to completely power 1.2 R1 buildings, and produce the thermal energy for an additional R1 building. This scenario scaled by a factor of 5 gave a 30 kW microturbine which produced the energy to completely power 6 R1 buildings, and provided the thermal energy for an additional 5 R1 buildings.

The CHP system model for the R1 single-family residential building used a 30 kW microturbine with an onboard air compressor, an electrical transformer, a heat recovery unit, an absorption chiller, chilled water coils and heating coils. This system provided the electricity and thermal energy needed to completely power 6 R1 residential buildings, and provided the thermal energy for an additional 5 R1 residential buildings.

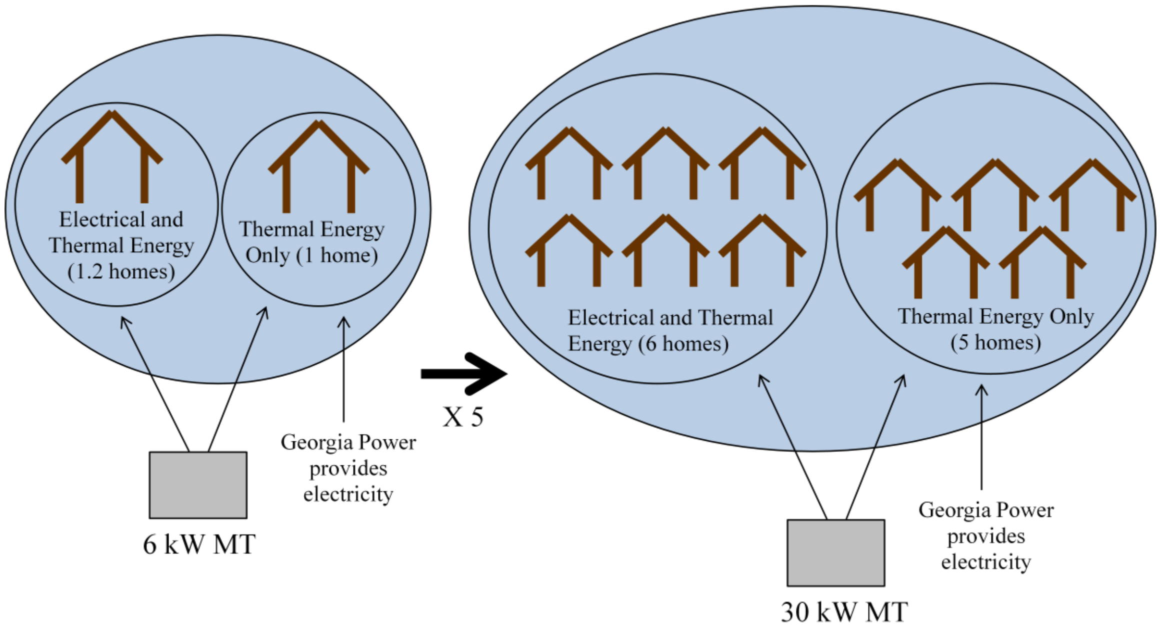


Figure 36: Diagram of Microturbine Scaling Process for R1 Residential Building

The CHP system model developed for the R1 building generated time-based data on the electrical and thermal energy provided by a CHP system with a 6 kW or 30 kW microturbine as the prime mover, and the electrical and thermal energy consumed by a set of R1 residential buildings.

4.4.3 R6 Residential Building Results

A CHP system model was developed for the R6 residential building using the time-based data on desired electric and thermal microturbine output. This monthly data is shown in Table 21 for the R6 residential building, where the desired electric and thermal microturbine output values were calculated using the eQUEST building load data. The desired electric and thermal microturbine output data was then entered into the HOMER energy model of the microturbine, along with inputs on the system component characteristics. The microturbine was assumed to run constantly and at full capacity, and the HOMER model simulated a microturbine system and the electric and thermal energy loads it met. The model provided information on the optimal size of microturbine, and generated time-based data on the electric and thermal energy provided by a microturbine system.

Table 21: Desired Electric and Thermal Microturbine Output for R6 Building - Calculations using eQUEST Building Load Data

Month	Electrical Energy (kWh)	Thermal Energy (kWh)
January	33480.00	16859.06
February	30190.00	14799.39
March	32890.00	13276.40
April	32020.00	18733.03
May	32780.00	28152.10
June	31700.00	34280.49
July	33000.00	38285.43
August	32660.00	36413.83
September	31920.00	30527.41
October	32970.00	16813.83
November	32160.00	8905.93
December	33400.00	12846.83

The HOMER model for the R6 residential building showed that a 60 kW microturbine was the smallest commercially available size which would completely meet the desired electric and thermal microturbine output. The microturbine was assumed to run constantly and at full capacity, so the microturbine produced the same amounts of electric and thermal energy each month. The electric and thermal energy provided by the 60 kW microturbine is shown in Table 22. The microturbine was sized to the R6 building so that the building was completely powered by the microturbine; as a result the microturbine produced excess energy throughout the year.

Table 22: Electric and Thermal Energy Provided by 60 kW Microturbine for R6 Building - Calculations Using eQUEST Building Load Data

Month	Electrical Energy (kWh)	Thermal Energy (kWh)
January	43200	75000
February	43200	75000
March	43200	75000
April	43200	75000
May	43200	75000
June	43200	75000
July	43200	75000
August	43200	75000
September	43200	75000
October	43200	75000
November	43200	75000
December	43200	75000

Figure 38 shows the desired electrical and thermal microturbine output for the R6 building with the electrical and thermal energy provided by the 60 kW microturbine. As in the case for the R1 scenario, the electrical and thermal energy provided by the 60 kW microturbine was in excess of the energy needed to power the building. The differences in microturbine energy production and building energy consumption are shown in Table 23. The table shows the microturbine energy production and building energy consumption for both electric and thermal energy, and the resulting excess electric and thermal energy. For the scenario of the R6 residential building powered by a 60 kW microturbine, all building energy demands were met, with about 25.3% excess electricity and about 69.8% excess thermal energy.

Table 23: Excess Electric and Thermal Energy for 60 kW Microturbine in R6 Building - Calculations Using eQUEST Building Load Data

	Electrical Energy (kWh/year)	Thermal Energy (kWh/year)
Microturbine Energy Production	525,600	905,018
Building Energy Consumption	392,740	273,749
Excess Energy	132,860	631,269

Shown in Figure 37 is a diagram of the energy provided by the 60 kW microturbine. The 60 kW microturbine, or two 30 kW microturbines, met all electric and thermal energy needs of the R6 residential building, with an excess 132,860 kWh/year of electricity and an excess of 631,269 kWh/year of thermal energy.

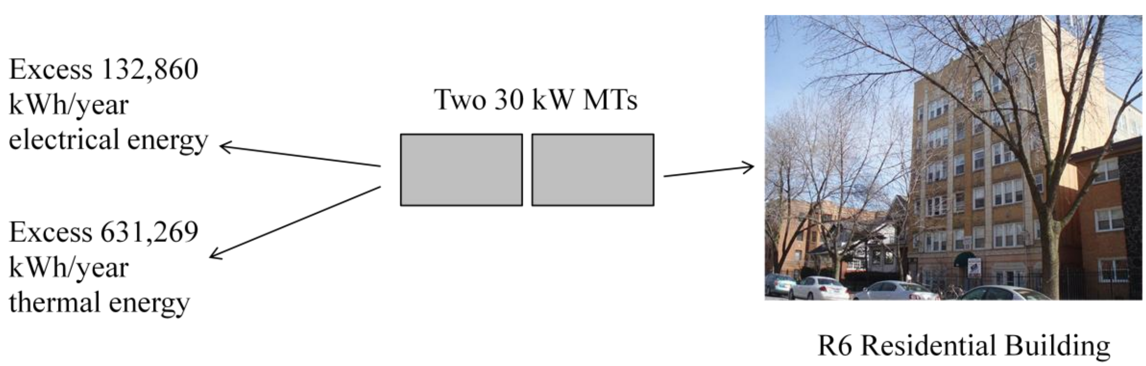


Figure 37: Diagram of Energy Provided by 60 kW Microturbine for R6 Building

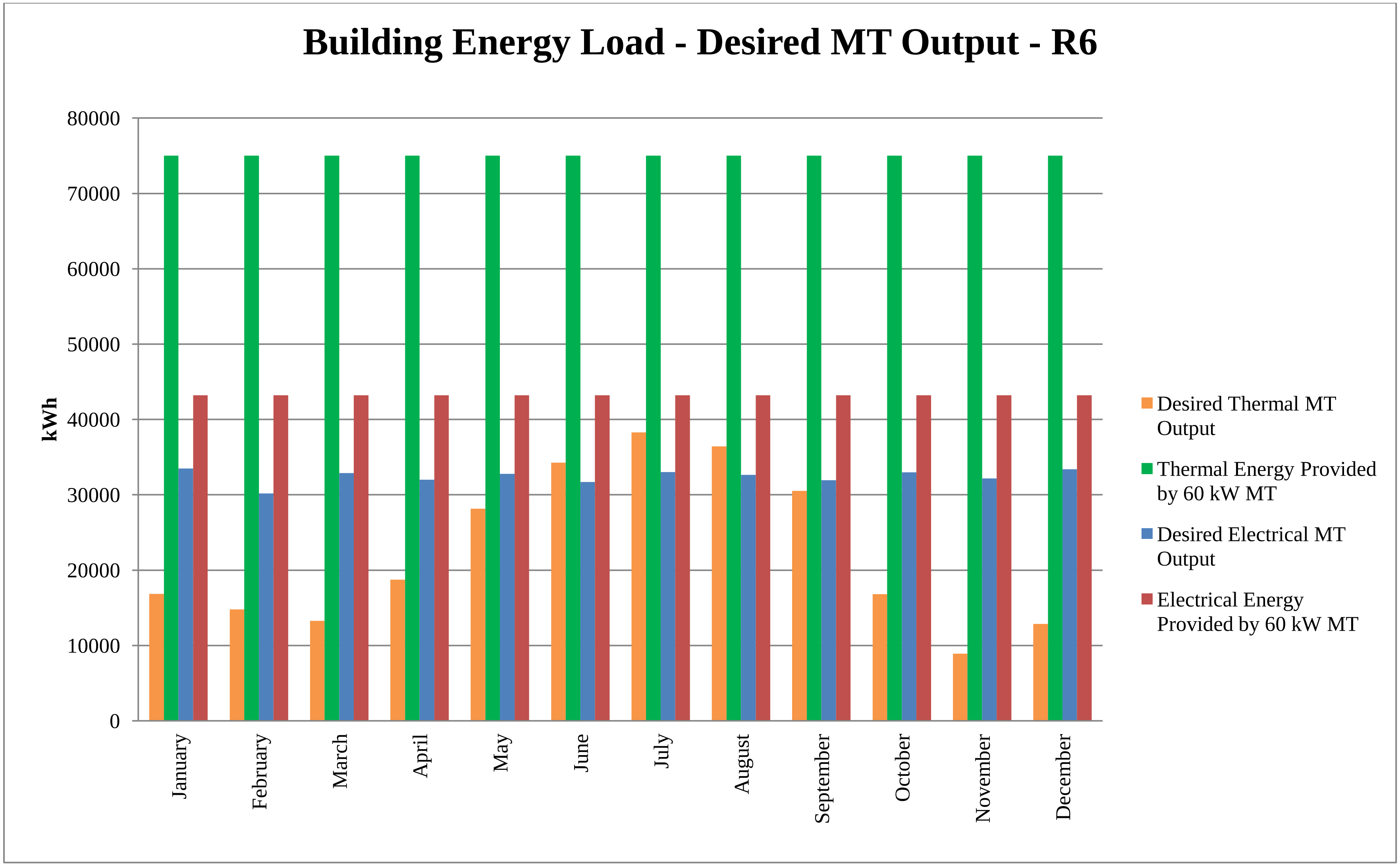


Figure 38: Desired Microturbine Output and Energy Provided by Microturbine - R6 Building - Calculations Using eQUEST Data

The CHP system model for the R6 6-story residential building used a 60 kW microturbine with an onboard air compressor, an electrical transformer, a heat recovery unit, an absorption chiller, chilled water coils and heating coils. This system provided the electricity and thermal energy needed to completely power an R6 residential building, with an excess 132,860 kWh/year of electricity and 631,269 kWh/year of thermal energy available for other uses. The CHP system model developed for the R6 building generated time-based data on the electrical and thermal energy provided by a CHP system with a 60 kW microturbine as the prime mover, and the electrical and thermal energy consumed by an R6 residential building.

4.4.4 Two-Story Office Building Results

A CHP system model was developed for the 2-story office building using the data on desired electric and thermal microturbine output. This monthly data is shown in Table 24. The desired electric and thermal microturbine output data for the office building was then entered into the HOMER model of the microturbine, along with inputs on the system component characteristics. The microturbine was assumed to run constantly and at full capacity, and the HOMER model simulated a microturbine system and the electric and thermal energy loads it met. The model generated time-based data on the electric and thermal energy provided by a microturbine, and provided information on the optimal size of microturbine for the office building scenario.

The HOMER model for the 2-story office building showed that a 30 kW microturbine was the smallest commercially available size which would completely meet the desired electric and thermal microturbine output.

Table 24: Desired Electric and Thermal Microturbine Output for Office Building - Calculations Using eQUEST Building Load Data

Month	Electrical Energy (kWh)	Thermal Energy (kWh)
January	11130.00	9483.02
February	10460.00	8388.81
March	12020.00	4321.48
April	10800.00	6326.53
May	11520.00	9657.68
June	11450.00	15018.85
July	10820.00	15854.01
August	11870.00	17270.10
September	10740.00	12630.51
October	11210.00	6164.69
November	10900.00	4233.21
December	11080.00	7811.09

As in the other scenarios, the microturbine was assumed to run constantly and at full capacity, so the microturbine produced the same amounts of electric and thermal energy each month. The electric and thermal energy provided by the 30 kW microturbine is shown in Table 25. The microturbine was sized to the office building so that the building was completely powered by the microturbine; as a result the microturbine produced excess energy throughout the year.

Table 25: Electric and Thermal Energy Provided by 30 kW Microturbine for Office Building - Calculations Using eQUEST Building Load Data

Month	Electrical Energy (kWh)	Thermal Energy (kWh)
January	21600	37700
February	21600	37700
March	21600	37700
April	21600	37700
May	21600	37700
June	21600	37700
July	21600	37700
August	21600	37700
September	21600	37700
October	21600	37700
November	21600	37700
December	21600	37700

Figure 39 shows the desired electrical and thermal microturbine output for the office building with the electrical and thermal energy provided by the 30 kW microturbine. As in the case for the R1 and R6 scenarios, the electrical and thermal energy provided by the 30 kW microturbine was in excess of the energy needed to power the building. The differences in microturbine energy production and building energy consumption are shown in Table 26. The table shows the microturbine energy production and building energy consumption for both electric and thermal energy, and the resulting excess electric and thermal energy. For the scenario of the 2-story office building powered by a 30 kW microturbine, all building energy demands were met, with about 48.5% excess electricity and about 73.8% excess thermal energy.

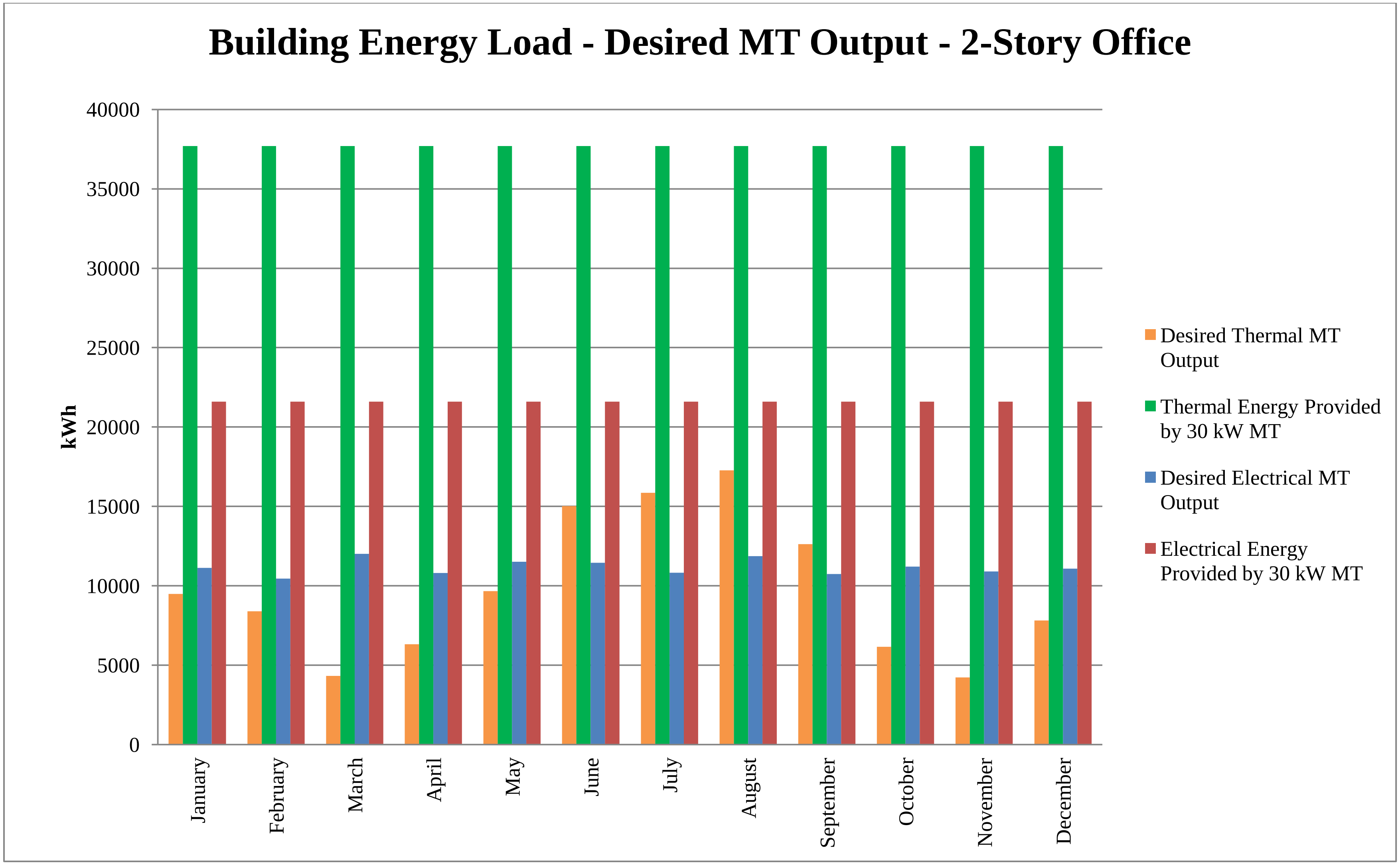


Figure 39: Desired Microturbine Output and Energy Provided by Microturbine - Office Building - Calculations Using eQUEST Data

Table 26: Excess Electric and Thermal Energy for 30 kW Microturbine in Office Building - Calculations Using eQUEST Building Load Data

	Electrical Energy (kWh/year)	Thermal Energy (kWh/year)
Microturbine Energy Production	262,800	452,509
Building Energy Consumption	135,415	118,625
Excess Energy	127,385	333,884

Shown in Figure 40 is a diagram of the energy provided by the 30 kW microturbine. The 30 kW microturbine met all electric and thermal energy needs of the office building, with an excess 127,385 kWh/year of electricity and an excess of 333,884 kWh/year of thermal energy.

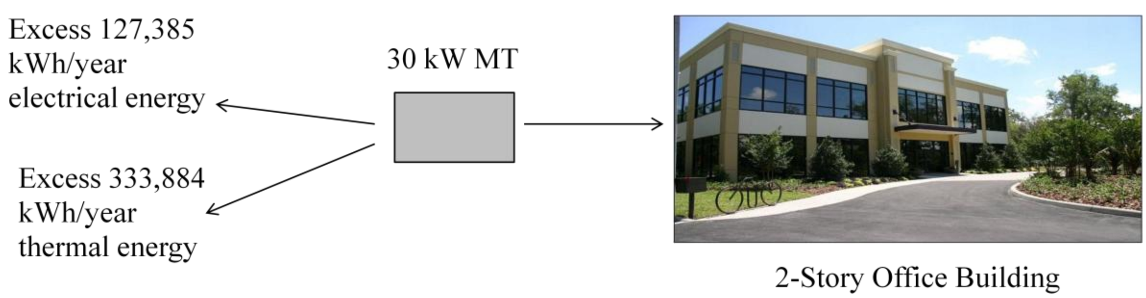


Figure 40: Diagram of Energy Provided by 30 kW Microturbine for Office Building

The CHP system model for the 2-story office building used a 30 kW microturbine with an onboard air compressor, an electrical transformer, a heat recovery unit, an absorption chiller, chilled water coils and heating coils. This system provided the electricity and thermal energy needed to completely power a 2-story office building, with an excess 127,385 kWh/year of electricity and 333,884 kWh/year of thermal energy available for other uses. The CHP system model developed for the office building generated time-based data on the electrical and thermal energy provided by a CHP system with a 30 kW microturbine as the prime mover, and the electrical and thermal energy consumed by a 2-story office building.

4.5 CHP System Model Results - Using EPlus Building Load Data

The CHP system model developed was again applied to three scenarios: an R1 single-family residential building, an R6 6-story residential building and a 2-story office building. For this analysis, the building energy demand model created in EPlus provided the electrical and thermal energy building load for each scenario. The building load data was used in the CHP system model to find the desired electrical and thermal microturbine output, taking system inefficiencies into consideration. These desired microturbine output values were compared with the output produced by a commercially available microturbine, and a microturbine was sized for each application. The development of the CHP system model for each scenario generated time-based data on the electrical and thermal energy provided by a CHP system, and the electrical and thermal energy consumed by the building.

4.5.1 Preliminary Calculations

Development of the CHP system model for each scenario began with the building energy demand model created in EPlus. EPlus produced monthly electric and gas consumption data listed by end use, and this data was then regrouped into the four end uses of the CHP system model: domestic hot water, space heating, space cooling and electricity. The building energy consumption data is listed in Appendix B in Tables 79, 80 and 81. Table 79 shows the R1 residential building load data in kWh, Table 80 shows the R6 residential building load data in kWh, and Table 81 shows the office building load data in kWh. The monthly data from Tables 79, 80 and 81 was then regrouped into the four end uses of the CHP system model. The end uses of space cooling, space heating and hot water were all considered part of the thermal energy load, while the electricity end use was the electrical energy load. The space cooling, space heating and hot water end uses listed in Tables 79, 80 and 81 were each considered their own end use for the CHP system model, and the end uses of vent fans, interior equipment and interior lights were all grouped into the electricity end use.

Once the building consumption data was regrouped into the end uses of the CHP system model, the inefficiencies of the CHP system were considered in the analysis. The same efficiency for each end use was used as in the CHP system model discussed in Section 4.3. The efficiency for domestic hot water was 0.68, the efficiency for space cooling was 0.51, and the efficiency for space heating was 0.68. As in the case of the CHP system model which used eQUEST building load data, it was assumed that there was negligible energy loss between the electrical output of the microturbine and the electricity available for end use, so this efficiency was considered 1. The efficiency values for each end use were used to calculate the energy which exited the microturbine. The data on the building energy load for each end use was divided by the composite inefficiency for that thermal end use. This gave the desired microturbine output. Desired microturbine output values were calculated for the end uses of space cooling, space heating and domestic hot water for each month. The desired microturbine output values for the electric energy load were the same as the electric energy needed to power the building, as the efficiency was assumed to be 1 in this case.

Once the desired microturbine output values were calculated for each end use, the parasitic loads due to the compressor in the microturbine and the recirculation pump in the HRU were added to the desired microturbine output values. The same assumptions were made as in the CHP system model discussed in Section 4.3. The recirculation pump required 720 kWh/month, and the compressor required 1440 kWh/month. The additional thermal energy requirement from the recirculation pump was added to the overall desired thermal microturbine output for each month, and the additional electrical energy requirement from the compressor was added to the desired electrical energy microturbine output for each month. The desired microturbine output values for the end uses of space cooling, space heating and domestic hot water were added to the parasitic load due to the HRU recirculation pump to find the monthly total thermal energy needed to be produced by the microturbine. The desired microturbine output value for electricity was added to the parasitic load due to the compressor to find the monthly total electricity needed to be produced by the microturbine.

Shown in Appendix B in Tables 82, 83 and 84 are the electrical and thermal energy loads with inefficiencies for the R1 residential building, the R6 residential building and the 2-story office building. The column of tables on the left side of the page shows the thermal energy loads, and the column of tables on the right side of the page shows the electric energy loads. Each small table in the set shows the electric or thermal energy load for a specific month. The 'End Output Needed' row gives the data on the building energy load for each end use, and the 'Composite Inefficiencies' row gives the efficiency value for each end use. The 'MT Output' row gives 'End Output Needed' for that end use divided by the corresponding efficiency value. The desired microturbine output values were summed for the electric and thermal energy loads, and the parasitic loads due to the compressor and the recirculation pump added to this total. The total given in the bottom right corner of each small table represents the total electric or thermal energy needed to be produced by the microturbine for that month, and is referred to as 'desired electric microturbine output' and 'desired thermal microturbine output' in the results.

