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OPTIMIZATION OF COMBINED COOLING, HEATING, AND POWER SYSTEMS (CCHP) OPERATIONAL STRATEGIES FOR DIFFERENT CLIMATE CONDITIONS

By

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OPTIMIZATION OF COMBINED COOLING, HEATING, AND POWER SYSTEMS (CCHP) OPERATIONAL STRATEGIES FOR DIFFERENT CLIMATE CONDITIONS

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This thesis investigates the different strategies of operation and optimization criteria that a CCHP system can be operated under. As energy concerns increase, a major issue for the United States will be the efficiency of energy production. Due to this desire for the most efficient supply of energy CCHP will play an increasingly important role in both domestic and commercial applications as waste heat utilization provides an added measure of efficiency. The different strategies of operation under which a CCHP system can be operated under, electric load following and thermal load following, are defined in addition to the different optimization criteria that a CCHP system can be operated under. The different strategies and optimization criteria of CCHP operation are simulated for five various climate regions in the United States and the results for primary energy consumption, CO_2 emissions, and cost of operation are compared.

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NOMENCLATURE

CDE	Carbon dioxide emissions reduction
CCHP	Combined cooling, heating and power
CHP	Combined heating and power
COP	Coefficient of performance
$cost$	Cost
E	Electric energy
e_{grid}	emission conversion factor for electricity
e_{fuel}	emission conversion factor for natural gas
E_m	Electric energy registered at the meter
E_{pgu}	PGU electricity
F_m	Fuel energy registered at the meter
F_{pgu}	PGU fuel energy consumption
F_{boiler}	Boiler fuel energy consumption
FEL	Following the electric load
FTL	Following the thermal load
HP	Combined Heating and Power
pec_{grid}	site-to-energy conversion factor for electricity

pec_{fuel}	site-to-energy conversion factor for natural gas
PEC	Primary energy consumption
PGU	Power generation unit
Q	Thermal energy from fuel
Q_R	Recovered waste heat
Q_{ch}	Heat required by the absorption chiller to handle the cooling load
Q_c	Building cooling load
Q_{hc}	heat required to handle the heating load
Q_h	Building heating load

Symbols

η	Efficiency level, ratio between useful output and input amount

Subscripts

boiler	Boiler
building	Building
c	Cooling
ch	Absorption Chiller
conventional	Reference building
excess	Excess electricity
fuel	Fuel
grid	Electricity required from the grid

h	Heating
pgu	Power generation unit
rec	Recovered heat

CHAPTER 1

INTRODUCTION

1.1. Literature Review

The term CCHP (combined cooling, heating, and power) describes all electrical power generation systems that utilize recoverable waste heat for space heating, cooling, and domestic hot water purposes. The main difference between CCHP systems and the typical methods of electric generation is the utilization of the waste heat rejected from the prime mover in order to satisfy the thermal demand of a facility (cooling, heating, or hot water needs).

The use of CCHP has been relatively commonplace in Europe since the 1990's as compared to even current use in the United States. Several studies of the feasibility of CCHP in different facilities have been done. The facilities that are typically studied are those of relatively large facilities (i.e. hospitals and hotels) that would benefit from the stand-alone nature of the CCHP system in addition to its possible cost savings. These feasibility studies have been performed for different climates and varying conditions in those climates throughout the year's weather cycle. These kinds of feasibility studieshave led to the conclusion that CCHP is a useful form of electric and thermal power generation that can grant significant energy savings over conventional methods and warrant further research and investigation in order to make its use more practical and commonplace.

Some of the issues preventing CCHP from being widespread in the United States are the need for individual maintenance of facilities and the high initial costs of installation. The maintenance costs (and time associated with these costs) may justify the use of conventional electric power for some facilities (and homeowners in the case of micro-CCHP) despite the potential cost and energy savings. The installation of a CCHP system involves several components as can be seen from the description of a CCHP system and while none of these components are extremely expensive, the initial cost of the CCHP system compared to the initial cost of conventional electrical power is significantly higher. Fortunately, the feasibility of further development of CCHP technologies has been aided by the energy policies by the most recent national energy plan (http://www.cogenerationtechnologies.com/). The National Energy Plan includes four specific recommendations to promote CCHP, three of which were: promotion of CCHP through flexible environmental permitting, issuing of guidance to encourage development of highly efficient and low-emitting CCHP systems through shortened lead times and greater certainty, and promotion of the use of CCHP at abandoned brownfield industrial or commercial sites.

One of the most basic goals of a CCHP system is to ensure that it is a more attractive option than traditional power supply. The end goals of CCHP systems are to ensure reduction of primary energy, cost, emissions, or a combination of two or more of these. To achieve these goals, CCHP systems are usually operated using two basic strategies: following the electric load (FEL) and following the thermal load (FTL). However, in addition to the operation strategies it is necessary to apply optimization criteria to guarantee the benefits of CCHP systems over conventional technologies. The CCHP operation strategy will dictate the loading and fuel consumption of the prime mover and thus the energy consumption profile of the CCHP system. In the case of FEL operation strategy, the prime mover is loaded in order to satisfy the electric demand of the facility through the generator that is part of the power generation set. The waste heat from this loading is then recovered in order to satisfy the thermal load of the facility. For this operation strategy, if the recovered thermal energy is not enough to handle the thermal load (cooling or heating) of the facility, additional heat has to be provided by the auxiliary boiler of the CCHP system. For FTL strategy, the prime mover is loaded such that the recovered waste heat will be adequate to supply the facility with the necessary thermal energy to satisfy the heating and cooling requirements. For this operation strategy the amount of electricity produced may or may not be enough to provide the electricity required by the building. Therefore, if the electricity produced is not enough to handle the electric load additional electricity has to be imported from the grid. Some researchers such as Cardona and Piacentino [2004, 2006], Jalalzadeh-Azar [2004], and Mago et al. [4] among others have investigated the operation of CCHP systems under these two operation strategies. Cardona and Piacentino [2004] refer to these two styles as Electric Demand Management (EDM) and Thermal Demand Management (TDM) strategies. The choice between EDM and TDM is usually governed by the loading of the prime mover as well as a few extraneous circumstances including the ability to sell back electricity to the grid or store it on site for later use via some battery system. In addition, the price of fuel versus that of electricity purchased from a traditional source can affect the management of a plant [2006]. Jalalzadeh-Azar [2004] performed a non-dimensional analysis of energy cost and primary energy consumption of CCHP systems utilizing a gas fired micro-turbine in three varying climates. In his analysis, the two main operational strategies were evaluated in the three differing climes. The results yielded an 11% reduction in total energy consumption when the CCHP operates FTL versus that of FEL. Mago et al. [4] studied the performance of CCHP and CHP (combined heating and power) systems operating FEL and FTL, based on primary energy consumption, operation cost, and emissions for different climate conditions. Their results showed that CCHP and CHP systems operated FTL reduce the PEC for all the evaluated cities. On the other hand, CHP systems operated FEL always increases the PEC. In their study, the only operation mode that reduces PEC and CDE while reducing the cost is CHP-FTL.

