The Pennsylvania State University

The Graduate School

College of Engineering

OPTIMIZATION OF BUILDING COOLING HEATING AND POWER

A Thesis in

Architectural Engineering

by

Bo Lin

Submitted in Partial Fulfillment
of the Requirements
for the Degree of

Master of Science

May 2012

The thesis of Bo Lin was reviewed and approved* by the following:

James D.Freihaut
Associate Professor of Architectural Engineering
Thesis Advisor

William P.Bahnfleth
Professor of Architectural Engineering

Steve Treado
Associate Professor of Architectural Engineering

Chimay J. Anumba
Professor of Architectural Engineering
Head of the Department of Architectural Engineering

*Signatures are on file in the Graduate School

ABSTRACT

In 2008, buildings consumed 40% of primary energy in US; and residential buildings consumed 22% of this primary energy consumption. Building cooling heating and power (BCHP) is considered a promising and affordable technology to reduce primary energy consumption, fuel costs and greenhouse gases emissions. The BCHP system simultaneously produces electricity and heat to achieve the high system fuel utilization efficiency. The wider implementation of BCHP system can further increase the reliability of the grid power system, fuel diversity and national security.

In this research, a comprehensive factor evaluation method of BCHP system implementation potential is presented. From the analysis, the top seven states are identified as most suitable to utilize technology. The realization of BCHP benefits depends on the system selection, integration and operation. The research further examined the effect of different types and number of primer movers, absorption cooling, vapor compression cooling, operational strategies on the performance of system, and, consequently, CHP system adoption. The IC engine and microturbine are the two major groups of prime mover systems. 32 different system combinations are calculated and compared for annual primary energy consumption, fuel cost; greenhouses gas emissions, system fuel utilization efficiency and overall building energy efficiency. From the results, the overall best performance scenario is selected and further optimized. In the operational strategy optimization, linear programming is the algorithm. In this optimization, objective functions and constraints are developed and defined.

The research results show that the implementation of an appropriate BCHP system can effectively reduce primary energy consumption, fuel cost and emission in residential buildings. A CHP related data base and an innovative evaluation method have been formed in the research. The parametric comparison between different system combinations can facilitate the design in the early phase with affordable time calculation. The operational strategy optimization demonstrates a manner to realize the maximum theoretical benefits of BCHP system.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGEMENTS

I would like to give my special gratitude to Dr. James Freihaut for his continuous guidance and countless support which made my study an enjoyable and memorable experience. Thank you for giving me the opportunity to research on this topic. Your encouragement is the power that keeps me moving forward. I would also like to thank Dr. Bahnfleth, Dr. Treado, Dr Srebric and Professor Ling for their helpful instructions which are life-long treasures for me. I am also extremely grateful to visiting scholar Dr. Zhao Chen for his endless help. To my colleagues, friends and family, thank you all for the support and guidance during the study. Finally, special thanks to my mother, you are the one who made me today.

Chapter 1

Introduction

In 2008, US consumed 20% global primary energy consumption and for building sector alone, it was responsible for 8% primary energy in the world (DOE, 2011). In 2009, buildings consumed 41% of total primary energy in the US; it is 149% higher than the consumption in 1980. The residential building sector constitutes 22% of this total primary energy use (21.21 Quadrillion Btu) (EIA, 2010). This includes space heating, water heating, space cooling, lighting, electronics and others. From the figure 1, it is obvious that space cooling and heating are the dominating consumption which takes 72% site energy consumption.

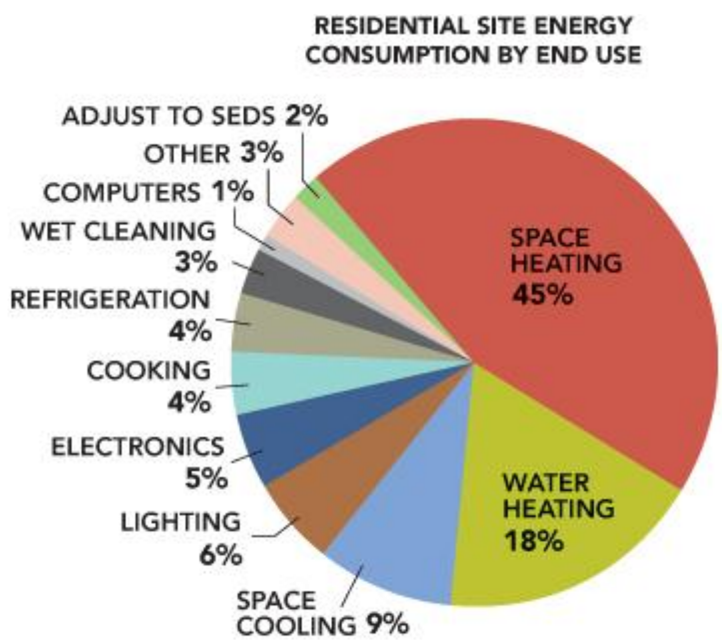


Figure 1—1 . Residential Energy Consumption by End Use (EIA Building Energy Data Book).

The increasing amount of Greenhouse gases in the atmosphere results in the global warming. Greenhouse gases absorbed thermal radiation from the surface of the earth and transferred back to the earth thus increases the temperature. In 2008, the emission is 5.84 billion metric tons of greenhouse gases, buildings takes up 37% tons of total emission (EIA, 2010).

From Figure1- 2, residential building sector emits 1.2 billion metric tons of Carbon Dioxide; almost 70% emission comes from the electricity production (EIA, 2010). This mainly results from the fact that 42% electricity comes from the fossil fuels (EIA, 2010).

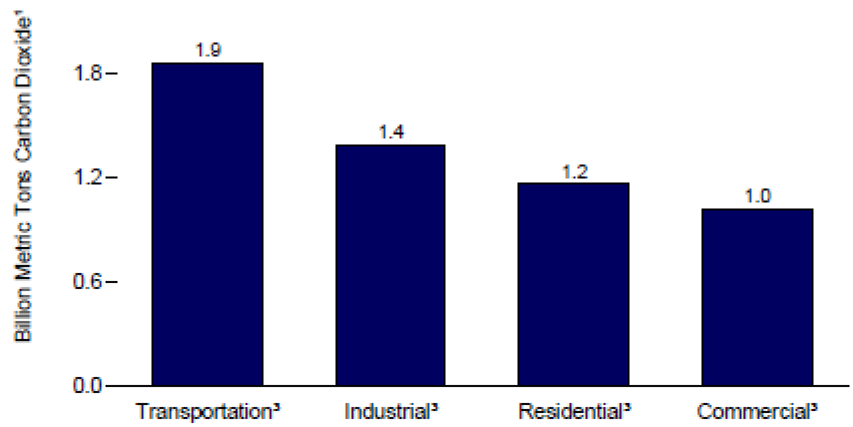


Figure 1—2 Carbon Dioxide Emissions by End Use Sector (Annual Energy Review).

So as to increase the total energy usage efficiency and reliability, reduce greenhouse gases emission, decrease economic cost and provide sustainable energy utilization, combined heat and power (CHP) in buildings is a promising solution. CHP is a sequential generation of electricity or shaft power, heating and cooling energy (ASHRAE, 2008), and it can exist in multiple facilities for instance universities, hospitals, military bases, commercial and residential buildings. According to (Maor, 2009), apartments buildings are the top three potential BCHP applications. In this research, the building type is mainly focus on the multi-residential apartments. CHP mainly contains a prime mover to produce shaft power. Prime movers include fuel cells, internal combustion engine, gas turbine, micro turbine, steam turbine and Stirling engine. Other components in CHP system are generator, heat recovery system, and electrical interconnection.

The typical work flow for CCHP is that the prime mover utilizes the natural gas (NG) to drive the generator for electricity production. The shaft power from the prime mover produces electricity or drives compressors in the vapor compression chiller, pumps and fans. The largest difference between separate power generation (SHP) and CHP is that the thermal energy from the system can be used for space heating, cooling, dehumidification and thermal storage. The recovered heat can produce steam or hot water (HW) for heating. When cooling load occurs, the waste heat can be used in absorption chiller. The utilization of by product heat dramatically increases the efficiency to 80%-90%, thereby decreasing the consumption for primary energy, and operational costs. Given the capital cost and safety consideration, single or double effect Lithium Bromide Absorption Chillers has been widely used. When there is not enough cooling/heating capacity, a supplementary burner or boiler will burn nature gas to provide extra heat. This installation of system can be referred as combined cooling, heat and power (CCHP) or buildings cooling, heating, and power (BCHP) or tri-generation.

In general, the difference between CHP and CCHP is that thermal energy is further used to offer space cooling. In winter when there is no cooling demand, CCHP or BCHP can be referred as CHP. Therefore, CHP is CCHP without the thermally activated equipment such as absorption chiller or adsorption chiller.

There are two basic operational strategy of the system. Follow the electric load (FEL) is to meet the electricity load of the building and the heat is the by-product. Follow the thermal load (FTL) is to satisfy the thermal demand for the building; therefore electricity is the by-product of heat (Anna Kathrine Hueffed, 2010). CHP system has a different capacity for the prime mover. The capacity from 1 kW to 500 MW falls into the range of CCHP (Wu & Wang, 2006). Capacity under 1 MW is small –scale, mini scale is less than 500 kW, “micro” is smaller than 20 kW (The European Association for the Promotion of Cogeneration, 2001)

The implementation of CHP and CCHP system reduces greenhouse gas emissions, because the natural gas is the major fuel source which is considered as the cleanest fossil fuel (NaturalGas.org, 2011b). For other prime movers, emission reducing technologies like lean burn, steam injection, three way catalyst, and selective catalyst have been utilized. By providing the same amount of electricity and thermal needs, CHP system consumes far less on-site energy, as a result, the emission is much less than separate heat and power generation.

CHP or BCHP as a form of distributed generation (DG), it eliminates the loss in transmission and distribution during the delivery of electricity from the grid. Unlike other types of DG-wind, solar and water turbine; CHP system is not limited by the time or the weather of the day so it can provide more reliable and flexible power generation. CHP or BCHP system can further reduce the need for electric grid infrastructure and capital investment from the power plant to improve electricity security. The electricity grid can be malfunction and susceptible to terrorists attack and natural disasters. A distributed, more flexible and integrated CHP system could prevent or at least, reduce the threat ; and provide necessary amount of electricity and cooling/heating energy for recovery. For example, in 2005 after Hurricanes Katrina, Mississippi Baptist Medical Center remained open and received patients from other medical facilities that cannot operate, additionally; this hospital provided emergency housing, lights, and surgeries in the disaster.

For micro-CHP or most BCHP, on site power generation are inherently packaged which takes less space per kilowatt than separate power generation (SHP). For examples, prime movers, electricity generators and heat recovery devices are integrated within one prefabricated case. This modular system takes less space and easier to assemble than on site erection system. Packaged system have been tested in the factory before shipping, and from the perspective of manufacture, packaged system promotes the manufacture of CHP.

The current CHP status in US

According to International Energy Agency (IEA), CHP system consists of 9% power generations in the US (Figure 1-3). When compared to countries in Europe, the share of CHP in electricity production is low. IEA predicts that in the year of 2030, CHP share of total electricity production can be up to 20% (Figure1- 4). Although the benefits of CHP system are obvious, but economic, technical and other barriers are occurred during the promotion of this technology. Capital investment can be high when compared with importing electricity from the grid. For example fuel cells have an impressive high efficiency and low emission rate, but the high initial investment results in long payback period. Standby charges and low buy back rates also contributed to the obstruction. In some regions, simultaneous load for heating or cooling doesn't happen very often, and the heat to power ratio is very unstable in some type of buildings therefore this severely reduces the efficiency of CHP. Social obstacles are also obvious. The owner is not familiar with CHP; as a result, funds for the investment are not enough because of the shortage of confidence. The government shows interests for the promotion of CHP, but some policies are ambiguous and time consuming to get a permit.

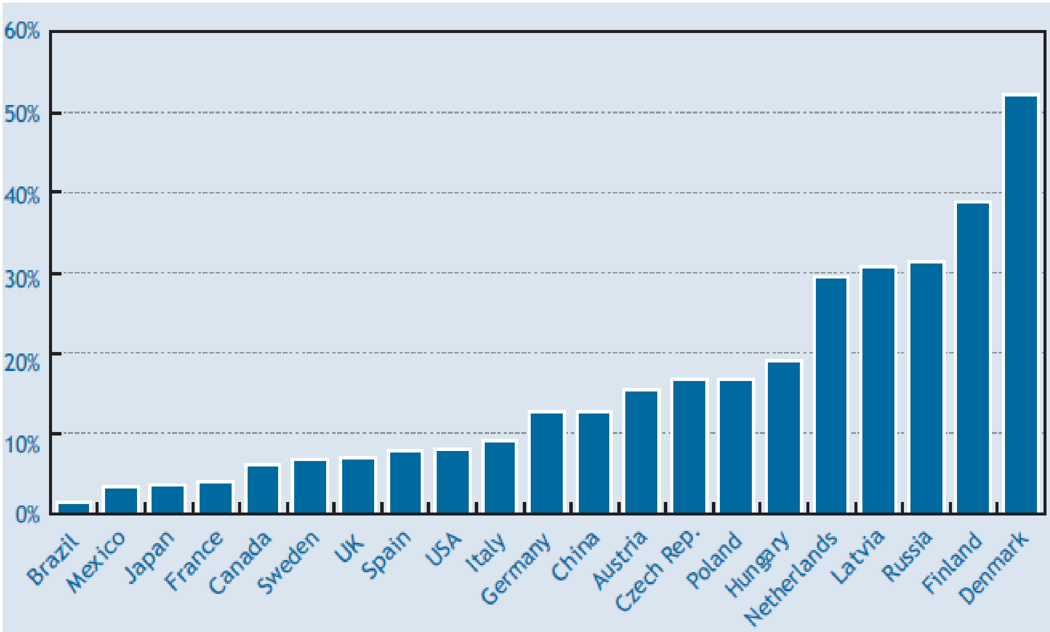


Figure 1—3 CHP as a Share of Total National Power Generation (IEA data and analysis; data merged from years 2001, 2005, 2006.)

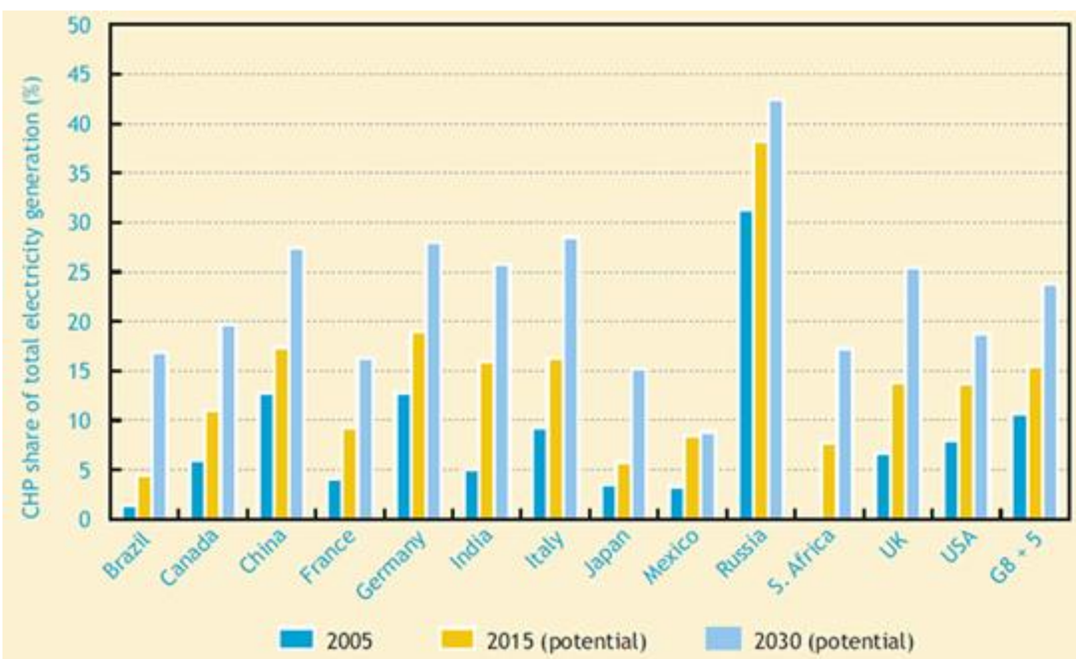


Figure 1—4Major economies' CHP potential under an accelerated CHP scenario (International Energy Agency, 2010)

Chapter 2 **Literature Review**

Technology Status and Evaluation

Prime Movers

CHP system contains several separate components: prime mover, electricity generator, heat recovery device and the connection to the grid. The purpose of prime mover is the conversion from the fuel energy into mechanical shaft power and rejects the heat. The shaft power can be used in the generator to produce electricity or directly drive the chiller. Currently major prime movers are steam turbines, reciprocating internal combustion engines(IC engines), combustion turbines (gas turbine), microturbines (MT), fuel cells, Stirling engines and Rankine cycle engines.

Steam Turbine

Steam turbines are the oldest prime mover technology in power plants and industries (ASHRAE, 2008). Based on different operating and design principles, steam turbines can be classified as follows: single or multi-stage turbine, impulse or reaction turbine, condensing and non-condensing turbine (Petchers, 2002). The condensing turbine is a closed Rankine Cycle. Non-condensing turbine also known as backpressure turbine, it operates at an exhausted pressure at atmospheric pressure or above. The steam can be further used in other process for example space heating. The condensing boiler has higher power generation efficiency than backpressure turbine but the efficiency will change as ambient environment changes (Energy and Environmental Analysis (an ICF International Company), 2008a).

Different from other prime mover technology, steam turbine doesn't directly transfer fuel energy into power generation; instead the electricity is the byproduct of heat production. This is a disadvantage for steam turbines if the demand for electricity is high; because the electrical efficiency of steam turbine is low (Deng, Wang, & Han, 2011). Condensing turbine has a higher electrical efficiency than backpressure turbine, but is more expansive and complex. Typically, due to the nature of steam turbine, the power to heat ratios is around 0.05 to 0.2; and available sizes are from 100 KW to 250 MW (Energy and Environmental Analysis (an ICF International Company), 2008a). The low power to heat ratio and high capacity basically eliminate the application of steam turbine in residential and commercial buildings but very common in power plants and industry applications.

Steam turbines have a very long operating life because of relatively simple design and few moving parts, when appropriately maintained and operated, steam turbines are highly reliable and have a life span more than 50 years (Petchers, 2002). The overhaul intervals can be several years (Energy and Environmental Analysis (an ICF International Company), 2008a), but routine maintenance include inspection for lubricating oil, leakage or erosion are monthly basis.

Reciprocating Engine (IC Engine)

IC engines are the most popular and widely used prime mover (Petchers, 2002). In North America, more than 35 million units of IC engines have been manufactured each year for automobiles, construction equipment and power generation applications (Energy and Environmental Analysis, Inc. an ICF Company, 2008). Spark ignited engine and Diesel engine are the two major types of IC engines. Spark engines work on Otto cycle while Diesel engines pressurize the fuel to a self-ignited temperature. Spark engine is more quiet and lighter than Diesel engine and because of smaller compression ratio, so it has a lower electrical efficiency than Diesel engine. However, highly qualified lean burn engines can approach same efficiency in diesel engines of similar size (Energy and Environmental Analysis, Inc. an ICF Company, 2008).

IC engines have multiple advantages. It is a proven a technology for more than 100 years which is very mature (UTRC, 2006). The engine is suitable for several types of fuels, including natural gas, propane, landfill gas, digested gas, diesel and heavier oils (ASHRAE, 2008). IC engines have electrical production efficiency from 25% to 40% based lower heating value (LHV) (Midwest CHP Application Center & Avalon Consulting,lnc, 2003). Besides of high electricity production efficiency at full load, IC engines have a good performance at part load. When operates at 50 % of full load, the efficiency is 8 to 10 percent less than rated efficiency; while the gas turbine will lose 15 to 25 percent of efficiency at half load (Energy and Environmental Analysis, Inc. an ICF Company, 2008). Due to the highly variability of commercial and residential buildings' load, the good part load performance makes IC engine a very attractive prime mover candidate. Additionally, IC engines are resistible to ambient environment change. Similar to gas turbine, the performance is subject to the change in ambient air temperature and altitude, however; the influence is small; generally the efficiency is reduced by 4% per 1000 feet altitude above 1000 feet and 1% for every 10°F (Energy and Environmental Analysis, Inc. an ICF Company, 2008)

For the IC engine, the waste heat can be recovered from the exhaust gases, jacket coolant, lubrication oil and cooling water. Most of recovered heat is hot water or low pressure (LP) steam because of the temperature of exhaust gases. The hot water and low pressure steam are favorable in commercial and residential buildings because those buildings mainly need hot water or LP steam for space heating and domestic hot water (DHW) (Maor, 2009). Also, the IC engines can start up very fast so they have widely used in peak shaving and emergency service.

Although IC engines are reliable, fast start up, high efficiency, but this technology still has drawbacks. IC engines have a large number of moving parts this result in the high cost of maintenance, noise and vibration. Frequently start the engine accelerates the wear of engine. Standby and emergency service causes heavier erosion (Petchers, 2002). IC engines in CHP application are installed indoors; the high noise emission requires attenuation and isolation for adjacent areas (ASHRAE, 2008). During the combustion of fuel, the emission of greenhouse gases is high. With the improvement of the technology in the last decade, catalyst and lean burn technology significantly reduce the amount of emission. To summarize, based on the heat to power ratio, capacity and operating characteristic, IC engine is an important option for micro-CHP.

Gas Turbine and Microturbine

Gas turbines have a history nearly 100 years and have been widely used in aircraft and marine propulsion. Nowadays, because of its high quality exhaust gases and low emission rate, gas turbines are ideal candidates for CHP applications.

Gas turbine can produce high temperature thermal output that can be utilized to meet different goals, for example space heating or sterilizers in hospitals. The high temperature exhaust gases make gas turbines attractive in industrial or institutional facilities. Generally, the size of gas turbine is from 37 KW to several hundred kilowatts or megawatts (Petchers, 2002). When the capacity of gas turbine is smaller than 1 MW then normally it is not economical as the low electrical efficiency and resultant high cost per kilowatt electricity (Deng et al., 2011). Since this research is mainly focus on multi-residential buildings, so gas turbine is not suitable for the study.

The micro-turbine had been tested in 1997 and been commercialized in the year of 2000 (Energy and Environmental Analysis (an ICF International Company), 2008b). They are the extensions from the gas turbine with the electrical capacity from 25 to 500 KW (UTRC, 2006).

Possible applications include base load power, peak shaving, backup or standby power or stand-alone power (grid independent).

With a very similar but simpler design than gas turbine, microturbine has relatively low electricity efficiency. Most designs featured with a recuperator as an internal heat exchanger (Energy and Environmental Analysis (an ICF International Company), 2008b). The recuperator captures the heat in the exhaust then heats the air going into the combustor. The engine equipped with a recuperator will have higher electrical efficiency but without it, the thermal efficiency will be higher.

Microturbines have several merits. The thermal output is from 400 to 600°F, it is applicable to satisfy thermal needs in buildings for instance LP steam and hot water. Although the turbine has extraordinarily high rotation speed, it has only one moving parts and no lubricating oil (Deng et al., 2011). Therefore it has less vibration during operation and longer service life than IC engine. Additionally, microturbines are very flexible for fuel. For example natural gas, liquefied petroleum gas (LPG), alcohol, propane and kerosene are suitable. And due to the low inlet air temperature and use natural gas as a primary fuel, NOx emission rate is less than 10 part per million(ppm) (Energy and Environmental Analysis (an ICF International Company), 2008b).

The main disadvantages include high initial cost, relatively low electrical efficiency but this maybe enough for residential buildings (UTRC, 2006). When the ambient environment changes, for example temperature and elevation increases, power output will decrease. This character is not favorable when altitude and temperature is high.

When the ambient environment changes, for example temperature and elevation increases, power output will decrease. This character is not favorable when altitude and temperature is high.

Fuel Cells

Different from other traditional prime mover technologies like boilers or internal combustion engines, fuel cells utilize electrochemical reaction to produce direct current which is similar to batteries. This technology has been tested for over 35 years and seemed as the power source for the future (Energy and Environmental Analysis, Inc., an ICF Company, 2008). Currently, four major types of fuel cells are: Proton exchange membranes FC, Solid oxide FC, Molten carbonate FC, Phosphoric acid FC. The basic information of fuel cells is in Table 1-1 (California Energy Commission, 2003)

Table 2-2-1.Summary of Fuel Cell.