Once the desired total electric and thermal energy microturbine output for each month was found, these numbers were compared with the output produced by a commercially available microturbine, and a microturbine was sized for each application. The development of the CHP system model for each scenario generated time-based data on the electrical and thermal energy provided by a CHP system, and the electrical and thermal energy consumed by the building.

4.5.2 R1 Residential Building Results

A CHP system model was developed for the R1 single-family residential building using the time-based data on desired electric and thermal microturbine output. This monthly data is shown in Table 27 for the R1 residential building, where the desired electric and thermal microturbine output values were calculated using the EPlus building load data. The data on the desired electric and thermal microturbine output was then entered into the HOMER energy model of the microturbine, along with inputs on the system component characteristics. The microturbine was assumed to run constantly and at full capacity. The HOMER model for the R1 residential building showed that a 6 kW microturbine was the smallest theoretical size which would completely meet the desired electric and thermal microturbine output. The microturbine was assumed to run constantly and at full capacity, so the microturbine produced the same amounts of electric and thermal energy each month. The electric and thermal energy provided by the 6 kW microturbine is shown in Table 28. The microturbine was sized to the R1 building so that the building was completely powered by the microturbine; as a result the microturbine produced excess energy throughout the year.

Table 27: Desired Electric and Thermal Microturbine Output for R1 Building - Calculations Using EPlus Building Load Data

Month	Electrical Energy (kWh)	Thermal Energy (kWh)
January	3098.91	2809.25
February	2975.44	2087.02
March	3180.25	1959.19
April	3148.13	2538.81
May	3151.54	3249.47
June	3145.64	3795.73
July	3175.12	4132.41
August	3201.09	3977.95
September	3098.39	3331.26
October	3151.85	2546.60
November	3031.24	1730.42
December	3151.36	2058.82

Table 28: Electric and Thermal Energy Provided by 6 kW Microturbine for R1 Building - Calculations Using EPlus Building Load Data

Month	Electrical Energy (kWh)	Thermal Energy (kWh)
January	4320	7500
February	4320	7500
March	4320	7500
April	4320	7500
May	4320	7500
June	4320	7500
July	4320	7500
August	4320	7500
September	4320	7500
October	4320	7500
November	4320	7500
December	4320	7500

Figure 41 shows the desired electrical and thermal microturbine output for the R1 building with the electrical and thermal energy provided by the 6 kW microturbine. The electrical and thermal energy provided by the 6 kW microturbine was greater than the desired electrical and thermal microturbine output for each month. These differences in microturbine energy production and building energy consumption are also shown in Table 29. The table shows the microturbine energy production and building energy consumption for both electric and thermal energy, and the resulting excess electric and thermal energy. For the scenario of the R1 residential building powered by a 6 kW microturbine, all building energy demands were met, with about 27.8% excess electricity and about 61.7% excess thermal energy.

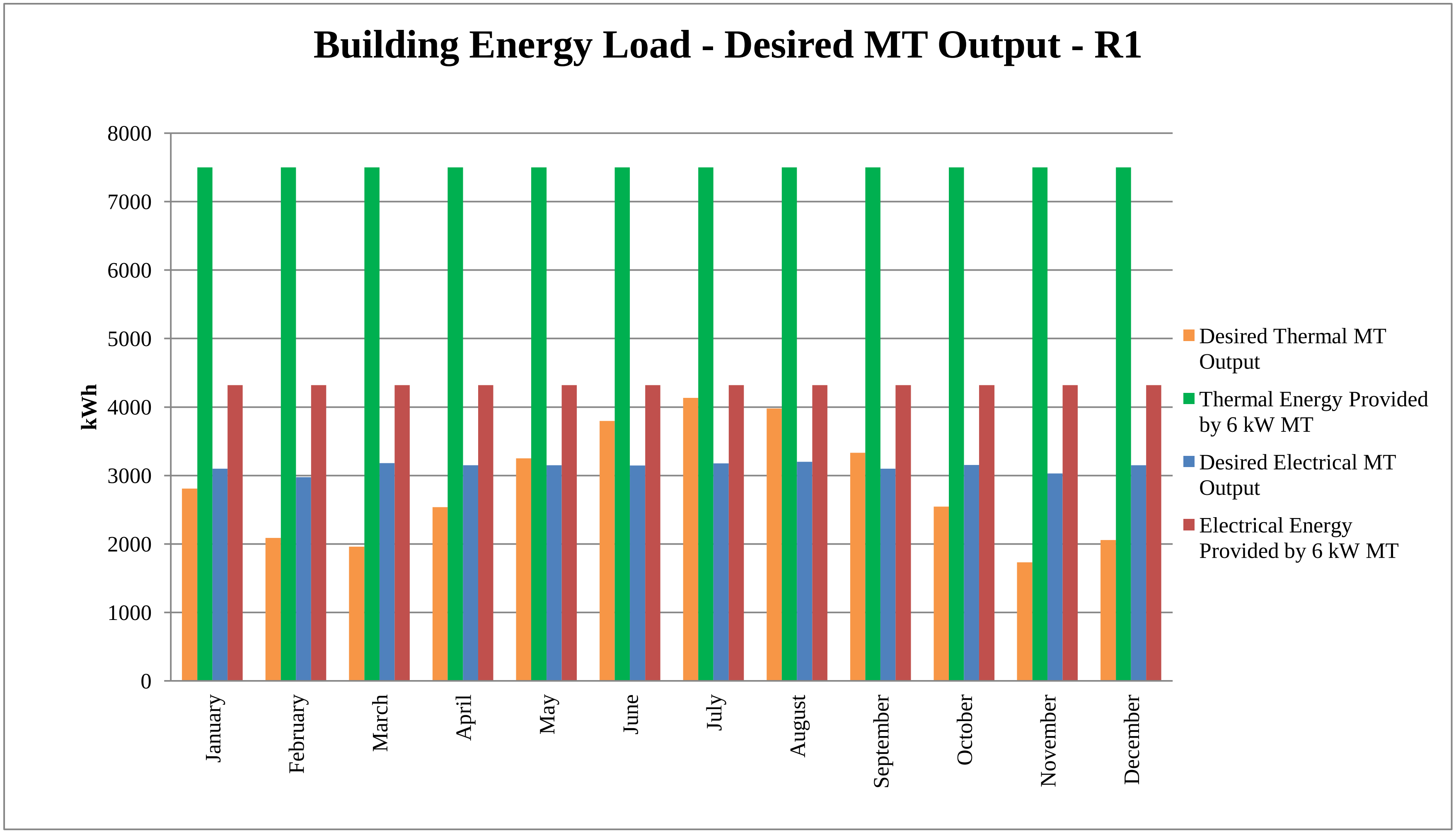


Figure 41: Desired Microturbine Output and Energy Provided by Microturbine - R1 Building - Calculations Using EPlus Data

Table 29: Excess Electric and Thermal Energy for 6 kW Microturbine in R1 Building - Calculations Using EPlus Building Load Data

	Electrical Energy (kWh/year)	Thermal Energy (kWh/year)
Microturbine Energy Production	52,560	90,498
Building Energy Consumption	37,960	34,675
Excess Energy	14,600	55,823

As in the case of the R1 CHP system model discussed in Section 4.3, the 6 kW microturbine was the smallest theoretical size which completely met the desired electric and thermal microturbine output for a R1 residential building, but microturbines are not currently commercially available at this size. In order for the CHP system design for the R1 building to be feasible, the theoretical 6 kW microturbine was scaled up to a commercially available size. The same assumptions were used as in the R1 CHP system model discussed in Section 4.3. The smallest commercially available microturbine size was considered 30 kW, so the theoretical microturbine system and its electrical and thermal loads were multiplied by a scaling factor of 5. The 6 kW microturbine powered one R1 building completely with 27.8% excess electricity and 61.7% excess thermal energy, so was able to power 1.2 R1 buildings completely, and produce the thermal energy for an additional R1 building. This scenario scaled by a factor of 5 gave a 30 kW microturbine which produced the energy to completely power 6 R1 buildings, and provided the thermal energy for an additional 5 R1 buildings. Although the building load data for this R1 CHP system model was slightly different than the load data for the R1 CHP system model discussed in Section 4.3, the microturbine size and resulting CHP system were the same.

The CHP system model for the R1 single-family residential building used a 30 kW microturbine with an onboard air compressor, an electrical transformer, a heat recovery unit, an absorption chiller, chilled water coils and heating coils. This system provided the electricity and thermal energy needed to completely power 6 R1 residential buildings, and provided the thermal energy for an additional 5 R1 residential buildings. The CHP system model developed for the R1 building generated time-based data on the electrical and thermal energy provided by a CHP system with a 6 kW or 30 kW microturbine as the prime mover, and the electrical and thermal energy consumed by a set of R1 buildings.

4.5.3 R6 Residential Building Results

A CHP system model was developed for the R6 residential building using the data on desired electric and thermal microturbine output. This monthly data is shown in Table 30. The data on the desired electric and thermal microturbine output was then entered into the HOMER model of the microturbine, along with inputs on the system component characteristics. The microturbine was assumed to run constantly and at full capacity, and the HOMER model simulated a microturbine system and the electric and thermal energy loads it met. The model provided information on the optimal size of microturbine, and generated time-based data on the electric and thermal energy provided by a microturbine.

The HOMER model for the R6 residential building showed that a 60 kW microturbine was the smallest commercially available size which would completely meet the desired electric and thermal microturbine output. The microturbine was assumed to run constantly and at full capacity, so the microturbine produced the same amounts of electric and thermal energy each month. The electric and thermal energy provided by the

60 kW microturbine is shown in Table 31. The microturbine was sized to the R6 building so that the building was completely powered by the microturbine; as a result the microturbine produced excess energy throughout the year.

Table 30: Desired Electric and Thermal Microturbine Output for R6 Building - Calculations Using EPlus Building Load Data

Month	Electrical Energy (kWh)	Thermal Energy (kWh)
January	28727.54	14407.47
February	26108.96	13184.00
March	28683.62	11095.20
April	27985.13	13927.69
May	28683.62	18519.12
June	27825.41	21523.36
July	28843.35	24450.67
August	28683.62	23526.80
September	27905.26	20113.96
October	28763.48	14329.44
November	27825.41	10216.01
December	28843.35	13213.46

Figure 42 shows the desired electrical and thermal microturbine output for the R6 building with the electrical and thermal energy provided by the 60 kW microturbine. As in the other scenarios, the electrical and thermal energy provided by the 60 kW microturbine was in excess of the energy needed to power the building. The differences in microturbine energy production and building energy consumption are shown in Table 32. The table shows the microturbine energy production and building energy consumption for both electric and thermal energy, and the resulting excess electric and thermal energy. For the scenario of the R6 residential building powered by a 60 kW microturbine, all building energy demands were met, with about 34.9% excess electricity and about 77.8% excess thermal energy. The 60 kW microturbine met all electric and thermal energy needs of the R6 building, with an excess of 183,594 kWh/year of electricity and an excess of 703,903 kWh/year of thermal energy. The building load data for this R6 building CHP system model was different than the load data for the R6 building CHP model discussed in Section 4.3, but the microturbine size and resulting CHP system were the same.

Table 31: Electric and Thermal Energy Provided by 60 kW Microturbine for R6 Building - Calculations Using EPlus Building Load Data

Month	Electrical Energy (kWh)	Thermal Energy (kWh)
January	43200	75000
February	43200	75000
March	43200	75000
April	43200	75000
May	43200	75000
June	43200	75000
July	43200	75000
August	43200	75000
September	43200	75000
October	43200	75000
November	43200	75000
December	43200	75000

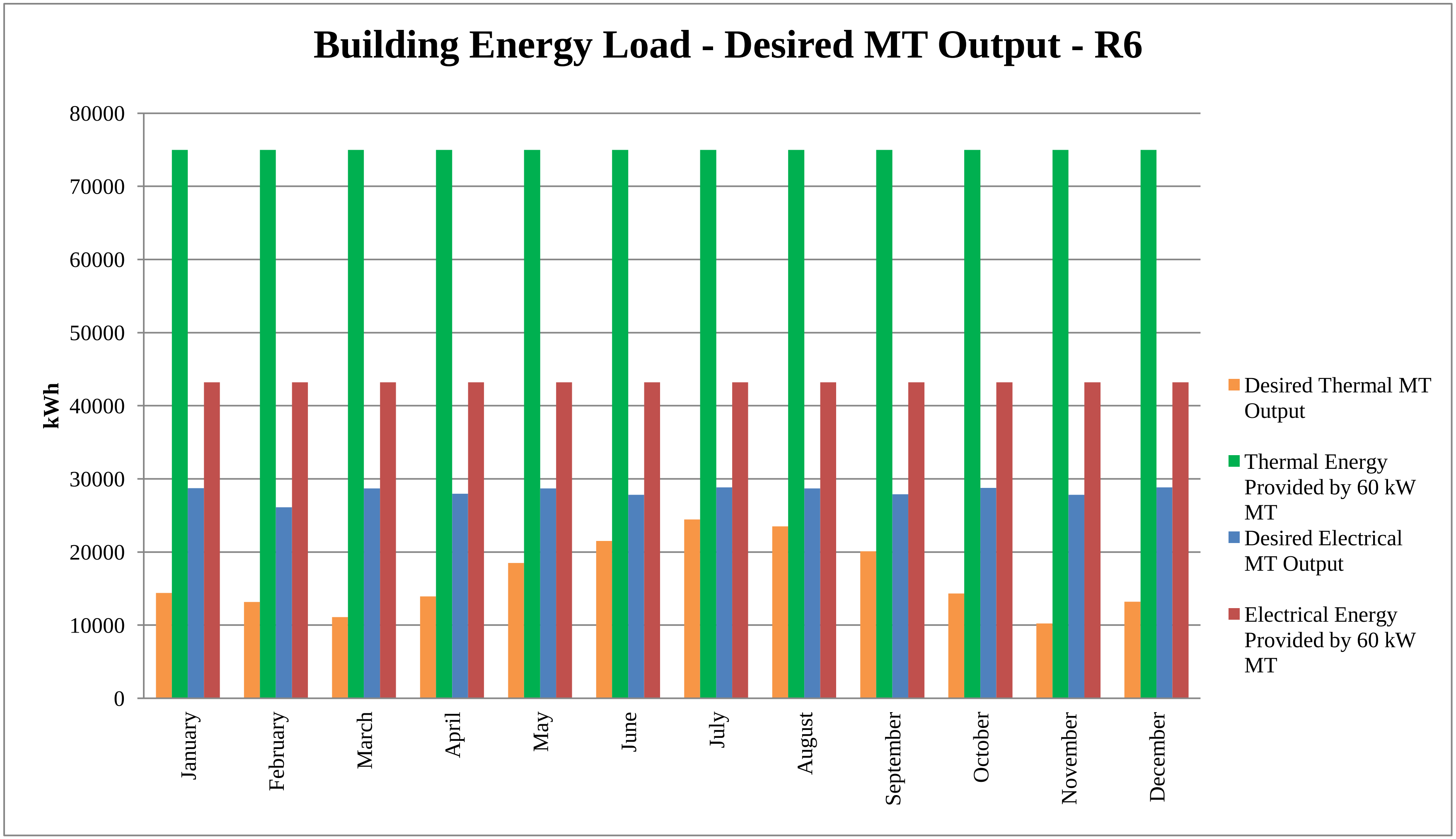


Figure 42: Desired Microturbine Output and Energy Provided by Microturbine - R6 Building - Calculations Using EPlus Data

Table 32: Excess Electric and Thermal Energy for 60 kW Microturbine in R6 Building - Calculations Using EPlus Building Load Data

	Electrical Energy (kWh/year)	Thermal Energy (kWh/year)
Microturbine Energy Production	525,600	905,018
Building Energy Consumption	342,006	201,115
Excess Energy	183,594	703,903

The CHP system model for the R6 6-story residential building used a 60 kW microturbine with an onboard air compressor, an electrical transformer, a heat recovery unit, an absorption chiller, chilled water coils and heating coils. This system provided the electricity and thermal energy needed to completely power an R6 residential building, with an excess 183,594 kWh/year of electricity and 703,903 kWh/year of thermal energy available for other uses. The CHP system model developed for the R6 building generated time-based data on the electrical and thermal energy provided by a CHP system with a 60 kW microturbine as the prime mover, and the electrical and thermal energy consumed by an R6 residential building.

4.5.4 Two-Story Office Building Results

A CHP system model was developed for the 2-story office building using the data on desired electric and thermal microturbine output. This monthly data is shown in Table 33. The desired electric and thermal microturbine output data for the office building was then entered into the HOMER model of the microturbine, along with inputs on the system component characteristics. The microturbine was assumed to run constantly and at full capacity, and the HOMER model simulated a microturbine system and the electric and thermal energy loads it met. The model generated time-based data on the electric and thermal energy provided by a microturbine, and provided information on the optimal size of microturbine for the office building scenario.

Table 33: Desired Electric and Thermal Microturbine Output for Office Building - Calculations Using EPlus Building Load Data

Month	Electrical Energy (kWh)	Thermal Energy (kWh)
January	9471.96	13067.27
February	8694.60	9686.28
March	9971.44	8302.40
April	9142.54	10021.54
May	9768.22	13076.04
June	9710.05	16028.13
July	9290.45	17293.49
August	10057.43	17208.92
September	9430.82	13675.64
October	9476.63	9488.51
November	9366.02	7711.19
December	9201.15	10608.01

The HOMER model for the 2-story office building showed that a 30 kW microturbine was the smallest commercially available size which would completely meet the desired electric and thermal microturbine output. As in the other scenarios, the microturbine was assumed to run constantly and at full capacity, so the microturbine produced the same amounts of electric and thermal energy each month. The electric and thermal energy provided by the 30 kW microturbine is shown in Table 34. The microturbine was sized to the office building so that the building was completely powered by the microturbine; as a result the microturbine produced excess energy through the year.

Table 34: Electric and Thermal Energy Provided by 30 kW Microturbine for Office Building - Calculations Using EPlus Building Load Data

Month	Electrical Energy (kWh)	Thermal Energy (kWh)
January	21600	37700
February	21600	37700
March	21600	37700
April	21600	37700
May	21600	37700
June	21600	37700
July	21600	37700
August	21600	37700
September	21600	37700
October	21600	37700
November	21600	37700
December	21600	37700

Figure 43 shows the desired electrical and thermal microturbine output for the office building with the electrical and thermal energy provided by the 30 kW microturbine. As in the case of the R1 and R6 scenarios, the electrical and thermal energy provided by the 30 kW microturbine was in excess of the energy needed to power the building. The differences in microturbine energy production and building energy consumption are shown in Table 35. The table shows the microturbine energy production and building energy consumption for both electric and thermal energy, and the resulting excess electric and thermal energy.

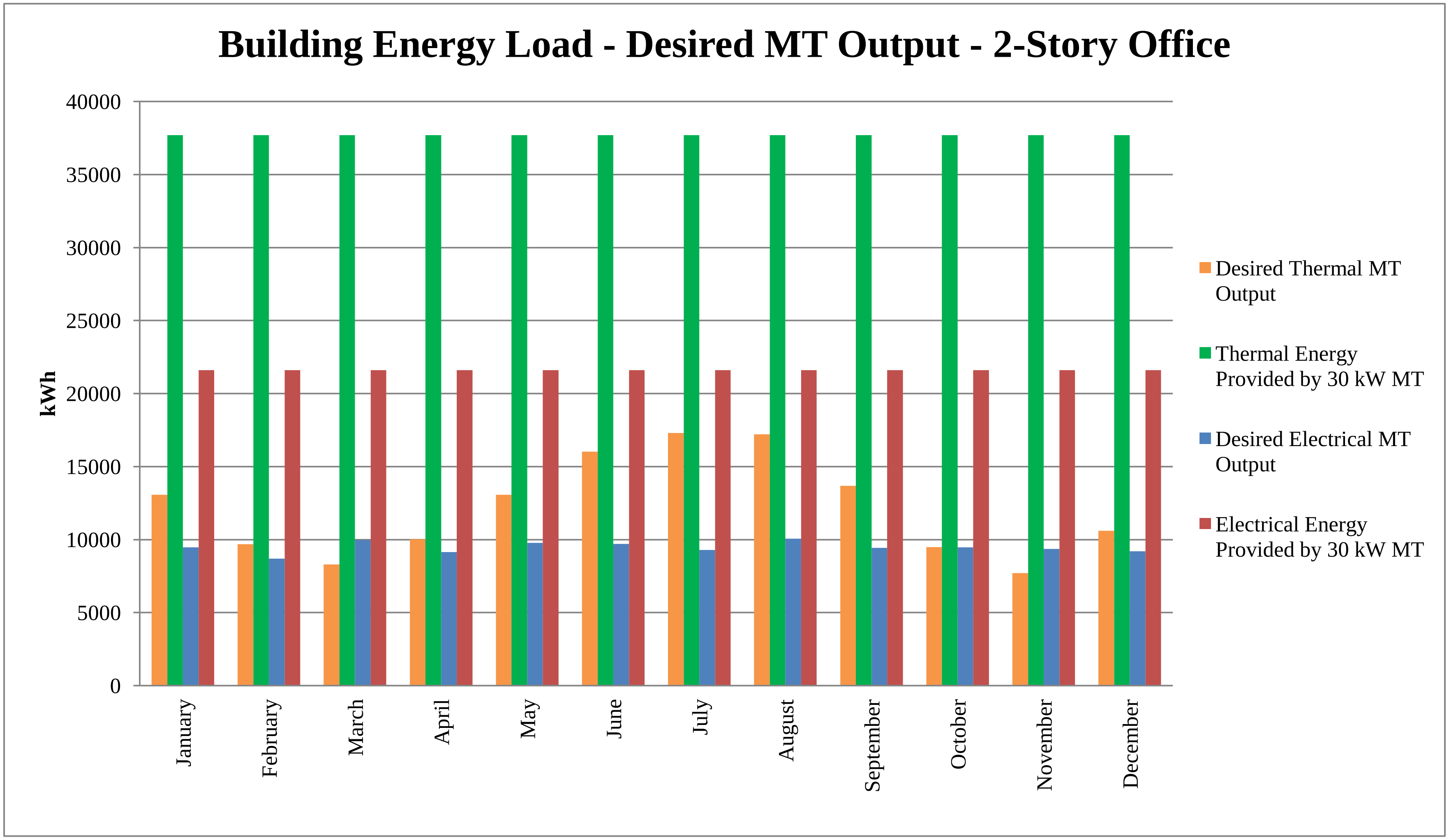


Figure 43: Desired Microturbine Output and Energy Provided by Microturbine - Office Building - Calculations Using EPlus Data

For the scenario of the 2-story office building powered by a 30 kW microturbine, all building energy demands were met, with about 56.4% excess electricity and about 67.3% excess thermal energy. The 30 kW microturbine met all electric and thermal energy needs of the office building, with an excess of 148,190 kWh/year of electricity and an excess of 304,319 kWh/year of thermal energy. The building load data for this office building CHP system model was different than the load data for the office building CHP model discussed in Section 4.3, but the microturbine size and resulting CHP system were the same.

Table 35: Excess Electric and Thermal Energy for 30 kW Microturbine in Office Building - Calculations Using EPlus Building Load Data

	Electrical Energy (kWh/year)	Thermal Energy (kWh/year)
Microturbine Energy Production	262,800	452,509
Building Energy Consumption	114,610	148,190
Excess Energy	148,190	304,319

The CHP system model for the 2-story office building used a 30 kW microturbine with an onboard air compressor, an electrical transformer, a heat recovery unit, an absorption chiller, chilled water coils and heating coils. This system provided the electricity and thermal energy needed to completely power a 2-story office building, with an excess 148,190 kWh/year of electricity and 304,319 kWh/year of thermal energy available for other uses. The CHP system model developed for the office building generated time-based data on the electrical and thermal energy provided by a CHP system with a 30 kW microturbine as the prime mover, and the electrical and thermal energy consumed by a 2-story office building.

4.6 CHP System Environmental Results

4.6.1 CHP System Emissions Results

An emissions characterization was performed for the CHP systems designed for the set of R1 single-family residential buildings, the R6 6-story residential building and the 2-story office building using the CHP Emissions Calculator (CEC). For each emissions characterization inputs were added to the CEC, then the emissions analysis was performed. The total emissions for each CHP system analyzed were compared with the total emissions due to a separate heat and power system of similar size. The CHP systems examined for the set of R1 residential buildings and the 2-story office building were each considered to have a 30 kW microturbine as the prime mover, since this was determined to be the optimal microturbine size for each of these scenarios. The CHP system for the R6 residential building was considered to have a 60 kW microturbine as the prime mover, since this was the optimal microturbine size for the R6 scenario. The size and number of microturbines for each building scenario was an input for the CEC, along with information including the fuel used for the CHP system, and the displaced electric and thermal systems.

Shown in Table 36 are the emissions analysis results for the 2-story office building, including the NO_x, SO_2, CO_2, CH_4, and N_2O emissions for the 30 kW CHP system studied. Table 36 also shows the emissions from the displaced electricity and thermal energy production, and the emissions reduction due to replacing the previous electricity and thermal energy systems with the 30 kW microturbine CHP system.

Table 36: Emissions Characterization for 30 kW CHP System in Office Building

	CHP System	Displaced Electricity Production	Displaced Thermal Production	Emissions/Fuel Reduction	Percent Reduction
NO_x (tons/year)	0.09	0.23	0.05	0.19	68%
SO_2 (tons/year)	0.00	1.05	0.00	1.05	100%
CO_2 (tons/year)	233	318	64	149	39%
CH_4 (tons/year)	0.00	0.005	0.00	0.005	100%
N_2O (tons/year)	0.00	0.005	0.00	0.005	100%
Total Greenhouse Gases (GHGs) (CO_2e tons/year)	233	320	64	151	39%
Fuel Consumption (MMBtu/year)	3980	3294	1099	413	9%

This reduction was divided by the total emissions due to displaced electricity and thermal energy systems to find the emissions percent reduction.