The operational strategy of a CCHP system can be described as an overriding management philosophy used to determine the manner in which a CCHP facility operates in. The CCHP strategy used strongly depends on the specific goal to be obtained from the CCHP operation. However, in addition to the operational strategies, optimization techniques have to be employed to guarantee the lowest cost of operation, reduction of the PEC, and/or reduction of CDE. It is also possible for the goal behind an operating strategy to be a combination of the above listed goals with a balance being sought between two or more. Several researchers have investigated different optimized operational strategies for CCHP systems. Some of these researchers are: Cardona and Piacentino [2003], Li et al. [2006], Chicco and Mancarella [2006], Sun et al. [2004], Zogg et al. [2005], and Fumo et al. [2008]. Cardona and Piacentino [2003] investigated a strategy to ensure Primary Energy Savings (PES). They found that the operation of a CCHP plant under this PES strategy allowed the engine to run at full load for almost 2800 hours per year thus increasing thermal energy produced. This increase in thermal energy production falls in line with the benefits of increased thermal production outlined by Moran et al. [2008]. Li et al. [2006] used a technique called Fuel Energy Savings Ratio (FESR) which gives the ratio of primary energy consumption of a CCHP system versus the separate production case. They reported that the heating and power mode is very efficient when evaluated with FESR while the cooling and power mode is usually a loss comparing to separate production using FESR. This point emphasizes the need to operate under a proper management strategy in order to ensure the best possible energy efficiency at all times during CCHP operation. Chicco and Mancarella [2006] furthered the evaluation method of primary energy and applied it specifically to trigeneration. They introduced a new performance assessing indicator, called Trigeneration Primary Energy Saving (TPES). This indicator evaluates the fuel energy savings obtained in a trigeneration plant as compared with separate, conventional production. Using this indicator, it was determined that nearly 70% rate of energy savings can be obtained with the use of trigeneration. Sun et al. [2004] utilized a Primary Energy Rate (PER) to compare the energetic efficiency of a combined system for cooling and heating to that of separate production. They defined the PER as the ratio of required output to primary energy demand where a higher PER is more favorable. Their analysis points to the possibility of 35% greater efficiency than a separate production case. Zogg et al. [2005] found that CCHP has the ability to achieve primary energy savings in two ways. First, if the CCHP system generates electricity at an efficiency higher than the grid and secondly, if the CCHP system cannot generate electricity at an efficiency better than the grid then energy savings depend upon the extent to which waste heat can be used to supply space heating and/or space cooling. Fumo at el. [2008] introduced the definition of Building Primary Energy Ratio (BPER) as a parameter to evaluate CCHP energy performance. The BPER measured the variation of the building primary energy when the building is operated without a CCHP system versus the building primary energy when a CCHP system is used. Their results showed that using the thermal efficiency alone is not the best approach to describe CCHP system energy performance and that using the BPER provides a more comprehensive CCHP evaluation.

As a result of the worldwide concern about global warming, consideration of greenhouse gas emissions has gained a lot of interest in the analysis of energy systems. Several researchers have evaluated and analyzed the benefits of CCHP systems in terms of reduction of pollutants for different applications. Some of them include: Mago et al. [2007], Chicco and Pierluigi [2007,2008,2009] , Wahlund et al. [2004], and Möllersten et al. [2003], among others. In general, they reported that CCHP systems have the potential and the ability to reduce the emission of carbon dioxide.

1.2. Statement of Objectives

The objective of this thesis is to analyze and optimize different CCHP operational strategies based on several optimization criterion such as: energy savings, operation cost reduction or minimum environmental impact. The performance of the different optimized operation strategies evaluated in this investigation is compared based on primary energy consumption (PEC), operation cost, and carbon dioxide emissions (CDE). In addition all the optimization criteria and strategies will be evaluated for different climate conditions to determine the performance of the CCHP under different electric, cooling, and heating loads.

CHAPTER 2

CCHP SYSTEM COMPONENTS, OPERATION STRATEGIES, AND OPTIMIZATION CRITERIA

When evaluating a CCHP system it is important to understand the system in order to fully understand the results of different management strategies. Because of this fact, this chapter presents an overview of typical CCHP systems and their components. Once, the system is defined the operation strategies and optimization criteria that are to be investigated in this thesis are discussed. Additionally, the effect of each operation strategy as well as the various optimization criteria will be outlined for the CCHP system under consideration.

2.1 Prime Mover

The central device of a CCHP system is the prime mover in use. The prime mover ultimately determines the overall fuel consumption of the CCHP system. Thus, every result of CCHP operation (cost of operation, primary energy consumption, and carbon dioxide emissions) is greatly affected by the choice of prime mover. There are two main types of prime mover commonly used in CCHP operation: the compression-ignition (CI) internal combustion engine, and the spark-ignition (SI) internal combustion engine.

2.1.1 CI Internal Combustion Engine

The CI engine converts the combustion of a fuel, achieved from the high level of compression designed into the combustion chamber, into useful mechanical shaft work. The CI engine is commonly used in the more industrial applications of the transportation industry as well as industrial type power generation units. Not surprisingly, the use of CI engines in these applications is for their longevity and efficiency, two traits that would also be logical choices for CCHP applications. However, CI engines typically convert 10% more of the fuel energy input into the engine into useful mechanical shaft work and thus 10% less of the fuel energy is available to a CCHP system as recoverable waste heat. This can be a detriment to a CCHP system that operates in an environment where the need for heating and cooling energy is more than that needed for electrical generation (Pullkrabek, 2004).

2.1.2 SI Internal Combustion Engine

The SI engine converts the combustion of a fuel, achieved from a spark inside the combustion chamber, into useful mechanical shaft work. The SI engine is very common in automobile applications as well as some light generation units. The SI engine typically rejects at least 70% of the fuel energy into the exhaust and/or coolant flows and thus allows for a convenient source of waste heat in CCHP applications. Additionally, SI engines are relatively cheap and easy to maintain and are able to run off of a variety of fuels ranging from commonly available gasoline to liquefied natural gas (LNG) (Pullkrabek, 2004). The combination of the common availability of SI engines, the ease of maintenance, high level of waste heat production, and the flexibility of fuel uses make the SI engine a good choice for the CCHP system prime mover.

2.2 Fuel Type

For both SI and CI engines there are a variety of fuel types that could be utilized. All of these fuels have various quantities that can be objectively evaluated against each other including: lower heating value (LHV), cost, and availability. Table 2.1 shows an overview of some of the various quantities mentioned as well as the application of each fuel.

Table 2.1. Fuels LHV and Application Overview (www.eere.energy.gov)

Fuel Type	**LHV (kJ/kg)**	**Possible Application**
Gasoline	41,868-44,194	SI
LNG	49,455	SI
Methanol	19,934	SI
Ethanol	26,749	SI
Propane	46,055	SI
No. 2 Diesel	41,868-44,194	CI
B2 Biodiesel	42,340	CI
B20 Biodiesel	41,436	CI
B100 Biodiesel	42,340	CI

From the information presented in Table 2.1 it is obvious that for SI engines the available fuels have a similar LHV except for Ethanol and Methanol. The much lower LHV for methanol and ethanol lead to further examination of the remaining fuels: gasoline, Propane, and LNG.

2.2.1 Gasoline

Gasoline is the most common fuel used in SI engines and is also the most easily available fuel with a very well developed production and distribution infrastructure. Gasoline is refined from crude oil that the majority of which is obtained from non-domestic sources and as such does not promote energy independence. Also, the carbon dioxide emissions are relatively high for gasoline, but much effort is being invested in reducing those emissions as gasoline is the primary fuel used in the transportation applications of SI engines (www.eere.energy.gov).

2.2.2 Propane

Propane is a hydrocarbon gas at normal pressures and temperatures that is produced as a by-product of natural gas processing and crude oil refining. Propane possesses a high octane rating and is a good candidate for SI engines. It is a non-toxic fuel that poses no threat to natural surroundings and has relatively low CDE compared to gasoline when combusted in a SI engine. There is an existing utility infrastructure for Propane throughout the United States and thus would be a good candidate as far as availability is concerned (Propane Technologies Review, 2006).

2.2.3 Natural Gas (LNG)

LNG is mostly Methane (CH_4) and is commonly produced from already existing petroleum reservoirs. LNG already has an existing utility infrastructure in place in the United States and thus has an advantage over any fuel source that does not. Also, LNG burns cleaner than gasoline in an SI engine. Shipley et al. (2008) point out that “Natural gas continues to be the preferred fuel for CCHP systems, representing 50-80% of annual CCHP capacity additions since 1990. This is primarily because natural gas is readily available at most industrial sites, is clean burning, and has historically been relatively plentiful and affordable". Shipley et al. (2008) also point out that despite the recent volatility and high price of LNG, "recent increases in domestic natural gas exploration and production hold promise moderate natural gas prices." For the reasons mentioned above, LNG has been selected as the fuel for the investigations pursued in this thesis.

2.3 Generator

In order to generate the electrical energy needed to satisfy the demand of the facility being serviced by a CCHP system an electrical generator is required. An electrical generator is a device that converts mechanical shaft energy into electrical energy). In the case of the CCHP system the prime mover supplies the useful shaft energy for conversion by the generator to electrical energy. Typically, generator efficiencies range from 85 to 95% (Hambley, 2005).