FC Type	PAFC	SOFC	MCFC	PEMFC
Commercially Available	Yes	No	Yes	Yes
Size Range	100-200 kW	1 kW-10 MW	250kW-10MW	3-250kW
Fuel	Natural gas, landfill gas, digester gas, propane	Natural gas, hydrogen, landfill gas, fuel oil	Natural gas, hydrogen	Natural gas, hydrogen, propane, diesel
Efficiency	36-42%	45-60%	45-55%	25-40%
Environmental	Nearly zero emissions	Nearly zero emissions	Nearly zero emissions	Nearly zero emissions
Other Features	HW (hot water)	HW (hot water, LP or HP steam)	HW (hot water, LP or HP steam)	HW (80℃ water)
Need reformer	Yes	No	No	Yes
Life	~40,000 hours			
Current Cost	4000/kW	N/A	N/A	~$5000/kW

Benefits of fuel cells are obvious: Since fuel cell use hydrogen and oxygen reaction to produce electricity so the efficiency is higher than other prime movers. And fuel cells basically have no moving parts, maintenance is only required for pumps, the reformer and blowers (UTRC, 2006). Fuel cells are packaged power generators so they are highly modular and noise is close to zero.

However, fuel cells as a high efficient and clean technology face several problems during the promotion. The expensive materials, complex design, unproven durability and low heat rate result in high initial investment, short of support infrastructure (Energy and Environmental Analysis, Inc., an ICF Company, 2008). Additionally, fuel cells change slowly in transient situation but the thermal and electrical demands in buildings vary frequently and fast. To summarize, fuel cells are promising power generation in the future, but currently, are not very economically feasible in residential buildings.

Stirling Engine

Stirling Engine has a history more than 100 years and was widely used before 1910. It is an external combustion engine which facilitates the control of combustion and results in low emission rate (Wu & Wang, 2006), and it is suitable for several fuels like natural gas and gasoline. Stirling engine has little moving parts and thus reduces the vibration during operation and wear on components.

Generally Stirling engine are small in sizes (1-25kW) (California Energy Commission, 2002), this could mean they can integrate in residential and portable devices (Wu & Wang, 2006).

The current cost for Stirling engine is very high, and the electrical efficiency generally is lower than the central power plant. For the application of Stirling engine in commercial or residential buildings, it still needs further research and development.

Table 2-2. Summaries of Prime Movers.

Source:(U.S. EPA Combined Heat and Power Partnership, 2008),(Wu & Wang, 2006)

Prime Mover	Steam Turbine	Spark ignition reciprocating engine	Compression ignition reciprocating engine	Combustion turbines	Microturbines	Fuel cells	Stirling engines
Capacity range	50kW-250 MW	< 5 MW in DG applications	$\leq 4\text{MW}$	500 kW to 250 MW	30 kW to 250 kW	5 kW to 2 MW	1 kW to 1.5 MW
Fuel used	Any	Natural gas, biogas, propane, landfill gas	Natural gas, biogas, propane, landfill gas	Natural gas, biogas, propane, oil	Natural gas, biogas, propane, oil	Hydrogen, natural gas, propane, methanol	Any
Electrical efficiency (%)	15-38%	35-45%	25-43%	22-36%	18-27%	30-63%	12-20%
Power to heat ratio	0.1-0.3	0.8-2.4	0.5-0.7	0.5-2	0.4-0.7	1-2	1.2-1.7
Thermal output	LP-HP steam	Hot water, LP steam	Hot water, LP steam	Heat, hot water, LP-HP steam	Heat, hot water, LP steam	Hot water, LP-HP steam	Hot water
Noise	High	High	High	Moderate	Moderate	Low	Moderate
NOx emissions (Kg/MWh)	Depend on source	0.2-10	10	0.036-0.05	0.015-0.036	0.0025-0.004	0.23
Availability (%)	Near 100%	92-97%	92-97%	90-98%	90-98%	>95%	90-95%
Part load performance	Poor	Good	Good	Poor	Fair	Good	Good
Hours to overhaul	>50,000	25,000-50,000	25,000-50,000	25,000-50,000	20,000-40,000	32,000-64,000	N/A
Initial cost($/ kW_e)	430-1.100	340-1000	800-1600	450-950	2400-3000	5000-6500	1300-2000

Operation Analysis and Optimization of CHP systems

With the development of building industry, the demand for electricity, cooling and heating are increasing. And because of the technology promotion and awareness of clean and high efficiency engines, the CHP system has been widely regarded as an environmental friendly and economically feasible solution. Optimized operation and analysis are important to maximize the efficiency, low emission rate and the quality of power in CHP system.

(Fred, 2009) compared biodiesel fuel with diesel fuel in a turbocharged engine. When the engine uses soy biodiesel fuel, the performance is close to diesel based engine except the higher consumption on the fuel. He also verified the benefits of BCHP system via the simulation of calibrated individual CHP system components in a commercial building. He built up a TRYSNS CHP system model that can be easily adjusted for different types of building and prime mover. His results showed that data center is an desire application because of flatten and high heating load. (Ji, 2005) studied the impact of fuel and dynamic response of prime mover. The efficiency would be reduced if the prime mover utilized propone on a natural gas based machine. The paper further researched on the transient performance of absorption chiller via Matlab simulation. The conclusion is that generally microturbine took 5 minutes to reach steady states while the absorption chiller needs one hour before getting stable.

(A K Hueffed & Mago, 2010) evaluated three different sizes of reciprocating engine in a commercial building. The operation schedules included follow thermal or electrical load (FTL/FEL) and constant load. The research looked into the performance at three locations In general. The research suggested that sometimes it is more advisable to turn off the system when it is beneficial to do so. The application of CHP in building will increase the LEED rating because of the high efficiency and low emission rate of CHP system. This research also looked into the impact of electricity price for the calculation. The average electricity calculation may deviate from the actual price results.

(Ayat E, 2006) looked into the life cycle optimization and integration of CHP system for commercial office buildings. The study model used a hypothetical example to make comparisons between environmental impact and economical expenditure. The research developed an hourly LCA optimization mode, simplified yearly LCA optimization model for long term and short period . The LCA model in the research can predict the life cycle influence for heating, cooling and lighting in the whole system. Also the models developed in the study can facilitate the design and analysis of CHP operation, but the research didn't show whether the results can be implemented in other types of buildings.

Many researchers investigated the follow the thermal load (FTL) and follow the electrical load (FEL) operation strategy.(Jalalzadeh-Azar, 2003) examined a gird parallel electrical load following CCHP system. (Jalalzadeh-Azar, 2004) also appraised a thermal load following CCHP system model with a parametric analysis, emphasizing the influence of subsystem on the waste heat utilization and fuel consumption. For the FEL analysis, hypothetical BCHP systems with parametric hourly simulations were performed. The fuel to electricity conversion efficiency and temperature of exhaust gases were the parameters in the evaluation. It was found that the increase in electricity generation efficiency dramatically reduce the fuel consumption. When considered the thermally activated equipment, double effect absorption chiller could only slightly improve the efficiency of the system. The conclusion is that a sophisticated single-effect absorption chiller is enough for the application of CHP system in the hypothetical office building. Additionally, the study mentioned the improvement of electrical equipment has a great potential to reduce the energy consumption. Additionally, the study mentioned the improvement of electrical equipment has a great potential to reduce the energy consumption. The FTL model was compared with previous FEL mode. It showed that the MT with a recuperator is better than the one without it, but the impact of implement double effect absorption chiller is not obvious which is a similar result from FEL study. However, when the heat to power ratio is small or the electrical generation efficiency increases, the double effect absorption chiller is more advantageous. When compared with two different models, the FTL is superior to FEL because of the high waste heat utilization of waste heat

(Maor, 2009) and (Agami Reddy & Maor, 2009) compared the near-optimal to optimal operation in BCHP with regard to the energy consumption and cost reduction. The optimal operational strategy often leads to the complexity of scheduling and control issues, because the thermal and electrical loads vary frequently in commercial/institutional buildings. The near optimal strategy doesn’t reschedule the on-line equipment, but optimize the control method. This research implemented a matrix for study, and defined equipment modeling equations and objective functions. The study discussed that near optimal operation generally costs more than optimal strategy. It suggested that schools benefits most when integrated with a supervisory control tool. The cost penalty ratio which means the excess cost to the optimal strategy has the largest the value during peak demand days. Operation and maintenance cost were found basically had no influence in the simulation, so they were ignored during the tests. It would be more advisable for researchers to test the results in real CHP facilities.

Linear programming (LP) is one of commonly used optimal energy dispatch algorithm. (Heejin Cho, Luck, Eksioglu, & Chamra, 2009) created a network flow model to accelerate the linear programs. The network flow model can effectively illustrate the energy demand, supply and flow, and constraints in individual components. The research optimized a CCHP system regard to the operational cost, primary energy consumption (PEC), and carbon dioxide emissions (CDE). The data demonstrated that there is no general trend in three optimization models for different locations. Optimizing one model may cause the increase in other two functions. The objective functions and constraints in the paper are suitable to other types of buildings.(H. Cho, Mago, Luck, & Chamra, 2009) further tested the liner programming algorithm. The algorithm provided the signals to the system as a control methodology. They applied the dispatch algorithm to a micro-CHP facility at MSU. The test data showed that the engine turns off from 6 pm to 7 am, the entire thermal electrical load are met by the grid and boiler. This is because during that time the demand for energy is low, so the efficiency of CHP system will be very low. . The research concluded that the linear programming is valid to optimize the system during the period, and the results from the case study verify the environmental and economic potential of CHP system. Their study only focused on one IC engine, the future research can extend the linear programming to multiple or different prime movers.

(Lahdelma & Hakonen, 2003) formulated a long term optimization problems in CHP into linear programming problems. The study forecasted the hourly load and decomposed the planning period into thousands of sub-hour models. Their study can be applied to a power plant, hydropower allocation and heat plant. (Rong & Lahdelma, 2005) furthered their previous research into trigeneration.

(Thorin, Brand, & Weber, 2005) did similar research in optimizing CHP facility by mixed integer linear-programming and Lagrangian relaxation. They tested the results in real steam turbines, gas turbines and boilers. To summarize, the linear programming is a valid algorithm for the optimization of BCHP.

Chapter 3 **Location Selection and Evaluation**

Research Motivation and Method

In the application of BCHP in residential buildings, it involves different aspects factors of market energy prices, environment, governmental policies, building load demand, the public acceptance for example variables could be the price of natural gas, electricity retail price, the weather, household units. For the policy makers or the owner and investors, to some degree, the market and potential of BCHP in each region is not clear. In this research, location selection is evaluated by comprehensively taken different related factors in to account. The evaluation will locate the region that has a synthetically desire combination of climate, energy consumption, electricity and natural gas rate and demographical information. This may also create a general data base for the application of BCHP and could be extended by future research.

In the researches of (ONSITE SYCOM, 2000), (UTRC, 2006) implemented weighting factors to evaluate the performance of system. The limitation of weighting factor is that it may be subjective to personal opinion and limitation of knowledge. So as to avoid that shortcoming, as a different approach and attempt, this research originally utilizes Principal Component Analysis (PCA) to assess the data.

Introduction of Principal Component Analysis (PCA)

In reality, it is challenging to assess problems with many variables or indexes, and there are usually some correlations among variables. So it is better to use fewer variables which contain original information as much as possible to illustrate the problem. This idea is usually called dimensional reduction. In the past literatures (Jonathon, 2009), (Jolliffe, 2002) introduce some matured and sophisticated methods called 'principal component analysis' (PCA) and factor analysis.' Both of them consider the new variables as linear combination of the original variables. These statistical methods can find some latent characteristic in the data which may offer us another distinct view to evaluate the system

PCA can be done by eigenvalue decomposition of a data covariance matrix. It is a mathematically orthogonal linear transformation that converts a set of observations of possibly correlated variables into a set of values of uncorrelated variables. The uncorrelated variables are the principal components. The number of principal components is less than or equal to the number of original variables (dimension reduction). The first principal component has the largest variance which means it has the strongest ability to cover the most of information of original variables. (The detailed PCA procedure is in the appendix A)

The benefits of PCA include: it reduces the number of variables the amount of work but convers the most information of data. It has been widely used as a tool in exploratory data analysis and predictive models. Secondly, the new variables are uncorrelated, this eliminates multiple colinearity, increases the objectivity of evaluation.

As a direct application of dimensional reduction, principal component analysis focus on how many variable we should use to cover the most information (variance) and how to construct uncorrelated variables (orthogonal). But the most important thing is whether we can use our professional knowledge to explain the new variables and the corresponding practical effects. This is an open difficulty and uncertainty which confuse statisticians and engineers for a long time. In this paper, the implementation of PCA is an exploration; it could be further refined by other researches in the future.

Location Selection Parameters

Energy Consumption: This identifies the largest energy usage contributors in the country. The high energy consumption states generally will have higher potential for energy conservation, emission and cost reductions. The energy consumption includes annual electricity (MMBTU) and natural gas (MMBTU) of residential buildings in each state.

Table 3-1. Electricity Consumption (Energy Information Agency EIA, 2011)

State	Electricity Consumption(MMBTU)	State	Electricity Consumption(MMBTU)
Alaska	7,170,648	Mississippi	68,505,804
Alabama	120,632,587	Montana	16,222,111
Arkansas	65,194,760	North Carolina	211,872,896
Arizona	110,507,950	North Dakota	15,040,029
California	296,998,546	Nebraska	34,415,558
Colorado	61,200,103	New Hampshire	15,342,298
Connecticut	44,680,255	New Jersey	103,416,084
DC	7,246,857	New Mexico	2,281,1904
Delaware	16,183,435	Nevada	39,646,319
Florida	418,716,427	New York	174,536,103
Georgia	209,538,783	Ohio	187,462,393
Hawaii	10,202,955	Oklahoma	80,951,226
Iowa	50,953,141	Oregon	64,973,526
Idaho	27,851,800	Pennsylvania	188,775,640
Illinois	166,265,571	Rhode Island	10,687,215
Indiana	120,971,846	South Carolina	112,414,158
Kansas	49,119,674	South Dakota	15,822,616
Kentucky	99682746	Tennessee	15,2689,497
Louisiana	112,460,414	Texas	472,404,695
Massachusetts	71,093,264	Utah	29,935,423
Maryland	99,002,003	Virginia	168,488,004
Maine	14,942,827	Vermont	7,342,107
Michigan	118,964,726	Washington	121,039,577
Minnesota	79,979,201	Wisconsin	77,412,321
Missouri	127,887,823	West Virginia	42,472,535
		Wyoming	9,308,585

Table 3-2. Natural Gas Consumption (US Energy Information Administration, 2010)

State	NG Consumption(MMBTU)	State	NG Consumption(MMBTU)
Alaska	19,203,040	Mississippi	28,145,612
Alabama	469,78,572	Montana	21,732,948
Arkansas	38,283,748	North Carolina	77,370,364
Arizona	39,356,980	North Dakota	10,899,884
California	494,079,416	Nebraska	41,267,004
Colorado	136,621,200	New Hampshire	5,980,904
Connecticut	44,193,720	New Jersey	228,900,648
DC	13,843,048	New Mexico	37,077,904
Delaware	10,330,372	Nevada	40,508,340
Florida	15,639,992	New York	416,194,024
Georgia	144,466,896	Ohio	296,551,272
Hawaii	511,944	Oklahoma	64,025,896
Iowa	72,366,060	Oregon	43,786,632
Idaho	24,386,216	Pennsylvania	241,044,412
Illinois	452,917,268	Rhode Island	18,415,592
Indiana	142,125,112	South Carolina	34,604,536
Kansas	73,060,988	South Dakota	13,564,460
Kentucky	55,846,100	Tennessee	81,165,740
Louisiana	48,686,080	Texas	233,399,176
Massachusetts	136,603,724	Utah	73,894,696
Maryland	85,014,572	Virginia	86,809,460
Maine	1,322,008	Vermont	3,430,436
Michigan	326,053,844	Washington	82,062,156
Minnesota	129,348,100	Wisconsin	127,671,432
Missouri	118,960,160	West Virginia	28,418,032
		Wyoming	28,145,612

Energy Expenditure: This data demonstrates the electricity and natural gas expenditure in each state. Due to the high efficiency of BCHP system, the state with high utility expenditure will have shorter payback period and more financial incentive to initiate the BCHP project.

Table 3-3.Total Residential Electrical Expenditure ($) and Total NG cost ($) (Energy Information Agency EIA, 2011)

State	Electrical cost($)	NG cost($)	State	Electrical cost($)	NG cost($)
Alaska	3.63E+08	1.91E+08	Mississippi	1.85E+09	3.07E+08
Alabama	3.36E+09	8.28E+08	Montana	4.26E+08	2.01E+08
Arkansas	1.55E+09	4.99E+08	North Carolina	5.63E+09	1.07E+09
Arizona	3.52E+09	6.76E+08	North Dakota	3.37E+08	89701380
California	1.32E+10	4.53E+09	Nebraska	8.2E+08	5.29E+08
Colorado	1.74E+09	1.17E+09	New Hampshire	7.15E+08	89189940
Connecticut	2.27E+09	6.37E+08	New Jersey	4.54E+09	3.24E+09
DC	2.52E+08	1.87E+08	New Mexico	6.52E+08	3.44E+08
Delaware	5.98E+08	1.79E+08	Nevada	1.53E+09	5.19E+08
Florida	1.43E+10	3.07E+08	New York	7.15E+09	6.09E+09
Georgia	5.59E+09	2.29E+09	Ohio	5.18E+09	3.66E+09
Hawaii	7.39E+08	18112260	Oklahoma	1.84E+09	7.09E+08
Iowa	1.37E+09	6.92E+08	Oregon	1.72E+09	6.18E+08
Idaho	6.67E+08	2.5E+08	Pennsylvania	6.01E+09	3.46E+09
Illinois	5E+09	3.96E+09	Rhode Island	4.57E+08	3.06E+08
Indiana	3.09E+09	1.49E+09	South Carolina	3.09E+09	5.02E+08
Kansas	1.25E+09	7.89E+08	South Dakota	3.83E+08	1.21E+08
Kentucky	2.22E+09	6.5E+08	Tennessee	3.74E+09	9.6E+08
Louisiana	2.41E+09	6.23E+08	Texas	1.61E+10	2.54E+09
Massachusetts	2.67E+09	1.97E+09	Utah	7.4E+08	6.43E+08
Maryland	3.89E+09	1.14E+09	Virginia	4.75E+09	1.17E+09
Maine	6.82E+08	21128980	Vermont	3.16E+08	57696730
Michigan	3.81E+09	3.57E+09	Washington	2.82E+09	1.11E+09
Minnesota	2.21E+09	1.13E+09	Wisconsin	2.56E+09	1.34E+09
Missouri	2.92E+09	1.46E+09	West Virginia	9.16E+08	4.08E+08
			Wyoming	2.33E+08	1.3E+08

Table 3-4. Total Residential Cost for Electricity and NG

State	Total Cost(NG&Elec)	State	Total Cost(NG&Elec)
Alaska	5.54E+08	Mississippi	2.16E+09
Alabama	4.18E+09	Montana	6.27E+08
Arkansas	2.05E+09	North Carolina	6.7E+09
Arizona	4.2E+09	North Dakota	4.27E+08
California	1.78E+10	Nebraska	1.35E+09
Colorado	2.91E+09	New Hampshire	8.04E+08
Connecticut	2.9E+09	New Jersey	7.78E+09
DC	4.39E+08	New Mexico	9.96E+08
Delaware	7.77E+08	Nevada	2.05E+09
Florida	1.46E+10	New York	1.32E+10
Georgia	7.88E+09	Ohio	8.84E+09
Hawaii	7.58E+08	Oklahoma	2.55E+09
Iowa	2.06E+09	Oregon	2.34E+09
Idaho	9.17E+08	Pennsylvania	9.47E+09
Illinois	8.95E+09	Rhode Island	7.63E+08
Indiana	4.59E+09	South Carolina	3.59E+09
Kansas	2.04E+09	South Dakota	5.03E+08
Kentucky	2.87E+09	Tennessee	4.7E+09
Louisiana	3.03E+09	Texas	1.86E+10
Massachusetts	4.65E+09	Utah	1.38E+09
Maryland	5.03E+09	Virginia	5.92E+09
Maine	7.03E+08	Vermont	3.74E+08
Michigan	7.39E+09	Washington	3.93E+09
Minnesota	3.34E+09	Wisconsin	3.89E+09
Missouri	4.38E+09	West Virginia	1.32E+09
		Wyoming	3.63E+08

Climate Weather Data: This look into the climate data in individual state, it includes annual cooling degree days, annual heating degree days and the sum of annual cooling and heating degree days. The high number degree days requires high demand for thermal load which offers a better opportunity to simultaneously utilize waste heat in the BCHP.

Table 3-5.Average Degree Days (National Climatic Data Center, 2011)

State	Average Degree days (2010)	State	Average Degree days (2010)
Alaska	1164.92	Mississippi	455.50
Alabama	467.00	Montana	722.17
Arkansas	488.08	North Carolina	472.08
Arizona	424.58	North Dakota	806.25
California	289.66	Nebraska	639.58
Colorado	619.67	New Hampshire	585.50
Connecticut	530.42	New Jersey	505.83
DC	446.25	New Mexico	476.67
Delaware	430.00	Nevada	472.08
Florida	380.83	New York	532.92
Georgia	454.583	Ohio	566.75
Hawaii	372.83	Oklahoma	485.17
Iowa	656.00	Oregon	434.92
Idaho	583.33	Pennsylvania	538.75
Illinois	597.25	Rhode Island	499.17
Indiana	489.83	South Carolina	455.42
Kansas	553.75	South Dakota	661.17
Kentucky	448.08	Tennessee	501.67
Louisiana	422.50	Texas	411.50
Massachusetts	525.42	Utah	596.92
Maryland	522.92	Virginia	496.47
Maine	508.83	Vermont	630.33
Michigan	602.50	Washington	444.17
Minnesota	724.67	Wisconsin	637.92
Missouri	553.92	West Virginia	539.58
		Wyoming	693.58

Demographic Information: The BCHP is more favorable for high household number with high energy consumption in both heating and cooling days in terms of the payback period analysis and energy expenditure perspective. The population and number of total housing units are factors that influence the demand for energy consumption

Table 3-6. Housing Units (US Census Bureau, 2010.-a)

State	Housing units, 2010	State	Housing units, 2010
Alaska	306,967	Mississippi	1,274,719
Alabama	2,171,853	Montana	2,347,201
Arkansas	1,316,299	North Carolina	4,327,528
Arizona	2,844,526	North Dakota	317,498
California	13,680,081	Nebraska	796,793
Colorado	2,212,898	New Hampshire	614,754
Connecticut	1,487,891	New Jersey	3,553,562
DC	296,719	New Mexico	901,388
Delaware	405,885	Nevada	1,173,814
Florida	8,989,580	New York	8,108,103
Georgia	4,088,801	Ohio	5,127,508
Hawaii	519,508	Oklahoma	1,664,378
Iowa	1,336,417	Oregon	1,675,562
Idaho	667,796	Pennsylvania	5,567,315
Illinois	5,296,715	Rhode Island	463,388
Indiana	2,795,541	South Carolina	2,137,683
Kansas	1,233,215	South Dakota	363,438
Kentucky	1,927,164	Tennessee	2,812,133
Louisiana	1,964,981	Texas	9,977,436
Massachusetts	2,808,254	Utah	979,709
Maryland	2,378,814	Virginia	3,364,939
Maine	721,830	Vermont	322,539
Michigan	4,532,233	Washington	2,885,677
Minnesota	2,347,201	Wisconsin	2,624,358
Missouri	2,712,729	West Virginia	881,917
		Wyoming	261,868

Table 3-7. Population and Median household income,2009 (US Census Bureau, 2010.-a)

State	Population	State	Population
Alaska	710,231	Mississippi	2,967,297
Alabama	4,779,736	Montana	989,415
Arkansas	2,915,918	North Carolina	9,535,483
Arizona	6,392,017	North Dakota	642,200
California	37,253,956	Nebraska	1,826,341
Colorado	5,029,196	New Hampshire	1,316,470
Connecticut	3,574,097	New Jersey	8,791,894
DC	601,723	New Mexico	2,059,179
Delaware	897,934	Nevada	2,700,551
Florida	18,801,310	New York	19,378,102
Georgia	9,687,653	Ohio	11,536,504
Hawaii	1,360,301	Oklahoma	3,751,351
Iowa	3,046,355	Oregon	3,831,074
Idaho	1,567,582	Pennsylvania	12,702,379
Illinois	12,830,632	Rhode Island	1,052,567
Indiana	6,483,802	South Carolina	4,625,364
Kansas	2,853,118	South Dakota	814,180
Kentucky	4,339,367	Tennessee	6,346,105
Louisiana	4,533,372	Texas	25,145,561
Massachusetts	6,547,629	Utah	2,763,885
Maryland	5,773,552	Virginia	8,001,024
Maine	1,328,361	Vermont	625,741
Michigan	9,883,640	Washington	6,724,540
Minnesota	5,303,925	Wisconsin	5,686,986
Missouri	5,988,927	West Virginia	1,852,994
		Wyoming	2,967,297

Utility rate: To be more economically viable, the region should have a relatively high electricity price and low natural gas price. The spark spread is good way to measure the difference. The utility rate is an important incentive for the customer to apply BCHP.