Shown in Table 37 are the emissions analysis results for the CHP system for the set of R1 residential buildings. This scenario used the same CHP system configuration and the same displaced electric and thermal systems as in the 2-story office building scenario, but the set of R1 buildings required additional electricity from the electric utility in order to power the 11 R1 buildings in the set completely. As a result, the emissions due to centralized electricity generation for 5 R1 buildings were added to the emissions totals due to the 30 kW CHP system and its equivalent separate heat and power system. The 30 kW CHP system for the set of R1 buildings provided the electricity and thermal energy for 6 R1 buildings, and the thermal energy for another 5 R1 buildings. The 5 R1 buildings which did not receive electricity from the CHP system were powered by electricity from the electric utility. The displaced electricity and thermal energy considered also powered 6 R1 buildings completely and provided the thermal energy for another 5 R1 buildings. In order to consider the set of 11 R1 buildings, the emissions due to powering 5 R1 buildings with electricity from the grid was added to the emissions totals for the CHP system and the displaced electricity production in Table 36. The emissions analysis results for the CHP system for the set of R1 buildings is shown in Table 37.

Table 37: Emissions Characterization for 30 kW CHP System in Set of R1 Residential Buildings

	CHP System	Displaced Electricity Production	Displaced Thermal Production	Emissions/Fuel Reduction	Percent Reduction
NO_x (tons/year)	0.28	0.42	0.05	0.19	40%
SO_2 (tons/year)	0.88	1.93	0.00	1.05	54%
CO_2 (tons/year)	498	583	64	149	23%
CH_4 (tons/year)	0.004	0.009	0.00	0.005	56%
N_2O (tons/year)	0.004	0.009	0.00	0.005	56%
Total Greenhouse Gases (GHGs) (CO_2e tons/year)	499	585	64	150	23%
Fuel Consumption (MMBtu/year)	6725	6039	1099	413	6%

Shown in Table 38 are the emissions analysis results for the CHP system in the R6 residential building. This scenario used the same CHP system configuration and the same displaced electric and thermal systems as the R1 and 2-story office building scenarios, but the R6 building required a 60 kW microturbine for its CHP system. Table

38 shows the NO_x, SO_2, CO_2, CH_4, and N_2O emissions for the 60 kW CHP system studied. As in the case of the previous scenarios, Table 38 also shows the emissions from the displaced electricity and thermal energy production, and the emissions reduction due to replacing the previous electricity and thermal energy systems with the 60 kW microturbine CHP system. This reduction was divided by the total emissions due to displaced electricity and thermal energy systems to find the emissions percent reduction.

Table 38: Emissions Characterization for 60 kW CHP System in R6 Building

	CHP System	Displaced Electricity Production	Displaced Thermal Production	Emissions/Fuel Reduction	Percent Reduction
NO_x (tons/year)	0.18	0.46	0.11	0.39	68%
SO_2 (tons/year)	0.00	2.10	0.00	2.10	100%
CO_2 (tons/year)	465	637	128	300	39%
CH_4 (tons/year)	0.00	0.01	0.00	0.01	100%
N_2O (tons/year)	0.00	0.01	0.00	0.01	100%
Total Greenhouse Gases (GHGs) (CO_2e tons/year)	466	640	129	303	39%
Fuel Consumption (MMBtu/year)	7960	6588	2198	826	9%

The CHP emissions characterizations performed analyzed the CHP systems designed for each of the scenarios studied. The set of R1 residential buildings and the 2-story office building CHP system models each included a 30 kW microturbine, and the R6 residential building CHP system model included a 60 kW microturbine. The emissions characterizations defined the net emissions for each of the scenarios examined. For the set of R1 residential buildings, the CHP system produced the electricity and thermal energy for 6 R1 buildings, the thermal energy for another 5 R1 buildings, and the electric utility provided electricity for 5 R1 buildings, so the emissions characterization gave the net emissions produced by powering this group of buildings. For the 2-story office building, the CHP system produced the electricity and thermal energy for one office building, with excess electrical and thermal energy. This was also the case for the R6 residential building; the CHP system designed produced the electricity and thermal energy for one R6 building, with excess electrical and thermal energy. Thus, the emissions characterization for the CHP system in the set of R1 buildings gave the emissions for producing the electrical and thermal energy for 11 R1 buildings. The emissions characterization for the CHP system in the office building gave the emissions for producing all electrical and thermal energy for the office building, and the emissions characterization for the CHP system in the R6 building gave the emissions for producing all electrical and thermal energy for the R6 building.

The emissions production values for the R1 building set, the R6 building and the 2-story office building shown in Tables 36, 37 and 38 were then normalized. The emissions production values shown in Tables 36, 37 and 38 were divided by the number of people in each building or building set to find the emissions production per person each year. The number of people in each building was determined based upon the square footage of each building and the maximum occupancy values for each building. The square footage was divided by the maximum occupancy to find the number of people occupying each building. The R1 residential building was assumed to be occupied by 4 people, the R6 residential building was assumed to be occupied by 70 people and the 2-story office building was assumed to be occupied by 65 people. Shown in Table 39 are the normalized emissions levels for the 30 kW CHP system in the office building. Shown in Table 40 are the normalized emissions levels for the 30 kW CHP system in the set of R1 residential buildings, and shown in Table 41 are the normalized emissions levels for the 60 kW CHP system in the R6 building.

Table 39: Normalized Emissions Levels for 30 kW CHP System in Office Building

	CHP System	Displaced Electricity Production	Displaced Thermal Production
NO_x (tons/person/year)	0.0014	0.0035	0.00077
SO_2 (tons/person/year)	0	0.016	0
CO_2 (tons/person/year)	3.58	4.89	0.98
CH_4 (tons/person/year)	0	0.000077	0
N_2O (tons/person/year)	0	0.000077	0
Total Greenhouse Gases (GHGs) (CO_2e tons/person/year)	3.58	4.92	0.98
Fuel Consumption (MMBtu/person/year)	61.23	50.68	16.91

Table 40: Normalized Emissions Levels for 30 kW CHP System in Set of R1 Residential Buildings

	CHP System	Displaced Electricity Production	Displaced Thermal Production
NO_x (tons/person/year)	0.0064	0.0095	0.0011
SO_2 (tons/person/year)	0.02	0.044	0
CO_2 (tons/person/year)	11.32	13.25	1.45
CH_4 (tons/person/year)	0.000091	0.00020	0
N_2O (tons/person/year)	0.000091	0.00020	0
Total Greenhouse Gases (GHGs) (CO_2e tons/person/year)	11.34	13.30	1.45
Fuel Consumption (MMBtu/person/year)	152.84	137.25	24.98

Table 41: Normalized Emissions Levels for 60 kW CHP System in R6 Building

	CHP System	Displaced Electricity Production	Displaced Thermal Production
NO_x (tons/person/year)	0.00257143	0.006571429	0.001571429
SO_2 (tons/person/year)	0	0.03	0
CO_2 (tons/person/year)	6.64	9.1	1.83
CH_4 (tons/person/year)	0	0.00014	0
N_2O (tons/person/year)	0	0.00014	0
Total Greenhouse Gases (GHGs) (CO_2e tons/person/year)	6.66	9.14	1.84
Fuel Consumption (MMBtu/person/year)	113.71	94.11	31.40

4.6.2 CHP System Water Consumption Results

Water consumption values were calculated for the CHP systems designed for the set of R1 single-family residential buildings, the R6 6-story residential building and the 2-story office building. These values were compared to the calculated water consumption of centralized energy generation systems for the set of R1 residential buildings, the R6 residential building and the 2-story office building. Water consumption values were calculated for the centralized energy generation system for each scenario using two different building energy consumption data sets. One building energy consumption data set came from the EPlus model, and the other came from the eQUEST model. Both building energy consumption data sets were used to determine the water consumption for the centralized energy generation system for each scenario, and these results were compared.

Shown in Table 42 are the water consumption values for the R1 building set, the R6 building and the 2-story office building for CHP and centralized energy generation for the base scenario. The base scenario used the Georgia generation mix for electric utilities but assumed no generation due to conventional hydroelectric energy. The base scenario also assumed a 7% transmission and distribution (T&D) loss for centralized electric energy.

Table 42: Water Consumption for R1 Building Set, R6 Building and 2-Story Office Building for CHP and Centralized Energy Generation - Base Scenario

Type of Energy Generation	Building Type	Water Consumption
CHP	R1 Building Set - 30 kW Microturbine - 11 Buildings	455,346 L H_2O/year
CHP	R6 Building - 60 kW Microturbine	15,768 L H_2O/year
CHP	Office Building - 30 kW Microturbine	7,884 L H_2O/year
Centralized - Using Eplus Data	R1 Building Set - 11 Buildings	985,063 L H_2O/year
Centralized - Using Eplus Data	R6 Building	1,161,073 L H_2O/year
Centralized - Using Eplus Data	Office Building	424,510 L H_2O/year
Centralized - Using eQUEST Data	R1 Building Set - 11 Buildings	975,875 L H_2O/year
Centralized - Using eQUEST Data	R6 Building	1,396,484 L H_2O/year
Centralized - Using eQUEST Data	Office Building	439,382 L H_2O/year

Table 43 shows the water consumption values for the R1 building set, the R6 building and the 2-story office building for CHP and centralized energy generation for the scenario of no T&D losses. This case used the same assumptions as the base scenario, except the centralized electric grid was assumed to have no T&D losses.

Table 43: Water Consumption for R1 Building Set, R6 Building and 2-Story Office Building for CHP and Centralized Energy Generation - No T&D Losses Scenario

Type of Energy Generation	Building Type	Water Consumption
CHP	R1 Building Set - 30 kW Microturbine - 11 Buildings	455,346 L H_2O/year
CHP	R6 Building - 60 kW Microturbine	15,768 L H_2O/year
CHP	Office Building - 30 kW Microturbine	7,884 L H_2O/year
Centralized - Using Eplus Data	R1 Building Set - 11 Buildings	916,154 L H_2O/year
Centralized - Using Eplus Data	R6 Building	1,079,821 L H_2O/year
Centralized - Using Eplus Data	Office Building	394,828 L H_2O/year
Centralized - Using eQUEST Data	R1 Building Set - 11 Buildings	907,603 L H_2O/year
Centralized - Using eQUEST Data	R6 Building	1,298,754 L H_2O/year
Centralized - Using eQUEST Data	Office Building	408,660 L H_2O/year

Table 44 shows the water consumption values for the R1 building set, the R6 building and the 2-story office building for CHP and centralized energy generation for the scenario of partial hydroelectric generation. This case used the same assumptions as the base scenario, but included conventional hydroelectric energy generation in the Georgia generation mix for electric utilities. Conventional hydroelectric energy generation was omitted from the generation mix for the base scenario because this 1% of the generation mix significantly altered the overall water consumption values. By excluding it from the generation mix in the base scenario, it was easier to view the differences in water consumption between the centralized energy generation and CHP systems for each building type.

Table 44: Water Consumption for R1 Building Set, R6 Building and 2-Story Office Building for CHP and Centralized Energy Generation - Partial Hydroelectric Generation Scenario

Type of Energy Generation	Building Type	Water Consumption
CHP	R1 Building Set - 30 kW Microturbine - 11 Buildings	913,304 L H_2O/year
CHP	R6 Building - 60 kW Microturbine	15,768 L H_2O/year
CHP	Office Building - 30 kW Microturbine	7,884 L H_2O/year
Centralized - Using Eplus Data	R1 Building Set - 11 Buildings	1,992,572 L H_2O/year
Centralized - Using Eplus Data	R6 Building	2,349,044 L H_2O/year
Centralized - Using Eplus Data	Office Building	858,484 L H_2O/year
Centralized - Using eQUEST Data	R1 Building Set - 11 Buildings	1,974,054 L H_2O/year
Centralized - Using eQUEST Data	R6 Building	2,825,373 L H_2O/year
Centralized - Using eQUEST Data	Office Building	888,566 L H_2O/year

The water consumption values for the R1 building set, the R6 building and the 2-story office building shown in Table 42 were then normalized. The base scenario values presented in Table 42 were divided by the number of people in each building or building set to find the water consumption per person each year. The number of people in each building was determined based upon the square footage of each building and the maximum occupancy values for each building. The square footage was divided by the maximum occupancy to find the number of people occupying each building. The R1 residential building was assumed to be occupied by 4 people, the R6 residential building was assumed to be occupied by 70 people and the 2-story office building was assumed to be occupied by 65 people. Shown in Table 45 are the normalized results for water consumption for CHP using the base scenario water consumption values. Shown in Table 46 are the normalized results for water consumption for centralized power using the base scenario water consumption values and the EPlus data, and shown in Table 47 are the normalized results for water consumption for centralized power using the base scenario water consumption values and the eQUEST data. The values presented in Tables 45, 46 and 47 are then compared visually in Figure 44.

Table 45: Normalized Results for Water Consumption for CHP - Base Scenario

Water Consumption for CHP	
R1 Building Set - 30 kW MT (11 buildings)	10,349 L H_2O/person/year
R6 Building - 60 kW MT	225 L H_2O/person/year
Office Building - 30 kW MT	121 L H_2O/person/year

Table 46: Normalized Results for Water Consumption for Centralized Power - Using EPlus Data - Base Scenario

Water Consumption for Centralized Power (Using EPlus Data)	
R1 Building Set (11 buildings)	22,388 L H_2O/person/year
R6 Building	16,587 L H_2O/person/year
Office Building	6,531 L H_2O/person/year

Table 47: Normalized Results for Water Consumption for Centralized Power - Using eQUEST Data - Base Scenario

Water Consumption for Centralized Power (Using eQUEST Data)	
R1 Building Set (11 buildings)	22,179 L H_2O/person/year
R6 Building	19,950 L H_2O/person/year
Office Building	6,760 L H_2O/person/year

The normalized results for water consumption showed that CHP energy generation required the least water consumption on a per person basis for each building scenario, and that the water consumption levels per person each year were closest between CHP generation and centralized energy generation for the R1 building scenario, which made sense since these building have the lowest occupancy densities of the buildings examined.

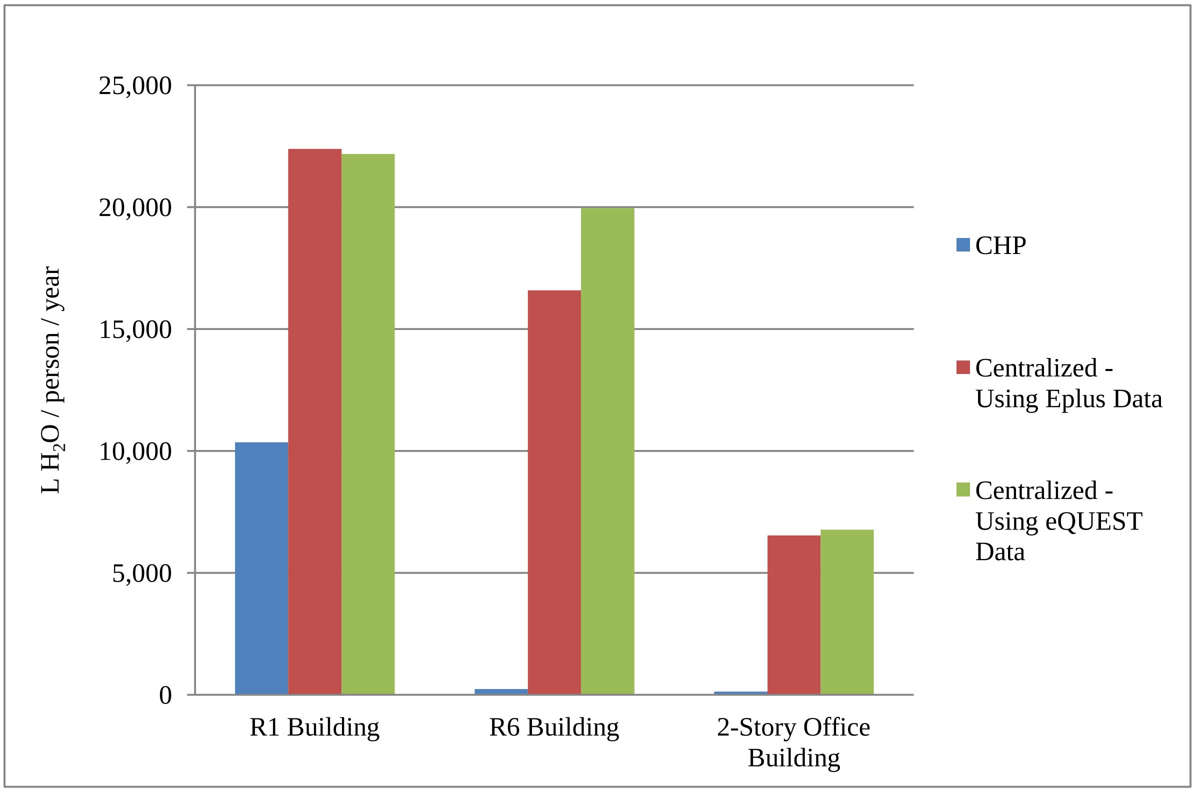


Figure 44: Normalized Results for Water Consumption for CHP and Centralized Energy Generation - Base Scenario

4.7 Discussion of CHP System Environmental Results

4.7.1 Discussion of CHP System Emissions Results

It was interesting to compare the emissions characterizations for the CHP systems and separate heat and power systems for each building scenario. The set of R1 buildings and the 2-story office building each used a 30 kW microturbine as the CHP system prime mover, while the R6 building used a 60 kW microturbine as the CHP system prime mover. The emissions results for the CHP systems were directly related to the microturbine size. The difference between the emissions due to the separate heat and power system and the emissions due to the CHP system was given by the emissions reduction. The emissions reduction for the 2-story office building was the same as the emissions reduction for the set of R1 buildings, since these scenarios used the same 30 kW microturbine. The emissions reduction for the R6 building was twice the emissions reduction for the other two building scenarios, since the R6 building used a 60 kW microturbine. The R6 building scenario overall had the greatest emissions reduction, while the 2-story office building had the next best emissions reduction, and the set of R1 buildings had the least emissions reduction. The set of R1 buildings had the least emissions reduction due to this scenario using partial electricity generation from electric utilities, which produced higher emissions levels.

It is also interesting to note that the amount of displaced electricity and thermal energy produced by centralized energy generation was calculated based upon the amount of electrical and thermal energy produced by the CHP system specified. Thus, if the CHP system considered included a 30 kW microturbine, the displaced electricity and thermal energy would be equal to the amount of electricity and thermal produced by the 30 kW microturbine-based CHP system. Because of this, the amounts of displaced electricity and thermal energy considered were slightly higher than the amounts which would have been needed to power each building scenario. This produced slightly higher emissions reduction results than would have been produced by considering the lower levels of displaced electricity and thermal energy needed to power each building scenario. However, the difference in emissions reduction results were not sufficient to significantly change the overall results.

4.7.2 Discussion of CHP System Water Consumption Results

Water consumption values for the CHP systems designed for the set of R1 buildings, the R6 building and the 2-story office building were compared to the water consumption values for the centralized energy generation systems serving the set of R1 buildings, the R6 building and the 2-story office building. This comparison was examined under different sets of assumptions. The first set of assumptions was considered the base scenario. The base scenario used the Georgia generation mix for electric utilities but assumed no generation due to conventional hydroelectric energy. The base scenario also assumed a 7% transmission and distribution (T&D) loss for centralized electric energy. The second set of assumptions considered no T&D losses. This scenario used the same assumptions as in the base scenario, but the T&D losses for centralized electric energy were 0%. The third and final scenario considered partial hydroelectric generation. This scenario again used the same assumptions as in the base scenario, but included conventional hydroelectric energy generation in the Georgia generation mix for electric utilities.

The base scenario showed that the water consumption values for the CHP systems were much lower than the water consumption values for the centralized energy generation systems for those same building scenarios. The water consumption value for the CHP system for the set of R1 residential buildings was less than 50% of the water consumption values for the centralized energy system for the set of R1 residential buildings. The CHP system for the R6 building consumed less than 5% of the water consumed for the centralized energy system for the same building. The CHP system for the 2-story office building also consumed less than 5% of the water consumed for the centralized energy system for the 2-story office building. Within the base scenario assumptions, CHP systems showed significant water consumption reductions from traditional centralized energy generation.

The scenario of no T&D losses produced lower water consumption values for the centralized energy generation than were calculated in the base scenario. This was due to less overall energy production at the power plant, since this case assumed that all energy produced at the power plant was available for end use consumption. The reduction in water consumption for the centralized energy generation resulted in less of a difference between the water consumption for the CHP systems and the water consumption for the centralized energy generation, although the differences were still significant. The water consumption value for the CHP system for the set of R1 buildings was still about 50% of the water consumption values for the centralized energy system for the set of R1 buildings. The CHP systems for the R6 building and 2-story office building each still consumed less than 5% of the water consumed for the centralized energy system for those same buildings. The scenario of no T&D losses slightly reduced the water consumption for centralized energy generation, but the water consumption savings between use of CHP systems and use of centralized energy generation was still significant.

The partial hydroelectric generation scenario significantly increased the water consumption related to centralized electricity generation. This resulted in increases in the water consumption values for the centralized energy generation systems, and for the CHP system for the set of R1 residential buildings, since it included some centralized electricity generation. The water consumption value for the CHP system for the set of R1 residential buildings was about 46% of the water consumption values for the centralized energy generation system for the set of R1 residential buildings in this case. The CHP systems for the R6 building and 2-story office building each consumed less than 1% of the water consumed for the centralized energy system for those same buildings. The partial hydroelectric generation scenario included a centralized energy generation system which consumed more water than in other scenarios, so the difference between the water consumption of the CHP systems and the water consumption of the centralized energy generation systems appeared more drastic than in other scenarios.

Water consumption values for the CHP systems designed for the set of R1 buildings, the R6 building and the 2-story office building were much lower than the water consumption values for the centralized energy generation systems serving the set of R1 buildings, the R6 building and the 2-story office building. The set of R1 buildings considered included some centralized electricity generation in the CHP system, so the water consumption differences between the two modes of energy generation for this building scenario were not as significant as for the other two building scenarios. However, all CHP systems examined provided at least 50% water savings over the centralized energy generation systems in each scenario.

4.8 CHP System Results Scaled to Metropolitan Atlanta

4.8.1 CHP System Model Results

The CHP system model results, including the microturbine sizing process, emissions characterization and water consumption values, were scaled up to Metropolitan Atlanta. This produced the number of CHP systems needed for Metro Atlanta energy generation from CHP for R1, R6 and 2-story office buildings, and the total emissions production and water consumption for this scenario. The CHP system model results were scaled up for both a present day scenario, and for a scenario of business as usual (BAU) in 2030. The present day scenario considered the number of CHP systems needed for Atlanta energy generation from CHP for R1, R6 and 2-story office buildings, and the resulting emissions characterization and water consumption if the current energy generation systems in Atlanta were replaced with CHP. The 2030 scenario considered the number of CHP systems needed for Atlanta energy generation from CHP for R1, R6 and 2-story office buildings, and the resulting emissions characterization and water consumption if energy consumption continued in a business as usual case, and if by 2030 the energy generation systems in Atlanta were replaced with CHP. For each scenario considered, only the R1, R6 and 2-story office buildings were replaced with CHP systems. Other types of buildings were not examined.

The number of R1, R6 and 2-story office buildings in Metro Atlanta in present day and in 2030 came from a paper examining urban growth scenarios in Atlanta (James, Sung et al. 2013). These values are shown in Table 48.

Table 48: Number of R1, R6 and 2-Story Office Buildings in Metro Atlanta in Present Day and in 2030 (James, Sung et al. 2013)

	Present Day	2030
Number of R1 Residential Buildings	1,170,283	1,783,935
Number of R6 Residential Buildings	12,727	18,052
Number of 2-Story Office Buildings	56,030	104,570

The number of R1, R6 and 2-story office buildings in Metro Atlanta for each scenario were divided by the number of buildings supplied by each CHP system to find the number of CHP systems needed for Metro Atlanta energy generation from CHP. Table 49 shows the number of CHP systems needed for sets of R1 residential buildings in present day and in 2030, the number of CHP systems needed for R6 residential buildings in present day and in 2030, and the number of CHP systems needed for 2-story office buildings in present day and in 2030. The number of CHP systems presented for each scenario would supply Metro Atlanta with CHP systems for the R1 residential buildings, the R6 residential buildings and the 2-story office buildings.

Table 49: Number of CHP Systems Needed for Metro Atlanta Energy Generation from CHP

	Present Day	2030
Number of CHP Systems for Sets of R1 Residential Buildings	106,389	162,175
Number of CHP Systems for R6 Residential Buildings	12,727	18,052
Number of CHP Systems for 2-Story Office Buildings	56,030	104,570

4.8.2 CHP System Emissions Results

Once the number of each building CHP system needed for the sets of R1 residential buildings, the R6 residential buildings and the 2-story office buildings was identified for Metro Atlanta, the total number of systems for each building type was multiplied by the environmental results for that system to find the overall environmental impact of using CHP to power all of that building type in Metro Atlanta. The results shown in Tables 36, 37 and 38 were multiplied by the number of CHP systems for that building type which would be installed. The results gave the total emissions production for each building type. This process was completed for both the present day scenario and for the BAU in 2030 scenario.