2.4 Heat Exchanger

The main advantage of a CCHP system over the conventional generation of power is that the waste heat from the prime mover is recovered and then used to provide cooling or heating. In order to recover the waste heat from the prime mover a heat exchanger is necessary. A heat exchanger is a device used to exchange heat energy between two or more fluid streams (Kakac and Liu, 2002). In the case of CCHP power generation, the heat exchanger is exchanging waste heat energy from the fluid streams of the exhaust and coolant of the prime mover to a working fluid that is used to supply heat energy to the absorption chiller and/or the heating coil. Typically, heat exchanger effectiveness ranges from 0.7 to 0.8.

2.5 Absorption Chiller

The cooling capability of a CCHP system is from the use of an absorption chiller. Absorption chillers differ from the more prevalent compression chillers in that the cooling effect is driven by heat energy, rather than mechanical energy. The absorption chiller uses recovered heat energy from the working fluid of the system in order to drive the cooling system for the facility being serviced. The coefficient of performance (COP) of absorption chillers depends on the type of systems. Single-effect absorption chillers have COPs of approximately 0.6-0.8 while double-effect absorption chillers have COPs of approximately 1.0 (New Buildings Institute, 1998).

2.6 Heating Coil

The heating capability of a CCHP system is from the use of a heating coil. The heating coil utilizes the heat energy present in the working fluid that is recovered from the waste heat of the prime mover. Typically, the efficiencies of heating coils are approximately 80%.

2.7 Boiler

Under the electric load following operation strategy, there is the possibility of not enough recovered waste heat in order to satisfy the heating and/or cooling demand of the facility. In this case additional heat energy must be supplied to the working fluid of the

CCHP thermal system. To achieve this, a boiler is used in the CCHP system. A boiler simply converts the fuel energy into heat energy that can be utilized. Thermal efficiencies of boiler range from 85 to 90% (Sun, et al., 2003).

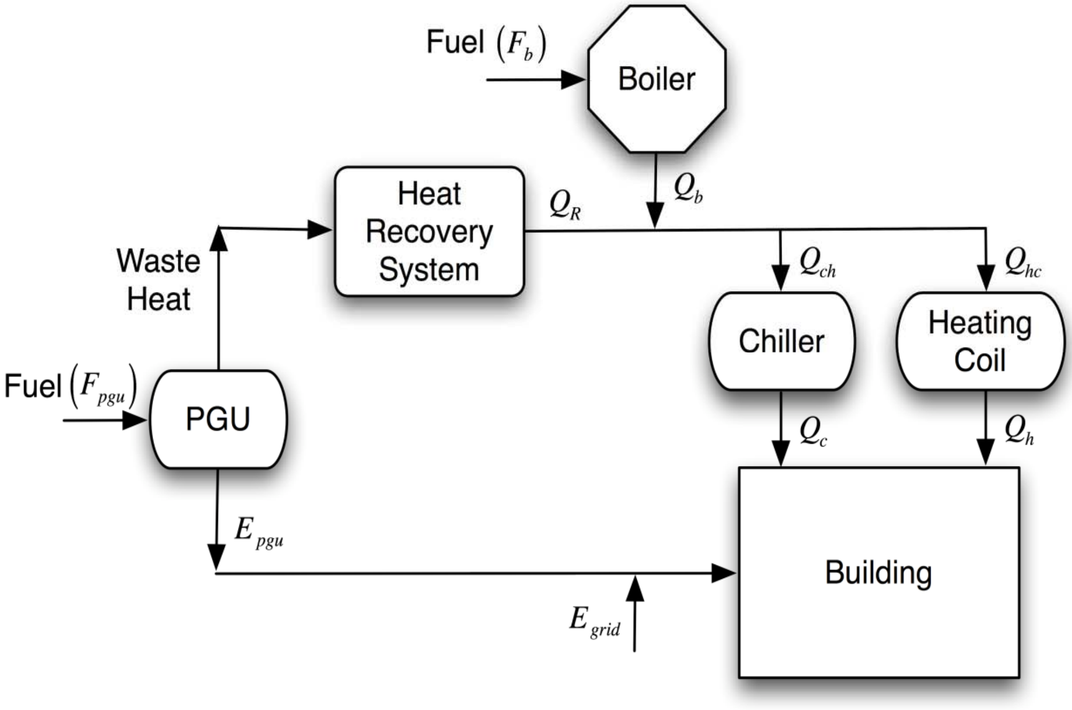

Figure 2.1. CCHP System Diagram.

2.8 Operation Strategy

The CCHP system can operate under two basic operational strategies. The first is with the prime mover following the electric load of the facility in order to always satisfy the electric demand (FEL). This mode ensures the bare minimum of fuel energy input into the prime mover that will satisfy the electric demand of the facility. The caveat to this operation strategy is that there is the potential for the prime mover to generate insufficient waste heat to satisfy the thermal demand of the facility. As was previously discussed, the addition of a boiler to increase heat energy into the thermal system is intended to compensate for this potential lack of heat energy. Consequently, in this case of insufficient heat energy, there is an additional fuel energy input into the system from the fuel energy fed to the boiler and this must be considered in addition to the fuel energy input to the prime mover. This additional fuel energy consumed means additional cost and CDE. These additional quantities must be evaluated in the case of boiler and prime mover operation. The second operation strategy for the CCHP system is that of following the thermal load of the facility (FTL). In this case the prime mover is operated in order to supply the exact amount of waste heat needed to satisfy the thermal demands of the facility. The caveat to this operation strategy is the potential for insufficient electric generation to satisfy the electric demand of the facility. In the case that there is not enough electric generation available from the FTL operation, then electricity have to be imported from the grid. This may increase the cost and emissions of the CCHP system as the conventional production of electricity and its CDE must be considered in addition to that of the prime mover itself.

2.9 Optimization Criteria

In addition to the two basic operational strategies, it is possible to consider further optimization of CCHP systems through the proposed optimization criteria. There are three proposed optimization criteria: primary energy, carbon dioxide emissions, and operating cost. Each of these three-optimization criterion can be applied under both operation strategies.

2.9.1 Primary Energy Optimization Criterion (PE-O)

The optimization criteria PE-O seeks to ensure the least possible consumption of primary energy by the facility being supplied. Primary energy is defined as energy that has not been subjected to any conversion or transformation processes. The EIA (2007) defines Primary Energy as “All energy consumed by end users, excluding electricity but including the energy consumed at electric utilities to generate electricity. (In estimating energy expenditures, there are no fuel-associated expenditures for hydroelectric power, geothermal energy, solar energy, or wind energy, and the quantifiable expenditures for process fuel and intermediate products are excluded.)”, and Primary Energy Consumption (PEC) is defined as “is the amount of site consumption, plus losses that occur in the generation, transmission, and distribution of energy.” Primary energy reduction is important because it is related to the energy resources and environmental impact. The measured site energy consumption can be converted into primary energy consumption utilizing site to primary energy conversion factors available at www.eere.energy.gov. Once the measured site energy consumption is converted to primary energy, the primary energy consumed under conventional operation can be compared to the primary energy consumed under CCHP operation, either FEL or FTL. The lower of these two quantities is then defined as the optimal operation for PEC whether that is CCHP operation (either FTL or FEL) or conventional operation and the facility should be run accordingly.

2.9.2 Emissions Reduction Optimization Criterion (ER-O)

The optimization criteria ER-O seeks to ensure the least possible CDE from the supply of electricity and thermal energy to the facility. CDE must be considered for the separate, conventional production of electricity as well as the possible emissions from prime mover (and possibly boiler) operation under CCHP operation. In order to define the least possible emissions, the CDE of both cases of production (CCHP or conventional) must be compared to each other. The lowest quantity of CDE between the conventional case and that of CCHP thus becomes the optimal CDE and the facility should be run accordingly.

2.9.3 Operating Cost Optimization Criterion (OC-O)

The optimization criteria OC-O seeks to ensure the least possible cost of operation for the facility. This criterion first considers the cost of separate conventional use of electricity in order to satisfy the electric load and fuel to satisfy the thermal demand, and then considers the total cost of CCHP operation in either FEL or FTL. Once both costs are known the optimal operating cost can then be defined as the lowest cost between the two known costs of CCHP operation and separate conventional production. Once this optimal cost is determined the facility should be run under the same case of production that has been determined to be the optimal case.