Table 3-8.Natural Gas Prices ($/thousand cubic feet), Average Electricity Retail Price Residential (c/kWh) (US Energy Information Administration, 2010.-b) ("Utility Rates | Combined Heat and Power Partnership | US EPA," 2010)

State	NG Prices($/thousand cubic feet)	Elec Price (c/kWh)	State	NG Prices($/thousand cubic feet)	Elec Price (c/kWh)
Alaska	10.23	16.43	Mississippi	11.22	9.95
Alabama	18.12	10.837	Montana	9.50	9.15
Arkansas	13.39	8.76	North Carolina	14.25	10.21
Arizona	17.65	10.98	North Dakota	8.46	8.09
California	9.43	15.16	Nebraska	13.18	8.91
Colorado	8.80	11.05	New Hampshire	15.33	16.32
Connecticut	14.81	19.29	New Jersey	14.54	16.58
DC	13.92	13.72	New Mexico	9.53	10.54
Delaware	17.79	13.83	Nevada	13.18	12.39
Florida	20.18	11.52	New York	15.05	18.56
Georgia	16.3	10.17	Ohio	12.68	11.27
Hawaii	36.37	28.10	Oklahoma	11.39	9.08
Iowa	9.83	10.39	Oregon	14.52	8.84
Idaho	10.54	7.954	Pennsylvania	14.74	12.79
Illinois	8.98	11.51	Rhode Island	17.06	15.85
Indiana	10.81	9.58	South Carolina	14.91	10.53
Kansas	11.10	9.91	South Dakota	9.14	8.88
Kentucky	11.96	8.58	Tennessee	12.16	9.32
Louisiana	13.15	8.91	Texas	11.19	11.58
Massachusetts	14.85	15.16	Utah	8.95	8.72
Maryland	13.73	14.41	Virginia	13.83	10.48
Maine	16.43	15.73	Vermont	17.29	15.56
Michigan	11.27	12.47	Washington	13.95	7.98
Minnesota	8.99	10.45	Wisconsin	10.76	12.55
Missouri	12.61	9.11	West Virginia	14.75	8.78
			Wyoming	9.39	8.75

Table 3-9. Spark Spread ($/kwh)

State	Spark Spread($/kwh)	State	Spark Spread($/kwh)
Alaska	0.119	Mississippi	0.050
Alabama	0.029	Montana	0.050
Arkansas	0.029	North Carolina	0.040
Arizona	0.032	North Dakota	0.044
California	0.110	Nebraska	0.031
Colorado	0.072	New Hampshire	0.096
Connecticut	0.128	New Jersey	0.102
DC	0.076	New Mexico	0.064
Delaware	0.060	Nevada	0.066
Florida	0.0267	New York	0.120
Georgia	0.030	Ohio	0.057
Hawaii	0.122	Oklahoma	0.041
Iowa	0.061	Oregon	0.025
Idaho	0.033	Pennsylvania	0.063
Illinois	0.076	Rhode Island	0.084
Indiana	0.048	South Carolina	0.039
Kansas	0.050	South Dakota	0.049
Kentucky	0.033	Tennessee	0.039
Louisiana	0.031	Texas	0.067
Massachusetts	0.087	Utah	0.048
Maryland	0.084	Virginia	0.044
Maine	0.085	Vermont	0.079
Michigan	0.075	Washington	0.019
Minnesota	0.065	Wisconsin	0.078
Missouri	0.036	West Virginia	0.023
		Wyoming	0.046

Spark Spread is the relative difference between the price of fuel and the price of power (EPA, 2010). In the calculation, it was assumed average BCHP efficiency is 80%.

Financial ability: The customer is a key variable in the application of CHP system. Their financial ability and attention to the high quality power will determine the investment of BCHP system. It is assumed that people with high income who emphasize the high equality of power will have better chances to pay for the initial cost for the BCHP system.

Table 3-10. Median household income, 2009 (US Census Bureau, 2010.-b)

State	Median household income, 2009	State	Median household income, 2009
Alaska	66,712	Mississippi	36,764
Alabama	40,547	Montana	55,621
Arkansas	37,888	North Carolina	43,754
Arizona	48,711	North Dakota	47,898
California	58,925	Nebraska	47,470
Colorado	55,735	New Hampshire	60,734
Connecticut	66,906	New Jersey	68,444
DC	58,906	New Mexico	42,830
Delaware	56,985	Nevada	53,310
Florida	44,755	New York	54,554
Georgia	47,469	Ohio	45,467
Hawaii	63,741	Oklahoma	41,716
Iowa	48,065	Oregon	48,325
Idaho	44,644	Pennsylvania	49,501
Illinois	53,974	Rhode Island	53,243
Indiana	45,427	South Carolina	42,580
Kansas	47,709	South Dakota	45,048
Kentucky	40,061	Tennessee	41,715
Louisiana	42,460	Texas	48,286
Massachusetts	64,057	Utah	55,183
Maryland	69,193	Virginia	59,372
Maine	45,708	Vermont	51,219
Michigan	45,254	Washington	56,479
Minnesota	55,621	Wisconsin	49,994
Missouri	45,149	West Virginia	120,381
	66,712	Wyoming	36,764

Emission Status: The natural gas is the major fuel source for the prime mover currently and foreseeable future. It is considered as the cleanest fossil fuel (NaturalGas.org, 2011b). The state with a high percentage coal in electricity production and emission factors will have a good potential to reduce greenhouse gas emissions via the implementation of natural gas based BCHP.

Table 3-11.Electricity Generation Percentage by Coal (Deru M & Torcellini P, 2007)

State	Coal(%)	State	Coal(%)
Alaska	9.9	Mississippi	40
Alabama	54.5	Montana	64.8
Arkansas	48.8	North Carolina	59.8
Arizona	38	North Dakota	93.7
California	1.1	Nebraska	63.9
Colorado	74	New Hampshire	17.1
Connecticut	13.1	New Jersey	18.3
DC	0	New Mexico	89.9
Delaware	60.5	Nevada	48.5
Florida	29.7	New York	16.4
Georgia	62.6	Ohio	86.5
Hawaii	14.1	Oklahoma	55.5
Iowa	81.6	Oregon	6.9
Idaho	0.9	Pennsylvania	54.4
Illinois	49.2	Rhode Island	0
Indiana	94.5	South Carolina	39.2
Kansas	73.9	South Dakota	48.2
Kentucky	91.1	Tennessee	59.3
Louisiana	24.1	Texas	38.1
Massachusetts	21.5	Utah	95.8
Maryland	21.5	Virginia	44.4
Maine	1.9	Vermont	0
Michigan	57.7	Washington	10.2
Minnesota	65	Wisconsin	97.6
Missouri	85.5	West Virginia	97.6
		Wyoming	96.7

Table 3-12.Total Emission Factors (lb. of pollutant per kWh of electricity) (Deru M & Torcellini P, 2007)

State	Emission Factors	State	Emission Factors
Alaska	3.36	Mississippi	3.39
Alabama	3.28	Montana	4.17
Arkansas	3.29	North Carolina	3.07
Arizona	3.44	North Dakota	5.64
California	3.43	Nebraska	3.82
Colorado	4.63	New Hampshire	1.73
Connecticut	1.46	New Jersey	1.86
DC	8.5	New Mexico	5.1
Delaware	4.94	Nevada	3.83
Florida	3.03	New York	2.06
Georgia	3.38	Ohio	4.59
Hawaii	3.84	Oklahoma	4.27
Iowa	5.08	Oregon	0.96
Idaho	0.47	Pennsylvania	3.22
Illinois	2.96	Rhode Island	2.25
Indiana	5.98	South Carolina	2.08
Kansas	4.7	South Dakota	3.05
Kentucky	5.11	Tennessee	3.06
Louisiana	3.21	Texas	4.04
Massachusetts	2.79	Utah	5.47
Maryland	3.72	Virginia	2.89
Maine	4.6	Vermont	0.037
Michigan	3.44	Washington	0.84
Minnesota	3.88	Wisconsin	4.27
Missouri	4.99	West Virginia	5.03
		Wyoming	5.63

The average electricity generation efficiency: The state with a low generation will have a greater potential to benefit more from the BCHP system.

Table 3-13.Average Electricity Generation Efficiency (Deru M & Torcellini P, 2007)

State	Efficiency	State	Efficiency
Alaska	29.24%	Mississippi	29.47%
Alabama	31.00%	Montana	31.99%
Arkansas	31.70%	North Carolina	32.55%
Arizona	32.43%	North Dakota	29.95%
California	33.08%	Nebraska	28.33%
Colorado	31.08%	New Hampshire	29.93%
Connecticut	31.05%	New Jersey	30.06%
DC	13.58%	New Mexico	29.42%
Delaware	26.87%	Nevada	30.05%
Florida	31.15%	New York	32.28%
Georgia	30.33%	Ohio	30.08%
Hawaii	27.09%	Oklahoma	31.15%
Iowa	28.24%	Oregon	61.20%
Idaho	63.86%	Pennsylvania	29.81%
Illinois	29.17%	Rhode Island	38.38%
Indiana	29.23%	South Carolina	30.31%
Kansas	28.31%	South Dakota	41.83%
Kentucky	28.61%	Tennessee	32.15%
Louisiana	30.44%	Texas	28.62%
Massachusetts	31.34%	Utah	29.96%
Maryland	30.78%	Virginia	28.51%
Maine	32.60%	Vermont	32.90%
Michigan	32.55%	Washington	58.24%
Minnesota	29.48%	Wisconsin	28.54%
Missouri	29.33%	West Virginia	30.65%
		Wyoming	28.53%

Natural gas availability: Natural gas is currently the dominant heating energy source and in the foreseeable future. The customer will be prone to initiate BCHP project if the natural gas pipe line is readily available. This factor will be quantified by the natural gas heating percentage in the residential buildings.

Table 3-14.Residential Natural Gas Heating Percentage (Energy Information Administration EIA, 2009)

State	NG Heating Percentage	State	NG Heating Percentage
Alaska	45.12%	Mississippi	45.12%
Alabama	25.00%	Montana	62.96%
Arkansas	32.79%	North Carolina	24.00%
Arizona	32.00%	North Dakota	43.55%
California	54.36%	Nebraska	55.56%
Colorado	57.14%	New Hampshire	20.00%
Connecticut	20.00%	New Jersey	73.68%
DC	24.00%	New Mexico	59.09%
Delaware	24.00%	Nevada	59.09%
Florida	6.94%	New York	52.38%
Georgia	35.85%	Ohio	54.95%
Hawaii	45.12%	Oklahoma	32.79%
Iowa	43.55%	Oregon	45.12%
Idaho	62.96%	Pennsylvania	29.58%
Illinois	71.67%	Rhode Island	20.00%
Indiana	54.95%	South Carolina	24.00%
Kansas	55.56%	South Dakota	43.55%
Kentucky	45.12%	Tennessee	26.67%
Louisiana	32.79%	Texas	41.90%
Massachusetts	41.18%	Utah	62.96%
Maryland	24.00%	Virginia	30.95%
Maine	20.00%	Vermont	20.00%
Michigan	72.73%	Washington	45.12%
Minnesota	43.55%	Wisconsin	54.55%
Missouri	36.84%	West Virginia	24.00%
		Wyoming	62.96%

Opportunity renewable fuel: Renewable fuels are naturally replenished which include biomass, wind power, hydropower, solar energy and geothermal energy .Those renewable fuels are low cost and environmental friendly. Biomass is considered in this research, it may enhance the fuel diversity and security.

Table 3-15.Biomass Feedstock (National Renewable Energy Laboratory NREL, n.d.)

State	Biomass Feedstock Tones/yr	State	Biomass Feedstock Tones/yr
Alaska	459,833	Mississippi	11,498,204
Alabama	9,824,763	Montana	5,444,711
Arkansas	10,556,431	North Carolina	10,560,532
Arizona	812,534	North Dakota	9,175,313
California	12,318,860	Nebraska	11,532,939
Colorado	3,147,489	New Hampshire	861,852
Connecticut	449,773	New Jersey	1,049,091
DC	56,180	New Mexico	473,972
Delaware	365,093	Nevada	260,545
Florida	20,491,007	New York	4,906,100
Georgia	12,402,723	Ohio	6,562,709
Hawaii	1,975,293	Oklahoma	3,430,936
Iowa	16,744,957	Oregon	12,713,637
Idaho	9,121,107	Pennsylvania	415,000,000
Illinois	17,665,692	Rhode Island	130,451
Indiana	9,193,399	South Carolina	437,000,000
Kansas	7,307,000	South Dakota	5,064,549
Kentucky	5,470,995	Tennessee	4,532,224
Louisiana	21,611,685	Texas	13,023,761
Massachusetts	950,311	Utah	387,988
Maryland	1,635,540	Virginia	6,774,035
Maine	3,878,453	Vermont	442,746
Michigan	10,342,384	Washington	10,740,135
Minnesota	22,982,973	Wisconsin	8,942,086
Missouri	7,182,384	West Virginia	2,158,578
		Wyoming	11,498,204

Table 3-16 gives the statistic summary of all the parameters.

Table 3-16. Statistic Summary of Variables

	Total Electricial Expenditure($)	Natural Gas Prices	Total NG cost($)	Population	Total Cost(NG&Elec)	Electrical Consumption	NG Consumption
Max	16,071,542,300	20.18	6,093,112,900	37253956	1.86E+10	4.72E+08	4.94E+08
Max Sample	Texas	Florida	New York	California	Texas	Texas	California
Minimum	233,285,900	8.46	21,128,980	563626	3.63E+08	7170648	1,322,008
Min Sample	Wyoming	North Dakota	Maine	Wyoming	Wyoming	Alaska	Maine
Average	3,068,723,756	12.58	1,189,086,332	6147096.92	4.26E+09	98,824,681	1.00E+08
Std Deviation	3,427,274,533	3.39	1,341,631,069	6860418.745	4.35E+09	97,575,113	1.18E+08
Hawaii	739,415,300	36.37	18,112,260	1360301	7.58E+08	10,202,955	511944
Deviate Average	-2,329,308,456	23.79	-1,170,974,072	- 47867095.92	-3.50E+09	-8.90E+07	-1.00E+08
	Spark Spread($/kwh)	**Elec Retail Price**	**Housing Units 2010**	**Median Household Income**	**Average Degree Days**	**Coal(%)**	**Total Emission Factors**
Max	0.13	19.29	13,680,081	120381	1.16E+03	97.6	8.50E+00
Max Sample	Connecticut	Connecticut	California	West Virgina	Alaska	Wisconsin	DC
Minimum	0.02	7.95	261,868	36764	2.90E+02	0	0.04
Min Sample	Washington	Idaho	Wyoming	Mississippi	California	Vermont	Vermont
Average	0.06	11.55	2,660,991	52102.98	524.94	48.07	3.6
Std Deviation	0.03	2.96	2,704,961	12720.19	133.01	31.7	1.55
Hawaii	0.12	28.1	519,508	63741	372.83	14.1	3.84
Deviate Average	0.06	16.55	-2,141,483	11638.02	-170.11	-33.97	0.24
	Elec Generation Efficiency(%)	**NG Heating Percentage**	**Biomass Feedstock**				
Max	63.86%	73.68%	437,044,641				
Max Sample	Idaho	New Jersey	South Carolina				
Minimum	13.58%	6.94%	56,180				
Min Sample	DC	Florida	DC				
Average	32.21%	41.53%	23,773,367				
Hawaii	8.15%	16.52%	83,179,354				
Std Deviation	27.09%	45.12%	1,975,293				
Deviate Average	-5.11%	3.59%	-21,798,074				

The table above summarizes characteristics of variables. It includes the maximum, minimum, average and stand deviation (Std Deviation). The Hawaii state has a separate row to describe the characters. The Hawaii state is very special in location, population, areas and natural resources, therefore it deviates from the average of the rest states substantially for example the electricity retail price, the natural gas consumption. Consequently, the Hawaii state requires a unique research approach. In this paper, the rest of reserach will exclude the Hawaii state.

Principal Component Analysis (PCA)

PCA is a matured method to identify the correlation between different factors which called latent variable. Each Principal Component describes one aspect of the problem which requires the explanation by the researcher. In most applications, statisticians and engineers agree that principal components' contribution up to 76% is enough to keep the accuracy of research.

In this research, the PCA is completed by MATLAB ®; the detailed procedure of PCA is in the appendix A. The following is the PCA results:

Table 3-17. Principal Component Analysis Results

EgeinValue	Difference	ContriRatio	CumContri
6.234	3.308	36.670	36.670
2.926	0.679	17.211	53.882
2.247	0.464	13.217	67.099
1.783	0.756	10.489	77.588
1.027	0.164	6.0436	83.631
0.864	0.122	5.082	88.713
0.742	0.322	4.365	93.078
0.421	0.122	2.475	95.553
0.299	0.108	1.760	97.313
0.191	0.028	1.122	98.436
0.162	0.098	0.955	99.390
0.061	0.038	0.380	99.770
0.026	0.019	0.156	99.926
0.008	0.003	0.045	99.971
0.005	0.005	0.029	100
0	0	0	100

EgeinValue: Eigenvalue of the principal component, the higher the eigenvalue, the higher the ability to cover information of data.

Difference: The difference between eigenvalue

ContriRatio: Contribution Ratio, meaning the percentage of information covered in the data set.

CumContri: Cumulative contribution of covering information, the sum of previous contribution ratio.

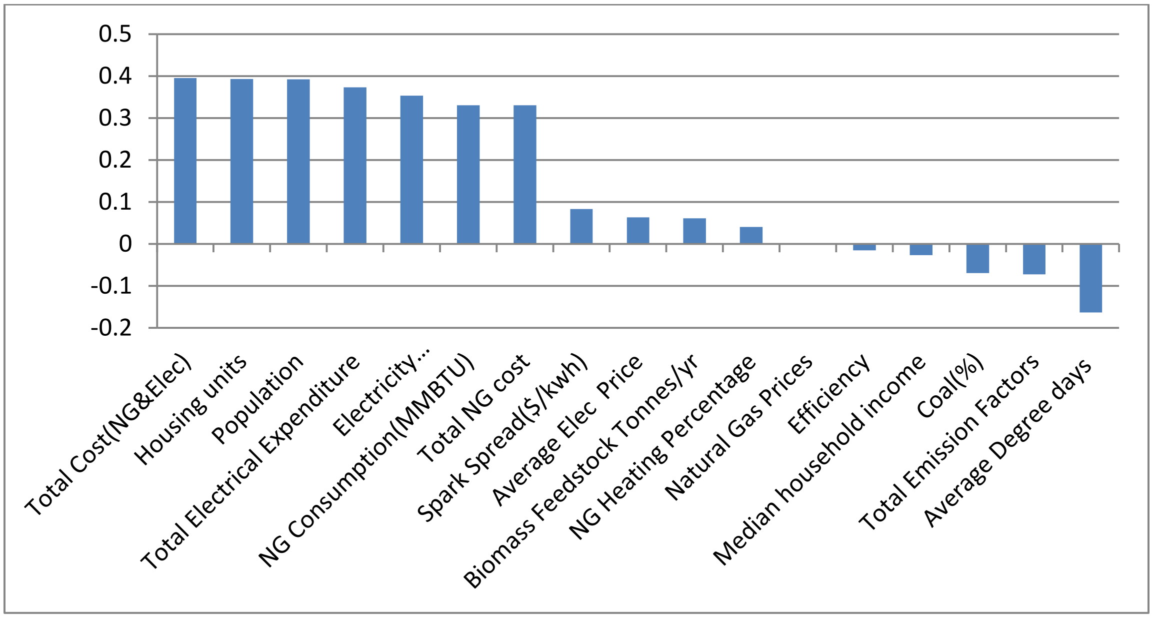
From the result, four components covered accumulative 77% of information; therefore the analysis can be based on those four components. Although this may lose some information, generally in reality, 75% accumulative contribution is acceptable by statisticians and engineers. Table 3-16 gives descriptions for four principal components.

Table 3-18. Description of Principal Component

standizedVar	PC1	PC2	PC3	PC4
Electrical Expenditure (X_1)	0.373152	0.017833	-0.12914	-0.11505
Natural Gas Prices (X_2)	-0.00024	-0.44528	-0.16288	-0.23661
Total NG cost($) ($X_3$)	0.330156	0.046203	0.233922	0.147452
Population(X_4)	0.391858	0.025146	-0.00048	-0.00888
Total Cost(NG&Elec) (X_5)	0.395446	0.028294	-0.02934	-0.04496
Elec Consumption(MMBTU) (X_6)	0.35287	0.082953	-0.20138	-0.13848
NG Consumption(MMBTU) (X_7)	0.330551	0.085558	0.264887	0.156541
Spark Spread($/kwh) ($X_8$)	0.083233	-0.36549	0.452005	0.046889
Elec Retail Price (c/kWh) (X_9)	0.063609	-0.50845	0.262483	-0.08557
Housing units, 2010 (X_{10})	0.392481	0.038255	-0.01951	-0.01952
Median household income (X_{11})	-0.02686	-0.19555	0.256491	-0.05934
Average Degree days) (X_{12})	-0.16318	0.112297	0.339702	0.215629
Coal (%) (X_{13})	-0.06978	0.270219	0.134163	-0.25363
Total Emission Factors (X_{14})	-0.0726	0.264219	0.251246	-0.50861
Efficiency (X_{15})	-0.01553	-0.02065	-0.31561	0.597047
NG Heating Percentage (X_{16})	0.040201	0.257449	0.358686	0.346033
Biomass Feedstock (X_{17})	0.060675	0.002322	-0.16227	-0.06421

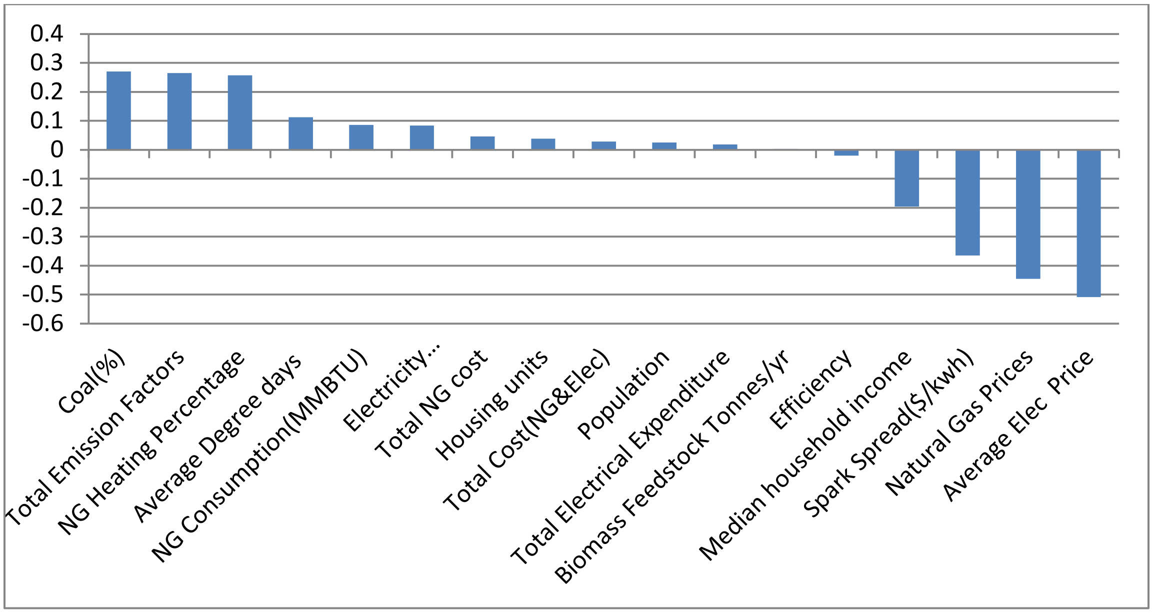
For each principal component, it has certain ability to cover information of the data set; and each factor has a coefficient; the higher the coefficient means this variable has more influence on the component thus it will have a contribution to the total data.