Shown in Tables 50, 51 and 52 are the total emissions production for sets of R1 residential buildings, R6 residential buildings and 2-story office buildings in Metro Atlanta in present day. The emissions due to the CHP systems and the corresponding displaced electricity and thermal energy production increased significantly from the data presented in Section 4.6.1, although the overall percent reduction in emissions production was the same for the scaled-up case as for the case of one CHP system.

Table 50: Total Emissions Production for R1 Residential Buildings in Metro Atlanta in Present Day

	CHP System	Displaced Electricity Production	Displaced Thermal Production	Emissions/Fuel Reduction	Percent Reduction
NO_x (million tons/year)	0.030	0.045	0.005	0.020	40%
SO_2 (million tons/year)	0.094	0.205	0	0.112	54%
CO_2 (million tons/year)	52.98	62.02	6.81	15.85	23%
CH_4 (million tons/year)	0.0004	0.0010	0	0.0005	56%
N_2O (million tons/year)	0.0004	0.0010	0	0.0005	56%
Total GHGs (CO_2e million tons/year)	53.09	62.24	6.81	15.96	23%
Fuel Consumption (MMBtu/year)	715,466,025	642,483,171	116,921,511	43,938,657	6%

It is important to note that since the displaced electricity and thermal energy production values were slightly overestimated in the data presented in Section 4.6.1, again the displaced electricity and thermal energy values in Tables 50, 51 and 52 were slightly overestimated. However, the difference between the emissions production for the centralized energy systems and for the CHP systems was still significant, and the CHP systems produced fewer total emissions than the centralized energy systems.

Table 51: Total Emissions Production for R6 Residential Buildings in Metro Atlanta in Present Day

	CHP System	Displaced Electricity Production	Displaced Thermal Production	Emissions/Fuel Reduction	Percent Reduction
NO_x (million tons/year)	0.002	0.006	0.001	0.005	68%
SO_2 (million tons/year)	0	0.027	0	0.027	100%
CO_2 (million tons/year)	5.92	8.11	1.63	3.82	39%
CH_4 (million tons/year)	0	0.0001	0	0.0001	100%
N_2O (million tons/year)	0	0.0001	0	0.0001	100%
Total GHGs (CO_2e million tons/year)	5.93	8.15	1.64	3.86	39%
Fuel Consumption (MMBtu/year)	101,306,920	83,845,476	27,973,946	10,512,502	9%

Table 52: Total Emissions Production for 2-Story Office Buildings in Metro Atlanta in Present Day

	CHP System	Displaced Electricity Production	Displaced Thermal Production	Emissions/Fuel Reduction	Percent Reduction
NO_x (million tons/year)	0.005	0.013	0.003	0.011	68%
SO_2 (million tons/year)	0	0.059	0	0.059	100%
CO_2 (million tons/year)	13.05	17.82	3.59	8.35	39%
CH_4 (million tons/year)	0	0.0003	0	0.0003	100%
N_2O (million tons/year)	0	0.0003	0	0.0003	100%
Total GHGs (CO_2e million tons/year)	13.05	17.93	3.59	8.46	39%
Fuel Consumption (MMBtu/year)	222,999,400	184,562,820	61,576,970	23,140,390	9%

Shown in Tables 53, 54 and 55 are the total emissions production for R1 residential buildings, R6 residential buildings and 2-story office buildings in Metro Atlanta in 2030. Again the emissions due to the CHP systems and the corresponding displaced electricity and thermal energy production increased significantly from the data presented in Section 4.6.1, although again the ratio between them remained the same. The total emissions production for each building scenario was higher for the 2030 case than in the present day case, since the number of buildings was greater.

Table 53: Total Emissions Production for R1 Residential Buildings in Metro Atlanta in 2030

	CHP System	Displaced Electricity Production	Displaced Thermal Production	Emissions/Fuel Reduction	Percent Reduction
NO_x (million tons/year)	0.05	0.07	0.0081	0.03	40%
SO_2 (million tons/year)	0.14	0.31	0	0.17	54%
CO_2 (million tons/year)	80.76	94.55	10.38	24.16	23%
CH_4 (million tons/year)	0.0006	0.0015	0	0.0008	56%
N_2O (million tons/year)	0.0006	0.0015	0	0.0008	56%
Total GHGs (CO_2e million tons/year)	80.93	94.87	10.38	24.33	23%
Fuel Consumption (MMBtu/year)	1,090,626,875	979,374,825	178,230,325	66,978,275	6%

The total emissions production for R1, R6 and 2-story office buildings in Metro Atlanta in both present day and 2030 were evaluated. These cases examined replacing centralized energy generation with energy generation from CHP systems, and analyzed the emissions savings due to this replacement. The comparison was performed for a present day scenario and a BAU scenario in 2030.

Table 54: Total Emissions Production for R6 Residential Buildings in Metro Atlanta in 2030

	CHP System	Displaced Electricity Production	Displaced Thermal Production	Emissions/Fuel Reduction	Percent Reduction
NO_x (million tons/year)	0.003	0.008	0.0020	0.007	68%
SO_2 (million tons/year)	0	0.038	0	0.0379	100%
CO_2 (million tons/year)	8.39	11.50	2.31	5.42	39%
CH_4 (million tons/year)	0	0.0002	0	0.0002	100%
N_2O (million tons/year)	0	0.0002	0	0.0002	100%
Total GHGs (CO_2e million tons/year)	8.41	11.55	2.33	5.47	39%
Fuel Consumption (MMBtu/year)	143,693,920	118,926,576	39,678,296	14,910,952	9%

Table 55: Total Emissions Production for 2-Story Office Buildings in Metro Atlanta in 2030

	CHP System	Displaced Electricity Production	Displaced Thermal Production	Emissions/Fuel Reduction	Percent Reduction
NO_x (million tons/year)	0.009	0.024	0.005	0.020	68%
SO_2 (million tons/year)	0	0.11	0	0.110	100%
CO_2 (million tons/year)	24.36	33.25	6.69	15.58	39%
CH_4 (million tons/year)	0	0.0005	0	0.0005	100%
N_2O (million tons/year)	0	0.0005	0	0.0005	100%
Total GHGs (CO_2e million tons/year)	24.36	33.46	6.69	15.79	39%
Fuel Consumption (MMBtu/year)	416,188,600	344,453,580	114,922,430	43,187,410	9%

4.8.3 CHP System Water Consumption Results

Once the number of building CHP systems needed for the sets of R1 residential buildings, the R6 residential buildings and the 2-story office buildings was identified for Metro Atlanta, the total number of systems for each building type was multiplied by the environmental results for that system to find the overall environmental impact of using CHP to power all of that building type in Metro Atlanta. The results shown in Table 42 were multiplied by the number of CHP systems for that building type which would be installed for both the present day scenario and for the BAU in 2030 scenario. The results gave the total water consumption for each building type.

Shown in Tables 56 and 57are the total water consumption values for R1 residential buildings, R6 residential buildings and 2-story office buildings in Metro Atlanta in present day and in 2030.

Table 56: Water Consumption for Metro Atlanta in Present Day

Type of Energy Generation	Building Type	Water Consumption
CHP	All R1 Buildings in Atlanta	48,444 million L H_2O/year
CHP	All R6 Buildings in Atlanta	201 million L H_2O/year
CHP	All 2-Story Office Buildings in Atlanta	442 million L H_2O/year
Centralized - Using Eplus Data	All R1 Buildings in Atlanta	104,800 million L H_2O/year
Centralized - Using Eplus Data	All R6 Buildings in Atlanta	14,777 million L H_2O/year
Centralized - Using Eplus Data	All 2-Story Office Buildings in Atlanta	23,785 million L H_2O/year
Centralized - Using eQUEST Data	All R1 Buildings in Atlanta	103,822 million L H_2O/year
Centralized - Using eQUEST Data	All R6 Buildings in Atlanta	17,773 million L H_2O/year
Centralized - Using eQUEST Data	All 2-Story Office Buildings in Atlanta	24,619 million L H_2O/year

The water consumption calculations for the present day and BAU in 2030 scenarios were based upon the base scenario assumptions utilized in Section 4.6.2.

Table 57: Water Consumption for Metro Atlanta in 2030

Type of Energy Generation	Building Type	Water Consumption
CHP	All R1 Buildings in Atlanta	73,846 million L H_2O/year
CHP	All R6 Buildings in Atlanta	285 million L H_2O/year
CHP	All 2-Story Office Buildings in Atlanta	824 million L H_2O/year
Centralized - Using Eplus Data	All R1 Buildings in Atlanta	159,753 million L H_2O/year
Centralized - Using Eplus Data	All R6 Buildings in Atlanta	20,960 million L H_2O/year
Centralized - Using Eplus Data	All 2-Story Office Buildings in Atlanta	44,391 million L H_2O/year
Centralized - Using eQUEST Data	All R1 Buildings in Atlanta	158,263 million L H_2O/year
Centralized - Using eQUEST Data	All R6 Buildings in Atlanta	25,209 million L H_2O/year
Centralized - Using eQUEST Data	All 2-Story Office Buildings in Atlanta	45,946 million L H_2O/year

4.9 CHP System Sensitivity Analysis

The analysis presented in Sections 4.4 and 4.5 was completed for the R1 residential building, the R6 residential building and the 2-story office building using different HVAC setpoints than those used previously. For the analysis presented in Sections 4.4 and 4.5 the heating setpoint was 68º F and the cooling setpoint was 78º F for the R1building and the R6 building. For the 2-story office building, the heating setpoint was 70º F and the cooling setpoint was 76º F. The CHP system model was again simulated for each building type, but the heating and cooling setpoints were altered. For the R1 residential building, the heating setpoint was 70º F and the cooling setpoint was 76º F. For the R6 residential building, the heating setpoint was 70º F and the cooling setpoint was 76º F. For the 2-story office building, the heating setpoint was 72º F and the cooling setpoint was 74º F. Each of these CHP system models were simulated using the new heating and cooling setpoints in order to analyze the sensitivity of the results to the thermostat setpoints used. Sections 4.9.1, 4.9.2 and 4.9.3 present the desired electric and thermal microturbine output for each building type when the new heating and cooling setpoints are used. These results were then compared to the electric and thermal energy provided by the microturbine for each scenario.

4.9.1 R1 Residential Building Results - eQUEST and EPlus

For the R1 residential building scenario, the heating setpoint was changed from 68º F to 70º F, and the cooling setpoint was changed from 78º F to 76º F in order to analyze the sensitivity of the results to the thermostat setpoints used for the CHP system model. Shown in Appendix A in Table 76 is the monthly energy consumption by end use for the R1 building when the energy modeling software used was eQUEST. Shown in Appendix B in Table 85 is the monthly energy consumption by end use for the R1 building when the energy modeling software used was EPlus. The data on the building energy consumption produced by each energy modeling software was used to calculate the desired electric and thermal microturbine output for the R1 building. This calculation was performed the same way as the calculations performed in Sections 4.4 and 4.5, but the thermostat setpoints used were different. Shown in Table 58 is the desired electric and thermal microturbine output for the R1 building where the calculations used the eQUEST building load data, and shown in Table 59 is the desired electric and thermal microturbine output for the R1 building where the calculations used the EPlus building load data.

Table 58: Desired Electric and Thermal Microturbine Output for R1 Building - Calculations Using eQUEST Building Load Data - Thermostat Setting Sensitivity

Month	Electrical Energy (kWh)	Thermal Energy (kWh)
January	3240.00	3217.57
February	3050.00	2837.71
March	3210.00	2301.58
April	3130.00	2475.54
May	3180.00	2764.44
June	3130.00	3016.30
July	3180.00	3164.44
August	3180.00	3060.74
September	3130.00	2754.57
October	3190.00	2289.18
November	3160.00	2111.11
December	3230.00	2765.60

The R1 building monthly energy consumption by end use for each set of thermostat settings was compared for both the eQUEST energy model and the EPlus energy model. For the eQUEST energy model, the change in thermostat setpoints impacted most of the energy consumption end uses. The energy consumption for both space cooling and hot water increased, the energy consumption for ventilation fans increased, and the energy consumption for the area lights increased slightly. The energy consumption for the end uses of pumps and auxiliary equipment and miscellaneous equipment remained about the same. The energy consumption for the end use of space heating was nearly doubled. For the EPlus energy model, the change in thermostat setpoints impacted fewer of the energy consumption end uses than in the case of the eQUEST model. When the thermostat setpoints for the EPlus energy model were changed, the energy consumption for space cooling increased, and the energy consumption for the ventilation fans increased slightly. The energy consumption for the end uses of hot water, interior equipment and interior lights all stayed the same. The energy consumption for the end use of space heating went up significantly, going from 1961 to 3055 kWh per year.

Table 59: Desired Electric and Thermal Microturbine Output for R1 Building - Calculations Using EPlus Building Load Data - Thermostat Setting Sensitivity

Month	Electrical Energy (kWh)	Thermal Energy (kWh)
January	3104.37	3397.66
February	2980.11	2557.52
March	3183.34	2152.23
April	3151.65	2731.28
May	3155.85	3436.18
June	3150.42	3992.51
July	3180.09	4344.82
August	3206.34	4184.82
September	3102.93	3518.44
October	3155.48	2703.34
November	3034.84	2015.23
December	3156.09	2626.30

Although the change in thermostat setpoints altered the building energy consumption, the energy consumption levels were not changed enough to impact the sizing of the CHP system for the R1 residential building. This scenario still required a 6 kW theoretical microturbine in order to completely power the R1 building. Shown in

Table 60 is the electrical and thermal energy provided by a 6 kW microturbine for the R1 residential building.

Table 60: Electric and Thermal Energy Provided by 6 kW Microturbine for R1 Building - Thermostat Setting Sensitivity

Month	Electrical Energy (kWh)	Thermal Energy (kWh)
January	4320	7500
February	4320	7500
March	4320	7500
April	4320	7500
May	4320	7500
June	4320	7500
July	4320	7500
August	4320	7500
September	4320	7500
October	4320	7500
November	4320	7500
December	4320	7500

The desired electrical and thermal microturbine output for each energy model and the electrical and thermal energy provided by the 6 kW microturbine are plotted in Figures 45 and 46. Overall the change in thermostat setpoints increased the thermal demand of the building and slightly increased the electrical demand of the building, but these changes were not enough to require a different size of CHP system for this scenario. It was interesting that each energy model showed similar changes in the energy consumption for the building heating and cooling end uses and showed an increase in energy consumption for the end use of ventilation fans, but that the changes in energy consumption for the other end uses varied slightly between models.

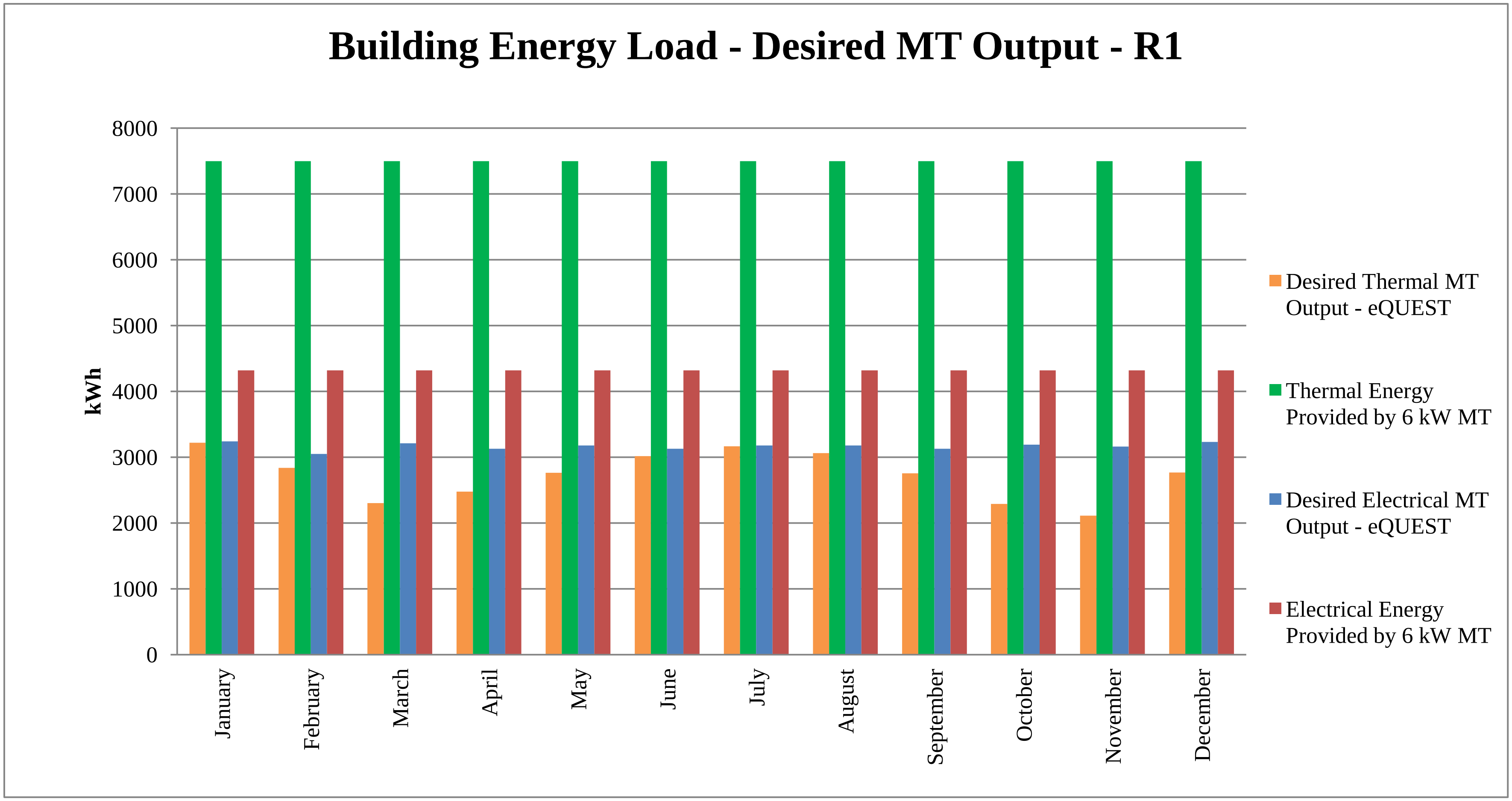


Figure 45: Desired Microturbine Output and Energy Provided by Microturbine for R1 Building - Thermostat Setting Sensitivity - Calculations Using eQUEST Data

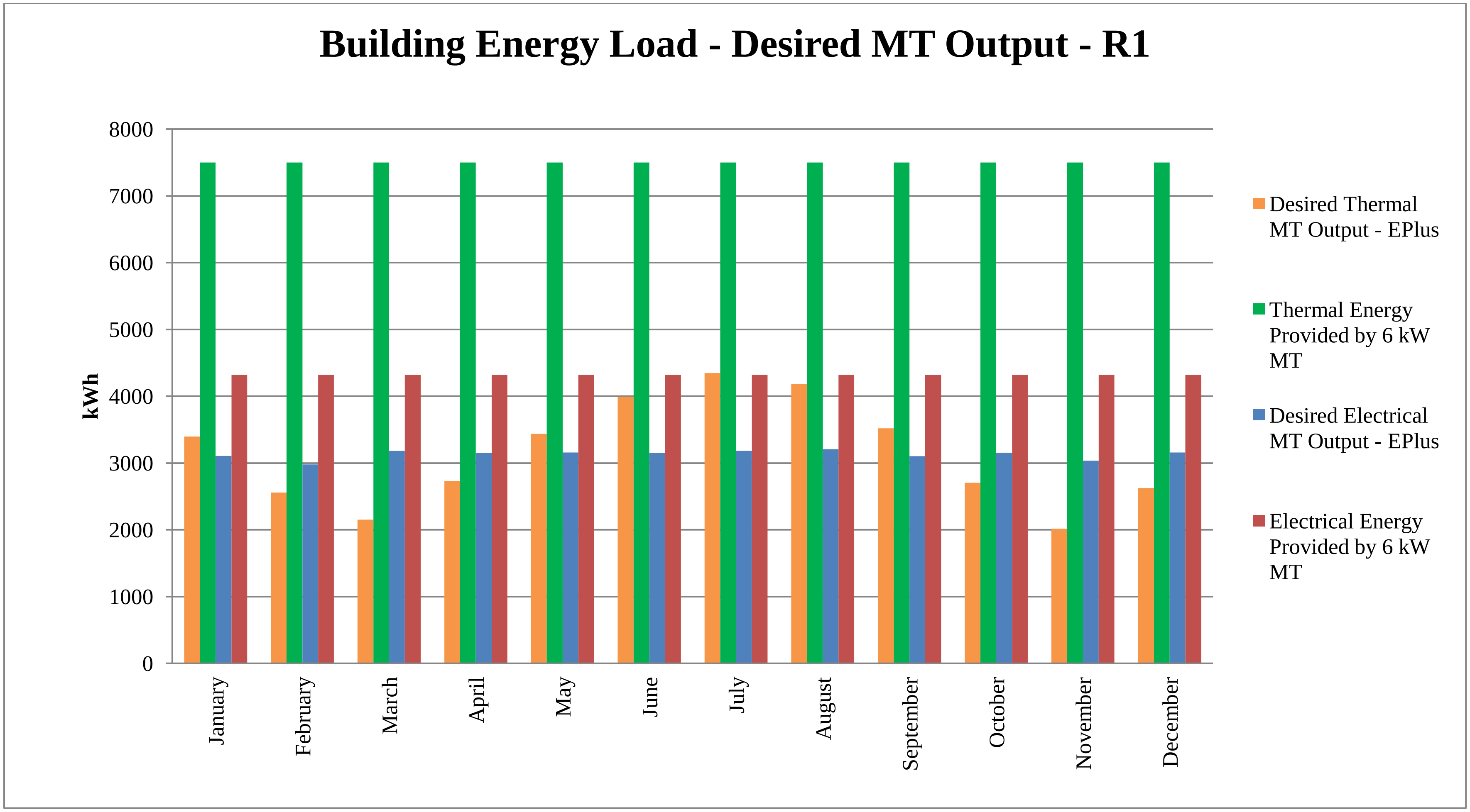


Figure 46: Desired Microturbine Output and Energy Provided by Microturbine for R1 Building - Thermostat Setting Sensitivity - Calculations Using EPlus Data

4.9.2 R6 Residential Building Results - eQUEST and EPlus

For the R6 residential building scenario, the heating setpoint was changed from 68º F to 70º F, and the cooling setpoint was changed from 78º F to 76º F in order to analyze the sensitivity of the results to the thermostat setpoints used for the CHP system model. Shown in Appendix A in Table 77 is the monthly energy consumption by end use for the R6 building when the energy modeling software used was eQUEST. Shown in Appendix B in Table 86 is the monthly energy consumption by end use for the R6 building when the energy modeling software used was EPlus. The data on the building energy consumption produced by each energy modeling software was used to calculate the desired electric and thermal microturbine output for the R6 building. This calculation was performed the same way as the calculations performed in Sections 4.4 and 4.5, but the thermostat setpoints used were different. Shown in Table 61 is the desired electric and thermal microturbine output for the R6 building where the calculations used the eQUEST building load data, and shown in Table 62 is the desired electric and thermal microturbine output for the R6 building where the calculations used the EPlus building load data.

The R6 building monthly energy consumption by end use for each set of thermostat settings was compared for both the eQUEST energy model and the EPlus energy model. For the eQUEST energy model, the change in thermostat setpoints again impacted most of the energy consumption end uses. The energy consumption for both space cooling and ventilation fans increased, and the energy consumption for the end uses of pumps and auxiliary equipment, miscellaneous equipment, hot water and area lights remained about the same. The energy consumption for the end use of space heating was nearly doubled, as in the case of the R1 building. For the EPlus energy model, the change in thermostat setpoints impacted fewer of the energy consumption end uses than in the case of the eQUEST model. When the thermostat setpoints for the EPlus energy model were changed, the energy consumption for space cooling increased, and the energy consumption for the ventilation fans increased slightly. The energy consumption for the end uses of hot water, interior equipment and interior lights all stayed the same. The energy consumption for the end use of space heating went up significantly, going from 11,019 to 19,555 kWh per year.

Table 61: Desired Electric and Thermal Microturbine Output for R6 Building - Calculations Using eQUEST Building Load Data - Thermostat Setting Sensitivity

Month	Electrical Energy (kWh)	Thermal Energy (kWh)
January	32870.00	22663.12
February	29730.00	17131.35
March	32620.00	13423.94
April	31310.00	17707.47
May	32290.00	24892.84
June	31430.00	30487.90
July	32290.00	33070.62
August	32290.00	32206.42
September	31430.00	27880.49
October	32370.00	16043.46
November	31800.00	9511.15
December	32800.00	15927.04

Table 62: Desired Electric and Thermal Microturbine Output for R6 Building - Calculations Using EPlus Building Load Data - Thermostat Setting Sensitivity

Month	Electrical Energy (kWh)	Thermal Energy (kWh)
January	28779.96	18236.63
February	26160.17	16372.09
March	28740.10	13007.00
April	28039.85	15437.50
May	28740.10	19849.96
June	27880.13	22931.82
July	28899.83	26076.63
August	28740.10	25100.82
September	27959.98	21529.35
October	28819.96	15780.82
November	27880.13	12347.62
December	28899.83	16886.26

Although the change in thermostat setpoints altered the building energy consumption, the energy consumption levels were not changed enough to impact the sizing of the CHP system for the R6 residential building. This scenario still required a 60 kW microturbine in order to completely power the R6 building. Shown in Table 63 is the electrical and thermal energy provided by a 60 kW microturbine for the R6 residential building.