CHAPTER 3

CCHP SYSTEM MODELING

This section presents the equations used to model the CCHP system. Schematic of a CCHP system is shown in Figure 2.1. From this figure it can be seen that fuel is supplied to the power generation unit (PGU) to produce the electricity needed for the building (lights, equipments, etc). The waste heat is recovered and used to produce cooling using an absorption chiller or heating using a heating coil. This section first discusses the CCHP system basic operation strategies (FEL and FTL) and then the application of different optimization criteria to these two strategies.

3.1 Basic CCHP Systems Operating Strategies

As previously stated, there are two basic strategies in which a CCHP system can be operated. Following the electric load of the facility (FTL) and following the thermal load of the facility (FTL). These are the most basic management decisions that can be followed for a CCHP system.

3.1.1 CCHP System Model Following the Electric Load

The total electric energy that has to be supplied by the PGU is the electricity needed by the building:

$$E_{pgu} = E_{building} \tag{3.1}$$

where $E_{building}$ is the building electric energy consumption including electric equipment, lights, etc. For the hour time step simulation, the electric energy demand from the PGU is assumed to be equal to the energy consumption for the specific hour.

The PGU fuel energy consumption can be estimated as

$$F_{pgu} = \frac{E_{pgu}}{\eta_{pgu}} \tag{3.2}$$

where η_{pgu} is the PGU thermal efficiency. The efficiency of the PGU is assumed to be constant independently of the electric demand.

The recovered waste heat from the prime mover can be estimated as

$$Q_R = F_{pgu}\,\eta_{rec}\left(1-\eta_{pgu}\right) \tag{3.3}$$

where Q_R is the recovered thermal energy and η_{rec} is the heat recovery system efficiency.

The heat required by the absorption chiller to handle the cooling load is estimated as

$$Q_{ch} = \frac{Q_c}{COP_{ch}} \tag{3.4}$$

where Q_c is the building thermal cooling load and COP_{ch} is the coefficient of performance of the absorption chiller.

The heat required to handle the heating load is estimated as

$$Q_{hc} = Q_h / \eta_{hc} \tag{3.5}$$

where Q_h is the building heating load and η_{hc} is the heating coil efficiency.

The CCHP system has to provide heating or cooling to the building at any specific hour during its operation. Therefore, if the recovered thermal energy is not enough to handle the thermal load (cooling or heating) additional heat has to be provided by the auxiliary boiler of the CHP system. Therefore,

For cooling: If $Q_R > Q_{ch} \rightarrow Q_{boiler} = 0$, or if $Q_R < Q_{ch} \rightarrow Q_{boiler} = Q_{ch} - Q_R$, (3.6)

For heating: if $Q_R > Q_{hc} \rightarrow Q_{boiler} = 0$ or if $Q_R < Q_{hc} \rightarrow Q_{boiler} = Q_{hc} - Q_R$, (3.7)

The boiler fuel energy consumption is computed as

$$F_{boiler} = \frac{Q_{boiler}}{\eta_{boiler}} \qquad (3.8)$$

where η_{boiler} is the boiler thermal efficiency.

The fuel energy consumption registered at the meter is estimated as

$$F_m = F_{pgu} + F_{boiler} \qquad (3.9)$$

3.1.2. CCHP System Model Following the Thermal Load

For this operation strategy the total heat that must be recovered from the PGU has to match the thermal energy required to handle the cooling or heating load. Therefore,

For cooling, $Q_R = Q_{ch}$ (3.10)

For Heating, $Q_R = Q_{hc}$ (3.11)

Since the recovered waste heat from the prime mover is known, the fuel energy can be estimated as

$$F_{pgu} = \frac{Q_R}{\eta_{rec}(1-\eta_{pgu})} \tag{3.12}$$

The total electric energy that is supplied by the PGU can be determined as:

$$E_{pgu} = F_{pgu}\eta_{pgu} \tag{3.13}$$

Since the system is following the thermal load, the amount of electricity produced may or may not be enough to provide the electricity required by the building. Therefore,

If $E_{pgu} < E_{building} \rightarrow E_{grid} = E_{building} - E_{pgu}$ (3.14)

If $E_{pgu} > E_{building} \rightarrow E_{excess} = E_{pgu} - E_{building}$ (3.15)

where E_{grid} is the amount of electricity required from the grid, and E_{excess} is the amount of excess electricity that can be exported or stored for future use.

Then, the only fuel energy consumption is the one used in the PGU.

$$F_m = F_{pgu} \tag{3.16}$$

For this operation mode the system may have excess electricity that could be stored or sold back to the grid. However, it is important to mention here that these options are not available in all locations. The use of the excess electricity generated onsite, represents a primary energy saving and cost reduction that could be taken into consideration when comparing this system with the conventional system.

3.2. CCHP Systems Optimization Criterion

In addition to the basic operating strategies described in Section 3.1 and 3.2, CCHP systems can be optimized based on different optimization criterion such as: energy savings, operation cost reduction, or minimum environmental impact (reduction of carbon dioxide). In general, to be able to apply any of the optimization criteria, the CCHP system energy consumption as well as the energy consumption for the conventional case must be determined.

3.2.1. Primary Energy Optimization Criterion (PE-O)

CCHP systems can be optimized to guarantee maximum energy savings. Therefore, the purpose of the PE-O is to minimize the PEC of the CCHP systems. This optimization technique is based on a comparison between the CCHP system's PEC (PEC_{CCHP}) with the PEC of the conventional case ($PEC_{conventional}$). The PEC for CCHP systems operating FEL and FTL strategies are given in Equations (3.17) and (3.18) respectively:

$$PEC_{CCHP-FEL} = F_m FCF_{PEC} \tag{3.17}$$

$$PEC_{CCHP-FTL} = E_m ECF_{PEC} + F_m FCF_{PEC} \tag{3.18}$$

where ECF_{PEC} and FCF_{PEC} are the site-to-primary energy conversion factors for electricity and fuel, respectively.

Since the conventional case used electricity and fuel to satisfy the electric and thermal demand of the building, the $PEC_{conventional}$ can be determined using Equation (3.18). For this case, if the PEC_{CCHP} is higher than the $PEC_{conventional}$, the CCHP operation consumes more primary energy than the conventional case and therefore, the CCHP should not be operated. On the other hand, if PEC_{CCHP} is lower than $PEC_{conventional}$, the

CCHP operation reduces the PEC and it should be utilized. Therefore, the optimized PEC can be determined as follows

$$\text{If } PEC_{CCHP} > PEC_{conventional} \rightarrow PEC_{opt} = PEC_{conventional} \tag{3.19}$$

$$\text{If } PEC_{CCHP} < PEC_{conventional} \rightarrow PEC_{opt} = PEC_{CCHP} \tag{3.20}$$

3.2.2. Operation Cost Optimization Criterion (OC-O)

The purpose of the OC-O is to minimize the cost of operation during CCHP systems operation. This optimization technique is based on a comparison between the CCHP systems operation cost ($Cost_{CCHP}$) with the cost of the conventional case ($Cost_{conventional}$). The total operation cost for CCHP systems operation FEL and FTL strategies are expressed in Equations (3.21) and (3.22), respectively:

$$Cost_{CCHP-FEL} = F_m Cost_{fuel} \tag{3.21}$$

$$Cost_{CCHP-FTL} = E_m Cost_{electricity} + F_m Cost_{fuel} \tag{3.22}$$

where $Cost_{fuel}$ and $Cost_{electricity}$ are the cost of fuel and electricity, respectively. As mentioned before, since the conventional case uses electricity and fuel to satisfy the building electric and thermal demand, the $Cost_{conventional}$ can be determined using Equation (3.22). For this optimization criterion, if the $Cost_{CCHP}$ is higher than the $Cost_{conventional}$, the CCHP should not be operated. On the other hand, if the $Cost_{CCHP}$ is lower than the $Cost_{conventional}$, the CCHP system should be operated. Therefore, the optimized cost of operation can be expressed as

If $Cost_{CCHP} > Cost_{conventional} \rightarrow Cost_{opt} = Cost_{conventional}$ (3.22)

If $Cost_{CCHP} < Cost_{conventional} \rightarrow Cost_{opt} = Cost_{CCHP}$ (3.23)