Figure 3—1 Factor coefficients in PC 1



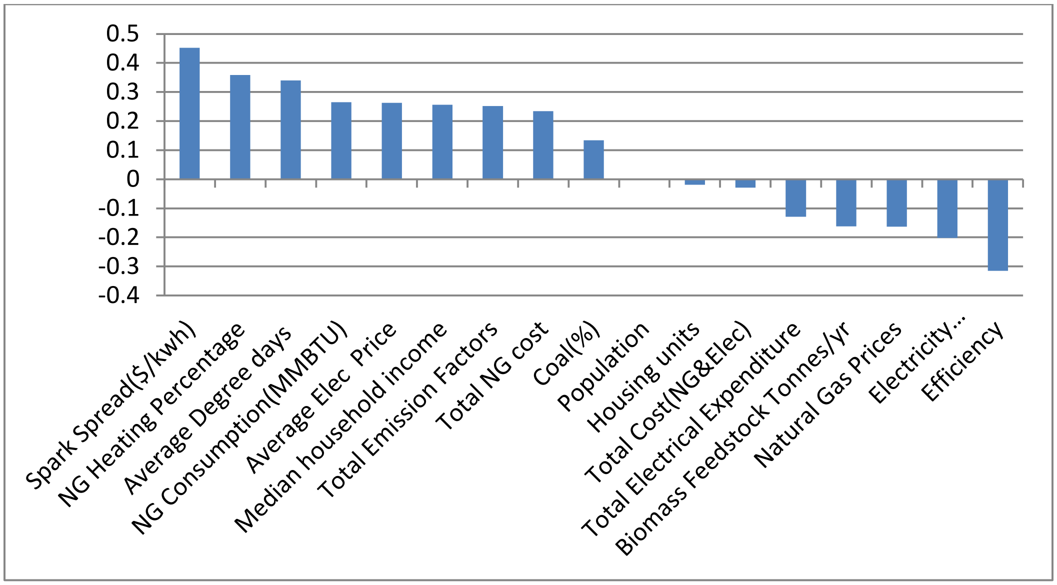
For the first component (PC1), the electricity/natural gas expenditure, population, total cost (NG&Elec), NG/electricity consumption, housing units and population has a dominant and relative close coefficient. This means the importance for those variables in the first principal component is close. When a state has high population, the total number of housing units generally is high. It is intuitively know that the large population and high number of housing units would result in the large quantity energy requirement, for example high electricity, natural gas consumption and expenditure. When the population is small, the cost and expenditure for energy usually will be lower. The state with a higher score in first component will obtain better absolute saving from the energy cost and consumption because of the high efficiency of BCHP system. From the analysis above, the first principal component is considered as the composite consumption and expenditure component which describes the information of energy consumption and expenditure for individual state. The score in principal component one is directly proportional to the application potential.

Figure 3—2 Factor coefficients in PC 2



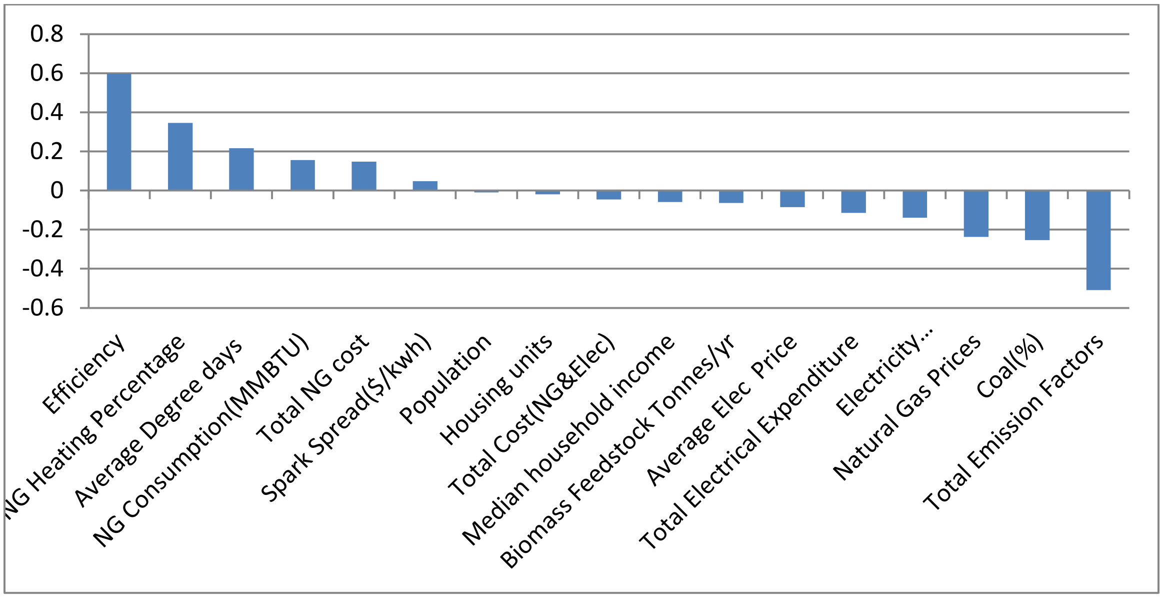
In the second component (PC2), natural gas price, spark spread, electricity retail price has a dominant coefficient on the component and they are negative. It demonstrates a possible effect of the price of energy on the application of BCHP system. When the cost of energy is high, the economics of BCHP is better in terms of the shorter payback period. People may tend to implement BCHP system because with same amount of fuel, the system simultaneously generates heat and power and more financial savings. The high spark spread also contributes to the application of BCHP; customers have more financial incentives to choose natural gas over electricity as energy source. However, because of the negative signal of those coefficients, the high score in principal component two will decrease the score in PC2. Therefore principal component two is considered as inversely proportional to the application of BCHP system.

Figure 3—3 Factor coefficients in PC 3



In the principal component three (PC3), it exhibits a probable internal effect of natural gas on the application of residential BCHP. The spark spread, natural gas heating percentage, average degree days, natural gas consumption and electricity price has a prevailing coefficient. A reasonable explanation is that a region with high average degree days for example heating degree days, natural gas consumption will be high because it is considered as the major heating fuel source (U.S. Energy Information Administration, 2010). In regions with high natural gas heating percentage and utilize it as a major heating fuel, the infrastructure is generally considered well developed and customer are more acceptable of natural gas. The large consumption of natural gas could result in a relatively low unitary price, so the high spark spread is favorable for dwellers to choose natural gas over electricity. A state with high natural gas heating percentage, consumption, degree days and spark spread means better chance to utilize to implement BCHP. In summary, the third component is considered a comprehensive natural gas effect component on the application. From the analysis, it is directly proportional to the potential of applying BCHP.

Figure 3—4 Factor coefficients in PC 4



The forth principal component (PC4), dominant factors include electricity generation efficiency, total emission factor, NG heating percentage and coal percentage (%) in the electricity generation. Electricity production efficiency is the largest positive (0.5970) and total emission factor is the largest negative (-0.5086). A state with high electricity generation efficiency will make BCHP system less competitive in terms of payback period, primary energy consumption and environmental benefits. The reason is that normally the electricity generation efficiency of prime mover is relatively higher than the power plant. If a power plant has high generation efficiency, the BCHP loss this advantage. The saving from primary energy and cost will be less. A low emission factor in traditional power generation would decrease the potential of applying BCHP system as well. Those states have less greenhouse gas emission and pollution than others even without BCHP system. The negative sign of emission factor indicates the smaller emission would increase the value of component four. Consequently, the fourth principal component is called negative environmental component and it varies inversely with the market potential of BCHP.

In summary, the first principal component has the largest contribution percentage which is 36.67%. It is called the composite consumption and expenditure component which is directly proportional to the market potential of BCHP system. The second principal component has the second largest contribution percentage (17.21%) to cover the information. It is a component describes the price of energy source on the application of BCHP. The third component is considered as comprehensive natural gas effect component which demonstrate a possible internal effect of natural gas on the application of residential BCHP. The last component takes up 10% contribution. It is a negative environmental component. The four principal components contribute to 77.6% of total information which is acceptable. Among four components, the first and the third principal component rise proportionately to the promotion potential of BCHP. The second and the fourth component are inversely proportional to the market potential of the system.

From the table 3-14, equations for four principal components are:

$$PC1=0.373152X_1 - 0.00024X_2 + 0.330156X_3 + 0.391858X_4 + 0.395446X_5 + 0.35287X_6 + 0.330551X_7 + 0.083233X_8 + +0.063609X_9 + 0.392481X_{10} - 0.02686X_{11} - 0.16318X_{12} - 0.06978X_{13} - 0.0726X_{14} - 0.01553X_{15} + 0.040201X_{16} + 0.060675X_{17}$$

$$PC2=0.017833X_1 - 0.44528X_2 + 0.046203X_3 + 0.025146X_4 + 0.028294X_5 + 0.082953X_6 - 0.085558X_7 - 0.36549X_8 - 0.50845X_9 + 0.038255X_{10} - 0.19555X_{11} - 0.112297X_{12} - 0.450219X_{13} - 0.264219X_{14} - 0.02065X_{15} + 0.257449X_{16} + 0.002322X_{17}$$

PC3=-0.12914$X_1 - 0.16288X_2 + 0.233922X_3 - 0.00048X_4 - 0.02934X_5 -$
$0.20138X_6 + -0.264887X_7 - 0.452005X_8 - 0.262483X_9 - 0.01951X_{10} + 0.256491X_{11} +$
$0.339702X_{12} - 0.134163X_{13} + 0.251246X_{14} - 0.31561X_{15}$+0.358686$X_{16}-0.16227X_{17}$

PC4=-0.11505$X_1 - 0.23661X_2 + 0.14752X_3 - 0.00888X_4 - 0.04496X_5 -$
$0.13848X_6 + 0.156541X_7 + 0.046889X_8 - 0.08557X_9 - 0.01952X_{10} - 0.05934X_{11} -$
$0.215629X_{12} - 0.25363X_{13} - 0.50861X_{14} - 0.597047X_{15}$+0.346033$X_{16}-0.06421X_{17}$

The final score for each state is the sum of the score at individual principal component multiplied by the component contribution percentage. The component which is directly proportionate to the application potential is given a positive sign. The negative sign means the component is in an inverse relationship to the application of BCHP system.

Final Score=36.67%·PC1-17.21%·PC2+13.21%·PC3-10.48%·PC4

The coefficient in front of each component is the contribution ratio for the individual principal component.

The final comprehensive score of each state is in the table below:

Table 3-19. Final Score of Each State in PCA

State	Score	State	Score
California	3.504	South Carolina	-0.252
New York	2.552	Maine	-0.26072
Texas	2.483	Rhode Island	-0.290
Florida	1.564	Nevada	-0.365
Illinois	1.187	Alaska	-0.376
New Jersey	1.176	Delaware	-0.388
Pennsylvania	1.166	Vermont	-0.409
Ohio	0.866	Louisiana	-0.418
Michigan	0.746	West Virginia	-0.547
Massachusetts	0.525	Oklahoma	-0.561
Connecticut	0.498	Iowa	-0.576
Georgia	0.480	Kentucky	-0.585
Maryland	0.438	Washington	-0.591
Virginia	0.241	Kansas	-0.595
North Carolina	0.240	Mississippi	-0.600
Wisconsin	-0.043	Arkansas	-0.750
DC	-0.099	New Mexico	-0.765
Arizona	-0.110	Utah	-0.830
Indiana	-0.123	Nebraska	-0.881
New Hampshire	-0.167	Montana	-0.940
Tennessee	-0.202	Oregon	-0.948
Missouri	-0.226	Wyoming	-1.125
Alabama	-0.230	South Dakota	-1.205
Colorado	-0.248	North Dakota	-1.243
Minnesota	-0.247	Idaho	-1.420

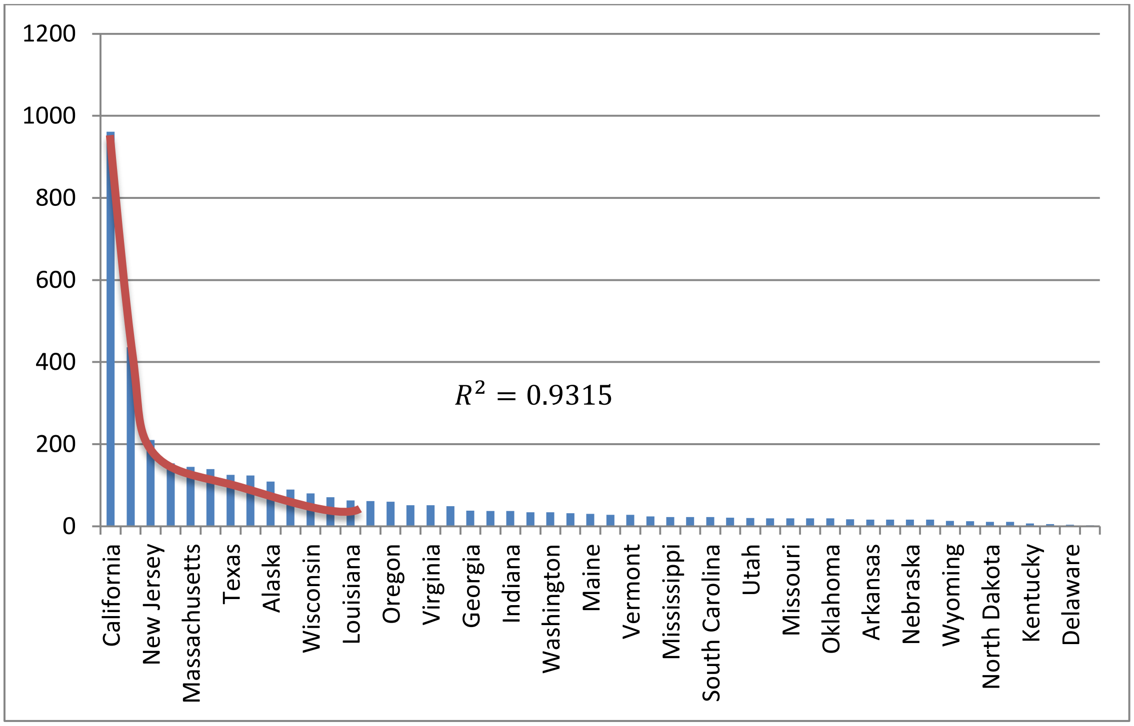
The top seven states are California, New York, Texas, Florida, Illinois, New Jersey and Pennsylvania. For regions, East North Central and Middle Atlantic region have higher potential.

The potential of BCHP application is hard to quantify, but the current total number of CHP facility is a good indication. In Table 3-18, it is clear that the top seven states have a high number of CHP facilities than the rest which is a supportive example of analysis above.

Table 3-20. Total CHP facility number in each state

State	Facility Number	State	Facility Number
California	961	**Tennessee**	28
New York	436	**Vermont**	28
New Jersey	210	**Rhode Island**	24
Connecticut	153	**Mississippi**	22
Massachusetts	145	**New Hampshire**	22
Illinois	139	**South Carolina**	22
Texas	125	**Maryland**	21
Pennsylvania	124	**Utah**	20
Alaska	109	**Idaho**	19
Michigan	89	**Missouri**	19
Wisconsin	80	**Montana**	19
Florida	71	**Oklahoma**	19
Louisiana	63	**Kansas**	17
North Carolina	61	**Arkansas**	16
Oregon	60	**Arizona**	16
Minnesota	51	**Nebraska**	16
Virginia	51	**New Mexico**	16
Ohio	49	**Wyoming**	13
Georgia	38	**Nevada**	12
Alabama	37	**North Dakota**	11
Indiana	37	**West Virginia**	11
Iowa	34	**Kentucky**	7
Washington	34	**South Dakota**	5
Colorado	32	**Delaware**	4
Maine	30	**DC**	2

Figure 3—5 The real CHP/ BCHP facilities number in each state



In Table 3-19, we can see the top seven states' rank in the first component and the rank in each component. In figure 3-5, the red line is the curve for results of high potential states. The blue line means the facilities number in reality. The R square of curve fit is 0.9315 which means the potential calculation model in the research is very accurate and matches the reality.

The first component is called the composite consumption and expenditure component and it has the highest contribution to the final score (36.67%). The state with large population generally has more housing units than the others and thus would give rise to the high energy consumption and expenditure. California, Texas and New York are the top three largest population states. Those states are the leading consumers for energy cost and usage. The high energy expenditure and consumption is an important incentive for the early adopters.

Table 3-21. Top Seven States' Rank in PC One

State	Population	Housing Unit	Electricity Cost	NG Cost	Total Elec/NG Cost	Elec Consumption	NG Consumption	Score in PC1
California	1	1	3	2	2	3	1	1
New York	3	4	4	1	4	8	3	2
Texas	2	2	1	7	1	1	7	3
Florida	4	3	2	37	3	2	41	5
Illinois	5	6	9	3	6	10	2	7
New Jersey	11	11	11	7	9	20	8	4
Pennsylvania	6	5	5	6	5	6	6	6

In the second principal component, good rank reverses proportionately to the market potential of BCHP from the previous analysis. The top seven states have generally high rank in natural gas price, and coal percentage therefore the score in PC 2 is low. The contribution percentage of PC 2 is 17.21 %. A high score in PC1 and low score in PC 2 indicate a good potential to expand BCHP system. The overall rank and score between the PC 1 and the PC 2 is in Figure 3-1

Table 3-22.Top Seven States' Rank in PC Two

State	NG Price	Elec Price	Spark Spread	Coal(%)	Score in PC2
California	43	10	4	46	37
New York	10	2	2	40	45
Texas	34	18	17	32	19
Florida	1	19	48	34	38
Illinois	47	20	14	25	13
New Jersey	16	3	5	38	42
Pennsylvania	15	14	21	24	29

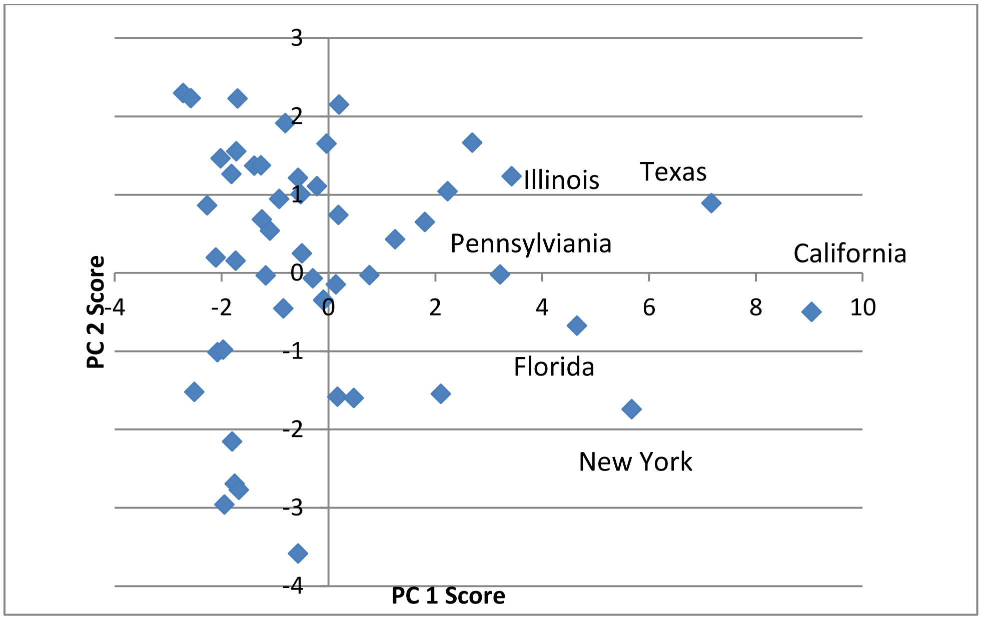


Figure 3—6 The overall rank and score between PC1 and PC2.

The third component is considered as a comprehensive natural gas effect component and the contribution rate is 13.21%. New York, California and New Jersey have a high spark spread from the data. The state with high natural gas heating percentage and spark spread, dwellers have more economical incentives to invest on the BCHP system, and since the high NG gas heating percentage, the infrastructure is considered well developed.. In PC 3, New York, Illinois, New Jersey and California have a high score.

Table 3-23.Top Seven States' Rank in PC Three

State	Spark Spread	NG Heating	Degree Days	NG Price	NG Consumption	NG Cost	Score in PC3
California	4	16	50	43	1	2	9
New York	2	17	22	10	3	1	2
Texas	17	27	48	34	7	7	37
Florida	47	50	49	1	41	37	50
Illinois	14	3	27	47	2	3	3
New Jersey	5	1	27	16	8	7	4
Pennsylvania	21	37	1	15	6	6	31

The fourth principal component is called negative environment component and the contribution rate is 10.48%. It describes the environmental consideration of traditional power generation. The principal component four varies inversely with the market potential of BCHP. Subsequently, the low score in PC 4 is good for the application of BCHP. From the top 7 seven states, Florida, Illinois and Pennsylvania have more improvement space in terms of environmental consideration.

Table 3-24.Top Seven States' Rank in PC Four

State	Elec Generation Efficiency	Total Emission Factor	NG Heating Percentage	Coal %	Score in PC4
California	6	26	16	46	13
New York	12	43	17	40	8
Texas	41	19	27	32	46
Florida	17	37	50	34	49
Illinois	4	38	3	25	4
New Jersey	28	44	1	38	7
Pennsylvania	33	32	37	24	38

From the principal component analysis, four components cover 77.59 % of information. Each component describes a different aspect of BCHP application potential. The comprehensive effect of the different factors is considered in the final score equation. The top seven states are California, New York, Texas, Florida, Illinois, New Jersey and Pennsylvania. In the second phase-system selection, a city will be randomly chosen from the top seven states.

Chapter 4 **System Selection and Evaluation**

The realization of the benefits of BCHP includes location selection, system sizing, selection, integration and operation. In this chapter, it focuses on the system selection and evaluation. A parametric analysis will be implemented to compare the overall performance of building and BCHP system between different system components combination. The system components include prime mover, absorption cooling chiller (AC), DX unitary system, air handling unit, boiler and duct burner. The results of parametric assessment contain primary energy consumption, greenhouse gases emission, total fuel cost, BCHP system efficiency and overall building system efficiency.

Building Description

The research uses the software EnergyPlus to simulate a hypothetical DOE benchmark mid-rise residential building as a reference building. From the Chapter 3, it gives seven top potential states. In Chapter 4, New York City is randomly chosen as the location of reference building. The simulation obtains the hourly electric, cooling and heating load. In the reference building system, the electricity grid meets all the electricity demand which includes lighting and plug load. The gas furnace satisfies the heating demand and DX unitary system with a COP of 3.67 meets the cooling load. The baseline building has a floor area of 3135m^2. The building has a totally insulated flat roof; the distance between floor to floor or floor to floor is 3.05m. The glazing to wall fraction is 15% in four directions. The reference HVAC system is gas furnace and DX unitary system.

Table 4-1. Building information summary.

Building types	Multifamily residential
Area(Sq. ft.)	33745
Floors	4
Window %	15
Building Shape	Rectangle
Available Fuel Types	Gas, Electricity

The building operates 24 hours a day, seven days per week for the whole year. The temperature set point for heating: the apartment set point is 22℃ all the year. The office at work day is from 9 am to 17 pm is 22℃. For other times, the set point is 16℃.

The Basic BCHP System Configuration

Since the topic of this research is residential buildings, so in Chapter 4 and Chapter 5, the prime mover focuses on IC engine and microturbine. For fuel cells, because the initial price is very high so the massive implementation in residential apartments is currently not available, it has been excluded from this research.

In BCHP system, natural gas is supplied to the prime mover and it generates electricity and rejects waste heat. The electricity is used to meet the electricity demand in the building for example lighting and office equipment. The excess amount of electricity can't be sold back to the grid. This is because generally it is not economically viable for the customer sale back to grid. In most states, this only allows by limited applications. When the residential house connects to the grid, it lowers the reliability of the grid (UTRC, 2006). If the prime mover can't meet the electricity demand, the shortage will be imported from the grid.

The recovered heat from the prime mover will be used to produce cooling and heating effect. If the recovered waste heat fails to meet the load, a boiler (for IC engines) or duct burner (for microturbines) will cover the shortage or when the DX unitary system presents, it will provide extra cooling ability.

In this research, it includes two different system configurations. In scenario one, it excludes DX unitary system. The shortage of cooling ability will be covered by the absorption chiller via the boiler or duct burner supplies the heat to the chiller. In scenario two, DX unitary system is included. When cooling demand occurs, the DX unitary system will offer cooling capacity to meet the total cooling load.