Table 63: Electric and Thermal Energy Provided by 60 kW Microturbine for R6 Building - Thermostat Setting Sensitivity

Month	Electrical Energy (kWh)	Thermal Energy (kWh)
January	43200	75000
February	43200	75000
March	43200	75000
April	43200	75000
May	43200	75000
June	43200	75000
July	43200	75000
August	43200	75000
September	43200	75000
October	43200	75000
November	43200	75000
December	43200	75000

The desired electrical and thermal microturbine output for each energy model and the electrical and thermal energy provided by the 60 kW microturbine are plotted in Figures 47 and 48. Overall the change in thermostat setpoints increased the thermal demand of the building and slightly increased the electrical demand of the building, but these changes were not enough to require a different size of CHP system for this scenario.

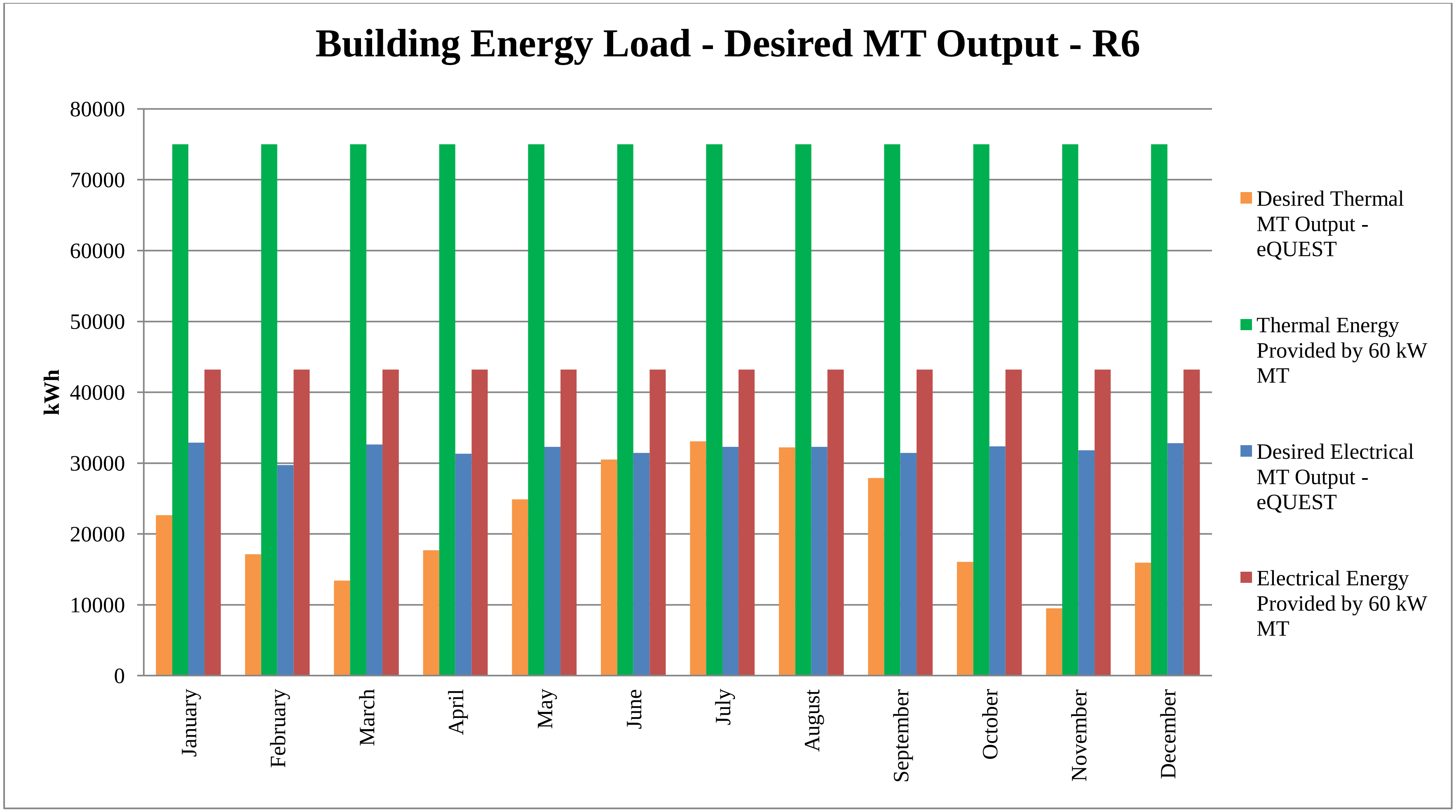


Figure 47: Desired Microturbine Output and Energy Provided by Microturbine for R6 Building - Thermostat Setting Sensitivity - Calculations Using eQUEST Data

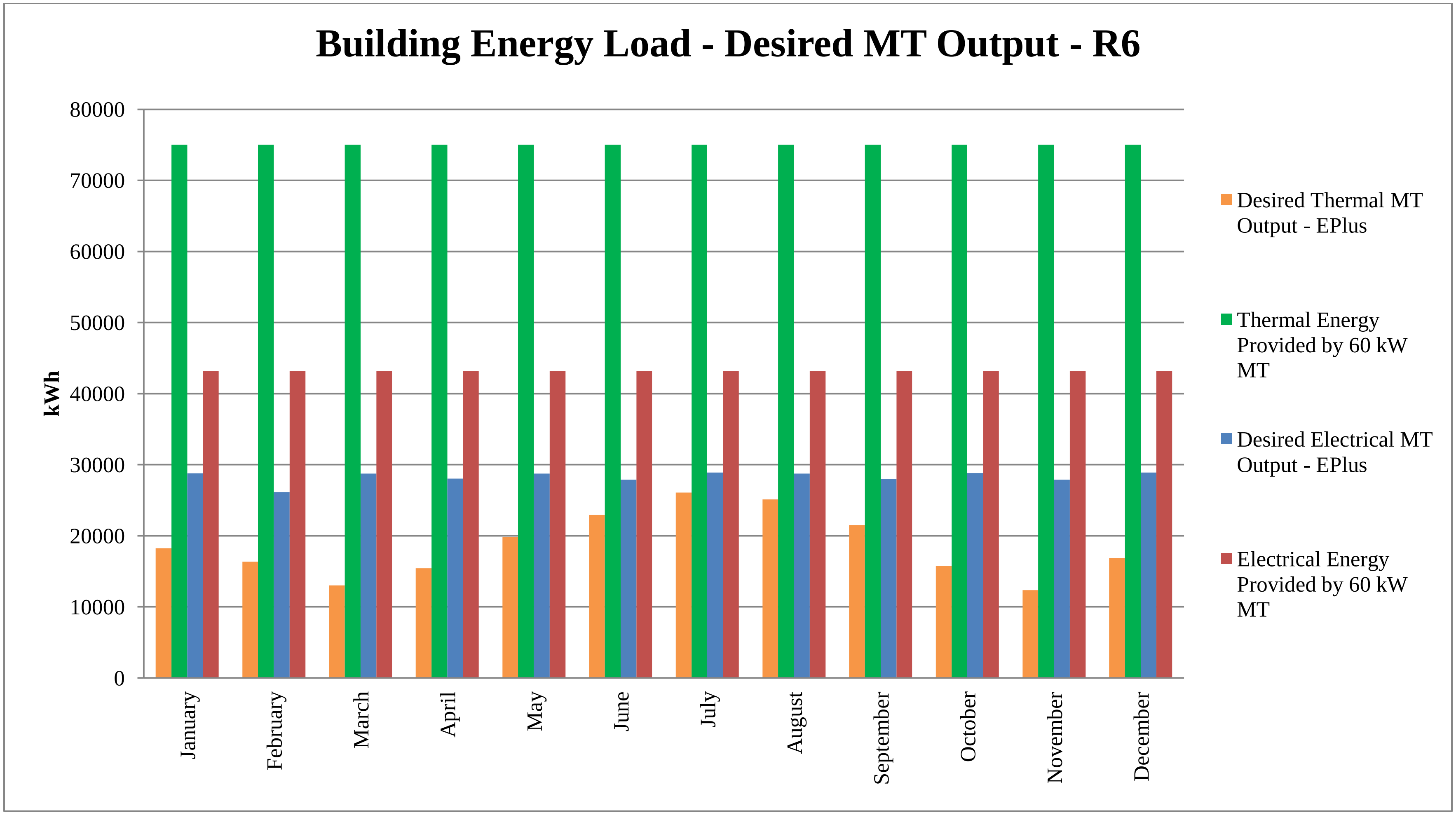


Figure 48: Desired Microturbine Output and Energy Provided by Microturbine for R6 Building - Thermostat Setting Sensitivity - Calculations Using EPlus Data

4.9.3 Two-Story Office Building Results - eQUEST and EPlus

For the 2-story office building scenario, the heating setpoint was changed from 70º F to 72º F, and the cooling setpoint was changed from 76º F to 74º F in order to analyze the sensitivity of the results to the thermostat setpoints used for the CHP system model. Shown in Appendix A in Table 78 is the monthly energy consumption by end use for the 2-story office building when the energy modeling software used was eQUEST. Shown in Appendix B in Table 87 is the monthly energy consumption by end use for the 2-story office building when the energy modeling software used was EPlus. The data on the building energy consumption produced by each energy modeling software was used to calculate the desired electric and thermal microturbine output for the office building. This calculation was performed the same way as the calculations performed in Sections 4.4 and 4.5, but the thermostat setpoints used were different. Shown in Table 64 is the desired electric and thermal microturbine output for the 2-story office building where the calculations used the eQUEST building load data, and shown in Table 65 is the desired electric and thermal microturbine output for the 2-story office building where the calculations used the EPlus building load data.

The 2-story office building monthly energy consumption by end use for each set of thermostat settings was compared for both the eQUEST energy model and the EPlus energy model. For the eQUEST energy model, the change in thermostat setpoints impacted several of the energy consumption end uses. The energy consumption for both space cooling and ventilation fans increased, and the energy consumption for the area lights increased slightly. The energy consumption for the end uses of pumps and auxiliary equipment, miscellaneous equipment, and hot water remained about the same.

The energy consumption for the end use of space heating was nearly doubled. For the EPlus energy model, the change in thermostat setpoints impacted only a few of the energy consumption end uses. When the thermostat setpoints for the EPlus energy model were changed, the energy consumption for space cooling increased, and the energy consumption for the ventilation fans increased slightly. The energy consumption for the end uses of hot water, interior equipment and interior lights all stayed the same. The energy consumption for the end use of space heating went up significantly, going from 16,094 to 27,499 kWh per year.

Table 64: Desired Electric and Thermal Microturbine Output for Office Building - Calculations Using eQUEST Building Load Data - Thermostat Setting Sensitivity

Month	Electrical Energy (kWh)	Thermal Energy (kWh)
January	11470.00	14639.21
February	10460.00	10435.48
March	11310.00	7154.48
April	11520.00	8464.61
May	11530.00	12268.56
June	10740.00	14507.65
July	11530.00	19480.49
August	11530.00	17885.43
September	10740.00	13712.59
October	11580.00	8891.63
November	10550.00	6793.42
December	11420.00	11213.20

Table 65: Desired Electric and Thermal Microturbine Output for Office Building - Calculations Using EPlus Building Load Data - Thermostat Setting Sensitivity

Month	Electrical Energy (kWh)	Thermal Energy (kWh)
January	9513.05	18022.73
February	8728.42	13642.70
March	9997.05	10921.00
April	9161.34	11421.16
May	9786.55	14027.67
June	9730.34	17034.00
July	9312.55	18410.39
August	10079.05	18303.72
September	9448.83	14618.20
October	9496.05	10899.27
November	9394.83	10974.74
December	9239.55	15391.13

The change in thermostat setpoints altered the building energy consumption, but the energy consumption levels were not changed enough to impact the sizing of the CHP system for the 2-story office building. This scenario still required a 30 kW microturbine in order to completely power the office building. Shown in Table 66 is the electrical and thermal energy provided by a 30 kW microturbine for the 2-story office building.

Table 66: Electric and Thermal Energy Provided by 30 kW Microturbine for Office Building - Thermostat Setting Sensitivity

Month	Electrical Energy (kWh)	Thermal Energy (kWh)
January	21600	37700
February	21600	37700
March	21600	37700
April	21600	37700
May	21600	37700
June	21600	37700
July	21600	37700
August	21600	37700
September	21600	37700
October	21600	37700
November	21600	37700
December	21600	37700

The desired electrical and thermal microturbine output for each energy model and the electrical and thermal energy provided by the 30 kW microturbine are plotted in Figures 49 and 50. As in the cases of the R1 and R6 residential buildings, the change in thermostat setpoints increased the thermal demand of the building and slightly increased the electrical demand of the building, but these changes were not enough to require a different size of CHP system for this scenario.

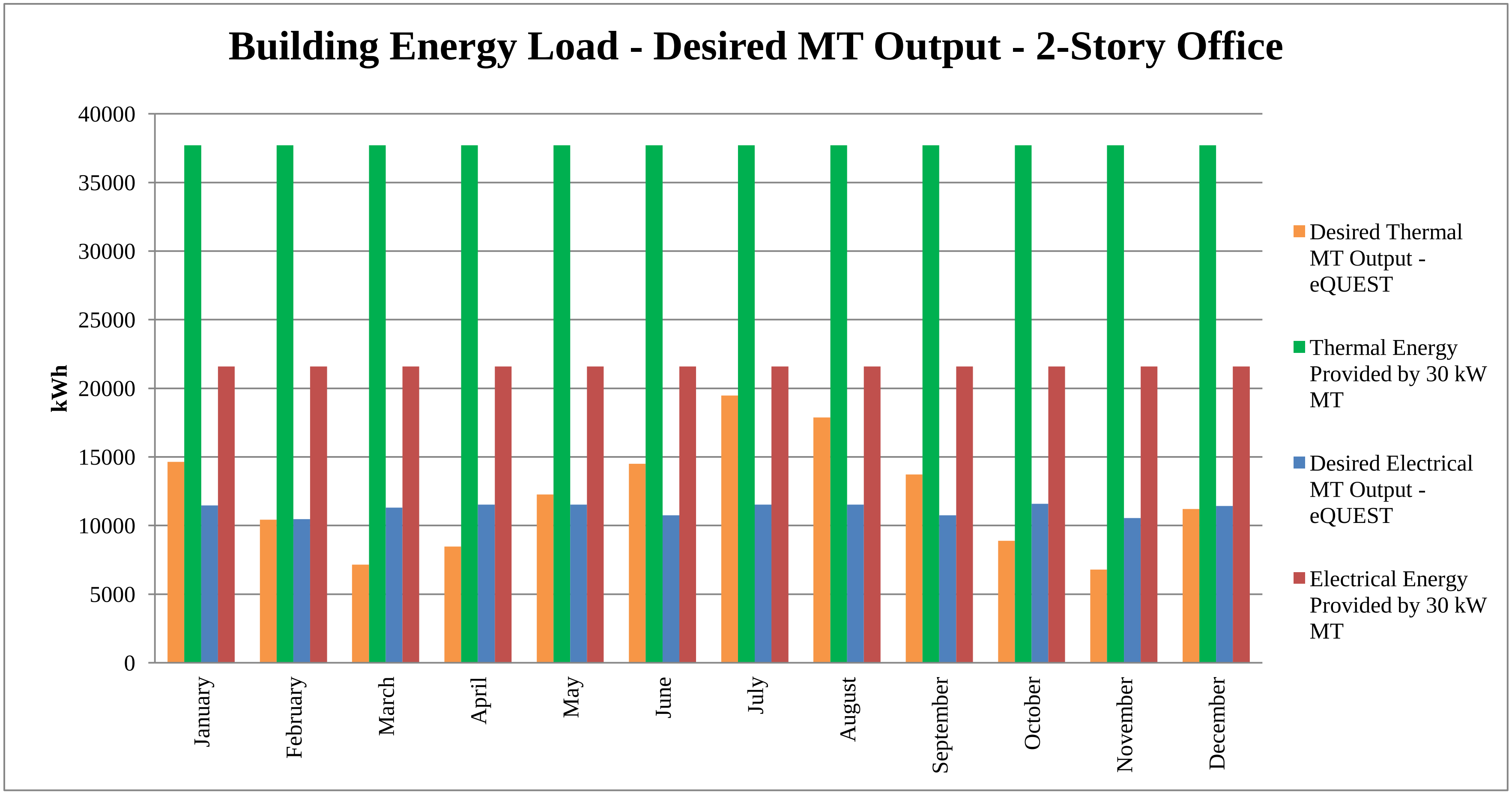


Figure 49: Desired Microturbine Output and Energy Provided by Microturbine for 2-Story Office Building - Thermostat Setting Sensitivity - Calculations Using eQUEST Data

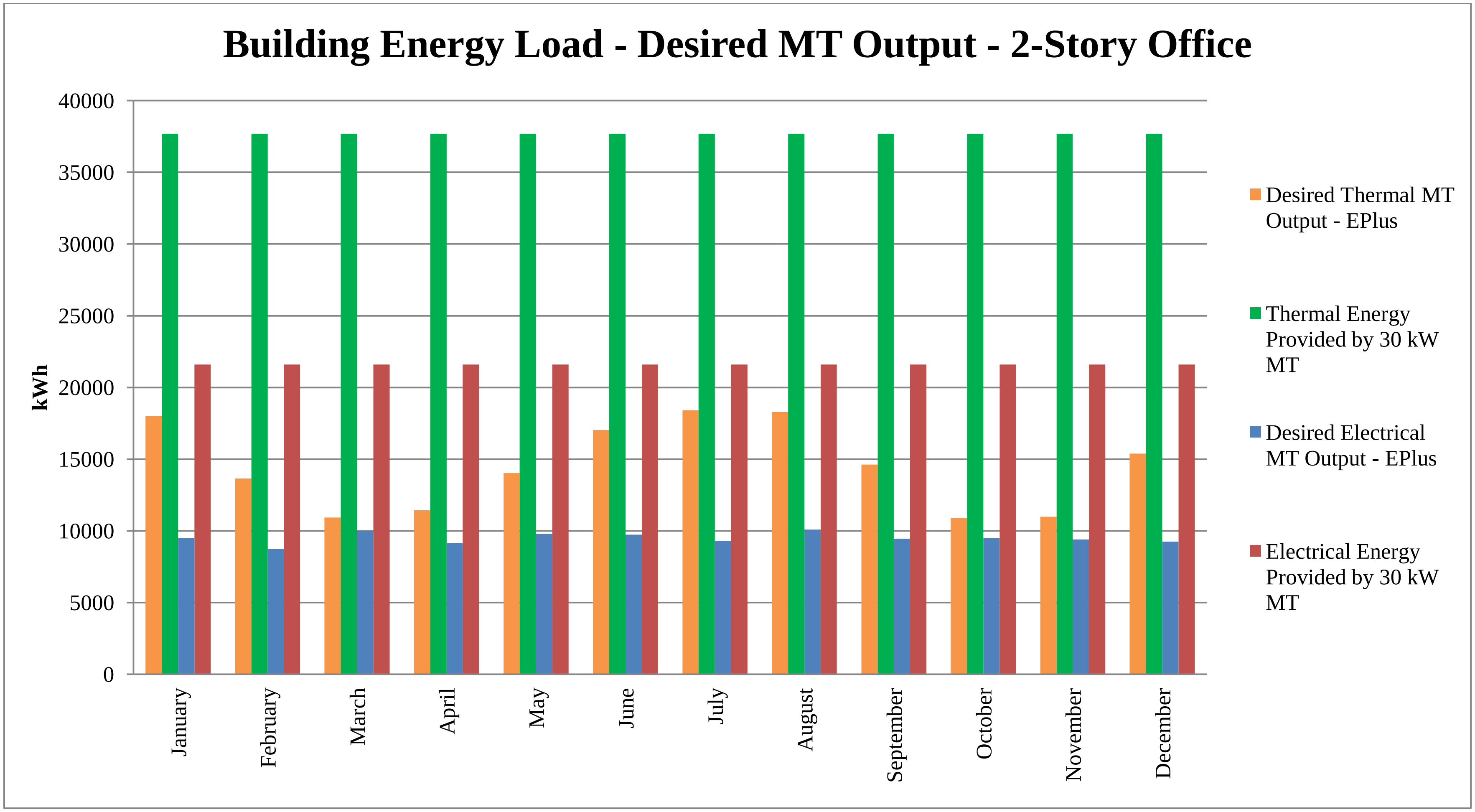


Figure 50: Desired Microturbine Output and Energy Provided by Microturbine for 2-Story Office Building - Thermostat Setting Sensitivity - Calculations Using EPlus Data

4.10 CHP System Results Summary

This chapter presented and discussed the results produced by the building energy demand models, the HOMER Energy model, and the CHP system model built in MS Excel. The results for each of these models were then tied together to present the full CHP system model for the three scenarios examined. The results for the full CHP system model using the eQUEST building load data were presented, followed by the results for the full CHP system model using the EPlus building load data. The full CHP system model using each of these data sets was given for the R1 residential building, the R6 residential building and the 2-story office building. The preliminary calculations performed for the full CHP system model were discussed, then the results for the desired electrical and thermal microturbine output and the optimal microturbine size for each scenario were presented. These results were given for the full CHP system model using each of the building load data sets simulated.

The full CHP system model designed for each of the three building scenarios were analyzed to determine the emissions and water consumption of each system. These results were compared with the emissions and water consumption due to traditional centralized energy systems. The CHP system environmental results were then discussed, and the CHP system model results were scaled up to Metropolitan Atlanta. This chapter provides information on the full CHP system models designed for the R1 residential building, the R6 residential building and the 2-story office building using two different sets of building load data. The results contribute to the understanding of CHP system functions in a range of scenarios, and this can lead to the deployment of CHP systems in a greater number of environments and applications.

CHAPTER 5

CONCLUSIONS

5.1 Summary

This thesis examined the use of a microturbine-based decentralized combined heat and power system and analyzed the technical and environmental feasibility of various system configurations. Energy models were developed for the microturbine-based combined heat and power system in order to analyze the system performance for urban residential and commercial scenarios. Development of the models also enabled the identification of the decentralized combined heat and power system environmental impacts, and the comparison of these to the impacts of a centralized energy system. Within this work the technical and environmental feasibility of the decentralized combined heat and power system was examined for three specific scenarios: an R1 single-family residential building, an R6 6-story residential building and a 2-story office building. The environmental impacts considered were the energy system water consumption, and the total NO_x, SO_2, CO_2, CH_4 and N_2O emissions produced by the system.

5.2 Research Questions

This thesis focused on the use of a decentralized microturbine-based CHP system for energy generation in urban environments. Various CHP system configurations were analyzed within the urban environment for technical and environmental feasibility. The feasibility of the microturbine-based CHP system was compared with the traditional centralized energy generation system in the context of the urban scenario. This led to the research question:

Is a microturbine-based decentralized CHP system more suitable for urban energy generation than certain centralized energy generation systems?

In order to answer this question, it was necessary to assess the technical and environmental feasibility of the microturbine-based decentralized CHP system for the urban environment. This was done by developing a model for the CHP system. This led to the following research question:

How should a microturbine-based decentralized CHP system be modeled to understand the system feasibility for urban scenarios and to determine the associated environmental impacts of this type of energy generation?

Developing a model for the microturbine-based decentralized CHP system made it possible to analyze the system performance for specific urban scenarios. In addition, a model enabled the identification of the decentralized CHP system environmental impacts, and the comparison of these to the impacts of a centralized energy system. Within this work the technical and environmental feasibility of the decentralized CHP system was examined for three specific scenarios: an R1 single-family residential building, an R6 6-story residential building and a 2-story office building. The environmental impacts considered were the energy system water consumption, and the total NO_x, SO_2, CO_2, CH_4, and N_2O emissions produced by the energy system.

The model developed for the microturbine-based CHP system was shown in Figure 20. The end use products for the model were electricity, domestic hot water, hot air and chilled air. The system was composed of a microturbine with an onboard air compressor, an electrical transformer, a heat recovery unit, an absorption chiller, a set of chilled water coils, and two sets of heating coils. The microturbine unit operated on natural gas and consisted of a compressor, recuperator, combustor, turbine and a generator.

The CHP system performance data for the R1 residential building, the R6 residential building and the 2-story office building was presented in Sections 4.4 and 4.5. Section 4.4 gave CHP system performance data based upon building energy demand data from eQUEST models, and Section 4.5 gave CHP system performance data based upon building energy demand data from EPlus models. Both models produced similar results regarding the sizing of the CHP system microturbine; a set of R1 residential buildings required a 30 kW microturbine, a R6 residential building required a 60 kW microturbine, and a 2-story office building required a 30 kW microturbine.