3.2.3. Emission Reduction Optimization Criterion (ER-O)

CCHP systems can be optimized to guarantee minimum environmental impact. Therefore, the purpose of the ER-O is to minimize the carbon dioxide emissions during CCHP systems operations. Similar to the other optimization criterions, this optimization technique is based on a comparison between the CCHP carbon dioxide emissions (CDE_{CCHP}) with the emissions of the conventional case ($CDE_{conventional}$). CDE_{CCHP} for CCHP system operating FEL and FTL are given in Equations (3.24) and (3.25), respectively:

$$CDE_{CCHP-FEL} = F_m FCF_{CDE} \tag{3.24}$$

$$CDE_{CCHP-FTL} = E_m ECF_{CDE} + F_m FCF_{CDE} \tag{3.25}$$

where ECF_{CDE} and FCF_{CDE} are the emission conversion factors for electricity and natural gas, respectively. The CDE for the conventional case ($PEC_{conventional}$) can be determined using Equation (3.25). For this optimization case, if the CCHP system produces more emissions than the conventional case, the CCHP should not be operated. On the contrary, if CCHP systems produce lower emissions than the conventional case, it should be operated. The optimized CDE can be determined as

If $CDE_{CCHP} > CDE_{conventional} \rightarrow CDE_{opt} = CDE_{conventional}$ (3.26)

If $CDE_{CCHP} < CDE_{conventional} \rightarrow CDE_{opt} = CDE_{CCHP}$ (3.24).

CHAPTER 4

SIMULATION RESULTS AND ANALYSIS

This chapter presents the results obtained using the CCHP operational strategies and optimization criteria described in Chapter III. A reference building was defined to compare the different operation strategies. The reference building was simulated using the software EnergyPlus (DOE) to obtain hourly site energy consumption data. General description of the building is presented in Table 4.1. Since the energy consumption profile of a building highly depends on the climate conditions, cities with different climate conditions were selected to evaluate the different operation strategies. These cities are: Columbus, MS; Miami, FL; Boston, MA; Minneapolis, MN; and San Francisco, CA.

4.1 Individual City Loads

The heating, cooling, and electrical loads throughout the United States can vary substantially due to the vastly differing climates that exist. Due to this variation in loadings throughout the country, it is necessary to evaluate and simulate the performance of CCHP systems under different climate conditions. In order to perform these simulations, the heating, cooling, and electrical loadings were found using the aforementioned DOE EnergyPlus Software. Figure 4.1 details the heating loads per month for each location. This figure illustrates that the highest heating loads, as expected, are present in the most northern cities of Minneapolis, MN and Boston, MA. Also of significant note is that there is no heating requirement for the city of Miami.

Table 4.1. General Description of the Simulated Building Using EnergyPlus

Orientation	Aligned with North
Building type	General Offices
Area	464.5 m^2 (15.24 m x 30.48 m)
Glass area	30% in each wall (windows and door)
People	18 for weekdays, 0 for weekend
Occupancy schedule	Until (fraction): 6 (0), 7 (0.1), 8 (0.5), 12 (1), 13(0.5), 16(1), 17 (0.5), 18 (0.1), 24 (0)
Electric equipment	3749 W
Equipment schedule	Same as for occupancy
Lights	5,017 W
Lights schedule	Until[a] (fraction)[b]: 6 (0.05), 7 (0.2), 17 (1), 18 (0.5), 24 (0.05); for weekends 24 (0.05)
Thermostat schedule:	
For heating	Until[a] (set point, °C)[c]: 6 (18), 22 (22), 24 (18)
For cooling	Until[a] (set point, °C)[c]: 6 (28), 22 (24), 24 (28)

a. Until: indicates the hour of the day until the specified fraction is considered.
b. Fraction: indicates the fraction of the total value of the variable that is considered in the calculation for that specific period of time.
c. Set point: indicates the temperature to be considered as the thermostat set point for that specific period of time.

Figure 4.2 illustrates the monthly cooling loads of the five locations. As can be seen from Figure 4.2, the highest cooling loads are present in the climates that are located in the more southern regions of the country such as Miami, FL and Columbus, MS. The peak monthly loads between these two locations are very similar while the curve for Miami, FL indicates the more constant need for cooling. On the other hand, Minneapolis is the city with the lowest cooling load throughout the year.

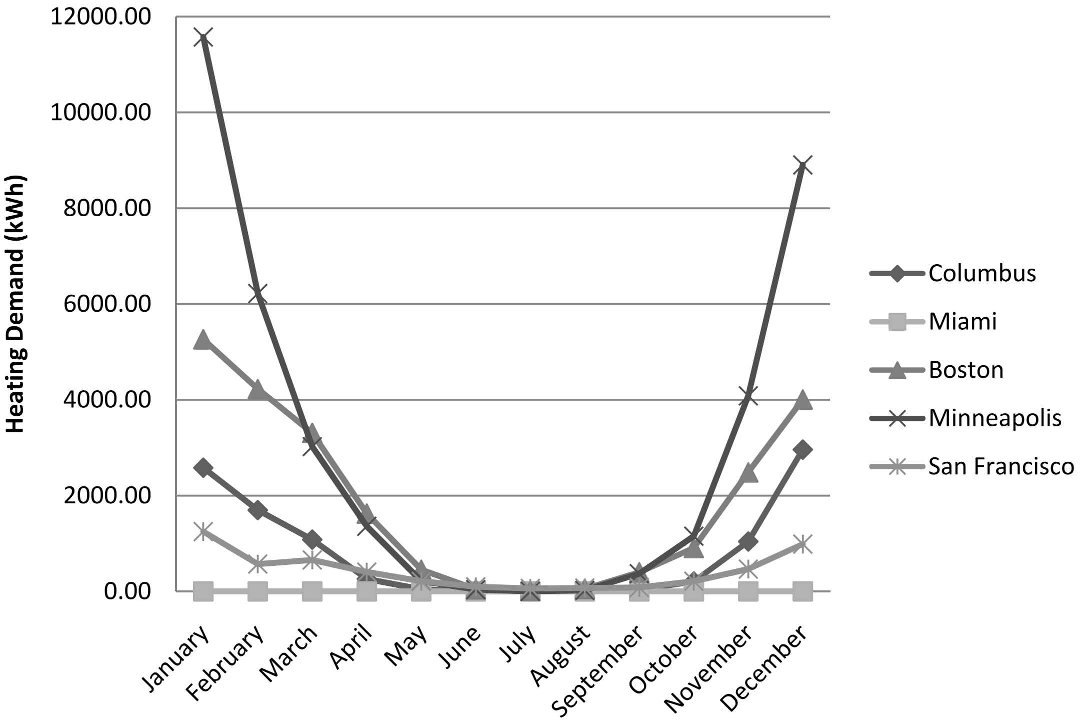

Figure 4.1. Heating Loads for Locations Evaluated

It is also useful to view the combined heating and cooling loads (thermal load of the facility) throughout the months of the year since the CCHP system utilizes recovered waste heat in order to satisfy the thermal load of the facilities. Figure 4.3 shows the yearly combined heating and cooling loads for each city under evaluation. This figure illustrates that San Francisco is the city with the overall lowest thermal loading. The combined thermal loads in San Francisco, CA never exceed 2000 kWh in one month of operation with a variation in loading from month to month of less than 2000kWh. On the other end of this spectrum is Minneapolis, MN, where there is a high combined thermal load in the winter months with an average load during the summer months with a variation of more than 9000 kWh between the peak month and lowest month. The rest of the locations are between these two extremes with different peak loadings and peak months depending on the climates and will thus provide a very good look at the extremes of various loadings and their impacts on the operation of CCHP systems.