Scenarios 1: Without Electrical Chiller

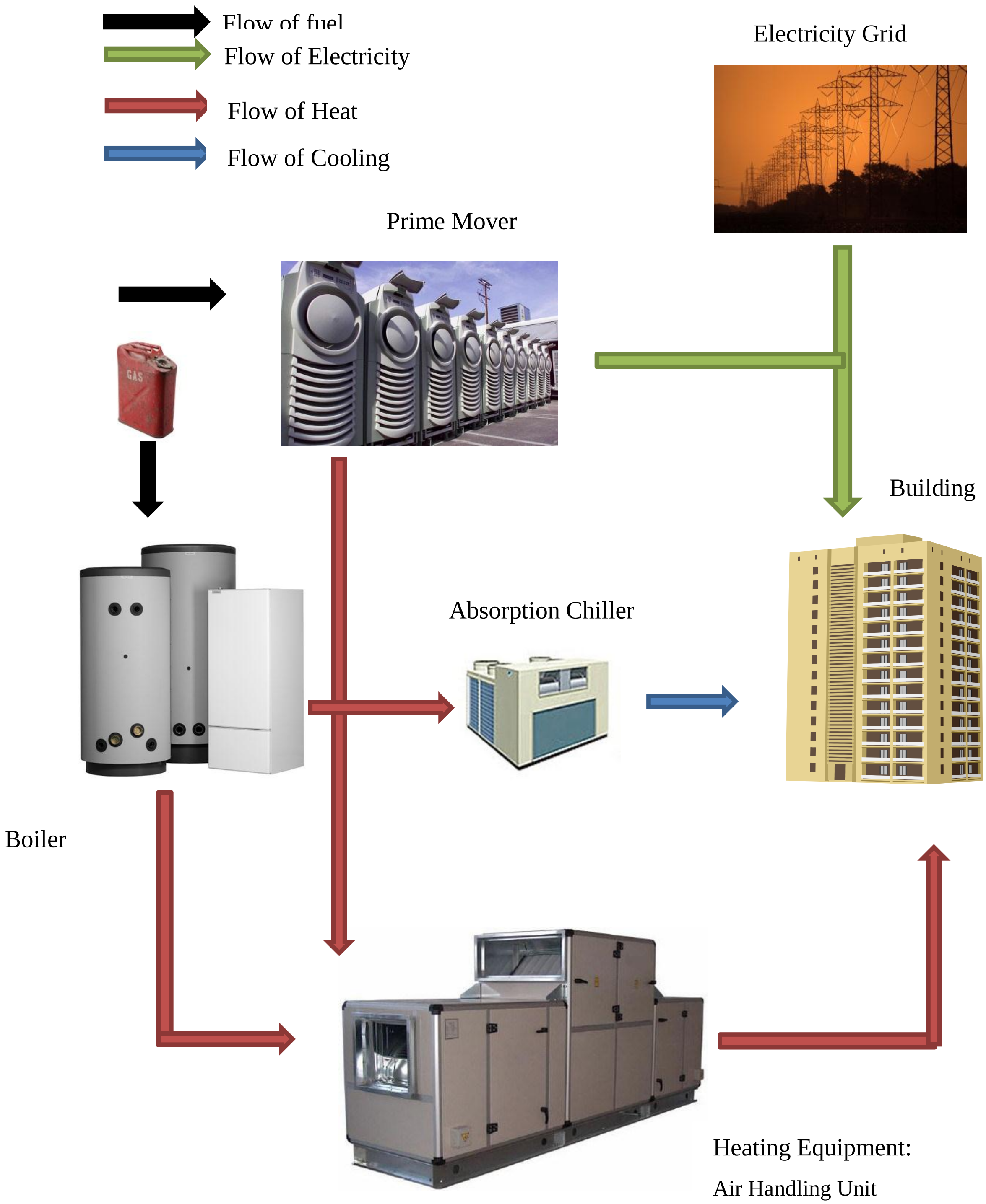


Figure 4—1. BCHP system configuration I.

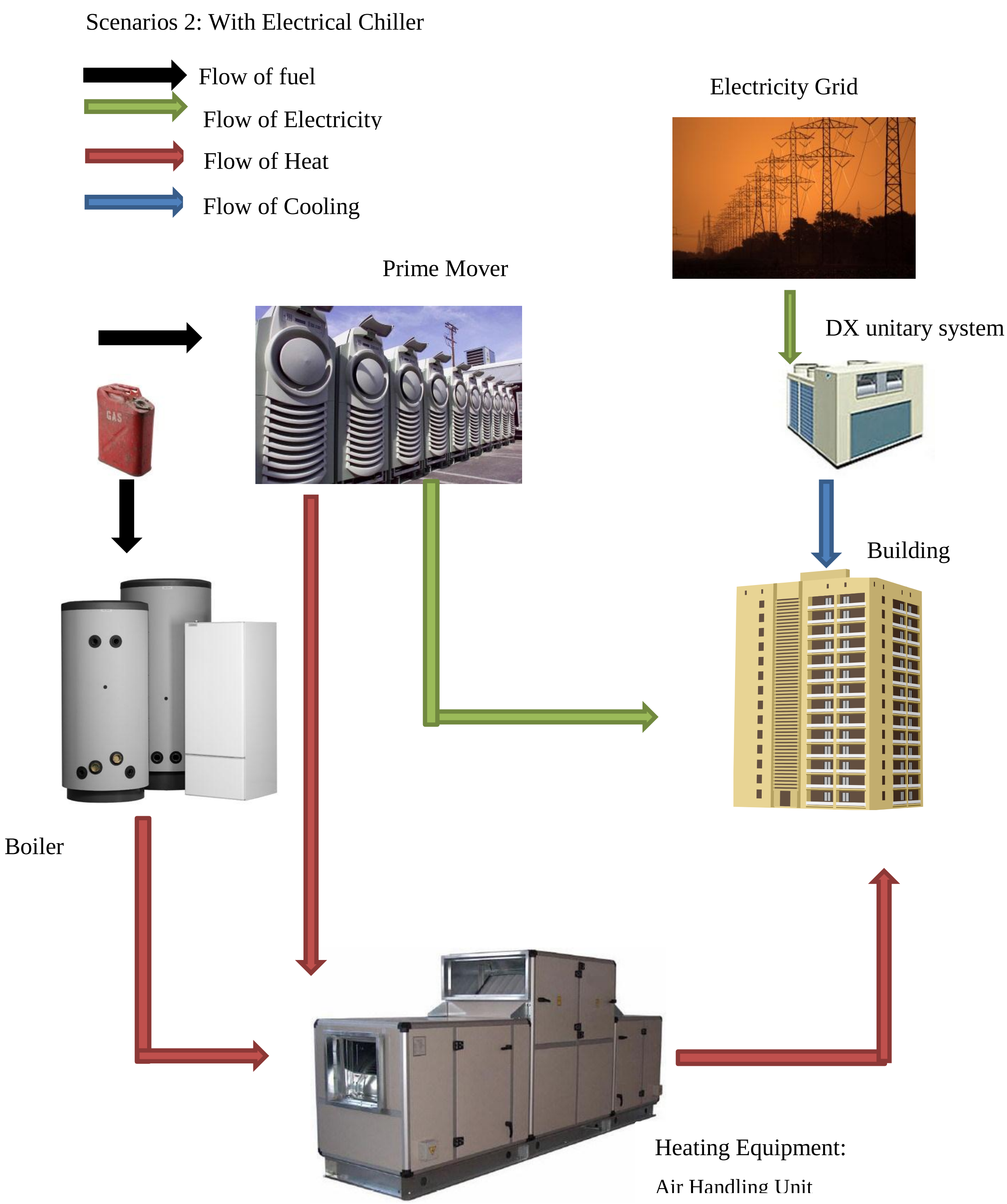


Figure 4—2. BCHP system configuration II.

Method of Parametric Analysis

The purpose of the parametric analysis is to examine the influence of different components and operation strategies on the combination of BCHP system. It is a preliminary comparison which can facilitate process in the early design phase of BCHP. According to the previous researches (ASHRAE, 2008),(Jalalzadeh-Azar, 2004),(A K Hueffed & Mago, 2010), follow the base load achieves the best system efficiency but may require a longer the payback period. In general, follow the thermal load is superior to follow the electrical load. Therefore, in this chapter, the operation of system is based on follow thermal load (FTL) and follow base thermal load (FBTL).

The assumptions in the parametric study are as followed:

1. The scope of this research is focused on the residential buildings so the types of prime movers are IC engine and microturbine. This is because the IC engine and microturbine has a good part load performance and relative high electrical generation efficiency. Besides, both microturbine and IC engines can effectively meet the demand for domestic hot water (DHW).
2. The minimum number of prime is one, the maximum number is two. In the scenario of two prime movers, it is preferable to have two equally sized and same type of prime mover, because this will be convenient for operation, maintenance and training.
3. For the IC engine, the heat recovery device recoveries waste heat to the hot water (HW). In microturbine, it recoveries heat from the exhaust gas. The recovered heat can be either used in absorption cooling or HW for space heating
4. The heat input of the absorption chiller is from the recovered heat, when the recovered heat can't meet the demand, a boiler or duct burner can provide extra heat.

5. The different operation strategies have direct impact of sizing the prime mover. The prime mover will be sized to meet the thermal load in FTL and base thermal load in FBTL.
6. The transient effects with absorption chiller or extra energy consumption during operations are neglected. The switching between different equipment could increase the wear of system and lose the efficiency, but this is out of the scope of this research.
7. Electricity and natural gas price are determined by the phase I study.
8. Simulation time step by defaults is one hour; this is consistent with the building load simulation in Energyplus.
9. IC engine and microturbine part load electrical efficiency will be based on a typical performance curve, but the effect of ambient temperature is neglected because it is small.
10. Pump or fan energy consumption is not considered in the optimization.
11. The boiler and heat recovery devices assume have a constant efficiency which is 0.8 and 0.85 respectively. The efficiency of air handling unit (AHU) is 0.9.
12. The excess amount of electricity will not sale back to the grid. An electrical heater will consume extra electricity for heating.
13. The electrical and thermal efficiency of prime mover are transient. The typical prime mover efficiency is based on the typical performance curve. This is because this research doesn't focus on improving the performance of prime mover by studying the effects of temperature, fuel injection, power to heat ratio. This assumption meets the objection of parametric analysis.

14. The whole operation strategy doesn't consider the problem in the interconnectivity of electricity grid. This is no credit for extra energy generation which means it excludes thermal storage and exporting electricity to the grid.

In conducting the parametric study, 8760 hourly load of the building is derived from the Energyplus. The calculation of different system combination includes total primary energy consumption, greenhouse gases emissions, total fuel cost, BCHP system efficiency and overall building efficiency. In the analysis, IC engine and microturbine are divided into two groups. The best BCHP system candidate is further optimized in Chapter 5 for detailed hourly linear programming optimization.

Table 4-2 and Table 4-3 describe the different system configurations for the analysis. IC engine and microturbine are in two groups, in each group the variations are the COP for single absorption or double effect absorption chiller and DX unitary system. The operational strategies include follow the thermal load (FTL) and follow the base thermal load (FBTL). The number of prime mover varies from one to two equally sized engines. The total number of configurations is 32.

From the past literature review (Jalalzadeh-Azar, 2004) and (Energy and Environmental Analysis (an ICF International Company), 2008b), the microturbine with the recuperator will have higher electrical efficiency and recuperated microturbine is more advantageous for the operation. The COP of absorption chiller varies from 0.7 to 1.05 and 1.19. This implies 50% and 70% more efficiency absorption chiller for higher COPs. The baseline COP is 0.7 which is reasonable for current technology (ASHRAE, 2008). The different number of prime movers is to investigate the impact of part load performance on the system and whole building.
The prime mover achieves the designed efficiency at the 100% load ratio, but the efficiency will decrease as the load ratio decreases. In the scenario of two prime movers, the size of prime movers is equal. This is good for the operation, staff training and maintenance.

Table 4-2. Scenario1 without VCC for Parametric Analysis

Scenario	Operation	IC Engine	AC COP	Scenario	Operation	IC Engine	AC COP
1	**FBTL**	**PG1**	**0.7**	**7**	**FTL**	**PG1**	**0.7**
2	**FBTL**	**PG1**	**1.05**	**8**	**FTL**	**PG1**	**1.05**
3	**FBTL**	**PG1**	**1.19**	**9**	**FTL**	**PG1**	**1.19**
4	**FBTL**	**PG1**	**0.7**	**10**	**FTL**	**PG1**	**0.7**
		PG2				**PG2**	
5	**FBTL**	**PG1**	**1.05**	**11**	**FTL**	**PG1**	**1.05**
		PG2				**PG2**	
6	**FBTL**	**PG1**	**1.19**	**12**	**FTL**	**PG1**	**1.19**
		PG2				**PG2**	

Scenario	Operation	Microturbine	AC COP	Scenario	Operation	Microturbine	AC COP
13	**FBTL**	**PG1**	**0.7**	**19**	**FTL**	**PG1**	**0.7**
14	**FBTL**	**PG1**	**1.05**	**20**	**FTL**	**PG1**	**1.05**
15	**FBTL**	**PG1**	**1.19**	**21**	**FTL**	**PG1**	**1.19**
16	**FBTL**	**PG1**	**0.7**	**22**	**FTL**	**PG1**	**0.7**
		PG2				**PG2**	
17	**FBTL**	**PG1**	**1.05**	**23**	**FTL**	**PG1**	**1.05**
		PG2				**PG2**	
18	**FBTL**	**PG1**	**1.19**	**24**	**FTL**	**PG1**	**1.19**
		PG2				**PG2**	

Notes: default COP=0.7 at ambient temperature of 95°F. Different COP presents COP for single effect or double effect absorption chiller under the current technology.

Table 4-3.Scenario2 with VCC for Parametric Analysis

Scenario	Operation	IC Engine	DX COP	Scenario	Operation	Microturbine	DX COP
25	**FBTL**	**PG1**	**3.67**	**29**	**FBTL**	**PG1**	**3.67**
26	**FBTL**	**PG1**	**3.67**	**30**	**FBTL**	**PG1**	**3.67**
		PG2				**PG2**	
27	**FTL**	**PG1**	**3.67**	**31**	**FTL**	**PG1**	**3.67**
28	**FTL**	**PG1**	**3.67**	**32**	**FTL**	**PG1**	**3.67**
		PG2				**PG2**	

Primary Energy Consumption:

This function describes the yearly primary energy consumption for the whole building. The consumption contributors include primary energy in the power plant to produce electricity, the amount of primary energy that converts to natural gas fuel input. Based on the research in last chapter, the New York state average electricity generation efficiency is 32.28% (transmission and distribution loss included). The natural gas conversion factor to primary energy is 1.047 (ENERGY STAR, 2005)

$$\mathrm{Fuel_{total}(kW)} = \sum_{1}^{8760}\left(\frac{\mathrm{E_{grid}}}{\eta_{\mathrm{grid}}} + \frac{\mathrm{E_{PM}}}{\eta_{\mathrm{PM}}}\cdot(1.047) + \frac{\mathrm{Q_{boiler}}}{\eta_{\mathrm{boiler}}}\cdot(1.047)\right)$$

$$\mathrm{E_{grid}} = \mathrm{E_{demand}} - \mathrm{E_{PM}}$$

$\mathrm{E_{grid}}$ is the electricity import from the grid. When the electricity production from the prime mover exceeds the electricity demand, the import is the zero. η_{grid} is the electricity generation efficiency which includes the loss in the production, transmission and distribution.

$\mathrm{E_{PM}}$ is the electricity produced by the prime mover, η_{PM} is the part load generation efficiency for the prime mover based on the performance curve. $\mathrm{Q_{boiler}}$ is the heat produced by the boiler and η_{boiler} is the heat generation efficiency for the boiler. By the assumption the boiler efficiency is 0.8.

Carbon Dioxide and toxic pollutant Emissions:

In a traditional system, the separate power plant produces electricity and heat is generated by a gas furnace or hot water heater. In a BCHP system, the heat and power mainly comes from the natural gas based prime mover, although this may increase the total natural gas consumption, the emission rate of carbon dioxide and toxic pollutants are reduced because the natural gas is considered as the cleanest fossil fuel (NaturalGas.org, 2011b) and the overall high efficiency of BCHP system may further decrease the greenhouse gas emission. In this research, calculated gases are carbon dioxide, methane and nitrous dioxide from electricity and natural gas production. The Table 4-4 showed the emission factor for electricity and natural gas (US Energy Information Administration, 2011),(NaturalGas.org, 2011a)

Table 4-4. Carbon dioxide and toxic pollutants conversion factors.

Electricity (tons/year-kWh)		
Carbon Dioxide	**Methane**	**Nitrous Dioxide**
3.09E-04	**7.89E-09**	**4.49E-09**
Natural Gas (tons/year-kWh)		
Carbon Dioxide	**Methane**	**Nitrous Dioxide**
2.00E-04	**1.47E-07**	**9.11E-07**

$$\text{Total Emission}\left(\frac{\text{tons}}{\text{year}}\right) = 0.00031 \cdot \text{Electricity(kW)} + 0.0002 \cdot \text{NG(kW)}$$

Total Fuel Expenditure:

(Agami Reddy & Maor, 2009) stated that operation and maintenance expenditure is very small compared with the fuel cost in prime mover and boiler is negligible, therefore in conducting the calculation, it only considers the total fuel expenditure. The price of electricity and natural gas in New York City is determined in Chapter 3 which is 18.6 c/kWh (0.186 $/kW) and 15.05 $/thousand cubic feet (0.066$/kW). In this research, selling electricity back to the grid is not available because it is not economically desirable for the customer and may be limited by certain applications. Once there is enough information for selling back price it can be added to the equation.

Total Fuel Expenditure:

$$\text{Cost (\$)} = 0.186 \cdot E_{grid}(kW) + 0.066 \cdot F_{boiler,duct\ burner}(kW) + 0.066 \cdot F_{prime\ mover}(kW)$$

System and Building Efficiency:

The system efficiency is the energy efficiency for the BCHP system; it describes the degree of BCHP system utilize the fuel to produce electricity and heat. The BCHP system input is the natural gas in the prime mover. The output is the electricity and recovered heat. One of the limitations of first law analysis is that it ignores the quality of energy.

BCHP System Efficiency:

$$\eta = \frac{(E_{PGU} + Q_{rec})}{Q_{fuel}}$$

From the perspective for the home owner and investor, the main concern is the overall building cost and performance. It is the reflection of the overall building energy operation. The equation is applicable for different types of system configuration and source of energy. The building total fuel inputs are the fuel consumptions in the prime mover, primary energy in the power plant, boiler or duct burner. The energy input for the building system is the electricity from the BCHP generator and grid, the recovered heat from the exhaust gas, the supplementary heat from the boiler or duct burner. In practice, the importance of overall building efficiency outweighs the BCHP system efficiency; this is because the overall building energy consumption is the final end energy usage.

Overall Building Efficiency:

$$\eta_{overal} = \frac{\left(E_{PM} + E_{grid} + Q_{total\ rec} + Q_{Boiler}\right)}{Q_{PM,fuel} + Q_{grid,fuel} + Q_{boiler,fuel}}$$

Building load simulation results and prime mover performance curve:

In the Energyplus, the software gives the hourly load profile for 8760 hours. Table 4-5, Table 4-6 shows the summary of the energy simulation. Figure 4-3 is the monthly summary in terms of electricity load, cooling load and heating load.

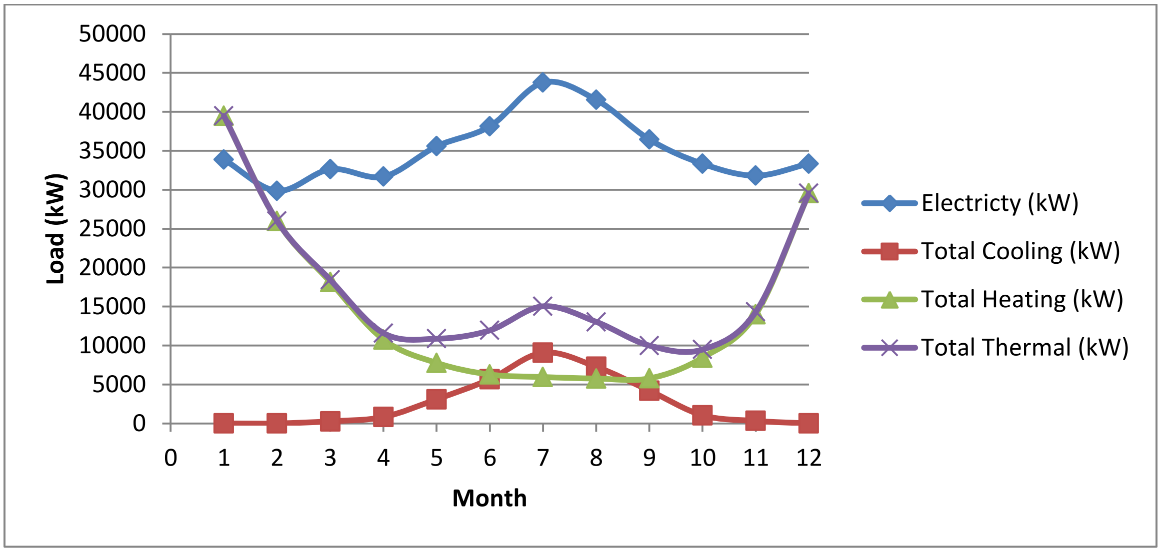
Table 4-5. The building monthly load summary.

	Electricity Load (kW)	Total Cooling (Kw)	Total Heating (kW)	Total Thermal (kW)
Max	43749.75	9080.11	39486.26	39486.83
Max Sample	July	July	Jan	Jan
Minimum	29862.69	0.19	5764.51	9485.23
Min Sample	Feb	Jan	Aug	Oct
Average	35168.06	2650.75	14828.60	17479.35
Std Deviation	4170.95	3198.15	11215.95	9379.22
Overall	422016.66	31809.03	177943.21	209752.25

Table 4-6. The building hourly load summary.

	Electrical Load (kW)	Cooling Load (kW)	Heating Load (kW)	Total Thermal Load (kW)
Max	104.89	29.21	165.56	165.56
Max Sample	05/21 13:00:00	07/25 16:00:00	06/17 18:00:00	02/03 16:00:00
Minimum	24.20	0	0.56	0.76
Minimum Sample	05/14 13:00:00	01/01 01:00:00	03/23 01:00:00	10/27 10:00:00
Average	48.18	5.19	26.55	31.74
Std Deviation	17.32	7.80	24.14	22.19

Figure 4—3 Building monthly load



From the summary above, the building has a base monthly electrical load above 30000 kW; it reached the peak electrical load from the July to August. The average heating load is higher than the cooling load because the location is in the north region of US. The base monthly heating load is around 5000 kW. The total thermal load achieved the highest value in the summer when there is a simultaneously need for cooling and heating, and at that time, the cooling demand is at its peak. From the figure 4-3, the major building operation cost is the electricity bill.

In the literature review, based on the up-to-date technology, the power to heat ratio of IC engine is from 0.5-0.7 (Wu & Wang, 2006), the size range is from 10 kW to over 5 MW (Energy and Environmental Analysis, Inc. an ICF Company, 2008). For the microturbine, the power to heat ratio is 1.2-1.7, the available size ranges from 15-300 kW (Wu & Wang, 2006). Therefore, for the follow base thermal load calculation, the prime mover capacity is 15 kW for both IC engine and microturbine. The power ratio is assumed 0.7 and 1.45 for IC engine and microturbine respectively. Thus the heat generation capacity is 10.5 kW and 21.75 kW respectively. In the scenarios for two prime movers of FBTL operation, the base thermal load is 21 kW and 43.5 kW respectively.

In the follow thermal load operation, from the simulation results the maximum thermal load is 166 kW; based on the power to heat ratio, the electrical capacity is 116 kW and 241 kW for the IC engine and microturbine respectively.

The prime mover can't achieve design efficiency at part load situation. The efficiency generally decreases with the load ratio. In conducting the calculation, the performance curve of prime mover is based on typical performance curve from (Energy and Environmental Analysis, Inc. an ICF Company, 2008) and (Capstone Turbine Corporation, 2011). Figure 4-4 and Figure 4-5 showed the performance curve for the IC engine and microturbine respectively.