The CHP system model developed also enabled the identification of the decentralized CHP system environmental impacts. Table 36 presented the emissions characterization for a 30 kW microturbine-based CHP system for a 2-story office building, and these numbers were compared to the emissions levels from a centralized separate heat and power system of similar size. Table 37 presented the emissions characterization for a 30 kW microturbine-based CHP system for a set of R1 residential buildings, and these numbers were compared to the emissions levels from a similarly sized centralized separate heat and power system. Table 38 presented the emissions characterization for a 60 kW microturbine-based CHP system, and these numbers were also compared to the emissions levels from a centralized separate heat and power system of similar size. When the emissions levels of the centralized separate heat and power systems were compared to the emissions levels of the similarly-sized CHP systems, the

CHP systems produced significantly lower levels of NO_x, SO_2, CO_2, CH_4 and N_2O. Table 42, 43 and 44 presented the water consumption for the R1 building set, for the R6 building and for the 2-story office building for CHP and centralized energy generation under various assumptions. For each scenario analyzed, the water consumption levels for the decentralized CHP systems were much lower than the water consumption levels for the centralized energy generation systems. At its highest level, the water consumption for the CHP system was still less than 50% of the water consumption for the centralized energy generation system.

The research questions posed in this thesis were addressed through the development of a model for a microturbine-based decentralized CHP system, and addressed through analysis of the system performance and environmental impacts for specific urban scenarios. The model developed shows the best way to simulate a microturbine-based decentralized CHP system in order to understand the system feasibility for urban scenarios and to determine the associated environmental impacts of this type of energy generation. The microturbine-based decentralized CHP system was shown to be more suitable for urban energy generation than certain centralized energy generation systems.

5.3 Future Work

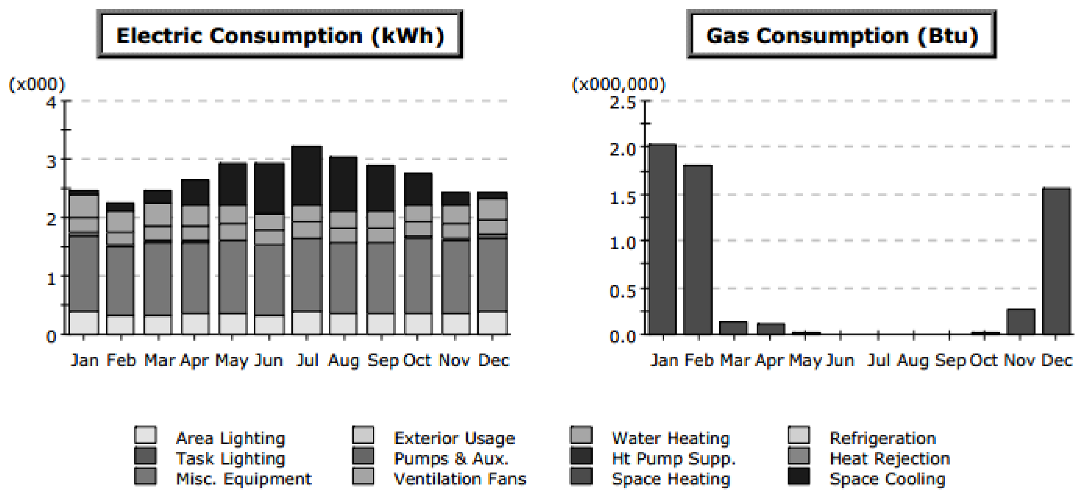
This thesis presented a model for a microturbine-based decentralized CHP system which made it possible to analyze the system performance and environmental impacts for specific urban scenarios. The work performed in this thesis will be useful in the future to researchers interested in modeling micro CHP buildings, whether those buildings are similar to the ones studied in this thesis, or have different uses. This work will also be useful to researchers interested in quantifying the water consumption due to CHP systems. Minimal water consumption work relative to CHP systems existed prior to this research, so this work makes a significant contribution in the area of water consumption quantification for CHP systems. Future research related to this thesis may involve modeling microturbine-based decentralized CHP systems using different building assumptions or weather data than the assumptions used in this work. It would be interesting to model the R1 building, R6 building and 2-story office building in various cities throughout the U.S. and examine the changes in system performance and environmental impacts. It would also be interesting to model these buildings using different internal loads and building geometry and examine the changes in CHP system performance, emissions levels and water consumption levels. The modeling of microturbine-based decentralized CHP systems makes it possible to analyze the system performance and environmental impacts for specific urban scenarios, and this analysis provides important data which contributes to the development and deployment of micro scale CHP systems in the U.S.

APPENDIX A

EQUEST MODEL BUILDING LOAD DATA

This appendix provides the R1 residential, R6 residential and office building load data for the Atlanta area produced by the eQUEST models. Tables 67, 68 and 69 present the R1 residential, R6 residential and office building consumption by end use data obtained from the eQUEST simulations.

Table 67: R1 Monthly Energy Consumption by End Use from eQUEST Model



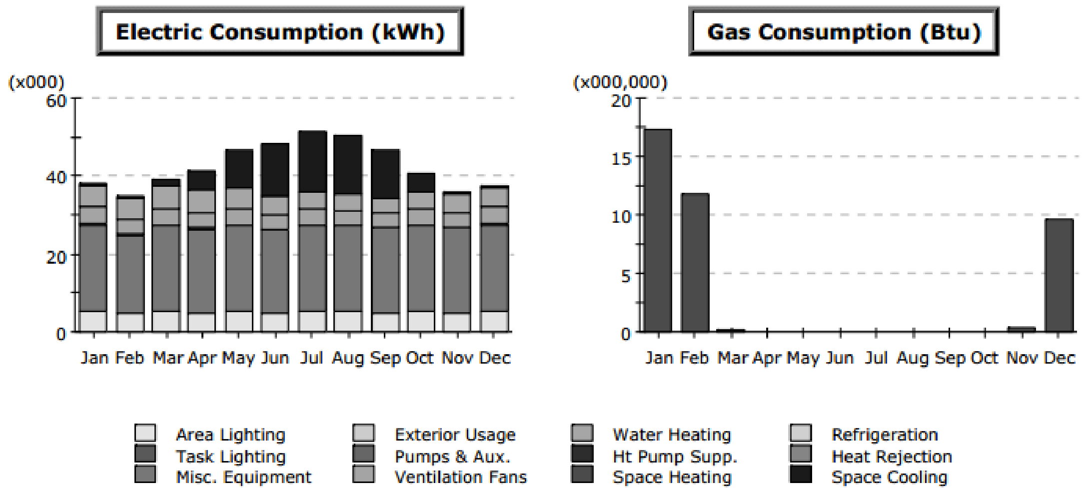
Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	0.07	0.13	0.23	0.43	0.69	0.86	1.01	0.93	0.80	0.53	0.23	0.09	5.99
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	-	-	-	-	-	-	-	-	-	-	-	-	-
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	0.39	0.36	0.39	0.37	0.35	0.30	0.29	0.26	0.26	0.29	0.31	0.35	3.94
Vent. Fans	0.26	0.23	0.25	0.25	0.25	0.24	0.26	0.25	0.25	0.26	0.25	0.26	3.02
Pumps & Aux.	0.06	0.04	0.03	0.01	-	-	-	-	-	0.01	0.03	0.05	0.23
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	1.30	1.15	1.25	1.23	1.27	1.21	1.28	1.25	1.23	1.28	1.24	1.28	14.98
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	0.39	0.33	0.34	0.35	0.36	0.33	0.38	0.34	0.35	0.37	0.37	0.38	4.28
Total	2.47	2.25	2.48	2.64	2.91	2.94	3.22	3.03	2.89	2.74	2.43	2.41	32.42

Gas Consumption (Btu x000,000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	-	-	-	-	-	-	-	-	-	-	-	-	-
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	2.03	1.80	0.12	0.11	0.01	-	-	-	0.00	0.02	0.27	1.57	5.93
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	-	-	-	-	-	-	-	-	-	-	-	-	-
Vent. Fans	-	-	-	-	-	-	-	-	-	-	-	-	-
Pumps & Aux.	-	-	-	-	-	-	-	-	-	-	-	-	-
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	-	-	-	-	-	-	-	-	-	-	-	-	-
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Total	2.03	1.80	0.12	0.11	0.01	-	-	-	0.00	0.02	0.27	1.57	5.93

Table 68: R6 Monthly Energy Consumption by End Use from eQUEST Model



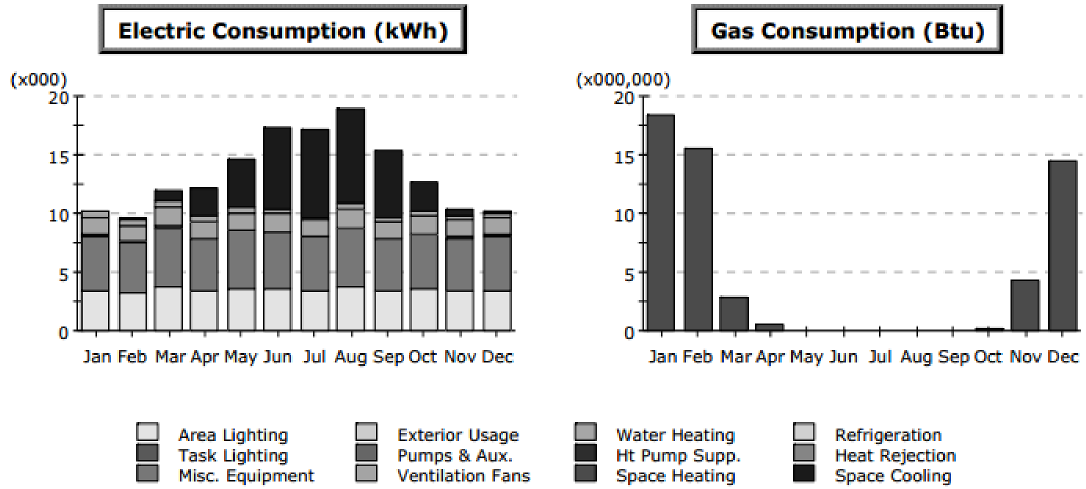
Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	0.11	0.45	1.72	4.80	9.83	13.42	15.74	14.95	12.12	4.93	0.63	0.07	78.77
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	-	-	-	-	-	-	-	-	-	-	-	-	-
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	5.68	5.46	6.15	5.75	5.41	4.76	4.37	4.16	3.96	4.29	4.58	5.27	59.85
Vent. Fans	4.11	3.69	4.03	3.96	4.06	3.91	4.11	4.03	3.96	4.08	3.96	4.11	48.00
Pumps & Aux.	0.46	0.33	0.23	0.10	-	-	-	-	-	0.08	0.24	0.39	1.82
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	22.28	20.07	22.10	21.52	22.16	21.41	22.27	22.10	21.52	22.22	21.52	22.27	261.44
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	5.19	4.66	5.09	5.00	5.12	4.94	5.18	5.09	5.00	5.15	5.00	5.19	60.62
Total	37.83	34.64	39.32	41.12	46.58	48.43	51.68	50.34	46.57	40.75	35.94	37.30	510.50

Gas Consumption (Btu x000,000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	-	-	-	-	-	-	-	-	-	-	-	-	-
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	17.29	11.75	0.11	0.03	-	-	-	-	-	-	0.36	9.63	39.17
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	-	-	-	-	-	-	-	-	-	-	-	-	-
Vent. Fans	-	-	-	-	-	-	-	-	-	-	-	-	-
Pumps & Aux.	-	-	-	-	-	-	-	-	-	-	-	-	-
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	-	-	-	-	-	-	-	-	-	-	-	-	-
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Total	17.29	11.75	0.11	0.03	-	-	-	-	-	-	0.36	9.63	39.17

Table 69: Office Building Monthly Energy Consumption by End Use from eQUEST Model



Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	0.08	0.16	0.85	2.42	4.20	6.93	7.40	8.09	5.78	2.46	0.57	0.13	39.09
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	-	-	-	-	-	-	-	-	-	-	-	-	-
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	0.41	0.40	0.48	0.42	0.43	0.40	0.34	0.37	0.33	0.36	0.36	0.39	4.69
Vent. Fans	1.43	1.36	1.64	1.43	1.57	1.57	1.43	1.64	1.43	1.50	1.43	1.43	17.85
Pumps & Aux.	0.31	0.22	0.15	0.06	-	-	-	-	-	0.05	0.16	0.26	1.22
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	4.61	4.28	4.98	4.54	4.86	4.79	4.61	4.98	4.54	4.73	4.54	4.61	56.08
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	3.34	3.16	3.81	3.33	3.65	3.65	3.34	3.81	3.33	3.49	3.33	3.34	41.58
Total	10.18	9.58	11.92	12.20	14.70	17.33	17.12	18.89	15.41	12.60	10.40	10.16	160.50

Gas Consumption (Btu x000,000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	-	-	-	-	-	-	-	-	-	-	-	-	-
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	18.42	15.57	2.79	0.47	0.01	0.04	0.03	0.05	0.01	0.12	4.27	14.41	56.19
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	-	-	-	-	-	-	-	-	-	-	-	-	-
Vent. Fans	-	-	-	-	-	-	-	-	-	-	-	-	-
Pumps & Aux.	-	-	-	-	-	-	-	-	-	-	-	-	-
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	-	-	-	-	-	-	-	-	-	-	-	-	-
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Total	18.42	15.57	2.79	0.47	0.01	0.04	0.03	0.05	0.01	0.12	4.27	14.41	56.19

All data obtained from eQUEST was converted into units of kWh. This conversion is shown in Table 70 for the R1 residential building, shown in Table 71 for the R6 residential building, and shown in Table 72 for the office building.

Table 70: R1 Residential Building Load Data Conversion

Electric Consumption	units: kWh												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	70	130	230	430	690	860	1010	930	800	530	230	90	6000
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	-	-	-	-	-	-	-	-	-	-	-	-	-
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	390	360	390	370	350	300	290	260	260	290	310	350	3920
Vent. Fans	260	230	250	250	250	240	260	250	250	260	250	260	3010
Pumps & Aux.	60	40	30	10	0	0	0	0	0	10	30	50	230
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	1300	1150	1250	1230	1270	1210	1280	1250	1230	1280	1240	1280	14970
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	390	330	340	350	360	330	380	340	350	370	370	380	4290
Total	2470	2240	2490	2640	2920	2940	3220	3030	2890	2740	2430	2410	32420

Gas Consumption	units: Btu												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Heat	2030000	1800000	120000	110000	10000	0	0	0	0	20000	270000	1570000	5930000
Total (Btu)	2030000	1800000	120000	110000	10000	0	0	0	0	20000	270000	1570000	5930000
Total (kWh)	594.9	527.5	35.2	32.2	2.9	0.0	0.0	0.0	0.0	5.9	79.1	460.1	1737.9

Table 71: R6 Residential Building Load Data Conversion

Electric Consumption	units: kWh												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	110	450	1720	4800	9830	13420	15740	14950	12120	4930	630	70	78770
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	-	-	-	-	-	-	-	-	-	-	-	-	-
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	5680	5460	6150	5750	5410	4760	4370	4160	3960	4290	4580	5270	59840
Vent. Fans	4110	3690	4030	3960	4060	3910	4110	4030	3960	4080	3960	4110	48010
Pumps & Aux.	460	330	230	100	0	0	0	0	0	80	240	390	1830
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	22280	20070	22100	21520	22160	21410	22270	22100	21520	22220	21520	22270	261440
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	5190	4660	5090	5000	5120	4940	5180	5090	5000	5150	5000	5190	60610
Total	37830	34660	39320	41130	46580	48440	51670	50330	46560	40750	35930	37300	510500

Gas Consumption	units: Btu												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Heat	17290000	11750000	110000	30000	0	0	0	0	0	0	360000	9630000	39170000
Total (Btu)	17290000	11750000	110000	30000	0	0	0	0	0	0	360000	9630000	39170000
Total (kWh)	5067.2	3443.6	32.2	8.8	0.0	0.0	0.0	0.0	0.0	0.0	105.5	2822.3	11479.6

Table 72: Office Building Load Data Conversion

Electric Consumption	units: kWh												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	80	160	850	2420	4200	6930	7400	8090	5780	2460	570	130	39070
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	-	-	-	-	-	-	-	-	-	-	-	-	-
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	410	400	480	420	430	400	340	370	330	360	360	390	4690
Vent. Fans	1430	1360	1640	1430	1570	1570	1430	1640	1430	1500	1430	1430	17860
Pumps & Aux.	310	220	150	60	0	0	0	0	0	50	160	260	1210
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	4610	4280	4980	4540	4860	4790	4610	4980	4540	4730	4540	4610	56070
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	3340	3160	3810	3330	3650	3650	3340	3810	3330	3490	3330	3340	41580
Total	10180	9580	11910	12200	14710	17340	17120	18890	15410	12590	10390	10160	160480

Gas Consumption	units: Btu												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Heat	18420000	15570000	2790000	470000	10000	40000	30000	50000	10000	120000	4270000	14410000	56190000
Total (Btu)	18420000	15570000	2790000	470000	10000	40000	30000	50000	10000	120000	4270000	14410000	56190000
Total (kWh)	5398.4	4563.1	817.7	137.7	2.9	11.7	8.8	14.7	2.9	35.2	1251.4	4223.2	16467.7

The data calculated in Tables 70, 71 and 72 was grouped into electrical and thermal energy needed by month, and system inefficiencies were applied to these loads to determine the necessary electrical and thermal outputs of the system prime mover. The calculations of the electrical and thermal energy microturbine outputs needed by month are shown in Table 73 for the R1 residential building, shown in Table 74 for the R6 residential building, and shown in Table 75 for the office building.

Table 73: Electrical and Thermal Energy Loads with Inefficiencies for R1 Residential Building - eQUEST Model

January		units: kWh		
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	70.00	390.00	594.93	1054.93
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	138.27	577.78	881.38	1597.43
Parasitic Load	-	-	-	720.00
Total	138.27	577.78	881.38	2317.43

January	units: kWh	
	Electricity	Total
End Output Needed	2010.00	2010.00
Composite Inefficiencies	-	-
MT Output	2010.00	2010.00
Parasitic Load	-	1440.00
Total	2010.00	3450.00

February		units: kWh		
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	130.00	360.00	527.53	1017.53
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	256.79	533.33	781.52	1571.65
Parasitic Load	-	-	-	720.00
Total	256.79	533.33	781.52	2291.65

February	units: kWh	
	Electricity	Total
End Output Needed	1750.00	1750.00
Composite Inefficiencies	-	-
MT Output	1750.00	1750.00
Parasitic Load	-	1440.00
Total	1750.00	3190.00

March		units: kWh		
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	230.00	390.00	35.17	655.17
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	454.32	577.78	52.10	1084.20
Parasitic Load	-	-	-	720.00
Total	454.32	577.78	52.10	1804.20

March	units: kWh	
	Electricity	Total
End Output Needed	1870.00	1870.00
Composite Inefficiencies	-	-
MT Output	1870.00	1870.00
Parasitic Load	-	1440.00
Total	1870.00	3310.00

April		units: kWh		
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	430.00	370.00	32.24	832.24
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	849.38	548.15	47.76	1445.29
Parasitic Load	-	-	-	720.00
Total	849.38	548.15	47.76	2165.29

April	units: kWh	
	Electricity	Total
End Output Needed	1840.00	1840.00
Composite Inefficiencies	-	-
MT Output	1840.00	1840.00
Parasitic Load	-	1440.00
Total	1840.00	3280.00

Table 73 Continued:

May		units: kWh		
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	690.00	350.00	2.93	1042.93
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	1362.96	518.52	4.34	1885.82
Parasitic Load	-	-	-	720.00
Total	1362.96	518.52	4.34	2605.82

May	units: kWh	
	Electricity	Total
End Output Needed	1880.00	1880.00
Composite Inefficiencies	-	-
MT Output	1880.00	1880.00
Parasitic Load	-	1440.00
Total	1880.00	3320.00

June		units: kWh		
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	860.00	300.00	0.00	1160.00
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	1698.77	444.44	0.00	2143.21
Parasitic Load	-	-	-	720.00
Total	1698.77	444.44	0.00	2863.21

June	units: kWh	
	Electricity	Total
End Output Needed	1780.00	1780.00
Composite Inefficiencies	-	-
MT Output	1780.00	1780.00
Parasitic Load	-	1440.00
Total	1780.00	3220.00

July		units: kWh		
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	1010.00	290.00	0.00	1300.00
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	1995.06	429.63	0.00	2424.69
Parasitic Load	-	-	-	720.00
Total	1995.06	429.63	0.00	3144.69

July	units: kWh	
	Electricity	Total
End Output Needed	1920.00	1920.00
Composite Inefficiencies	-	-
MT Output	1920.00	1920.00
Parasitic Load	-	1440.00
Total	1920.00	3360.00

August		units: kWh		
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	930.00	260.00	0.00	1190.00
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	1837.04	385.19	0.00	2222.22
Parasitic Load	-	-	-	720.00
Total	1837.04	385.19	0.00	2942.22

August	units: kWh	
	Electricity	Total
End Output Needed	1840.00	1840.00
Composite Inefficiencies	-	-
MT Output	1840.00	1840.00
Parasitic Load	-	1440.00
Total	1840.00	3280.00

September		units: kWh		
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	800.00	260.00	0.00	1060.00
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	1580.25	385.19	0.00	1965.43
Parasitic Load	-	-	-	720.00
Total	1580.25	385.19	0.00	2685.43

September	units: kWh	
	Electricity	Total
End Output Needed	1830.00	1830.00
Composite Inefficiencies	-	-
MT Output	1830.00	1830.00
Parasitic Load	-	1440.00
Total	1830.00	3270.00

Table 73 Continued:

October		units: kWh		
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	530.00	290.00	5.86	825.86
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	1046.91	429.63	8.68	1485.23
Parasitic Load	-	-	-	720.00
Total	1046.91	429.63	8.68	2205.23

October	units: kWh	
	Electricity	Total
End Output Needed	1920.00	1920.00
Composite Inefficiencies	-	-
MT Output	1920.00	1920.00
Parasitic Load	-	1440.00
Total	1920.00	3360.00

November		units: kWh		
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	230.00	310.00	79.13	619.13
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	454.32	459.26	117.23	1030.81
Parasitic Load	-	-	-	720.00
Total	454.32	459.26	117.23	1750.81

November	units: kWh	
	Electricity	Total
End Output Needed	1890.00	1890.00
Composite Inefficiencies	-	-
MT Output	1890.00	1890.00
Parasitic Load	-	1440.00
Total	1890.00	3330.00

December		units: kWh		
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	90.00	350.00	460.12	900.12
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	177.78	518.52	681.66	1377.96
Parasitic Load	-	-	-	720.00
Total	177.78	518.52	681.66	2097.96

December	units: kWh	
	Electricity	Total
End Output Needed	1970.00	1970.00
Composite Inefficiencies	-	-
MT Output	1970.00	1970.00
Parasitic Load	-	1440.00
Total	1970.00	3410.00

Table 74: Electrical and Thermal Energy Loads with Inefficiencies for R6 Residential Building - eQUEST Model

January		units: kWh		
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	110.00	5680.00	5067.20	10857.20
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	217.28	8414.81	7506.96	16139.06
Parasitic Load	-	-	-	720.00
Total	217.28	8414.81	7506.96	16859.06

January	units: kWh	
	Electricity	Total
End Output Needed	32040.00	32040.00
Composite Inefficiencies	-	-
MT Output	32040.00	32040.00
Parasitic Load	-	1440.00
Total	32040.00	33480.00

Table 74 Continued:

February		units: kWh		
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	450.00	5460.00	3443.59	9353.59
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	888.89	8088.89	5101.61	14079.39
Parasitic Load	-	-	-	720.00
Total	888.89	8088.89	5101.61	14799.39

February	units: kWh	
	Electricity	Total
End Output Needed	28750.00	28750.00
Composite Inefficiencies	-	-
MT Output	28750.00	28750.00
Parasitic Load	-	1440.00
Total	28750.00	30190.00

March		units: kWh		
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	1720.00	6150.00	32.24	7902.24
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	3397.53	9111.11	47.76	12556.40
Parasitic Load	-	-	-	720.00
Total	3397.53	9111.11	47.76	13276.40

March	units: kWh	
	Electricity	Total
End Output Needed	31450.00	31450.00
Composite Inefficiencies	-	-
MT Output	31450.00	31450.00
Parasitic Load	-	1440.00
Total	31450.00	32890.00

April		units: kWh		
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	4800.00	5750.00	8.79	10558.79
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	9481.48	8518.52	13.03	18013.03
Parasitic Load	-	-	-	720.00
Total	9481.48	8518.52	13.03	18733.03

April	units: kWh	
	Electricity	Total
End Output Needed	30580.00	30580.00
Composite Inefficiencies	-	-
MT Output	30580.00	30580.00
Parasitic Load	-	1440.00
Total	30580.00	32020.00

May		units: kWh		
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	9830.00	5410.00	0.00	15240.00
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	19417.28	8014.81	0.00	27432.10
Parasitic Load	-	-	-	720.00
Total	19417.28	8014.81	0.00	28152.10

May	units: kWh	
	Electricity	Total
End Output Needed	31340.00	31340.00
Composite Inefficiencies	-	-
MT Output	31340.00	31340.00
Parasitic Load	-	1440.00
Total	31340.00	32780.00

June		units: kWh		
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	13420.00	4760.00	0.00	18180.00
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	26508.64	7051.85	0.00	33560.49
Parasitic Load	-	-	-	720.00
Total	26508.64	7051.85	0.00	34280.49

June	units: kWh	
	Electricity	Total
End Output Needed	30260.00	30260.00
Composite Inefficiencies	-	-
MT Output	30260.00	30260.00
Parasitic Load	-	1440.00
Total	30260.00	31700.00

Table 74 Continued:

July		units: kWh		
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	15740.00	4370.00	0.00	20110.00
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	31091.36	6474.07	0.00	37565.43
Parasitic Load	-	-	-	720.00
Total	31091.36	6474.07	0.00	38285.43