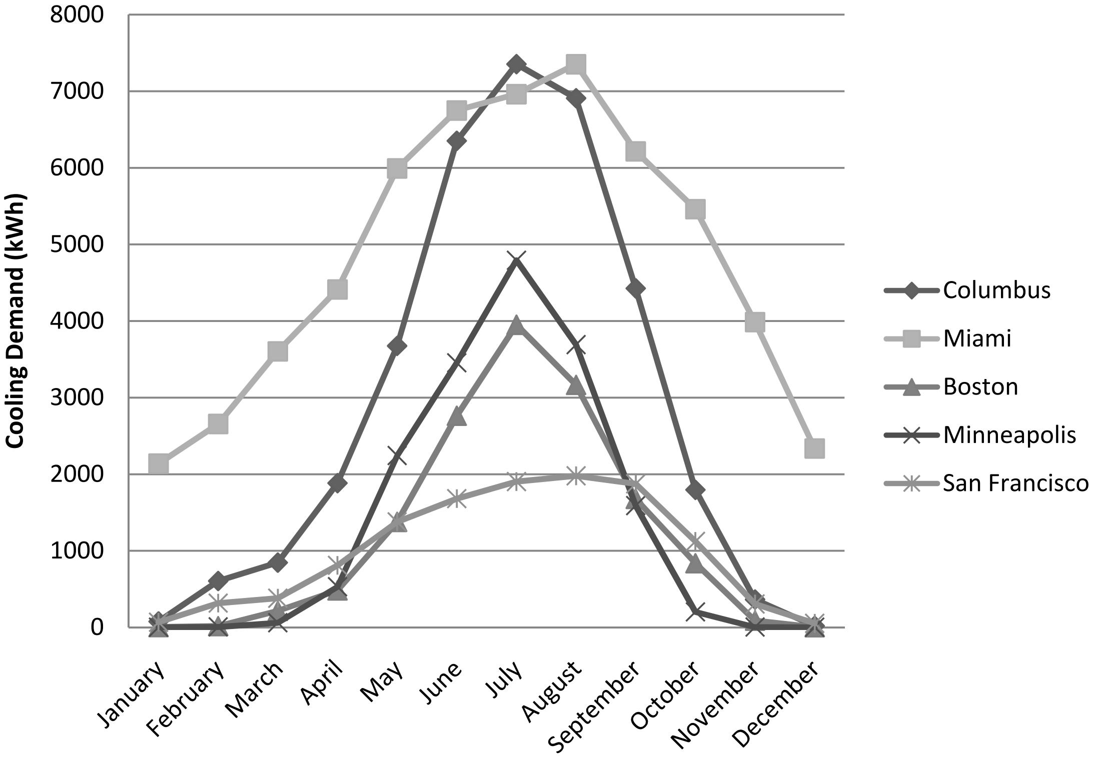

Figure 4.2.   Cooling Loads for Locations Evaluated

The monthly electric loads of the different locations throughout the calendar year are given in Figure 4.4. These loads only consider the electricity necessary to power office equipment, lights, etc., as well as the fans necessary for the HVAC operation of the facility. From Figure 4.4 it can be seen that a relatively constant electrical loading exists between all five locations despite the previously described widely varying thermal loads of the facilities. This common loading is due to the regular electrical requirements of the facility with only the variation of HVAC fans being introduced into the electrical loading. Without the need for cooling or heating generation power to be provided through electrical generation the need for electrical power of a facility is virtually the same no matter the location. This fact provides a very useful observation and will help to shape the applicability of the various operation strategies under investigation in this thesis.

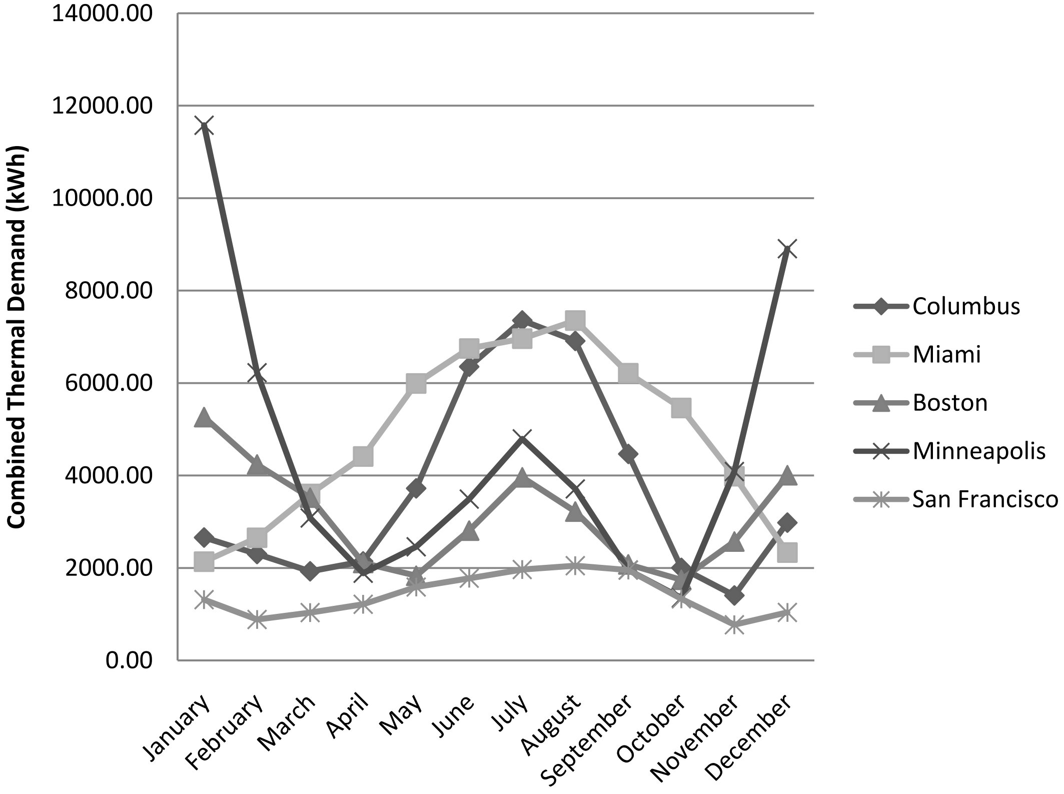

Figure 4.3. Combined Monthly Heating and Cooling Loads

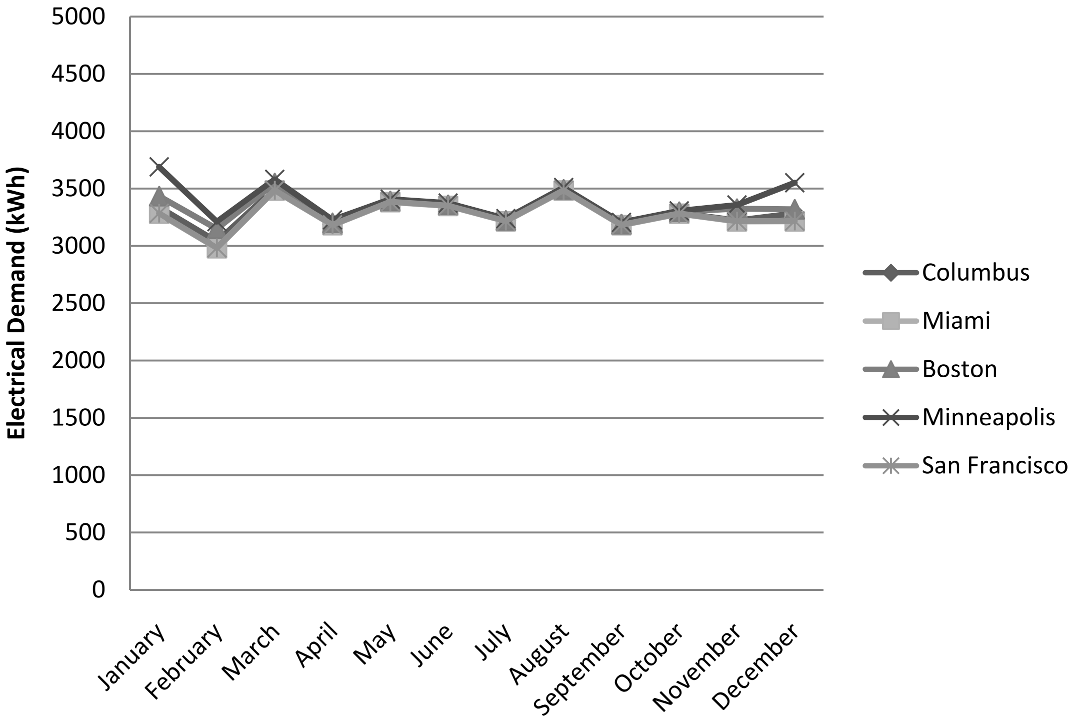

Figure 4.4. Monthly Electrical Loads for Locations Evaluated

4.2 Costs and Emissions Variables

In order to obtain the most accurate simulations, the cost of the fuel and electricity for each of the selected cities must be considered. Equally important for the simulations are the emissions conversion factors that must be used for the production of conventional grid electricity and fuel for each of the five locations under consideration. Table 4.2 shows the values used to determine the total cost of operation for the different systems and operation strategies.