Figure 4—4 IC Engine load performance curve

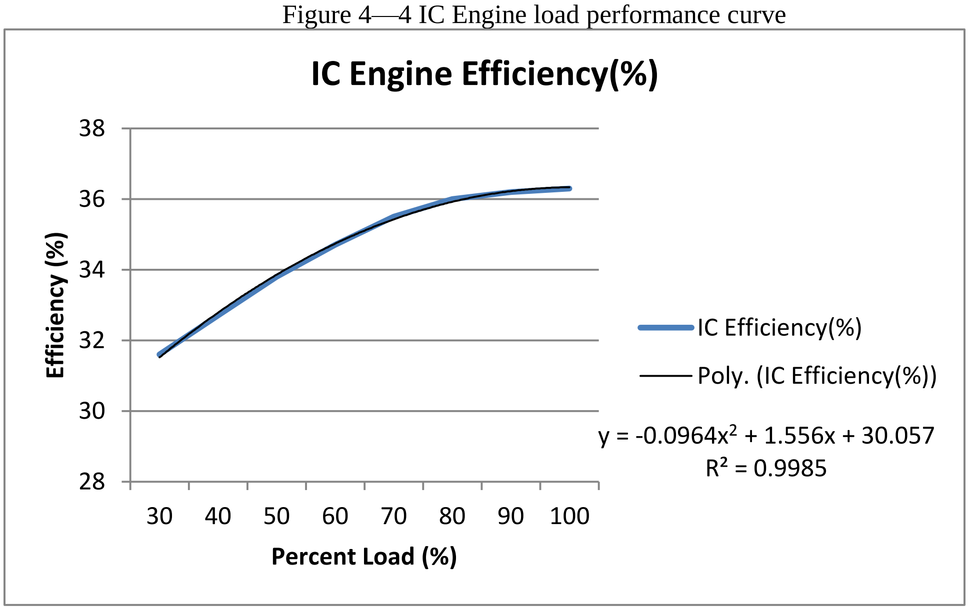
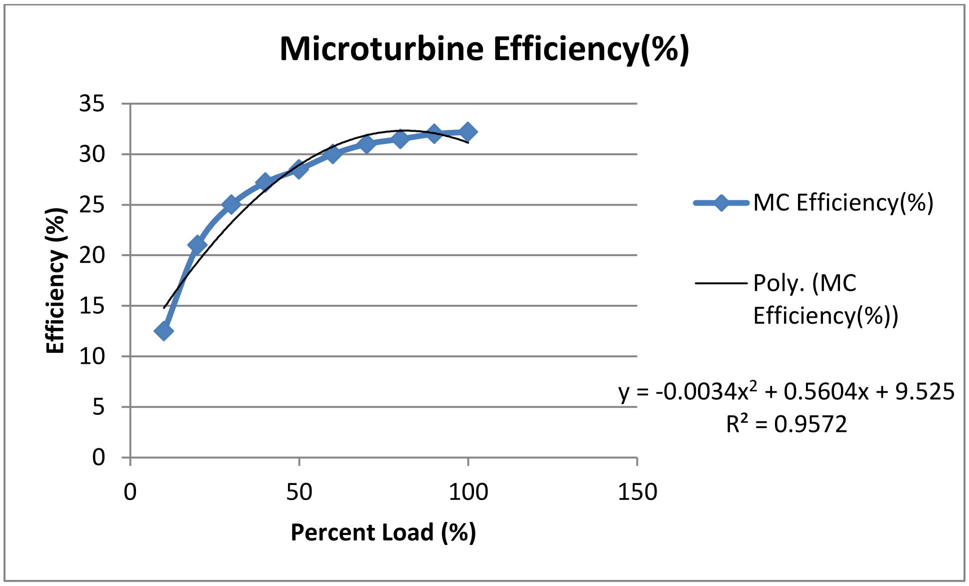


Figure 4—5 Microturbine part load performance Curve.



From the regression analysis in the figure, the part load efficiency equations for IC engine and microturbine are:

$$\text{Efficiency (\%)} = -0.0964(\text{Load Percentage})^2 + 1.556(\text{Load Percentage}) + 30.057$$

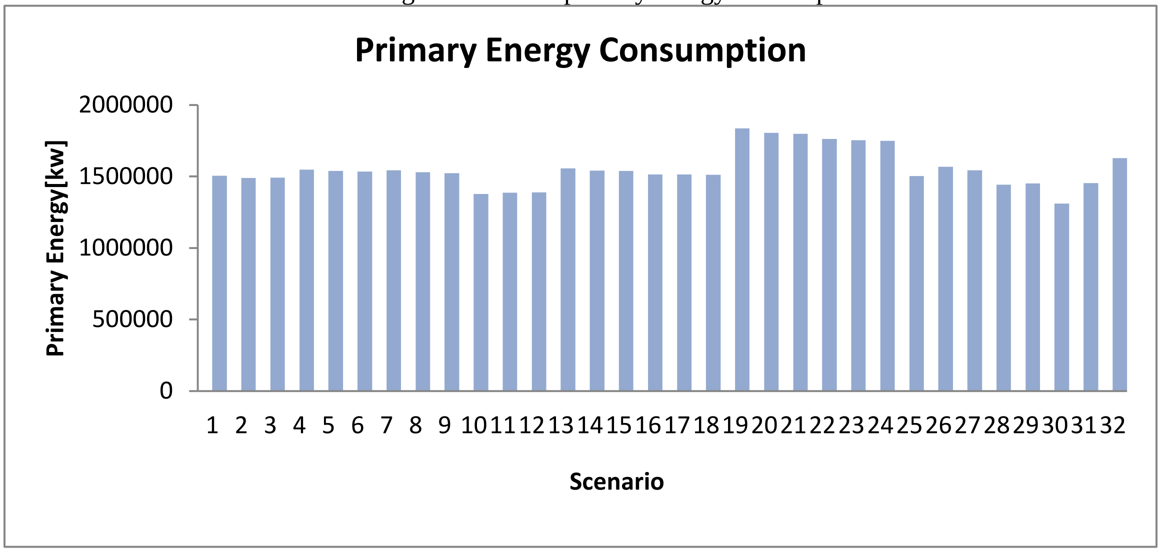
$$\text{Efficiency (\%)} = -0.0034(\text{Load Percentage})^2 + 0.5604(\text{Load Percentage}) + 9.525$$

Results and Discussions

Primary Energy Consumption

Figure 4-6 shows the results of primary energy consumption for different scenarios.

Figure 4—6 The primary energy consumption.



In the IC engine with absorption chiller (Scenarios 1-12), the implementation of high COP absorption chiller results in less primary consumption. Increasing the COP from single effect to double effect by 50% and 70%, the primary energy reduction is only 1% to 2%. The saving percentage is small compared with the increase percentage of COPs. This may result from that when the high COP reduces the thermal demand for the prime mover, but in the other hand, the electricity import from the grid increases as the output of prime decreases. The savings from the double effect absorption chiller is neutralized by the electricity import from the grid. Another reason is that, the absorption chiller only work when there is demand for cooling, from Figure 4-1, the heating load is the major thermal load, and cooling is mainly required only from May to September.

Among the IC engine with absorption chiller scenarios, two equally sized prime movers with FTL strategy have superior performances (Scenario 10, 11 and 12). In the FTL, the average electricity production from the prime mover is higher than the base load following. The primary energy consumption for 1 kW of electricity is 2.97 times higher than the 1 kW of natural gas. The result of high electricity production is the deduction of electricity import from the grid. When two prime movers operate simultaneously, one of them operates at the highest efficiency. When there only one prime mover is in operation, FBTL is better than FTL in terms of prime mover efficiency. The main reason is that for the FBTL operation, the prime mover operates at full load- the desired efficiency. In the FTL mode, the capacity of prime mover has to meet the largest thermal load, but from the perspective of whole year operation, in the 96% of the time the load demand is below the 50% of the peak load. Consequently, in most time of operation, the system was operating at low part low ratio. For IC engine, when the part load ratio is below 50%, the electricity generation efficiency is close or even lower than the separate power plant. This is supportive evidence that for two equally sized prime movers during FTL, the performance is much better than one prime mover's operation because one prime mover operates high part load efficiency.

When microturbine operates with an absorption chiller (Scenario 13-24), the conclusion is similar to IC engines. The FTL with two equally sized prime movers has the lowest prime mover consumption. In the FTL, the electricity production from the BCHP system is higher than the FBTL, thus decrease the primary energy consumption at the power plant. Additionally, two prime movers increase the part load performance of the prime mover. When two prime movers are on line simultaneously, one prime mover is at the desire efficiency. For one microturbine engine set operation, FBTL is superior to the FTL. This is because at FTL, most of situations, the engine operates at low part load ratio and reduced efficiency.

For the operation with DX unitary system (Scenario 25-32), the general conclusion is the same as the scenarios with absorption cooling. The comparison between DX unitary system and absorption cooling in terms of primary energy consumption is that two types of cooling system consumes close amount of primary energy to produce the same amount of cooling energy. For example, a double effect absorption unit with a COP of 1.2, the conversion factor for natural to the primary energy is 1.047, so the overall conversion factor is 0.87. For electrical chiller with a COP of 3.67, the electricity conversion factor to primary energy is 3.1, so the overall conversion factor is 0.84.There is no great advantage of choosing one type of cooling system over the other in terms of primary energy consumption.

Among all the combinations, Scenario 30 has the lowest primary consumption. It is a system with two microturbines operating on the FBTL strategy. Microturbine has a high power to ratio than steam engine and IC engine. With same amount of heat production, microturbine can save more primary energy than the IC engine. When operate with two prime movers, prime mover has high part load ratio and one prime mover always operates at the full design load. The FBTL operation with two prime movers showed the impact of prime mover capacity on the total energy consumption. Although it is not the optimum size of prime mover, it is an example that the optimum size of prime mover is between the base thermal load and the peak load (ASHRAE, 2008). The group of two IC engines with FTL strategy has the second best performance. During the operation, one of two prime movers is operated at full load and thus achieved high overall system efficiency. Another reason is that IC engines have better part load performance than the microturbine, so in the FTL operation, especially when most of the time the building operates under 50% of full load, the good part load efficiency of IC engine outweighs the performance of microturbine.

In the overall performance evaluation, IC engine has lower average energy consumption; the main result is that IC engine has high part load efficiency. In the building operation, especially for the peak load design BCHP system, most of the times the building is operated under the design load. The low part load efficiency deteriorates the benefits and purpose of utilizing BCHP system. IC engine is very responsive at transient load and has good part load efficiency; therefore, it is an idea candidate for the residential BCHP system design.

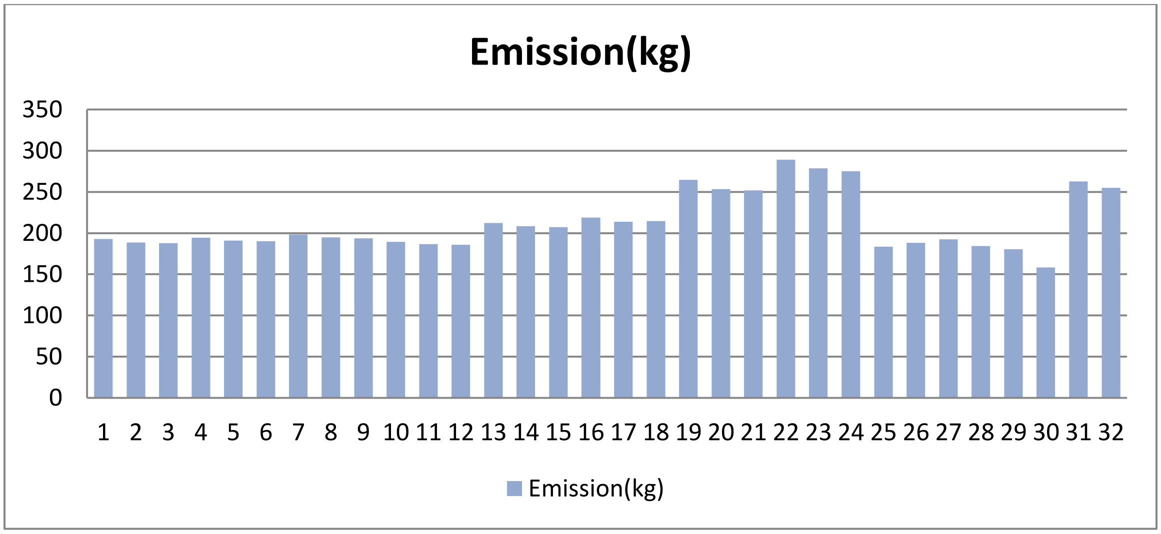
Carbon Dioxide and toxic pollutant Emission

From the Table 4-4, the emission equation is:

$$\text{Total Emission}\left(\frac{\text{tons}}{\text{year}}\right) = 0.00031 \cdot \text{Electricity(kW)} + 0.0002 \cdot \text{NG(kW)}$$

Figure 4-7 shows the results of total emission for different scenarios.

Figure 4—7 Total emission (kg) for different scenarios.



For the operation of IC engine with absorption chiller, the maximum emission variation is 15 % and this is close to the primary energy variation 11%. From the emission defining equation, a high number of primary energy consumption tends to have higher total emission. The Figure 4-8 and Figure 4-9 are normalized parametric comparison and show this trend.

Figure 4—8 Relative evaluation of energy consumption and emission (Scenario 1-17)

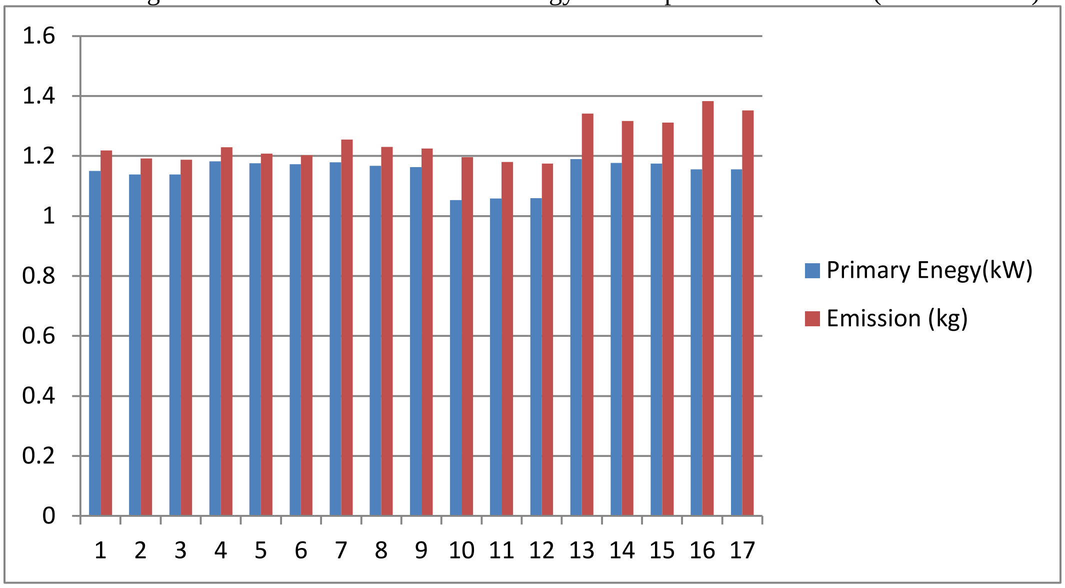
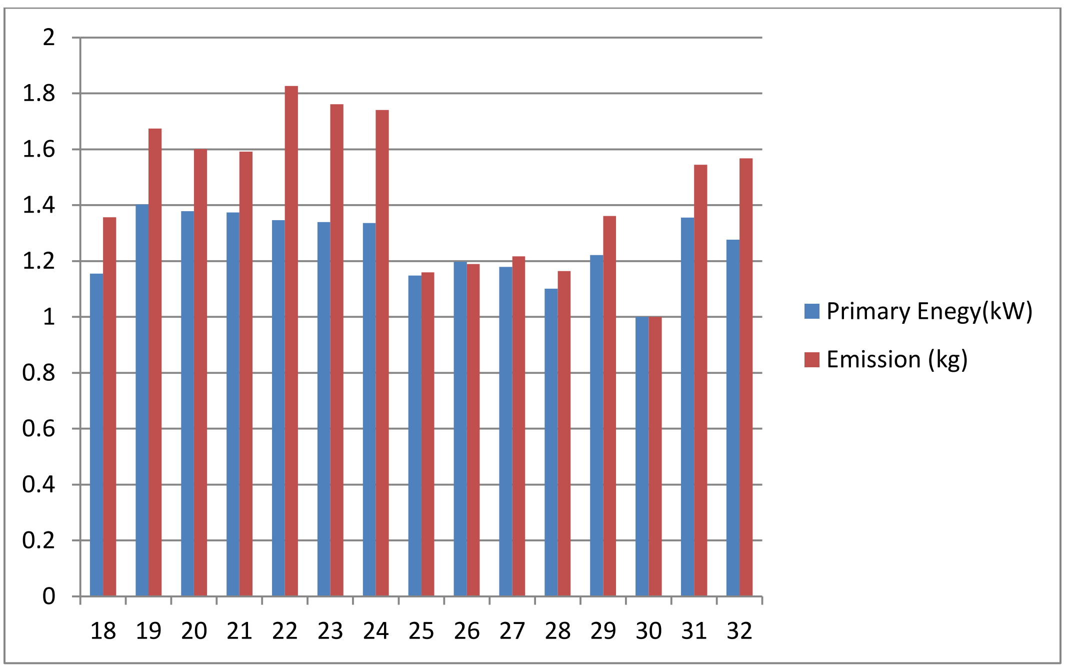


Figure 4—9 Relative evaluation of energy consumption and emission (Scenario 18-32)



Scenarios from 1 to 18 have average low primary energy consumption than scenarios 19 to 24, so the average emission is lower than the scenarios from 19 to 24. This demonstrates the importance of reducing the energy consumption. The natural gas and coal are fossil fuels, the direct utilization results in the greenhouse gases emission and the greenhouse gases that absorb thermal radiation and re-radiate back to earth.

Scenario 30 has the lowest primary energy consumption and the total emission. The group of two IC engines with FTL strategy has the second best performance. In the operation of FTL strategy, average IC engine emission rate is lower than the microturbine. From the analysis of the primary energy consumption, the main reason is that the IC engines have better performance at part load. In this simulation, 96% of the time building is under the 50% of peak load, the performance at part load will determine the global outcome in terms of primary energy consumption, emission and average efficiency.

Total Fuel Expenditure

The total fuel cost includes the natural gas consumption in the boiler and prime mover and the electricity import from the grid. From the location selection analysis, the price for natural gas is 18.6 c/kWh (0.186 $/kW) and 15.05 $/thousand cubic feet (0.066$/kW). In the calculation, selling electricity back to the grid is not accessible because this is not economically advisable and maybe prohibited by the policy at some states. The total fuel cost is given by the equation below.

Total Fuel Expenditure:

$$\text{Cost (\$)} = 0.186 \cdot E_{\text{grid}} + 0.066 \cdot F_{\text{boiler,duct burner}} + 0.066 \cdot F_{\text{prime mover}}$$

Although from the equation, with same amount of energy production, the cost of electricity is 2.8 times higher than the cost electricity, this doesn’t mean the percentage of electricity in the total primary energy consumption is determinant of the fuel cost. To minimize the total fuel cost, this needs the tradeoff between the electricity and natural gas consumption while at the meantime meet the building load. This will be achieved in the next chapter, the detailed optimization with linear programming. Figure 4-10 shows the percentage of electricity in the primary consumption.

Figure 4—10 Electricity percentage in the total primary energy consumption

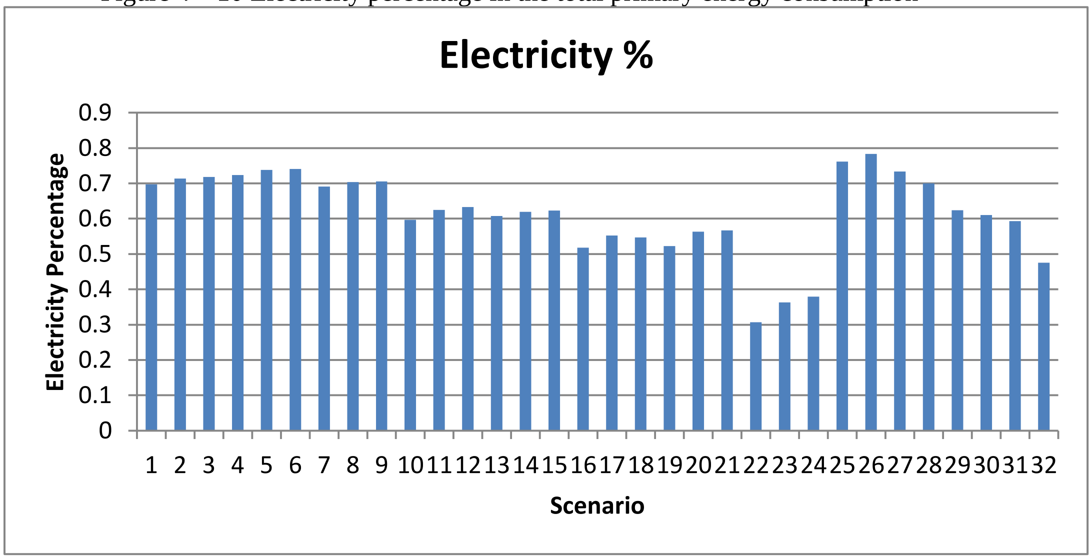
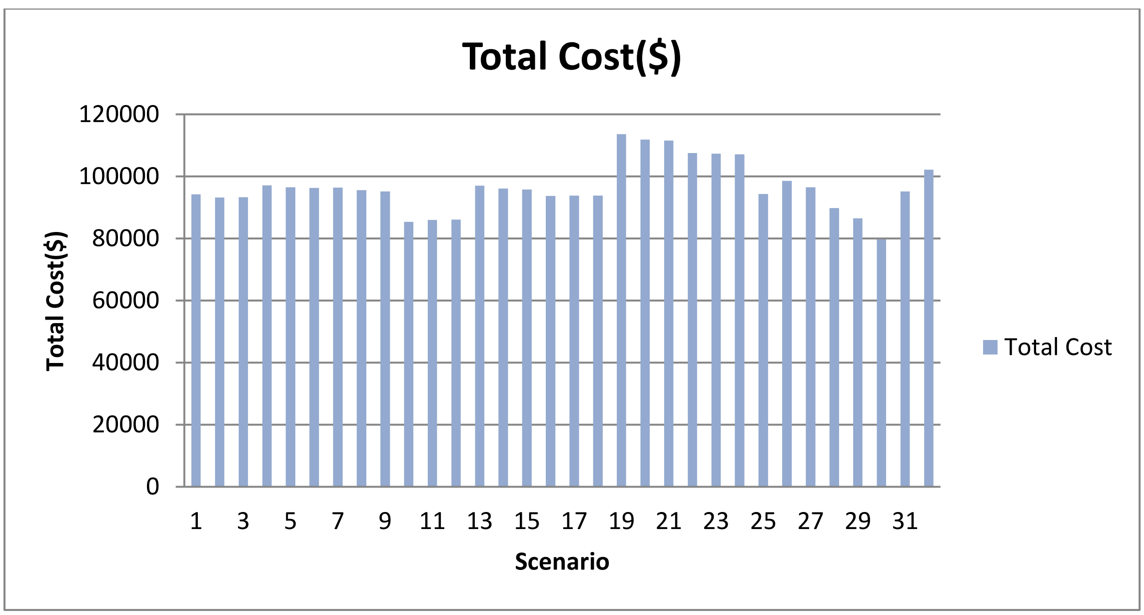


Figure 4-11 gives calculation results of total fuel cost.

Figure 4—11 Total Fuel Cost



By comparison of figure 4-9 and figure 4-10, scenario 26 has the highest electricity percentage but the highest cost is scenario 19. The low percentage of electricity consumption will significantly increase the natural gas consumption in the microturbine with absorption cooling in FTL strategy. This is because the microturbine has a low heat to power ratio, and the electric part load efficiency is relatively low, so this requires even more natural gas consumption to meet the load. Among all the scenarios, scenario 30 has the lowest fuel cost. The IC engine group with the absorption cooling in FTL is the second best.

System and Overall Building Efficiency

The system efficiency demonstrates the efficiency of fuel utilization within the BCHP system boundary. It combines the electricity generation productivity and heat recovery efficiency.

BCHP System Efficiency:

$$\eta=\frac{(E_{PGU}+Q_{rec})}{Q_{fuel}}$$

The overall building efficiency has a different system boundary from the BCHP system efficiency. The input is the primary energy consumption to make electricity and natural gas in the grid or boiler respectively. The output is the energy supply to meet the heating, cooling and electrical demand. The importance of overall building energy efficiency should outweigh the system efficiency.