July	units: kWh	
	Electricity	Total
End Output Needed	31560.00	31560.00
Composite Inefficiencies	-	-
MT Output	31560.00	31560.00
Parasitic Load	-	1440.00
Total	31560.00	33000.00

August		units: kWh		
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	14950.00	4160.00	0.00	19110.00
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	29530.86	6162.96	0.00	35693.83
Parasitic Load	-	-	-	720.00
Total	29530.86	6162.96	0.00	36413.83

August	units: kWh	
	Electricity	Total
End Output Needed	31220.00	31220.00
Composite Inefficiencies	-	-
MT Output	31220.00	31220.00
Parasitic Load	-	1440.00
Total	31220.00	32660.00

September		units: kWh		
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	12120.00	3960.00	0.00	16080.00
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	23940.74	5866.67	0.00	29807.41
Parasitic Load	-	-	-	720.00
Total	23940.74	5866.67	0.00	30527.41

September	units: kWh	
	Electricity	Total
End Output Needed	30480.00	30480.00
Composite Inefficiencies	-	-
MT Output	30480.00	30480.00
Parasitic Load	-	1440.00
Total	30480.00	31920.00

October		units: kWh		
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	4930.00	4290.00	0.00	9220.00
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	9738.27	6355.56	0.00	16093.83
Parasitic Load	-	-	-	720.00
Total	9738.27	6355.56	0.00	16813.83

October	units: kWh	
	Electricity	Total
End Output Needed	31530.00	31530.00
Composite Inefficiencies	-	-
MT Output	31530.00	31530.00
Parasitic Load	-	1440.00
Total	31530.00	32970.00

November		units: kWh		
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	630.00	4580.00	105.51	5315.51
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	1244.44	6785.19	156.30	8185.93
Parasitic Load	-	-	-	720.00
Total	1244.44	6785.19	156.30	8905.93

November	units: kWh	
	Electricity	Total
End Output Needed	30720.00	30720.00
Composite Inefficiencies	-	-
MT Output	30720.00	30720.00
Parasitic Load	-	1440.00
Total	30720.00	32160.00

Table 74 Continued:

December		units: kWh		
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	70.00	5270.00	2822.27	8162.27
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	138.27	7807.41	4181.15	12126.83
Parasitic Load	-	-	-	720.00
Total	138.27	7807.41	4181.15	12846.83

December	units: kWh	
	Electricity	Total
End Output Needed	31960.00	31960.00
Composite Inefficiencies	-	-
MT Output	31960.00	31960.00
Parasitic Load	-	1440.00
Total	31960.00	33400.00

Table 75: Electrical and Thermal Energy Loads with Inefficiencies for Office Building - eQUEST Model

January		units: kWh		
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	80.00	410.00	5398.37	5888.37
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	158.02	607.41	7997.58	8763.02
Parasitic Load	-	-	-	720.00
Total	158.02	607.41	7997.58	9483.02

January	units: kWh	
	Electricity	Total
End Output Needed	9690.00	9690.00
Composite Inefficiencies	-	-
MT Output	9690.00	9690.00
Parasitic Load	-	1440.00
Total	9690.00	11130.00

February		units: kWh		
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	160.00	400.00	4563.12	5123.12
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	316.05	592.59	6760.17	7668.81
Parasitic Load	-	-	-	720.00
Total	316.05	592.59	6760.17	8388.81

February	units: kWh	
	Electricity	Total
End Output Needed	9020.00	9020.00
Composite Inefficiencies	-	-
MT Output	9020.00	9020.00
Parasitic Load	-	1440.00
Total	9020.00	10460.00

March		units: kWh		
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	850.00	480.00	817.67	2147.67
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	1679.01	711.11	1211.36	3601.48
Parasitic Load	-	-	-	720.00
Total	1679.01	711.11	1211.36	4321.48

March	units: kWh	
	Electricity	Total
End Output Needed	10580.00	10580.00
Composite Inefficiencies	-	-
MT Output	10580.00	10580.00
Parasitic Load	-	1440.00
Total	10580.00	12020.00

Table 75 Continued:

April		units: kWh		
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	2420.00	420.00	137.74	2977.74
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	4780.25	622.22	204.06	5606.53
Parasitic Load	-	-	-	720.00
Total	4780.25	622.22	204.06	6326.53

April	units: kWh	
	Electricity	Total
End Output Needed	9360.00	9360.00
Composite Inefficiencies	-	-
MT Output	9360.00	9360.00
Parasitic Load	-	1440.00
Total	9360.00	10800.00

May		units: kWh		
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	4200.00	430.00	2.93	4632.93
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	8296.30	637.04	4.34	8937.68
Parasitic Load	-	-	-	720.00
Total	8296.30	637.04	4.34	9657.68

May	units: kWh	
	Electricity	Total
End Output Needed	10080.00	10080.00
Composite Inefficiencies	-	-
MT Output	10080.00	10080.00
Parasitic Load	-	1440.00
Total	10080.00	11520.00

June		units: kWh		
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	6930.00	400.00	11.72	7341.72
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	13688.89	592.59	17.37	14298.85
Parasitic Load	-	-	-	720.00
Total	13688.89	592.59	17.37	15018.85

June	units: kWh	
	Electricity	Total
End Output Needed	10010.00	10010.00
Composite Inefficiencies	-	-
MT Output	10010.00	10010.00
Parasitic Load	-	1440.00
Total	10010.00	11450.00

July		units: kWh		
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	7400.00	340.00	8.79	7748.79
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	14617.28	503.70	13.03	15134.01
Parasitic Load	-	-	-	720.00
Total	14617.28	503.70	13.03	15854.01

July	units: kWh	
	Electricity	Total
End Output Needed	9380.00	9380.00
Composite Inefficiencies	-	-
MT Output	9380.00	9380.00
Parasitic Load	-	1440.00
Total	9380.00	10820.00

August		units: kWh		
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	8090.00	370.00	14.65	8474.65
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	15980.25	548.15	21.71	16550.10
Parasitic Load	-	-	-	720.00
Total	15980.25	548.15	21.71	17270.10

August	units: kWh	
	Electricity	Total
End Output Needed	10430.00	10430.00
Composite Inefficiencies	-	-
MT Output	10430.00	10430.00
Parasitic Load	-	1440.00
Total	10430.00	11870.00

Table 75 Continued:

September		units: kWh		
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	5780.00	330.00	2.93	6112.93
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	11417.28	488.89	4.34	11910.51
Parasitic Load	-	-	-	720.00
Total	11417.28	488.89	4.34	12630.51

September	units: kWh	
	Electricity	Total
End Output Needed	9300.00	9300.00
Composite Inefficiencies	-	-
MT Output	9300.00	9300.00
Parasitic Load	-	1440.00
Total	9300.00	10740.00

October		units: kWh		
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	2460.00	360.00	35.17	2855.17
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	4859.26	533.33	52.10	5444.69
Parasitic Load	-	-	-	720.00
Total	4859.26	533.33	52.10	6164.69

October	units: kWh	
	Electricity	Total
End Output Needed	9770.00	9770.00
Composite Inefficiencies	-	-
MT Output	9770.00	9770.00
Parasitic Load	-	1440.00
Total	9770.00	11210.00

November		units: kWh		
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	570.00	360.00	1251.41	2181.41
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	1125.93	533.33	1853.95	3513.21
Parasitic Load	-	-	-	720.00
Total	1125.93	533.33	1853.95	4233.21

November	units: kWh	
	Electricity	Total
End Output Needed	9460.00	9460.00
Composite Inefficiencies	-	-
MT Output	9460.00	9460.00
Parasitic Load	-	1440.00
Total	9460.00	10900.00

December		units: kWh		
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	130.00	390.00	4223.15	4743.15
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	256.79	577.78	6256.52	7091.09
Parasitic Load	-	-	-	720.00
Total	256.79	577.78	6256.52	7811.09

December	units: kWh	
	Electricity	Total
End Output Needed	9640.00	9640.00
Composite Inefficiencies	-	-
MT Output	9640.00	9640.00
Parasitic Load	-	1440.00
Total	9640.00	11080.00

Table 76: R1 Monthly Energy Consumption by End Use from eQUEST Model - Thermostat Setting Sensitivity

Electric Consumption	units: kWh x000												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	0.08	0.13	0.24	0.42	0.66	0.84	0.93	0.9	0.76	0.49	0.22	0.09	5.76
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	-	-	-	-	-	-	-	-	-	-	-	-	-
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	0.53	0.5	0.56	0.54	0.5	0.43	0.41	0.38	0.36	0.4	0.42	0.49	5.52
Vent. Fans	0.23	0.21	0.23	0.22	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	2.73
Pumps & Aux.	0.06	0.04	0.03	0.01	0	0	0	0	0	0.01	0.03	0.05	0.23
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	1.23	1.11	1.23	1.19	1.23	1.19	1.23	1.23	1.19	1.23	1.19	1.23	14.48
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	0.28	0.25	0.28	0.27	0.28	0.27	0.28	0.28	0.27	0.28	0.27	0.28	3.29
Total	2.41	2.24	2.57	2.65	2.9	2.96	3.08	3.02	2.81	2.64	2.36	2.37	32.01

Gas Consumption	units: Btu x000,000												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Heat	3.58	2.58	0.64	0.29	0	0	0	0	0	0.02	0.77	2.63	10.51
Total	3.58	2.58	0.64	0.29	0	0	0	0	0	0.02	0.77	2.63	10.51

Table 77: R6 Monthly Energy Consumption by End Use from eQUEST Model - Thermostat Setting Sensitivity

Electric Consumption	units: kWh x000												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	0.16	0.52	1.69	4.27	8.18	11.5	13.1	12.82	10.78	4.54	0.79	0.19	68.54
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	-	-	-	-	-	-	-	-	-	-	-	-	-
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	5.68	5.46	6.15	5.75	5.41	4.76	4.37	4.16	3.96	4.29	4.58	5.27	59.84
Vent. Fans	3.79	3.42	3.79	3.62	3.76	3.67	3.76	3.76	3.67	3.76	3.7	3.79	44.49
Pumps & Aux.	0.46	0.33	0.23	0.1	0	0	0	0	0	0.08	0.24	0.39	1.83
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	22	19.86	21.99	21.19	21.94	21.3	21.94	21.94	21.3	21.94	21.36	22	258.76
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	5.18	4.68	5.17	4.96	5.15	5.02	5.15	5.15	5.02	5.15	5.06	5.18	60.87
Total	37.27	34.27	39.02	39.89	44.44	46.25	48.32	47.83	44.73	39.76	35.73	36.82	494.33

Gas Consumption	units: Btu x000,000												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Heat	30.43	16.80	0.59	0.08	0.00	0.00	0.00	0.00	0.00	0.00	1.03	16.18	65.10
Total	30.43	16.80	0.59	0.08	0.00	0.00	0.00	0.00	0.00	0.00	1.03	16.18	65.10

Table 78: Office Building Monthly Energy Consumption by End Use from eQUEST Model - Thermostat Setting Sensitivity

Electric Consumption	units: kWh x000												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	0.13	0.44	0.98	2.58	5.48	6.71	9.22	8.42	6.33	3.4	0.99	0.18	44.86
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	-	-	-	-	-	-	-	-	-	-	-	-	-
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	0.43	0.4	0.44	0.46	0.43	0.36	0.37	0.36	0.33	0.37	0.35	0.41	4.71
Vent. Fans	1.5	1.36	1.5	1.58	1.58	1.43	1.58	1.58	1.43	1.58	1.36	1.5	17.98
Pumps & Aux.	0.31	0.22	0.15	0.06	0	0	0	0	0	0.05	0.16	0.26	1.21
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	4.73	4.28	4.73	4.79	4.86	4.54	4.86	4.86	4.54	4.86	4.42	4.73	56.2
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	3.49	3.16	3.49	3.65	3.65	3.33	3.65	3.65	3.33	3.65	3.17	3.49	41.71
Total	10.59	9.86	11.29	13.12	16	16.37	19.68	18.87	15.96	13.91	10.45	10.57	166.67

Gas Consumption	units: Btu x000,000												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Heat	30	19.01	8.86	4.53	0.2	0	0	0	0	2.09	8.29	21.95	94.93
Total	30	19.01	8.86	4.53	0.2	0	0	0	0	2.09	8.29	21.95	94.93

APPENDIX B

EPLUS MODEL INPUTS AND BUILDING LOAD DATA

This appendix provides the hourly load schedules used in the EPlus models for the R1 residential and R6 residential buildings. This appendix also provides the R1 residential, R6 residential and office building load data for the Atlanta area produced by the EPlus models. Shown in Figures 44 to 60 are the weekday and weekend hourly load profiles for the occupancy, lighting, cooking, refrigeration and miscellaneous equipment loads. These load schedules were used in the R1 and R6 building EPlus energy models.

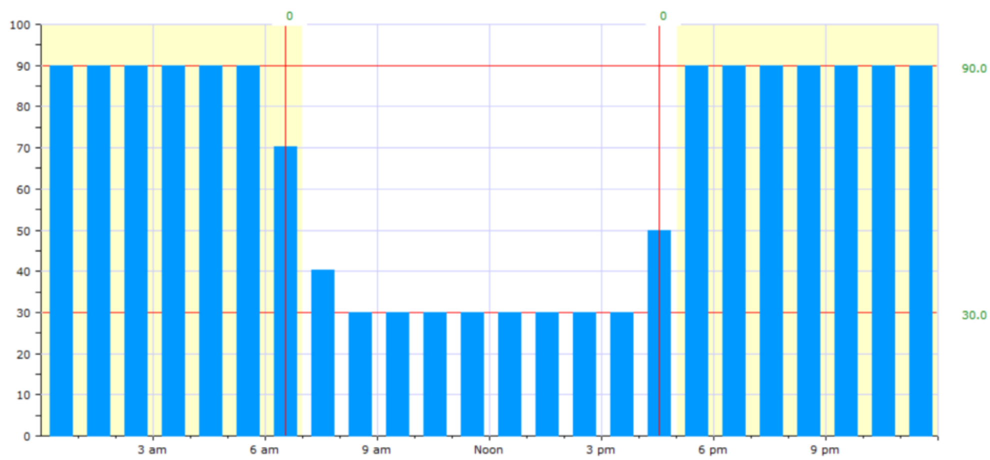


Figure 51: Hourly Occupancy Profile for Monday to Friday

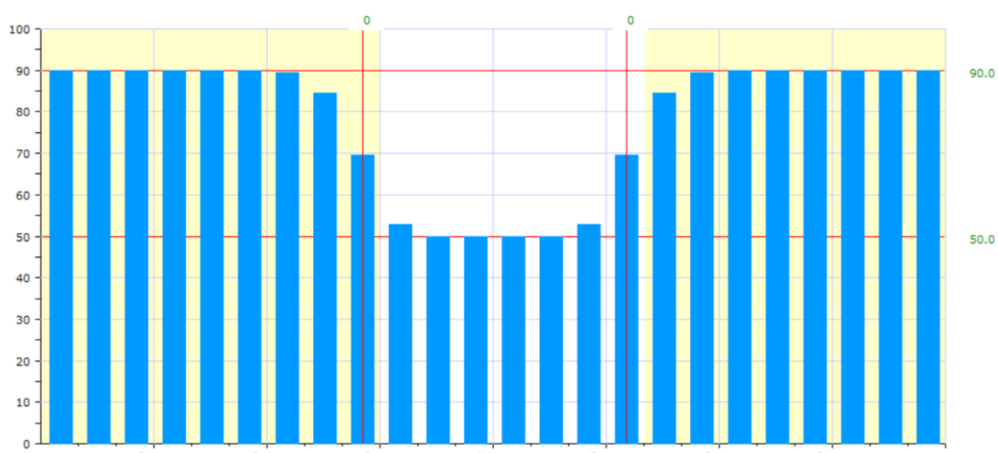


Figure 52: Hourly Occupancy Profile for Saturday and Sunday

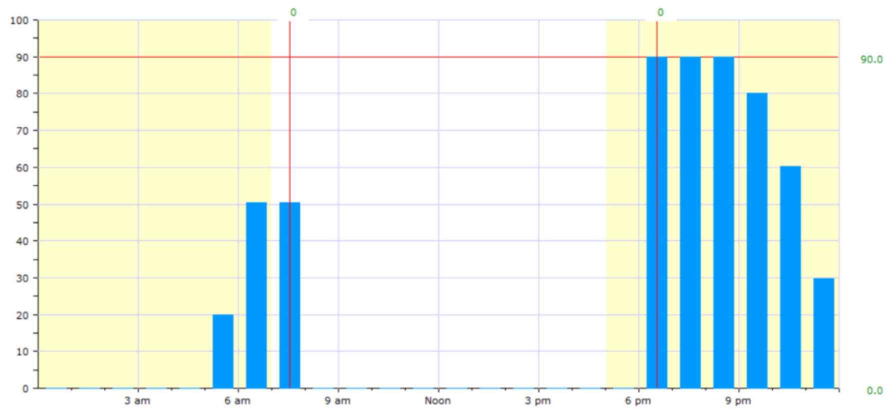


Figure 53: Hourly Lighting Profile for Monday to Friday

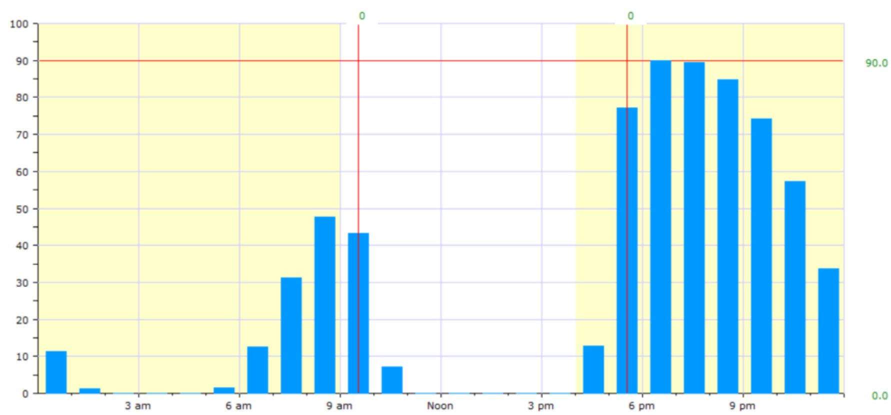


Figure 54: Hourly Lighting Profile for Saturday and Sunday

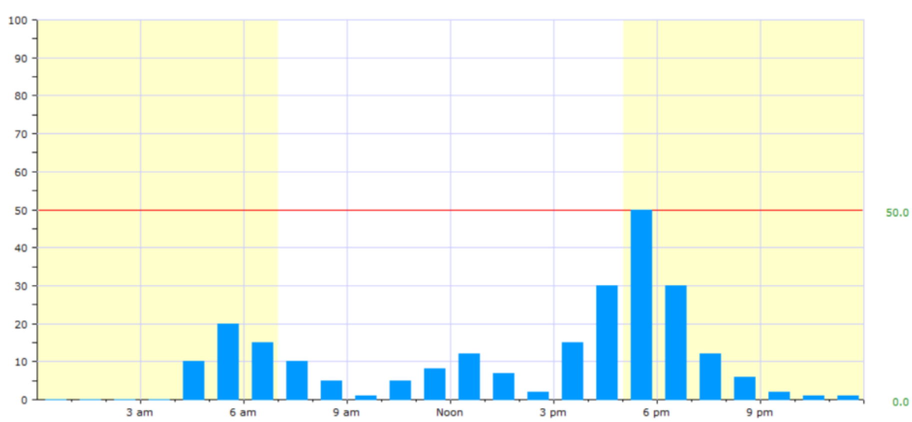


Figure 55: Hourly Cooking Profile for Monday to Friday

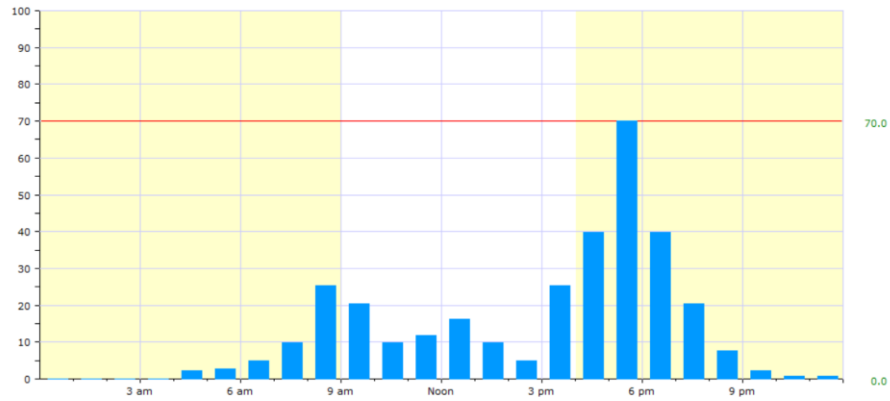


Figure 56: Hourly Cooking Profile for Saturday and Sunday

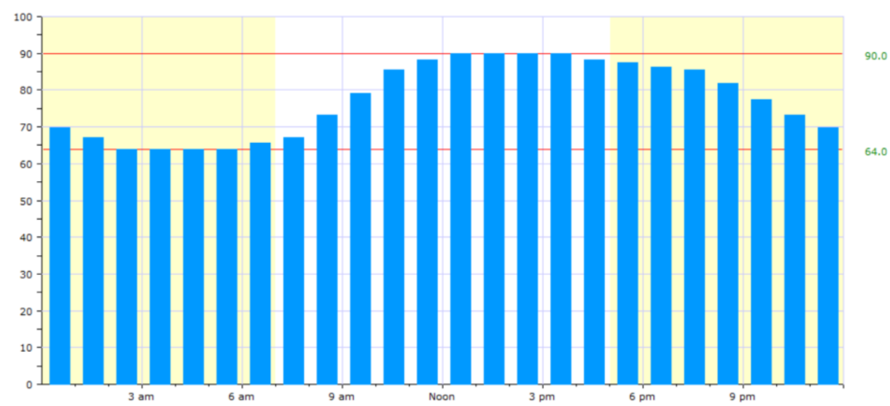


Figure 57: Hourly Refrigeration Profile for Monday to Friday

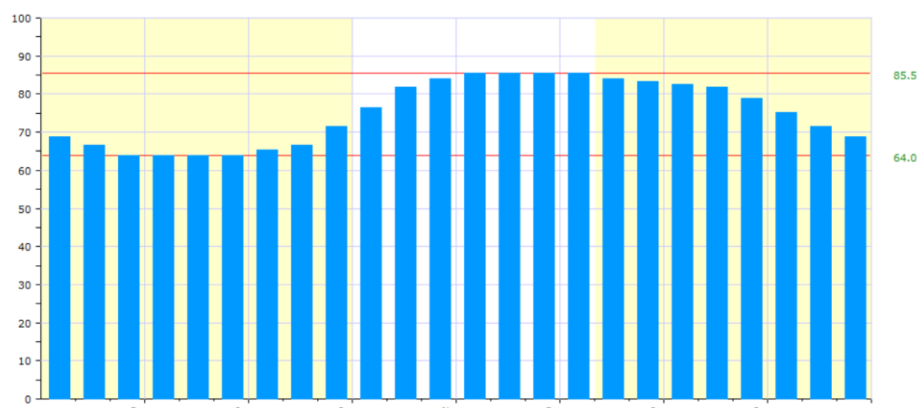


Figure 58: Hourly Refrigeration Profile for Saturday and Sunday

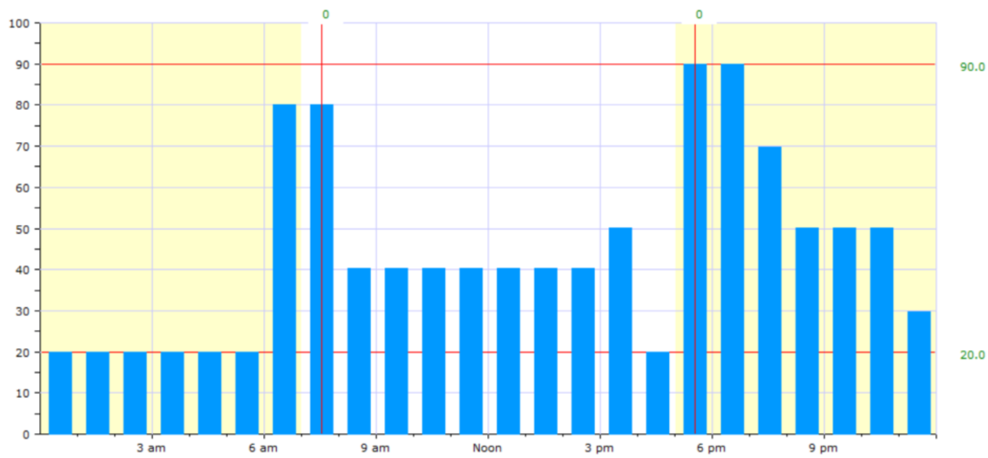


Figure 59: Hourly Miscellaneous Equipment Profile for Monday to Friday

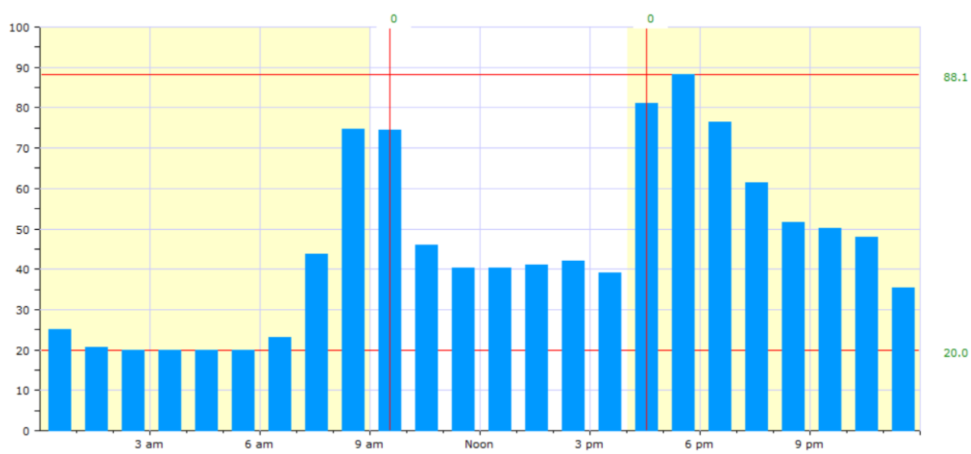


Figure 60: Hourly Miscellaneous Equipment Profile for Saturday and Sunday

The EPlus energy models provided load data for the R1 residential building, the R6 residential building and the office building located in the Atlanta area. Table 79, 80 and 81 present the R1 residential, R6 residential and office building consumption by end use data obtained from the EPlus simulations. All data obtained from EPlus was in units of kWh, so no conversions were necessary.