Table 4.2. Electricity and Natural Gas Prices used in the Calculations [EPA, 2008]

City	Columbus, MS	Miami, FL	Boston, MA	Minneapolis, MN	San Francisco, CA
Electricity ($/kWh)	0.078	0.076	0.108	0.074	0.119
Natural Gas ($/MBtu)	8.08	10.98	11.30	9.98	8.10

* *Values obtained in August 2008*

From Table 4.2, it can be seen that the natural gas costs are significantly lower in Columbus, MS and San Francisco, CA. On the other hand, the highest LNG cost is that present in Boston, MA. In addition, Table 4.1 illustrates that San Francisco has the highest cost of conventional electricity. Conversely, the lowest electricity price is present in Minneapolis, MN. The fact that San Francisco, CA has a high conventional electricity price and a low natural gas price would point to a potential savings under CCHP operation if the need for conventional electricity importation is eliminated and replaced with sufficiently efficient electrical generation from the LNG powered prime mover.

Emissions conversion factors allow determining the amount of CDE per kWh of electricity as well as kWh of fuel energy consumed. There are different emission conversion factors for each location due to the differences in electricity production that exist in the different regions of the United States. Table 4.3 presents the carbon dioxide emissions conversion factors for electricity and natural gas for all the evaluated cities.

Table 4.3. CDE Conversion Factors for Electricity and Natural Gas [EPA, 2008]

	Electricity (tons/year-kWh)	Natural Gas (tons/year-kWh)
Columbus, MS	0.000749	0.0002
Miami, FL	0.000662	0.0002
Boston, MA	0.000455	0.0002
Minneapolis, MN	0.000826	0.0002
San Francisco, CA	0.000439	0.0002

** Values obtained in August 2008*

From Table 4.3 it can be seen that there is a wide variation in the production of CDE per kWh of conventional electricity used. San Francisco, CA and Boston, MA are the locations with the lowest CDE production levels from the conventional grid system and thus will probably see the lowest improvement in emissions while operating using a CCHP system. However, the remaining three locations have more possible CDE reductions due to relatively higher emissions per kWh delivered conventionally. The CDE for natural gas combustion is significantly lower than that of conventional electricity consumption in all five locations. It is important to note the fact that this conversion factor is applicable regardless of the location and thus there is the potential for an emissions reduction in any location under consideration depending upon the efficiency of CCHP production needed to meet electrical and thermal demands.

4.3 Individual Location Simulation Results

Now that all the variables that are needed in each simulation are known it is possible to present and evaluate each individual location's simulation results. CCHP systems operated FEL and FTL strategies are evaluated and optimized based on: primary energy consumption (PEC), operation cost, and carbon dioxide emissions (CDE). The comparison of the CCHP optimized strategies with the conventional operation allows for conclusions to be drawn about the applicability of CCHP operation in each of the five locations as well as the best optimization strategy. The results for all the cities include the performance of CCHP-FEL and CCHP-FTL with and without the optimization criteria. It is important to mention here that in the results figures, a negative number implies a reduction while a positive number implies an increase.

4.3.1 Columbus, MS

The change in PEC from the case of conventional production is shown in Figure 4.5. The conventional case for the facility located in Columbus, MS results in a PEC of 183,257 kWh per calendar year. From Figure 4.5 it can be seen that the only case in which a reduction in PEC does not occur is the case of simple CCHP-FEL. On the other hand, CCHP-FTL nets a slight reduction in PEC. It is important to mention here that any of the optimization criteria significantly reduces the PEC as compared with the conventional case. The greatest reduction of PEC is obtained for CCHP-FTL system operated under the PE-O optimization criteria as expected since this is the optimization seeking the best possible reduction in PEC. In general for the city of Columbus, CCHP-FTL presents better results in terms of PEC than CCHP-FEL.

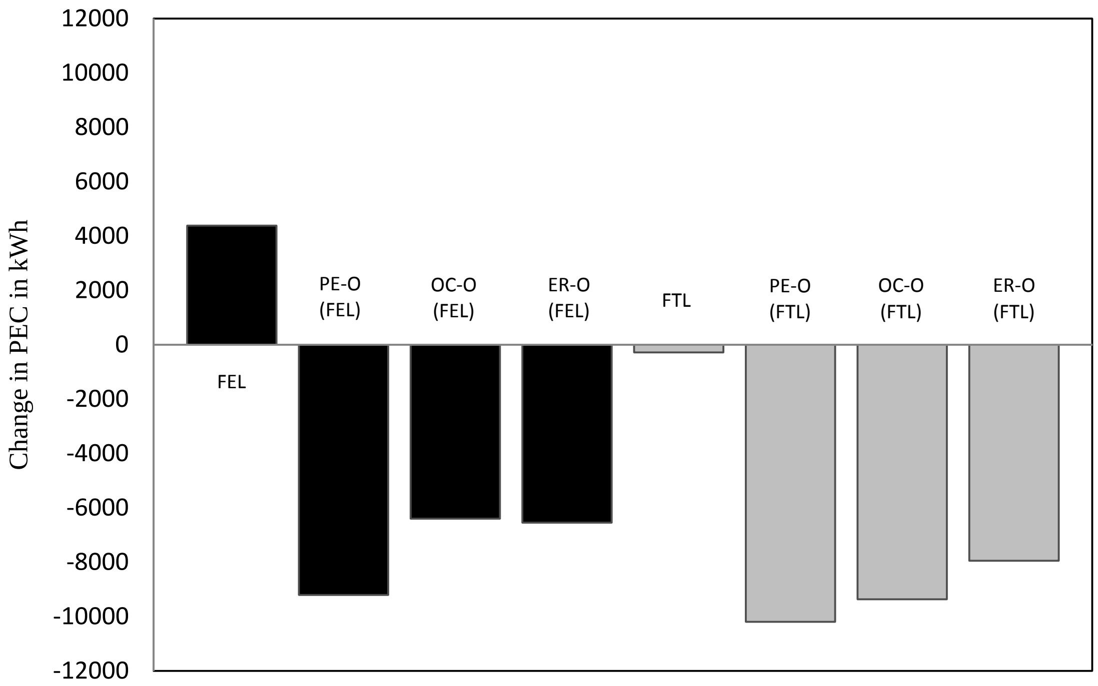

Figure 4.5. Change in PEC in kWh for Columbus, MS.

The change in CDE with respect to the conventional case is presented in Figure 4.6. The CDE for the conventional case are 39.1 tons of CO_2 annually. Figure 4.6 illustrates that every case of CCHP operation yields a reduction in CDE. In terms of emissions, CCHP-FEL yields better results than CCHP-FTL operating without any optimization criteria. The greatest reduction of CDE is obtained for CCHP-FEL operated under the emission optimization criteria.

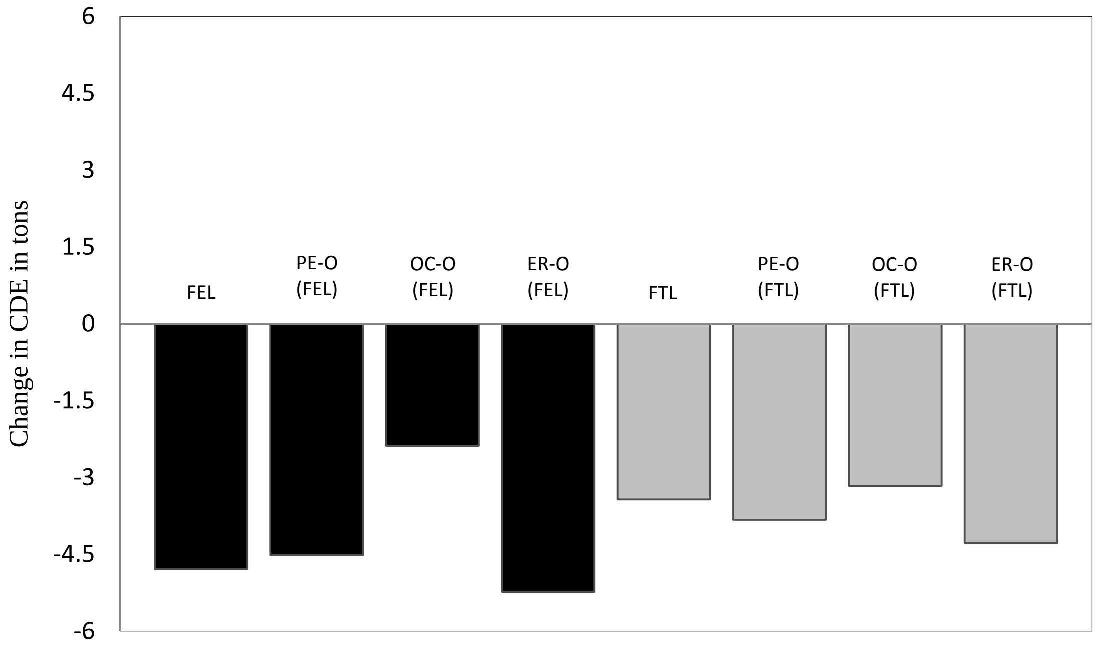

Figure 4.6. Change in CDE in tons for Columbus, MS.