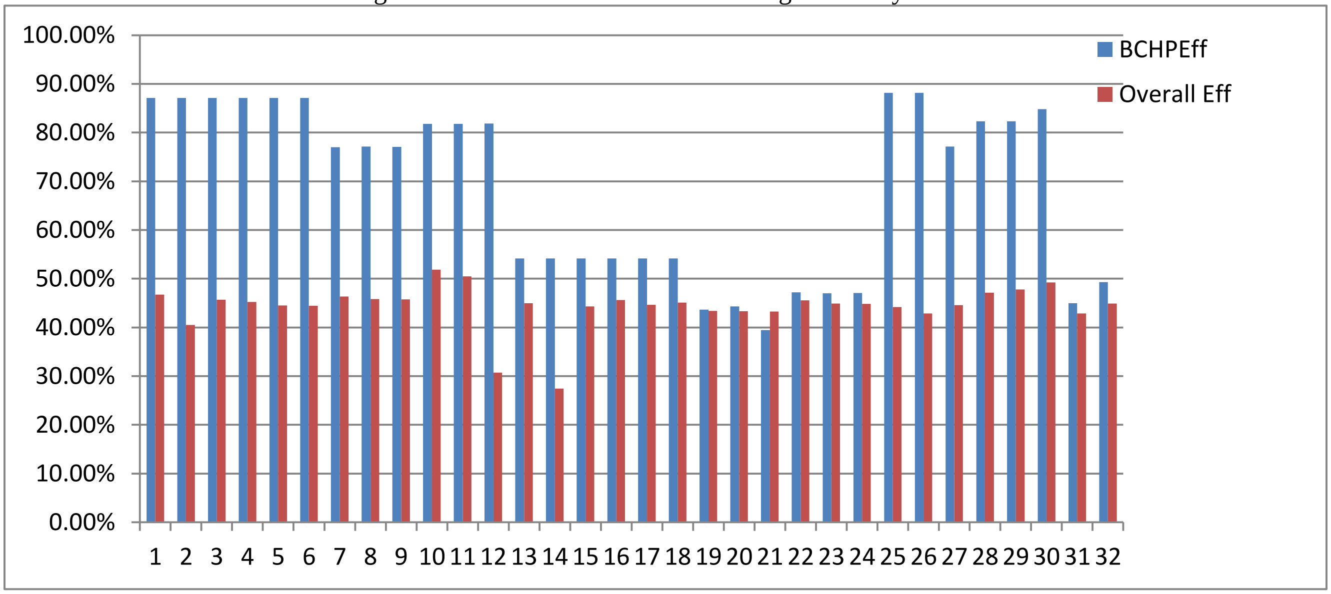
Overall Building Efficiency:

$$\eta_{overal}=\frac{(E_{PGU}+E_{grid}+Q_{total\ rec}+Q_{Boiler})}{Q_{PM,fuel}+Q_{grid,fuel}+Q_{boiler,fuel}}$$

Both equations are available for different types of system or operation strategy. One limitation of first law energy analysis is that it can’t distinguish the quality of energy.

Nevertheless, it still offers an understanding of energy utilization. Figure 4-12 shows the BCHP system efficiency and the overall building efficiency.

Figure 4—12 BCHP and overall building efficiency



From the figure, it clearly shows that there is no direct relationship between the overall efficiency and BCHP system efficiency. The group of FBTL for IC engine (Scenario 1 to 6, 25 and 26) and microturbine (Scenario 29 to 30) has the highest system efficiency. This is because in the FBTL design, the capacity of prime mover is set to meet the base load of the building, thus in the operation process, the system operates at the full load which is the highest theoretical efficiency. In the FTL operation, two equally sized engines are better than one prime mover in terms of system efficiency. The reason is when two prime movers are running; one is at the full load-the highest design efficiency. The capacity of two prime mover based design is only 50% of the peak load design capacity, therefore, even at low load situation, the system still has relatively high part load efficiency. This parametric simulation demonstrates the impact of prime mover size on the system efficiency. The smaller the size of prime mover yields lower energy consumption and fuel cost within the BCHP system.

For the overall building efficiency, each scenario has a relatively close efficiency which is between 40 to 50%. The top three are scenario 10, 11 and 30.

To summarize, this chapter looked into the effect prime mover size, operation strategy and HVAC components on the energy consumption, expenditure, emission and efficiency of BCHP system and the whole building. In conducting the parametric comparison, hourly load simulation was derived from the Energyplus. A multi-residential building was simulated based on New York City weather file. The simulation provides the hourly cooling, heating and electrical demand. The criterion for comparison is the yearly primary energy consumption and fuel expenditure for the building and BCHP system operation, total emissions from the electricity and natural gas consumption. The candidate systems are the IC engine and microturbine, the number of prime movers varies from 1 to 2, and operation strategies include FTL and FBTL strategy. Two system configurations consists the body of comparison. The prime mover provides the heat and simultaneously produces the electricity. The heat could be used in the absorption chiller for cooling or meet the heating demand. The shortage of thermal or electrical demand can be met by the boiler, duct burner or the grid. The research also looked into the impact of single effect and double effect absorption cooling. The double effect absorption cooling could only slightly improve the energy consumption and fuel cost. This may result from that a high efficiency absorption chiller decreases the thermal demand for the prime mover, but the decrease is offset by the electrical import from the grid. Also the cooling load demand is only required in certain amount of time. In evaluating the total primary energy consumption and fuel cost, scenario 30 has the best performance. The second best among all the scenarios is the group two IC engines with AC in the FTL operation.

In the scenario of IC engines operating with the DX unitary system, when the system operates with only one prime mover, FBTL is superior to the FTL; this is because of the high part load performance at the FBTL. In the FTL operation, tow equally sized prime movers is better than one prime mover system configuration. From the building load data analysis, more than 96% of the time the building is under 50% of the peak load, the peak load design system was damaged by the low part load ratio.

For microturbine with absorption chiller system, the conclusion is analogous to the IC engine. In the operation with DX unitary system, the primary energy consumption for cooling is close to the absorption chiller. The advantage of high COP of DX unitary system is offset by the high primary energy conversion factor for the electricity.

In the analysis of total emission, reducing the total amount of primary energy is important in the reduction of greenhouse gases emission. In the calculation, the included greenhouse gases are carbon dioxide, methane and nitrous dioxide. The general trend is that the annual emission grows proportionately with the energy consumption.

For the system and overall building efficiency parametric evaluation, there is no direct relationship between the overall efficiency and BCHP system efficiency. The group of FBTL for IC engine and microturbine has the highest system efficiency. This is because in the FBTL design, the capacity of prime mover is set to meet the base load of the building, the prime mover is operated at full load when it is online; but they only have an average overall building efficiency. Scenario 30 doesn’t have the highest system efficiency but has the best overall building efficiency.

Based on the previous analysis, scenario 30 has the best comprehensive outstanding performance. It is a two microturbines based design with DX unitary system and FBTL system.

Table 4-7 The Summary of Calculation Results

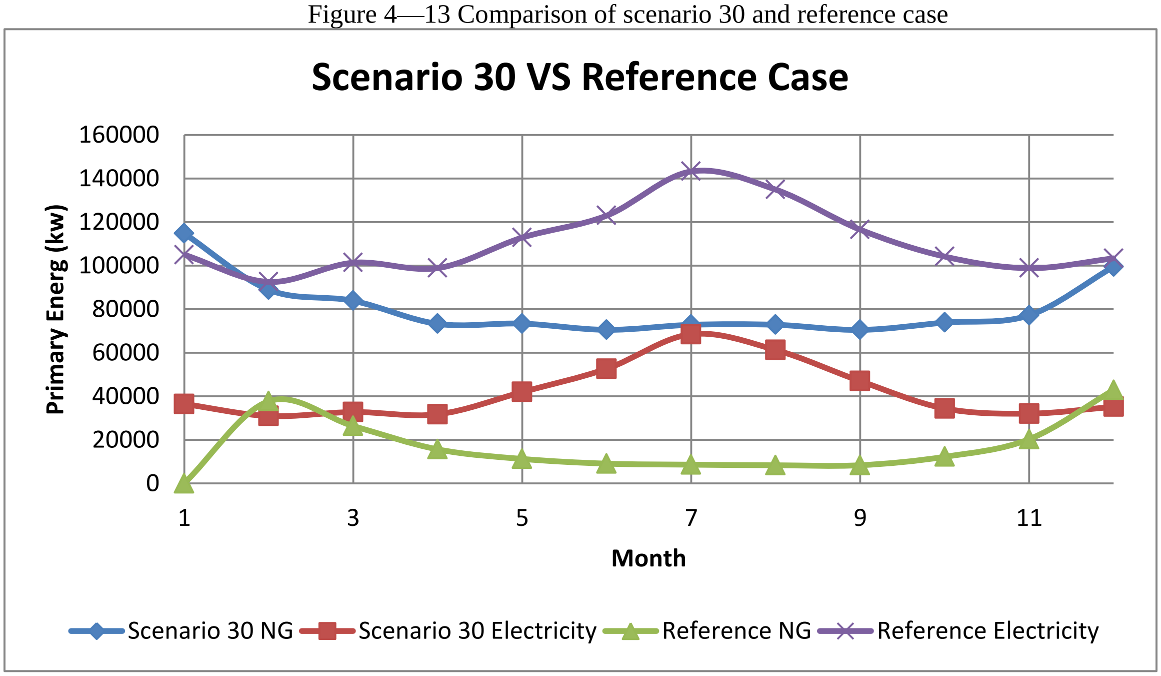
Scenario	Primary Energy[kw]	Emission(ton)	Cost($)	BCHPEff	Overall Eff
1	1506361.99	192.68	91765.15	87.12%	46.74%
2	1490403.02	188.48	90721.85	87.12%	40.54%
3	1491053.03	187.86	90738.40	87.12%	45.70%
4	1548683.17	194.39	94221.50	87.12%	45.24%
5	1539226.07	191.098	93576.77	87.12%	44.52%
6	1535069.51	190.26	93313.34	87.12%	44.42%
7	1543775.54	198.45	94076.71	77.03%	46.34%
8	1529000.03	194.68	93114.87	77.12%	45.80%
9	1523400.72	193.80	92768.13	77.07%	45.73%
10	1378778.77	189.24	84416.62	81.82%	51.86%
11	1386354.99	186.61	84759.82	81.76%	50.51%
12	1387985.55	185.85	84827.31	81.87%	30.74%
13	1557457.52	212.18	95304.49	54.15%	44.95%
14	1541729.77	208.31	94285.01	54.15%	27.43%
15	1538121.85	207.37	94049.60	54.15%	44.30%
16	1513646.39	218.76	93036.28	54.15%	45.65%
17	1513253.60	213.86	92852.90	54.15%	44.66%
18	1512784.92	214.54	92848.46	54.15%	45.12%
19	1837149.41	264.76	112895.60	43.63%	43.38%
20	1804964.11	253.28	110692.60	44.30%	43.32%
21	1799514.02	251.84	110336.20	39.46%	43.25%
22	1762823.28	289.02	109478.90	47.19%	45.58%
23	1754541.03	278.56	108664.90	47.01%	44.93%
24	1750065.34	275.27	108303.10	47.07%	44.84%
25	1503237.73	183.37	91281.60	88.16%	44.16%
26	1567736.98	188.06	95093.76	88.16%	42.90%
27	1543934.31	192.43	93887.61	77.15%	44.55%
28	1442285.17	184.21	87852.76	82.33%	47.16%
29	1452165.22	180.46	86513.15	82.33%	47.81%
30	1309644.49	158.20	79670.16	84.79%	49.26%
31	1453510.03	262.58	95207.40	44.97%	42.85%
32	1628902.58	255.00	102189.60	49.31%	44.94%

Table 4-7.The comparison between scenario 30 and the reference system

	Primary Energy[kw]	Emission(ton)	Total Cost($)	Overall Eff
Reference building	1596568.47	183.21	96580.03	40.41%
Scenario 30	1309644.49	158.20	79670.16	49.26%
Variation Percentage	17.97%	13.65%	17.51%	21.91%

Scenario 30 has the largest saving percentage at the primary energy consumption and total fuel cost. Figure 4-13 gives the monthly operation data between scenario 30 and the reference building.

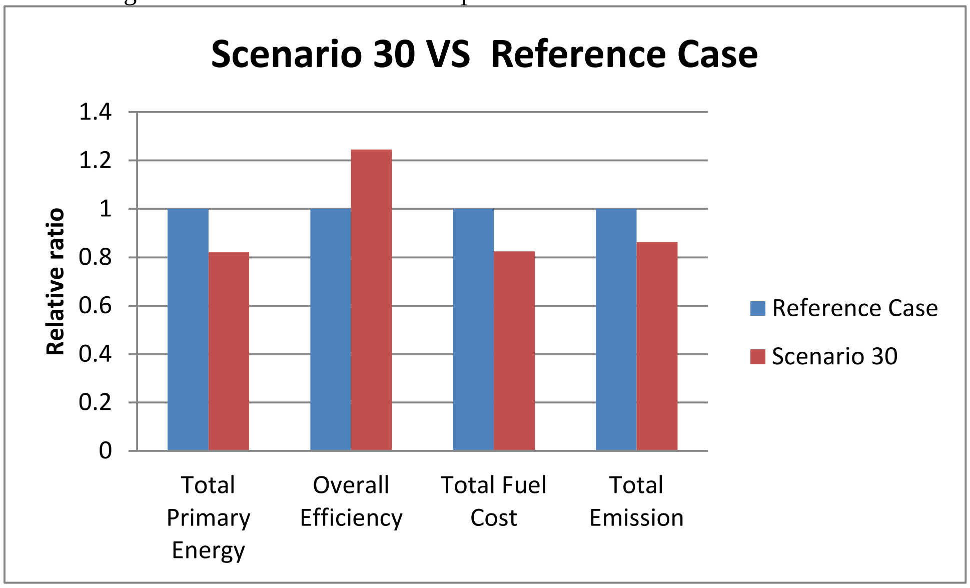
Figure 4—13 Comparison of scenario 30 and reference case



From the figure, scenario 30 has a very constant monthly electricity import. The high power to heat ratio compensate the electricity primary energy consumption and the two primary mover operation strategy increases the system efficiency.

So as to show the benefits of scenario 30 more clearly, Figure 4-14 is the comparison ratio figure. The baseline system is the reference building operation system.

Figure 4—14 Relative ration comparison between scenario 30 and reference case



From the above analysis, scenario 30 is chosen to be the system that is further optimized with detail hourly linear programming.

Chapter 5 **The Optimization of Operation Strategy**

The benefits of BCHP system are high energy efficiency, low emissions and increased the reliability of grid. The realization of all the benefits above requires a good system design, construction, integration and operation. In the previous chapters, the research looked into the location selection and system design procedures, in this chapter, the research focus on the optimization of operation strategy.

The optimization of BCHP operation is complicated because of different characters of system components, the building load for heating, cooling and electricity varies every hour and the options for energy source includes electricity grid, natural gas in the duct burner and prime mover. In conventional operation strategy, it is based on predetermined principals for example follow the thermal load or electrical load. The benefits of traditional operation scheme are that it focuses on the efficiency of BCHP system and utilization of waste heat. (H. Cho, Luck, Mago, & Chamra, 2009) suggests that it is appropriate to optimize the operation based on the cost, emission and primary energy consumption. In this research, the optimization is trying to minimize the annual primary energy consumption, fuel cost and total emissions. The results can show the possible maximum theoretical benefits of BCHP system in terms of three objective topics.

The validity of linear programming (LP) of optimizing the BCHP and CHP systems has been demonstrates in several studies (R. Lahdelma & Hakonen, 2003),(Anna Kathrine Hueffed, 2010)(H. Cho, Mago, et al., 2009)(Yokoyama, Ito, & Matsumoto, 1994)(Sakawa, Kato, & Ushiro, 2002). Linear programming is a mathematical method for optimization of linear objective functions. The LP calculates a point in the function has the smallest or largest value.(Heejin Cho et al., 2009) implemented LP equations on an IC engine for commercial building optimization. They also tested this method on a micro-CHP facility at Mississippi state university. The results of LP presents different amount of energy produced by prime mover, electricity grid and auxiliary equipment (boiler and duct burner) in terms of minimizing the primary energy consumption, emission and fuel cost.

Objective functions for fuel cost, primary energy consumption and emission:

Total fuel cost:

This objective function describes the goal of minimizing the total fuel cost in the operation of BCHP system and simultaneously meets the heating, cooling and electrical demand.

$$F(t) = \text{Min}\sum_{1}^{8760}\left[P_{elec}E_{grid} + P_{NG}F_{auxiliary} + P_{NG}F_{PM} - P_{exce\ elec}E_{exce\ elec}\right]$$

P_{elec}, P_{NG} represent the price for 1 kWh electricity from the grid and the price for purchasing 1 kW natural gas in the boiler or duct burner. E_{grid} means the net amount of electricity import from the power plant. $F_{auxiliary}$ is the amount of natural gas consumption in the duct burner to meet the load. The last term $P_{exce\ elec}E_{exce\ elec}$ is the total revenue for selling electricity back to the grid. $P_{exce\ elec}$ is the price for selling back and $E_{exce\ elec}$ is the excess amount of electricity production. From the assumptions in this research, the excess amount electricity is used in the electric heater and selling back to the grid is not allowed. Once there is enough of selling electricity back to the grid, the last component can be added back to the equation.

To reduce the total fuel cost, one requirement of the equation is that the increase natural gas cost must be smaller or equal to the decrease in the electricity purchase expenditure.

Another topic of the optimization is to minimize the total primary energy consumption. The primary energy consumption is the energy consumption at the site plus the loss in the transmission, distribution and the generation. The effect of loss in the transmission, distribution and generation is included in the electricity generation efficiency and natural gas conversion factor.

Primary energy consumption:

$$F(t) = \mathrm{Min}\ \sum_{1}^{8760}\left[\frac{E_{grid}}{\eta_{grid}} + \frac{F_{auxiliary}}{\eta_{auxiliary}} \cdot 1.047 + \frac{E_{PM}}{\eta_{PM}} \cdot 1.047 - \frac{E_{exce}}{\eta_{grid}}\right]$$

Where η_{grid}, $\eta_{auxiliary}$ η_{PM} are the electricity generation efficiency, duct burner and prime mover natural gas utilization efficiency respectively. 1.047 is the natural gas conversion factor from site energy to primary energy (ENERGY STAR, 2005). The last term is the replaced primary energy consumption in the power plant by extra electricity production in the prime mover. Based on the previous assumption, this component is set to zero in the calculation.

Greenhouse gas emission:

The total greenhouse gas emission is calculated from the Table 4-4. The emission is in two groups: the emission from the electricity production and natural gas utilization. The objective function is expressed as follows:

$$F(t) = \mathrm{Min}\sum_{1}^{8760}\left[GHG_{elec}E_{grid} + GHG_{NG}F_{PM} + GHG_{NG}F_{auxiliary} - GHG_{elec}E_{exce}\right]$$

GHG_{elec} and GHG_{NG} is the greenhouse gas emission per kW consumption for electricity and natural gas.

Constraints in the LP optimization:

In the calculation of objective functions, the objective function is met by simultaneously satisfy the building heating, cooling and electrical demand, and this is also has to under the limitations in the system components and physical laws. The constraint equation is set to meet those requirements. It involves in the first law energy analysis, system component characteristics and building load demand.

Overall energy constraint:

$$E_{grid} + F_{PM} + F_{auxiliary} - E_{exce} - E_{total\ loss} \geq Energy_{required}$$

Where E_{grid} is the net electricity import from the grid, $F_{PM}, F_{auxiliary}$ are the natural gas fuel intake in the prime mover and duct burner. E_{exce} is the excess amount of electricity sells back to the grid which is zero in the calculation. $E_{total\ loss}$ is the energy loss in the system.

$$Energy_{required} = E_{electricity} + Q_{cooling} + Q_{heating} + Q_{d\ HW}$$

$Energy_{required}$ is the energy requirement in the building which is the electrical demand, cooling, heating demand and thermal demand for the hot water.

The electricity import from the grid is depending on the relationship between the electrical demand from the building and the electricity production in the prime mover.

$E_{grid} = 0$ When $E_{PM} > E_{required}$

$E_{grid} = E_{required} - E_{PM}$ When $E_{PM} < E_{required}$

$E_{grid} = E_{required}$ When $E_{required} < \min E_{PM}$

Prime mover energy conservation:

$$E_{PM} + Q_{rec} + E_{loss,PM} = F_{PM}$$

$$E_{loss,PM} = (1 - \eta_{PM,elec} - \eta_{PM,thermal}) \cdot F_{PM}$$

Where E_{PM} is the electricity production from the prime mover Q_{rec} is the recovered heat in the heat recovery device. $E_{loss,PM}$ is the energy loss in the prime mover. F_{PM} is the total fuel in put in the natural gas.

Duct burner energy conservation:

$$Q_{duct\ burner} - Q_{loss,burner} = F_{duct\ burner}$$

$Q_{duct\ burner}$ is the heat produced by the duct burner. $Q_{loss,burner}$ is the heat loss in the duct burner. $F_{duct\ burner}$ is the total natural gas consumption in the duct burner.

The heat produced by the duct burner depends on the demand between building heating load and the heat production in the prime mover.

$$Q_{loss,burner} = (1 - \eta_{boiler}) \cdot F_{burner}$$

$$Q_{burner} = 0 \qquad \text{When } Q_{rec} > Q_{required}$$

$$Q_{burner} = Q_{required} - Q_{rec} \qquad \text{When } Q_{rec} < Q_{required}$$

Electricity demand balance:

The electricity balance ensures that the building's power demand includes lights, electrical equipment and miscellaneous electrical loads must be satisfied by the grid and prime mover.

$$E_{grid} + E_{PM} - E_{exce} = E_{demand}$$

This equation means that electricity is supplied from the grid, prime mover to meet the building electrical load.

Thermal demand balance:

This is equation guarantees that thermal demand for cooling, heating and hot water can be met by the system. The thermal demand is met by the heat produced by the duct burner, recovered heat from the heat recovery device and electrical chiller.

$$Q_{heating} + Q_{cooling} + Q_{DHW} = Q_{duct\ burner} + Q_{rec} + Q_{elec\ chiller}$$

Where $Q_{heating}$, Q_{DHW} are the heating demand for space heating and hot water respectfully.

$Q_{duct\ burner}$, Q_{rec} are the heat produced from the boiler and recovered by the heat recovery device. $Q_{elec\ chiller}$ is the cooling energy produced by the electrical chiller.

Heating demand balance:

$$Q_{heating} \leq Q_{duct\ burner} + Q_{rec}$$

This equation means that the space heating demand is met by the duct burner and recovered heat.

System efficiency limitation:

$$Q_{rec} = \eta_{rec}\ Q_{waste}$$

$$Q_{duct\ burner} = \eta_{duct\ burner} F_{duct\ burner}$$

Where η_{rec} is the heat recovery device efficiency and Q_{waste} is the heat produced by the prime mover.

The fuel consumption for the prime mover:

In the linear programming, the objective and constraint equations are required to be linear. (H. J. Cho, 2009) developed a fixed point iteration method and direct fuel to energy conversion method. In (H. Cho, Luck, et al., 2009), they looked into the prime mover from 15 kW to 1400 kW, the relationship between the fuel and energy production in this research for a typical 15 kW prime mover is $F_{PM} = 2.61 \cdot E_{PM} + 6.8$

Therefore the general expression is:

$F_{PM} = 2.61 \cdot E_{PM} + 6.8$ if $E_{PM} > 0$

$F_{PM} = 0$ if $E_{PM} = 0$

Simulation Results:

The LP based optimization is based on the primary energy consumption, emission and fuel cost. The LP optimized the hourly load from the building energy simulation. The reduction in primary energy, emission and fuel cost depend on the tradeoff between different energy demand, system characteristics and the relocation of energy production. The optimization of one topic may increase or decrease other two objective functions. Table 5-1, 5-2 and 5-3 gives the optimized results.