Table 79: R1 Monthly Energy Consumption by End Use from EPlus Model

Electric Consumption	units: kWh												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	54	125	358	669	1021	1306	1468	1390	1071	666	234	64	8427
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Humidifier	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	-	-	-	-	-	-	-	-	-	-	-	-	-
Heat Recovery	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	345	312	345	334	345	334	345	345	334	345	334	345	4067
Vent. Fans	12	7	8	14	22	27	30	29	22	14	5	6	197
Pumps & Aux.	-	-	-	-	-	-	-	-	-	-	-	-	-
Ext. Equipment	-	-	-	-	-	-	-	-	-	-	-	-	-
Interior Equip.	1251	1160	1316	1284	1284	1275	1293	1316	1242	1288	1205	1293	15206
Exterior Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Interior Lights	396	368	416	410	406	404	412	416	394	409	381	412	4825
Total	2059	1972	2443	2711	3078	3346	3549	3497	3064	2723	2160	2121	32723

Gas Consumption	units: kWh												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Heat	992	444	14	2	0	0	0	0	0	0	35	473	1961
Total	992	444	14	2	0	0	0	0	0	0	35	473	1961

Table 80: R6 Monthly Energy Consumption by End Use from EPlus Model

Electric Consumption	units: kWh												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	172	408	1265	2933	5196	6840	8199	7731	6126	3062	822	185	42940
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Humidifier	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	-	-	-	-	-	-	-	-	-	-	-	-	-
Heat Recovery	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	5086	4594	5086	4922	5086	4922	5086	5086	4922	5086	4922	5086	59888
Vent. Fans	375	371	411	397	411	397	411	411	397	411	397	411	4798
Pumps & Aux.	-	-	-	-	-	-	-	-	-	-	-	-	-
Ext. Equipment	-	-	-	-	-	-	-	-	-	-	-	-	-
Interior Equip.	20652	18645	20587	20070	20587	19940	20717	20587	20005	20652	19940	20717	243101
Exterior Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Interior Lights	6261	5653	6246	6078	6246	6048	6276	6246	6063	6261	6048	6276	73700
Total	32546	29671	33595	34401	37526	38148	40689	40061	37514	35472	32130	32675	424427

Gas Consumption	units: kWh												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Heat	3923	3275	230	82	0	0	0	0	0	17	392	3100	11019
Total	3923	3275	230	82	0	0	0	0	0	17	392	3100	11019

Table 81: Office Building Monthly Energy Consumption by End Use from EPlus Model

Electric Consumption	units: kWh												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	1438	1689	2977	4226	5951	7456	8087	8044	6265	4107	2290	1448	53976
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Humidifier	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	-	-	-	-	-	-	-	-	-	-	-	-	-
Heat Recovery	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	405	366	405	392	405	392	405	405	392	405	392	405	4769
Vent. Fans	87	70	75	96	128	153	161	161	129	92	64	72	1288
Pumps & Aux.	-	-	-	-	-	-	-	-	-	-	-	-	-
Ext. Equipment	-	-	-	-	-	-	-	-	-	-	-	-	-
Interior Equip.	4849	4383	5079	4655	4964	4886	4733	5079	4770	4849	4770	4733	57751
Exterior Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Interior Lights	3096	2801	3377	2951	3237	3232	2956	3377	3092	3096	3092	2956	37263
Total	9875	9309	11913	12321	14685	16118	16342	17066	14648	12549	10608	9614	155046

Gas Consumption	units: kWh												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Heat	6012	3435	744	251	0	0	0	0	0	38	1274	4339	16094
Total	6012	3435	744	251	0	0	0	0	0	38	1274	4339	16094

The data in Tables 79, 80 and 81 was grouped into electrical and thermal energy needed by month, and system inefficiencies were applied to these loads to determine the necessary electrical and thermal outputs of the microturbine. The calculations of the desired electrical and thermal energy microturbine outputs needed by month are shown in Table 82 for the R1 residential building, shown in Table 83 for the R6 residential building, and shown in Table 84 for the office building.

Table 82: Electrical and Thermal Energy Loads with Inefficiencies for R1 Residential Building - EPlus Model

January	units: kWh			
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	54.41	345.42	992.28	1392.11
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	107.48	511.73	1470.04	2089.25
Parasitic Load	-	-	-	720.00
Total	107.48	511.73	1470.04	2809.25

January	units: kWh	
	Electricity	Total
End Output Needed	1658.91	1658.91
Composite Inefficiencies	-	-
MT Output	1658.91	1658.91
Parasitic Load	-	1440.00
Total	1658.91	3098.91

February	units: kWh			
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	124.85	311.99	444.28	881.12
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	246.62	462.21	658.19	1367.02
Parasitic Load	-	-	-	720.00
Total	246.62	462.21	658.19	2087.02

February	units: kWh	
	Electricity	Total
End Output Needed	1535.44	1535.44
Composite Inefficiencies	-	-
MT Output	1535.44	1535.44
Parasitic Load	-	1440.00
Total	1535.44	2975.44

March	units: kWh			
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	357.54	345.42	14.31	717.27
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	706.25	511.73	21.20	1239.19
Parasitic Load	-	-	-	720.00
Total	706.25	511.73	21.20	1959.19

March	units: kWh	
	Electricity	Total
End Output Needed	1740.25	1740.25
Composite Inefficiencies	-	-
MT Output	1740.25	1740.25
Parasitic Load	-	1440.00
Total	1740.25	3180.25

Table 82 Continued:

April		units: kWh		
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	668.70	334.28	1.82	1004.80
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	1320.89	495.23	2.70	1818.81
Parasitic Load	-	-	-	720.00
Total	1320.89	495.23	2.70	2538.81

April	units: kWh	
	Electricity	Total
End Output Needed	1708.13	1708.13
Composite Inefficiencies	-	-
MT Output	1708.13	1708.13
Parasitic Load	-	1440.00
Total	1708.13	3148.13

May		units: kWh		
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	1021.48	345.42	0.00	1366.90
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	2017.74	511.73	0.00	2529.47
Parasitic Load	-	-	-	720.00
Total	2017.74	511.73	0.00	3249.47

May	units: kWh	
	Electricity	Total
End Output Needed	1711.54	1711.54
Composite Inefficiencies	-	-
MT Output	1711.54	1711.54
Parasitic Load	-	1440.00
Total	1711.54	3151.54

June		units: kWh		
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	1306.38	334.28	0.00	1640.66
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	2580.50	495.23	0.00	3075.73
Parasitic Load	-	-	-	720.00
Total	2580.50	495.23	0.00	3795.73

June	units: kWh	
	Electricity	Total
End Output Needed	1705.64	1705.64
Composite Inefficiencies	-	-
MT Output	1705.64	1705.64
Parasitic Load	-	1440.00
Total	1705.64	3145.64

July		units: kWh		
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	1468.47	345.42	0.00	1813.89
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	2900.68	511.73	0.00	3412.41
Parasitic Load	-	-	-	720.00
Total	2900.68	511.73	0.00	4132.41

July	units: kWh	
	Electricity	Total
End Output Needed	1735.12	1735.12
Composite Inefficiencies	-	-
MT Output	1735.12	1735.12
Parasitic Load	-	1440.00
Total	1735.12	3175.12

August		units: kWh		
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	1390.27	345.42	0.00	1735.69
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	2746.21	511.73	0.00	3257.95
Parasitic Load	-	-	-	720.00
Total	2746.21	511.73	0.00	3977.95

August	units: kWh	
	Electricity	Total
End Output Needed	1761.09	1761.09
Composite Inefficiencies	-	-
MT Output	1761.09	1761.09
Parasitic Load	-	1440.00
Total	1761.09	3201.09

Table 82 Continued:

September		units: kWh		
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	1071.24	334.28	0.00	1405.52
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	2116.03	495.23	0.00	2611.26
Parasitic Load	-	-	-	720.00
Total	2116.03	495.23	0.00	3331.26

September	units: kWh	
	Electricity	Total
End Output Needed	1658.39	1658.39
Composite Inefficiencies	-	-
MT Output	1658.39	1658.39
Parasitic Load	-	1440.00
Total	1658.39	3098.39

October		units: kWh		
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	665.65	345.42	0.00	1011.07
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	1314.86	511.73	0.00	1826.60
Parasitic Load	-	-	-	720.00
Total	1314.86	511.73	0.00	2546.60

October	units: kWh	
	Electricity	Total
End Output Needed	1711.85	1711.85
Composite Inefficiencies	-	-
MT Output	1711.85	1711.85
Parasitic Load	-	1440.00
Total	1711.85	3151.85

November		units: kWh		
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	234.28	334.28	35.38	603.94
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	462.78	495.23	52.41	1010.42
Parasitic Load	-	-	-	720.00
Total	462.78	495.23	52.41	1730.42

November	units: kWh	
	Electricity	Total
End Output Needed	1591.24	1591.24
Composite Inefficiencies	-	-
MT Output	1591.24	1591.24
Parasitic Load	-	1440.00
Total	1591.24	3031.24

December		units: kWh		
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	64.01	345.42	472.94	882.37
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	126.44	511.73	700.65	1338.82
Parasitic Load	-	-	-	720.00
Total	126.44	511.73	700.65	2058.82

December	units: kWh	
	Electricity	Total
End Output Needed	1711.36	1711.36
Composite Inefficiencies	-	-
MT Output	1711.36	1711.36
Parasitic Load	-	1440.00
Total	1711.36	3151.36

Table 83: Electrical and Thermal Energy Loads with Inefficiencies for R6 Residential Building - EPlus Model

January		units: kWh		
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	172.20	5086.39	3923.05	9181.64
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	340.15	7535.39	5811.93	13687.47
Parasitic Load	-	-	-	720.00
Total	340.15	7535.39	5811.93	14407.47

January	units: kWh	
	Electricity	Total
End Output Needed	27287.54	27287.54
Composite Inefficiencies	-	-
MT Output	27287.54	27287.54
Parasitic Load	-	1440.00
Total	27287.54	28727.54

February		units: kWh		
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	408.00	4594.16	3275.04	8277.20
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	805.93	6806.16	4851.91	12464.00
Parasitic Load	-	-	-	720.00
Total	805.93	6806.16	4851.91	13184.00

February	units: kWh	
	Electricity	Total
End Output Needed	24668.96	24668.96
Composite Inefficiencies	-	-
MT Output	24668.96	24668.96
Parasitic Load	-	1440.00
Total	24668.96	26108.96

March		units: kWh		
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	1264.94	5086.39	230.28	6581.61
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	2498.65	7535.39	341.16	10375.20
Parasitic Load	-	-	-	720.00
Total	2498.65	7535.39	341.16	11095.20

March	units: kWh	
	Electricity	Total
End Output Needed	27243.62	27243.62
Composite Inefficiencies	-	-
MT Output	27243.62	27243.62
Parasitic Load	-	1440.00
Total	27243.62	28683.62

April		units: kWh		
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	2933.23	4922.31	81.91	7937.45
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	5794.03	7292.31	121.35	13207.69
Parasitic Load	-	-	-	720.00
Total	5794.03	7292.31	121.35	13927.69

April	units: kWh	
	Electricity	Total
End Output Needed	26545.13	26545.13
Composite Inefficiencies	-	-
MT Output	26545.13	26545.13
Parasitic Load	-	1440.00
Total	26545.13	27985.13

Table 83 Continued:

May	units: kWh			
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	5196.01	5086.39	0.00	10282.40
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	10263.72	7535.39	0.00	17799.12
Parasitic Load	-	-	-	720.00
Total	10263.72	7535.39	0.00	18519.12

May	units: kWh	
	Electricity	Total
End Output Needed	27243.62	27243.62
Composite Inefficiencies	-	-
MT Output	27243.62	27243.62
Parasitic Load	-	1440.00
Total	27243.62	28683.62

June	units: kWh			
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	6839.97	4922.31	0.00	11762.28
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	13511.05	7292.31	0.00	20803.36
Parasitic Load	-	-	-	720.00
Total	13511.05	7292.31	0.00	21523.36

June	units: kWh	
	Electricity	Total
End Output Needed	26385.41	26385.41
Composite Inefficiencies	-	-
MT Output	26385.41	26385.41
Parasitic Load	-	1440.00
Total	26385.41	27825.41

July	units: kWh			
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	8198.86	5086.39	0.00	13285.25
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	16195.28	7535.39	0.00	23730.67
Parasitic Load	-	-	-	720.00
Total	16195.28	7535.39	0.00	24450.67

July	units: kWh	
	Electricity	Total
End Output Needed	27403.35	27403.35
Composite Inefficiencies	-	-
MT Output	27403.35	27403.35
Parasitic Load	-	1440.00
Total	27403.35	28843.35

August	units: kWh			
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	7731.15	5086.39	0.00	12817.54
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	15271.41	7535.39	0.00	22806.80
Parasitic Load	-	-	-	720.00
Total	15271.41	7535.39	0.00	23526.80

August	units: kWh	
	Electricity	Total
End Output Needed	27243.62	27243.62
Composite Inefficiencies	-	-
MT Output	27243.62	27243.62
Parasitic Load	-	1440.00
Total	27243.62	28683.62

September	units: kWh			
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	6126.46	4922.31	0.00	11048.77
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	12101.65	7292.31	0.00	19393.96
Parasitic Load	-	-	-	720.00
Total	12101.65	7292.31	0.00	20113.96

September	units: kWh	
	Electricity	Total
End Output Needed	26465.26	26465.26
Composite Inefficiencies	-	-
MT Output	26465.26	26465.26
Parasitic Load	-	1440.00
Total	26465.26	27905.26

Table 83 Continued:

October		units: kWh		
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	3062.01	5086.39	17.30	8165.70
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	6048.41	7535.39	25.63	13609.44
Parasitic Load	-	-	-	720.00
Total	6048.41	7535.39	25.63	14329.44

October	units: kWh	
	Electricity	Total
End Output Needed	27323.48	27323.48
Composite Inefficiencies	-	-
MT Output	27323.48	27323.48
Parasitic Load	-	1440.00
Total	27323.48	28763.48

November		units: kWh		
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	822.00	4922.31	391.50	6135.81
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	1623.70	7292.31	580.00	9496.01
Parasitic Load	-	-	-	720.00
Total	1623.70	7292.31	580.00	10216.01

November	units: kWh	
	Electricity	Total
End Output Needed	26385.41	26385.41
Composite Inefficiencies	-	-
MT Output	26385.41	26385.41
Parasitic Load	-	1440.00
Total	26385.41	27825.41

December		units: kWh		
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	185.14	5086.39	3099.84	8371.37
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	365.71	7535.39	4592.36	12493.46
Parasitic Load	-	-	-	720.00
Total	365.71	7535.39	4592.36	13213.46

December	units: kWh	
	Electricity	Total
End Output Needed	27403.35	27403.35
Composite Inefficiencies	-	-
MT Output	27403.35	27403.35
Parasitic Load	-	1440.00
Total	27403.35	28843.35

Table 84: Electrical and Thermal Energy Loads with Inefficiencies for Office Building - EPlus Model

January		units: kWh		
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	1438.08	405.01	6011.96	7855.05
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	2840.65	600.01	8906.61	12347.27
Parasitic Load	-	-	-	720.00
Total	2840.65	600.01	8906.61	13067.27

January	units: kWh	
	Electricity	Total
End Output Needed	8031.96	8031.96
Composite Inefficiencies	-	-
MT Output	8031.96	8031.96
Parasitic Load	-	1440.00
Total	8031.96	9471.96

Table 84 Continued:

February		units: kWh		
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	1688.64	365.82	3434.90	5489.36
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	3335.59	541.96	5088.74	8966.28
Parasitic Load	-	-	-	720.00
Total	3335.59	541.96	5088.74	9686.28

February	units: kWh	
	Electricity	Total
End Output Needed	7254.60	7254.60
Composite Inefficiencies	-	-
MT Output	7254.60	7254.60
Parasitic Load	-	1440.00
Total	7254.60	8694.60

March		units: kWh		
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	2976.86	405.01	743.96	4125.83
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	5880.22	600.01	1102.16	7582.40
Parasitic Load	-	-	-	720.00
Total	5880.22	600.01	1102.16	8302.40

March	units: kWh	
	Electricity	Total
End Output Needed	8531.44	8531.44
Composite Inefficiencies	-	-
MT Output	8531.44	8531.44
Parasitic Load	-	1440.00
Total	8531.44	9971.44

April		units: kWh		
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	4226.49	391.95	251.27	4869.71
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	8348.62	580.67	372.25	9301.54
Parasitic Load	-	-	-	720.00
Total	8348.62	580.67	372.25	10021.54

April	units: kWh	
	Electricity	Total
End Output Needed	7702.54	7702.54
Composite Inefficiencies	-	-
MT Output	7702.54	7702.54
Parasitic Load	-	1440.00
Total	7702.54	9142.54

May		units: kWh		
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	5951.49	405.01	0.00	6356.50
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	11756.03	600.01	0.00	12356.04
Parasitic Load	-	-	-	720.00
Total	11756.03	600.01	0.00	13076.04

May	units: kWh	
	Electricity	Total
End Output Needed	8328.22	8328.22
Composite Inefficiencies	-	-
MT Output	8328.22	8328.22
Parasitic Load	-	1440.00
Total	8328.22	9768.22

June		units: kWh		
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	7455.78	391.95	0.00	7847.73
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	14727.47	580.67	0.00	15308.13
Parasitic Load	-	-	-	720.00
Total	14727.47	580.67	0.00	16028.13

June	units: kWh	
	Electricity	Total
End Output Needed	8270.05	8270.05
Composite Inefficiencies	-	-
MT Output	8270.05	8270.05
Parasitic Load	-	1440.00
Total	8270.05	9710.05

Table 84 Continued:

July		units: kWh		
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	8086.57	405.01	0.00	8491.58
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	15973.47	600.01	0.00	16573.49
Parasitic Load	-	-	-	720.00
Total	15973.47	600.01	0.00	17293.49

July	units: kWh	
	Electricity	Total
End Output Needed	7850.45	7850.45
Composite Inefficiencies	-	-
MT Output	7850.45	7850.45
Parasitic Load	-	1440.00
Total	7850.45	9290.45

August		units: kWh		
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	8043.76	405.01	0.00	8448.77
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	15888.91	600.01	0.00	16488.92
Parasitic Load	-	-	-	720.00
Total	15888.91	600.01	0.00	17208.92

August	units: kWh	
	Electricity	Total
End Output Needed	8617.43	8617.43
Composite Inefficiencies	-	-
MT Output	8617.43	8617.43
Parasitic Load	-	1440.00
Total	8617.43	10057.43

September		units: kWh		
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	6264.83	391.95	0.00	6656.78
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	12374.97	580.67	0.00	12955.64
Parasitic Load	-	-	-	720.00
Total	12374.97	580.67	0.00	13675.64

September	units: kWh	
	Electricity	Total
End Output Needed	7990.82	7990.82
Composite Inefficiencies	-	-
MT Output	7990.82	7990.82
Parasitic Load	-	1440.00
Total	7990.82	9430.82

October		units: kWh		
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	4106.86	405.01	37.92	4549.79
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	8112.32	600.01	56.18	8768.51
Parasitic Load	-	-	-	720.00
Total	8112.32	600.01	56.18	9488.51

October	units: kWh	
	Electricity	Total
End Output Needed	8036.63	8036.63
Composite Inefficiencies	-	-
MT Output	8036.63	8036.63
Parasitic Load	-	1440.00
Total	8036.63	9476.63

Table 84 Continued:

November		units: kWh		
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	2289.55	391.95	1274.37	3955.87
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	4522.57	580.67	1887.96	6991.19
Parasitic Load	-	-	-	720.00
Total	4522.57	580.67	1887.96	7711.19

November	units: kWh	
	Electricity	Total
End Output Needed	7926.02	7926.02
Composite Inefficiencies	-	-
MT Output	7926.02	7926.02
Parasitic Load	-	1440.00
Total	7926.02	9366.02

December		units: kWh		
	Space Cool	Hot Water	Space Heat	Total
End Output Needed	1447.56	405.01	4339.32	6191.89
Composite Inefficiencies	0.51	0.68	0.68	-
MT Output	2859.38	600.01	6428.62	9888.01
Parasitic Load	-	-	-	720.00
Total	2859.38	600.01	6428.62	10608.01

December	units: kWh	
	Electricity	Total
End Output Needed	7761.15	7761.15
Composite Inefficiencies	-	-
MT Output	7761.15	7761.15
Parasitic Load	-	1440.00
Total	7761.15	9201.15

Table 85: R1 Monthly Energy Consumption by End Use from EPlus Model - Thermostat Setting Sensitivity

Electric Consumption	units: kWh												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	93	175	424	748	1116	1406	1576	1495	1166	745	294	112	9350
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Humidifier	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	-	-	-	-	-	-	-	-	-	-	-	-	-
Heat Recovery	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	345	312	345	334	345	334	345	345	334	345	334	345	4067
Vent. Fans	17	12	11	18	26	32	35	34	27	18	9	11	250
Pumps & Aux.	-	-	-	-	-	-	-	-	-	-	-	-	-
Ext. Equipment	-	-	-	-	-	-	-	-	-	-	-	-	-
Interior Equip.	1251	1160	1316	1284	1284	1275	1293	1316	1242	1288	1205	1293	15206
Exterior Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Interior Lights	396	368	416	410	406	404	412	416	394	409	381	412	4825
Total	2103	2027	2513	2794	3177	3451	3662	3607	3163	2806	2223	2174	33699

Gas Consumption	units: kWh												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Heat	1338	695	56	26	0	0	0	0	0	0	148	792	3055
Total	1338	695	56	26	0	0	0	0	0	0	148	792	3055

Table 86: R6 Monthly Energy Consumption by End Use from EPlus Model - Thermostat Setting Sensitivity

Electric Consumption	units: kWh												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	361	669	1684	3471	5851	7553	9022	8528	6843	3629	1186	412	49209
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Humidifier	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	-	-	-	-	-	-	-	-	-	-	-	-	-
Heat Recovery	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	5086	4594	5086	4922	5086	4922	5086	5086	4922	5086	4922	5086	59888
Vent. Fans	427	422	467	452	467	452	467	467	452	467	452	467	5459
Pumps & Aux.	-	-	-	-	-	-	-	-	-	-	-	-	-
Ext. Equipment	-	-	-	-	-	-	-	-	-	-	-	-	-
Interior Equip.	20652	18645	20587	20070	20587	19940	20717	20587	20005	20652	19940	20717	243101
Exterior Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Interior Lights	6261	5653	6246	6078	6246	6048	6276	6246	6063	6261	6048	6276	73700
Total	32787	29983	34070	34993	38237	38915	41568	40914	38285	36095	32548	32958	431357

Gas Consumption	units: kWh												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Heat	6256	5079	962	384	25	0	0	0	0	241	1345	5263	19555
Total	6256	5079	962	384	25	0	0	0	0	241	1345	5263	19555

Table 87: Office Building Monthly Energy Consumption by End Use from EPlus Model - Thermostat Setting Sensitivity

Electric Consumption	units: kWh												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	1837	2067	3386	4639	6410	7965	8652	8598	6742	4527	2685	1836	59344
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Humidifier	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	-	-	-	-	-	-	-	-	-	-	-	-	-
Heat Recovery	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	405	366	405	392	405	392	405	405	392	405	392	405	4769
Vent. Fans	128	104	101	115	146	173	183	183	147	111	93	110	1594
Pumps & Aux.	-	-	-	-	-	-	-	-	-	-	-	-	-
Ext. Equipment	-	-	-	-	-	-	-	-	-	-	-	-	-
Interior Equip.	4849	4383	5079	4655	4964	4886	4733	5079	4770	4849	4770	4733	57751
Exterior Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Interior Lights	3096	2801	3377	2951	3237	3232	2956	3377	3092	3096	3092	2956	37263
Total	10315	9721	12348	12752	15162	16647	16930	17642	15143	12988	11032	10041	160720

Gas Consumption	units: kWh												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Heat	8825	5601	1966	646	31	0	0	0	0	430	2950	7050	27499
Total	8825	5601	1966	646	31	0	0	0	0	430	2950	7050	27499

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