Table 5-1. The Table of Optimized Primary Energy Consumption

	Reference Building	Optimized System	Variation(%)
Primary Energy	1,596,568	1,229,664	-22.98%
Fuel Cost	96,580	81,178	-15.95%
Emission	183	246	34.39%

Table 5-2. The Table of Optimized Fuel Cost

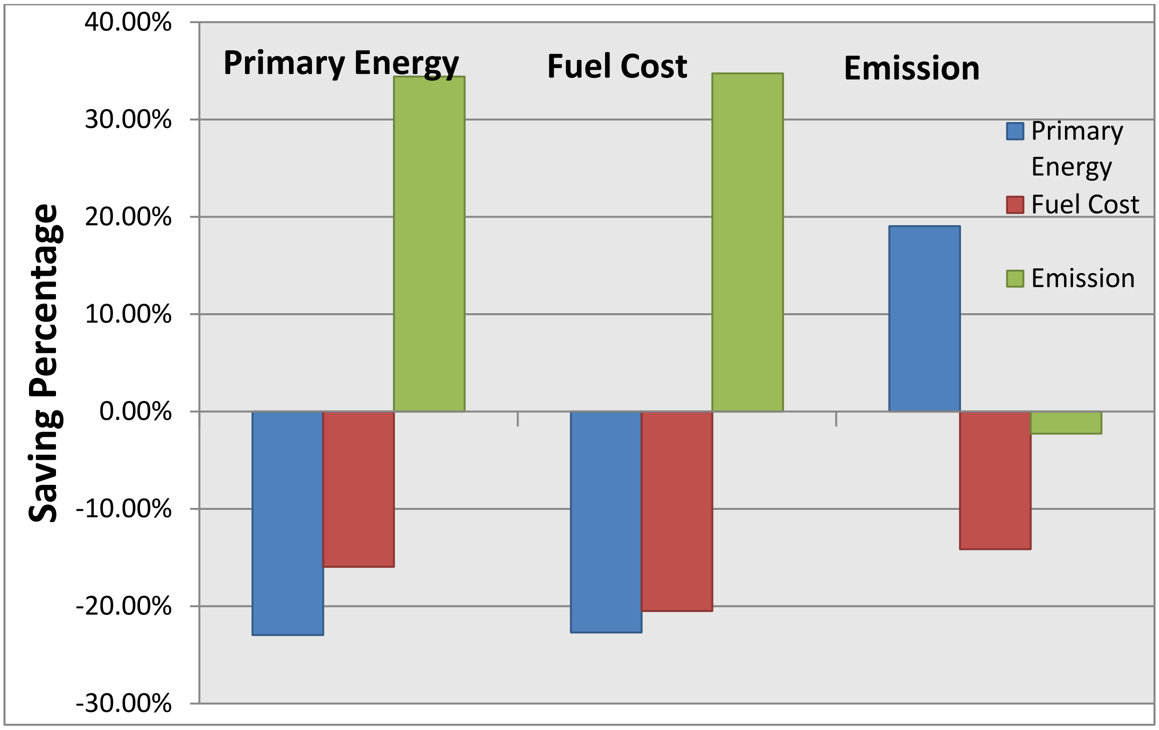
	Reference Building	Optimized System	Variation(%)
Primary Energy	1,596,568	1,233,784	-22.72%
Fuel Cost	96,580	76,771	-20.51%
Emission	184	248	34.75%

Table 5-3.The Table of Optimized Emission

	Reference Building	Optimized System	Variation(%)
Primary Energy	1,596,568	1,900,494	19.04%
Fuel Cost	96,580	82,911	14.15%
Emission	183	179	-2.29%

From the table above, optimization of one function could lead to the increase or decrease other two topics. It should be noticed that the negative number in the variation is the saving percentage. The negative number implies an increase compared to the reference case. In each optimization mode, the corresponding topic reached the highest saving among three optimization modes. For example, the possible maximum theoretical saving for primary energy consumption from the BCHP is 22.98%, while in the fuel cost optimization, the saving percentage decreased to 22.72%. The optimization of primary energy achieves the maximum saving percentage among three objective functions, which is 22.98 %, and the fuel cost also decreased by 15.95%. In the minimization of fuel cost, it is slightly lower than the FBTL and saved up to 20.51% than the reference case. In the minimization of primary and fuel cost functions, the annual emission increased by 34.39%. In contrary, in the optimization of annual emission, the primary energy consumption increased by 19.04% than the reference building. Therefore, there is no general trend between the change of target equation and other two objective functions. The change of one function could lead to the increase or decrease in the other two equations. This results from the tradeoff between different percentage of fuel to meet the load, the cost and fuel emission rate. Figure 5-1shows the variation of objective with respect to the reference building.

Figure 5-1. Variations of primary energy consumption, fuel cost and emission.



Summary:

In this chapter, a linear programming based operation strategy has been developed and simulated in the Matlab. The objective functions are the annual primary energy consumption, fuel cost and greenhouse gases emission. The primary energy is the raw fuel consumption that includes the site energy, energy loss in transmission, distribution and conversion. The comparison of primary energy gives a global view of building energy consumption. The reference building on site energy consumptions are the electricity and natural gas. In conducting the calculation, the electricity and natural gas conversion factor have been implemented to convert the onsite energy consumption into the primary energy consumption. The electricity conversion for the New York

City is 3.1 and for natural gas it is 1.047. Similarly, the annual greenhouse gas emission conversion factor is used for electricity and natural gas. The annual fuel cost consists of the purchase of electricity from the grid and natural gas. Selling extra electricity back to the grid is not included in the calculation. This is because it is generally not economically feasible for the customer and it is limited by the policies in some states. Once there is enough information for selling electricity back to the grid, it can add back to the equation.

The building hourly load is simulated in the Energyplus and imported into the linear programming simulator. The upper bound and lower bound of variables, the equalities and inequalities of variables are determined based on the first law energy conservation, system characteristics and simultaneously satisfying the building electrical, cooling and heating demand.

The LP simulator determines the optimal solution at each hour, the total number of iteration is 8760 for each objective function. From the simulation results, the maximum saving for primary energy is 22.98%, the maximum deduction of fuel cost is 20.51% and emission is 2.29%. This optimized operational strategy further increased the advantages of BCHP system. In the optimization of objective function, it may cause the increase or decrease of other objective functions. There is no general relationship between the trends of change. From the analysis, the performance of BCHP system is affected by the weather condition, electricity and natural gas cost, building load, system characteristic .The LP simulation results demonstrate the maximum theoretical savings from the BCHP system. In reality, transient effects of system and control system have to be considered.

Chapter 6 **Discussion and Conclusions**

This study of building cooling heating and power system shows that the utilization of BCHP system has the potential to increase the building total efficiency and decrease primary energy consumption, fuel cost and greenhouse gases emission. In the practice, the application of BCHP generally involves different factors including energy market prices, weather, governmental policies, regional information and building loads. Traditional methods to evaluate the market potential have some limitations, for example the weighting factor mehod. This method is simple and obvious, but it may be subject to personal knowledge and needs. So as to increase the objectivity of evaluation and reduce the work load, this research originally implemented principal component analysis as the evaluation methodology. In the analysis, the research comprehensively gathered BCHP related factors information to form the BCHP analysis data base at state level. Based on the PCA, four components cover 77.6% of information. The first component describes the energy consumption and expenditure. The second component is the collective influence of energy price and environmental effect. The third component comprehensively considered natural gas effect on the application. The last component is the negative environmental component. From the analysis, the top seven high potential states are California, New York, Texas, Florida, Illinois, New Jersey and Pennsylvania. At region level, East North Central and Middle Atlantic region have higher potential for the application of BCHP.

In the second phase of analysis, it emphasizes on the system selection and evaluation. A DOE benchmark building is the reference building for the simulation. The parametric analysis calculated primary energy consumption, fuel cost, annual greenhouse gases emission, BCHP system and overall building efficiency. There are two basic system configurations, the components include prime mover, absorption chiller, DX unitary system, air handling equipment and heat recovery devices. The research looked into the effect of absorption chiller, different types and number of prime movers and operational strategies. The total number of system combination is 32. Based on the comprehensive comparison, scenario 30 (FBTL ,two microturbines with DX unitary system) has superior overall performance. The group of two IC engines with absorption chiller in FTL is the second best. The scenario 30 is further optimized with linear programming. It was found that although the double effect absorption chiller has 50% higher COP than single effect absorption chiller, the single effect chiller is enough for the multi-residential building. This is because the high COP reduces the waste heat requirement, but this is offset by the more electricity import from the grid. The prime mover has certain power to heat ratio, so when the waste heat demand decreases, the electricity production decreases as well. From the load profile of the building, the major thermal demand is heating, the cooling is only required at short period of the year, for example in August. In terms of primary energy consumption, the calculation shows there is no distinctive advantage for DX system over absorption chiller. The electricity production has a high site to primary energy conversion factor than natural gas. The absorption chiller uses more natural gas but because of the low conversion factor, the primary energy consumption is very close. For the traditional operational strategy, the FBTL is generally superior to FTL. The low part load efficiency of primary reduces the benefits of BCHP system. In the FBTL operation, the primary operates at full capacity which is the maximum efficiency. In the FTL operation, two prime mover system has better performance than the one prime mover system. This is also mainly results from the two primary movers achieves higher average operation efficiency.

In Chapter 5, scenario 30 is optimized by linear programming. In the optimization, primary energy consumption, fuel cost and greenhouse gases emission functions are defined.

Based on the first law analysis, system components characteristics and building load demand, optimization constraints have been given. In the simulation, the LP simulator optimized the solution at each hour. The optimized solution shows that the maximum primary energy consumption saving is 22.98%, the maximum deduction of fuel cost is 20.51% and emission decreased by 2.29%. The optimization of one target function may increase another object function. There are no general trends between these relationships. The LP further optimized the benefits of BCHP, it demonstrates the maximum theoretical savings from the BCHP system.

In the future research, the BCHP data base could further refined by other researches. The data base could add more related variables. The similar data base could be created at different region level, for example at city or country level. The PCA is an attempt to evaluate the different factors. It is advisable to implement other evaluation method to give more objective and insightful ideas. The possible solutions for example are feature selection and non-parametric monitor. The analysis of simulation results is based on the gathered factors and may vary based on different research. In the system selection, future research should differentiate the quality of energy, for example exergy analysis. The exergy analysis provides more accurate and insightful understanding of fuel utilization and system efficiency. The optimized operational strategy shows the theoretical benefits of BCHP, the transient effect of system components should be included in the future researches. The study of Non-linear optimization should put more emphasis on in the future. By the linear optimization, several assumptions have to make because every equation or constraint has to be linear. The assumptions compromise the accuracy of research results. The non-linear optimization is better to simulate the situation in reality.

Reference

Agami Reddy, T., & Maor, I. (2009). Cost penalties of near-optimal scheduling control of BCHP systems: Part II - Modeling, optimization, and analysis results. *2009 ASHRAE Winter Conference, January 25, 2009 - January 28, 2009,* ASHRAE Transactions (Vol. 115 PART 1, pp. 287-307). Chicago, IL, United states: Amer. Soc. Heating, Ref. Air-Conditoning Eng. Inc.

ASHRAE. (2008). *2008 ASHRAE Handbook- Systems and Equipment (I-P)*. American Society of Heating, Refrigerating and Air-Conditioning Engineers.

Ayat E, O. (2006, April 3). LIFE CYCLE OPTIMIZATION MODEL FOR INTEGRATED COGENERATION AND ENERGY SYSTEMS APPLICATIONS IN BUILDINGS. University of Pittsburgh.

California Energy Commission. (2002, January 18). Distributed Energy Resources Guide: Stirling Engines. Retrieved from http://www.energy.ca.gov/distgen/equipment/stirling_engines/stirling_engines.html

California Energy Commission. (2003, August 19). Distributed Energy Resources Guide: equipment - Fuel Cells. Retrieved from http://www.energy.ca.gov/distgen/equipment/fuel_cells/fuel_cells.html

Capstone Turbine Corporation, C. C. (2011). Capstone Turbine Corporation. Retrieved January 16, 2012, from http://www.microturbine.com/

Cho, H. J. (2009). Dynamic simulation and optimal real-time operation of CHP systems for buildings. *ProQuest Dissertations And Theses; Thesis (Ph.D.)--Mississippi State University, 2009.; Publication Number: AAI3352267; ISBN: 9781109088106; Source:*

Dissertation Abstracts International, Volume: 70-04, Section: B, page: 2403.; 167 p. Retrieved January 25, 2012, from http://adsabs.harvard.edu/abs/2009PhDT........50C

Cho, H., Luck, R., Mago, P. J., & Chamra, L. M. (2009). Assessment of CHP System Performance With Commercial Building Benchmark Models in Different U.S. Climate Zones. *ASME Conference Proceedings*, *2009*(48906), 81-96. doi:10.1115/ES2009-90094

Cho, H., Mago, P. J., Luck, R., & Chamra, L. M. (2009). Evaluation of CCHP systems performance based on operational cost, primary energy consumption, and carbon dioxide emission by utilizing an optimal operation scheme. *Applied Energy*, *86*(12), 2540-2549. doi:16/j.apenergy.2009.04.012

Deng, J., Wang, R. Z., & Han, G. Y. (2011). A review of thermally activated cooling technologies for combined cooling, heating and power systems. *Progress in Energy and Combustion Science*, *37*(2), 172-203. doi:16/j.pecs.2010.05.003

Deru M, & Torcellini P. (2007, June). Source Energy and Emission Factors for Energy Use in Building. National Renewable Energy Laboratory.

DOE. (2011, March). BUILDING ENERGY DATA BOOK. US Department of Energy. Retrieved from http://buildingsdatabook.eren.doe.gov/

EIA. (2010, August 19). Annual Energy Review. US Energy Information Administration. Retrieved from http://www.eia.gov/totalenergy/data/annual/

EIA, Energy Information Agency. (2011). Electricity - Data - U.S. Energy Information Administration (EIA). *Energy Information Admnistration*. Retrieved October 11, 2011, from http://www.eia.gov/electricity/data.cfm#sales

EIA, Energy Information Administration. (2009). Residential Energy Consumption Survey. US. Energy Information Administration.

Energy and Environmental Analysis (an ICF International Company). (2008a, December). Technology Characterization:Steam Turbines. Environmental Protection Agency

Combined Heat and Power Partnership Program Washington, DC. Retrieved from http://www.epa.gov/chp/documents/catalog_chptech_steam_turbines.pdf

Energy and Environmental Analysis (an ICF International Company). (2008b, December). Technology Characterization:Microturbines. Environmental Protection Agency Combined Heat and Power Partnership.

Energy and Environmental Analysis, Inc. an ICF Company. (2008, December). Technology Characterization:Reciprocating Engines. Environmental Protection Agency Combined Heat and Power Partnership Program Washington, DC.

Energy and Environmental Analysis, Inc., an ICF Company. (2008, December). Technology Characterization:Fuel Cells. Environmental Protection Agency Combined Heat and Power Partnership Program.

ENERGY STAR, E. P. A. (2005). ENERGY STAR Performance RatingsMethodology for Incorporating Source Energy UseThe. Retrieved from http://www.energystar.gov/ia/business/evaluate_performance/site_source.pdf

EPA, E. P. A. (2010). Definitions. Retrieved December 20, 2011, from http://www.epa.gov/chp/definitions.html

Fred, B. (2009, May 11). Combined cooling, heating, power, and ventilation (CCHP/V) systems integration. Carnegie Mellon University.

Heejin Cho, Luck, R., Eksioglu, S. D., & Chamra, L. M. (2009). Cost-optimized real-time operation of CHP systems. *Energy and Buildings*, Energy Build. (Switzerland), *41*(4), 445-51.

Hueffed, A K, & Mago, P. J. (2010). Influence of prime mover size and operational strategy on the performance of combined cooling, heating, and power systems under different cost structures. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy*, *224*(5), 591-605. doi:10.1243/09576509JPE922

Hueffed, Anna Kathrine. (2010, May). Analysis and optmization of CHP, CCHP, CHP-ORC, and CCHP-ORC systems. Mississippi State University.

Jalalzadeh-Azar, A. A. (2003). A parametric analysis of a grid-independent BCHP system-focusing on impact of technological advancements. *ASHRAE TRANSACTIONS TECHNICAL AND SYMPOSIUM PAPERS*, ASHRAE Transactions (Vol. 109 PART 2, pp. 69-78). Kansas City, MO, United states: Amer. Soc. Heating, Ref. Air-Conditoning Eng. Inc.

Jalalzadeh-Azar, A. A. (2004). A comparison of electrical- And thermal-load-following CHP systems. *Technical and Symposium Papers - 2004 Annual Meeting of the American Society of Heating, Refrigerating and Air-Conditioning Engineers, June 26, 2004 - June 30, 2004*, ASHRAE Transactions (Vol. 110, pp. 85-94). Nashville, TX, United states: Amer. Soc. Heating, Ref. Air-Conditoning Eng. Inc.

Ji, B. (2005, November 3). Performance Investigation of CHP Equipment. University of Maryland, College Park.

Jolliffe, I. (2002). *Principal component analysis* (2nd ed.). New York: Springer.

Jonathon, S. (2009, April 22). A tutorial on Principal Components Analysis. Center for Neural Science, New York University. Retrieved from http://www.snl.salk.edu/~shlens/pca.pdf

Lahdelma, R., & Hakonen, H. (2003). An efficient linear programming algorithm for combined heat and power production. *European Journal of Operational Research*, Eur. J. Oper. Res. (Netherlands), *148*(1), 141-51.

Maor, I. (2009). Cost penalties of near-optimal scheduling control of BCHP systems: part I—selection of case study scenarios and data generation. *ASHRAE Transactions*, *115*(1), 271.

Midwest CHP Application Center, & Avalon Consulting,lnc. (2003, September). Combined Heat and Power Resource Guide.

Natinoal Climatic Data Center, U. . D. of C. (2011). Divisional Data Select. *National Environmental Satellite.Data,and Information Service*. Retrieved October 10, 2011, from http://www7.ncdc.noaa.gov/CDO/CDODivisionalSelect.jsp#

National Renewable Energy Laboratory NREL. (n.d.). BioFuels Atlas | maps.nrel.gov. Retrieved December 20, 2011, from http://maps.nrel.gov/biomass

NaturalGas.org. (2011a). NaturalGas.org. Retrieved January 19, 2012, a from http://www.naturalgas.org/environment/naturalgas.asp

NaturalGas.org, F. E. R. C. (2011b). Natural Gas and the Environment. Retrieved from http://www.naturalgas.org/environment/naturalgas.asp

ONSITE SYCOM, E. C. (2000, January). The Market and Technical Potential for Combined Heat and Power in the Industrial Sector. Energy Information Administration.

Petchers, N. (2002). *Combined Heating, Cooling & Power Handbook: Technologies & Applications : An Integrated Approach to Energy Conservation*. Fairmont Press.

Rong, A., & Lahdelma, R. (2005). An efficient linear programming model and optimization algorithm for trigeneration. *Applied Energy*, *82*(1), 40-63.

Sakawa, M., Kato, K., & Ushiro, S. (2002). Operational planning of district heating and cooling plants through genetic algorithms for mixed 0–1 linear programming. *European Journal of Operational Research*, *137*(3), 677-687. doi:10.1016/S0377-2217(01)00095-9

The European Association for the Promotion of Cogeneration. (2001, March). A GUIDE TOCOGENERATION. The European Association for the Promotion of Cogeneration. Retrieved from www.cogen.org

Thorin, E., Brand, H., & Weber, C. (2005). Long-term optimization of cogeneration systems in a competitive market environment. *Applied Energy*, Appl. Energy (UK), *81*(2), 152-69.

U.S. Energy Information Administration, (EIA). (n.d.). Household heating fuels. Retrieved November 2, 2011, from http://www.eia.gov/todayinenergy/detail.cfm?id=3690#

U.S. EPA Combined Heat and Power Partnership. (2008, December). Catalog of CHP Technologies. EPA.

US Census Bureau. (n.d.-a). State and County QuickFacts. Retrieved October 25, 2011, a from http://quickfacts.census.gov/qfd/index.html

US Census Bureau. (n.d.-b). The 2012 Statistical Abstract: Income, Expenditures, Poverty, & Wealth. Retrieved October 25, 2011, b from http://www.census.gov/compendia/statab/cats/income_expenditures_poverty_wealth.html

US Energy Information Administration. (2011). Voluntary Reporting of Greenhouse Gases Program - Electricity Factors. Retrieved July 4, 2011, from http://www.eia.gov/oiaf/1605/coefficients.html

US Energy Information Administration. (n.d.-a). Natural Gas Delivered to Residential Consumers. Retrieved October 12, 2011, a from http://www.eia.gov/dnav/ng/ng_cons_sum_a_EPG0_vrs_mmcf_a.htm

US Energy Information Administration. (n.d.-b). Average Residential Natural Price. *EIA*. Retrieved October 12, 2011, b from http://www.eia.gov/dnav/ng/ng_pri_sum_a_EPG0_PRS_DMcf_a.htm

Utility Rates | Combined Heat and Power Partnership | US EPA. (n.d.). Retrieved November 3, 2011, from http://www.epa.gov/chp/state-policy/utility.html#two

UTRC. (2006, June). Micro-CHP Systems for Residential ApplicationsFinal Report. U.S. Department of Energy National Energy Technology Laboratory.

Wu, D. W., & Wang, R. Z. (2006). Combined cooling, heating and power: A review. *Progress in Energy and Combustion Science*, *32*(5-6), 459-495.

Yokoyama, R., Ito, K., & Matsumoto, Y. (1994). Optimal Sizing of a Gas Turbine Cogeneration Plant in Consideration of Its Operational Strategy. *Journal of Engineering for Gas Turbines and Power*, *116*(1), 32-38. doi:10.1115/1.2906806

Appendix

Principal Component Analysis Method

Suppose that $X = (X_1, X_2, \cdots\cdots, X_p)'$ is a random vector, which exists second moment.

Denote$\mu = \varepsilon(X)$,$\Sigma = D(X)$ the mean and covariance matrix of the random vector X respectively. Considering a linear combination of X,

$$\begin{cases} Y_1 = l_1'X = l_{11}X_1 + \cdots + l_{p1}X_p \\ \quad \cdots \quad \cdots \quad \cdots \\ Y_p = l_p'X = l_{1p}X_1 + \cdots + l_{pp}X_p \end{cases}$$

It's easy to see that

$Var(Y_i) = l_i' \sum l_i$,

$Cov(Y_{i,} Y_j) = l_i' \sum l_j \quad i, j = 1, \cdots, p.$

If we hope to use $Y_1$to instead the vector$X = (X_1, X_2, \cdots\cdots, X_p)$, it means that the new variable Y_1 should include the information of the vector$X = (X_1, X_2, \cdots\cdots, X_p)$ as much as possible.

Under the constraint of $l_i' l_i$=1, $i = 1, \cdots, p$ we maximize the variance to get the Y_i which is called the $(i-1)th$ principal component. In addition, we also want the ith principal component does not include any information in $(i-1)th$ one. In statistical language, that is

$$Cov(Y_{i-1,} Y_j) = 0$$

Using the knowledge of linear algebra, we can show that,

$$max_{l_i' l_i = 1} Var(Y_i) = \lambda_i$$

$$l_i = t_i$$

Where the λ_i is the ith largest eigenvalue of Σ and t_i is the corresponding eigenvector. In practice, Σ is usually an unknown matrix. We estimate it via the samples by the following formula.

Set sample matrix is

$$X = \begin{bmatrix} X_{11} & X_{12} & \cdots & X_{1p} \\ X_{21} & X_{22} & \cdots & X_{1p} \\ \cdots & \cdots & \cdots & \cdots \\ X_{n1} & X_{n2} & \cdots & X_{np} \end{bmatrix}$$

After standardization for every column of X ,we can compute the sample correlation matrix as

$$R = \frac{1}{n} X'X$$

R is considered as a good estimator ofΣ. So we can obtain all principal components as we mentioned before. Denote the P principal components of matrix R as$Z_1, \cdots, Z_P$. Plug in the sample data, the principal components of n samples is

$$Z = (z_{ij}) = \begin{bmatrix} X_{11} & X_{12} & \cdots & X_{1p} \\ X_{21} & X_{22} & \cdots & X_{1p} \\ \cdots & \cdots & \cdots & \cdots \\ X_{n1} & X_{n2} & \cdots & X_{np} \end{bmatrix} = (z_{(1)}, z_{(2)}, \cdots, z_{(p)})$$

Now we create some criteria to decide how many principal we should select. Two indicators are introduced to assist us. First one is contribution ratio of the ith principal component which is defined as $\lambda_i / \sum_1^p \lambda_k$. And the second one is the cumulative contribution of the first mth principal components which is defined as $\sum_1^m \lambda_i / \sum_1^p \lambda_j$. They both have an intuitive explanation that how much information could be explain by principal components as the λ_i is the variance of ith principal component. Generally, we select m to make the cumulative contribution ratio up to 75%. However, the ideal situation is the first one or two principal components have much larger contribution ratio and they also cover more than 75% contribution in total.