The change in cost of operation from the conventional case for each of the CCHP strategies is shown in Figure 4.7. The total operation cost for the conventional case is $4315/year. Figure 4.7illustrates that CCHP operated FEL and FTL without any optimization criteria increases the cost of operation with respect to the conventional case. In addition to that, not all the optimization criteria reduce the operational cost. For CCHP-FEL the only way to achieve cost saving is operating the system under the cost optimization criteria. On the other hand, for CCHP-FTL optimizing the system based on PEC and cost give cost reduction as compared with the conventional case. However, when CCHP-FTL is optimized based on emissions, the operational cost increases. The greatest reduction of cost of operation is given when the CCHP-FTL is operated under the cost optimization criteria. In general for the city of Columbus, operating the CCHP system FTL under any of the optimization criteria provides better results than operating the CCHP system FEL. The results obtained for Columbus reflect the fact that optimizing one parameter may increase or decrease the other two.

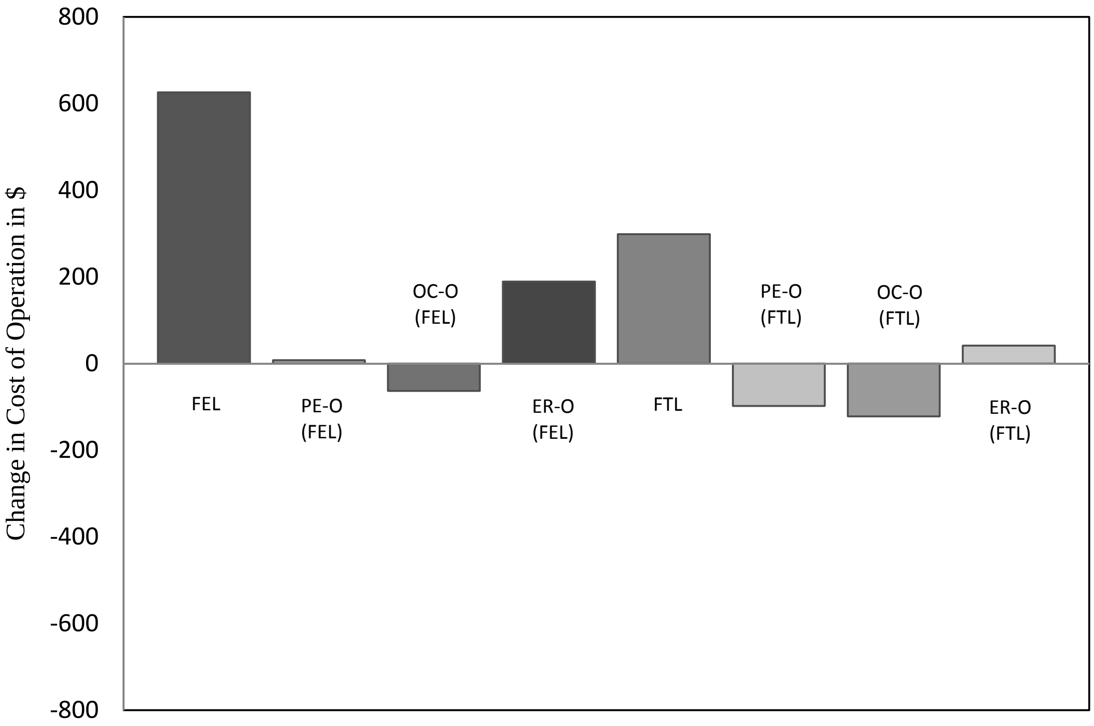

Figure 4.7. Change in Cost of Operation in $ for Columbus, MS.

4.3.2 Miami, FL

The change in primary energy consumption from the conventional case of each of the simulations for Miami, FL is shown in Figure 4.8. For the conventional case the the PEC was195,628 kWh per calendar year. From Figure 4.8 it can be seen that when both CCHP FEL and FTL are optimized based on cost, the results obtained for the PEC are the same as the conventional case. The simple case of CCHP-FTL nets a slight reduction in

PEC while all remaining simulations provide a slightly more significant primary energy savings. In this location, CCHP-FEL shows better primary energy savings than CCHP-FTL. The greatest reduction of primary energy consumption is resultant when the system is operated under CCHP-FEL using the optimization criteria of PE-O as expected as this is the optimization seeking the best possible reduction in PEC.

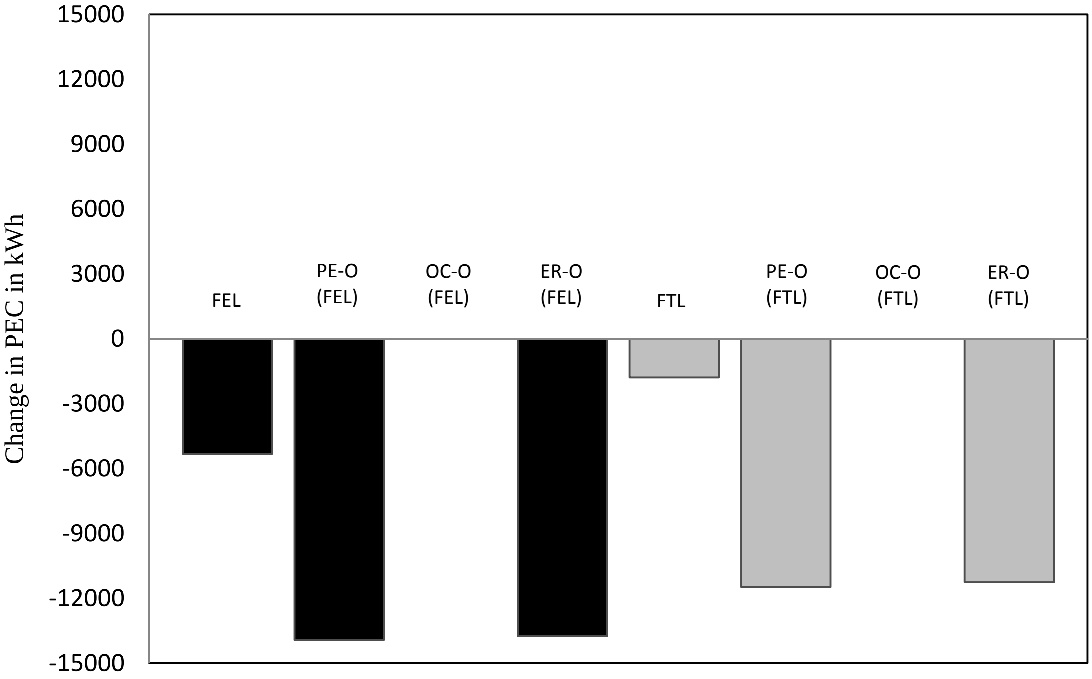

Figure 4.8. Change in PEC in kWh for Miami, FL.

The change in CDE from the conventional case for each of the simulations is shown in Figure 4.9. The CDE obtained for the conventional case are 38.74 tons of CO_2 annually. Figure 4.9 shows that every case of CCHP operation yields a reduction in CDE. CCHP-FEL gives better reduction of CDE than CCHP-FTL. The least possible CDE occur under CCHP-FEL while utilizing the optimization criterion of ER-O as expected.

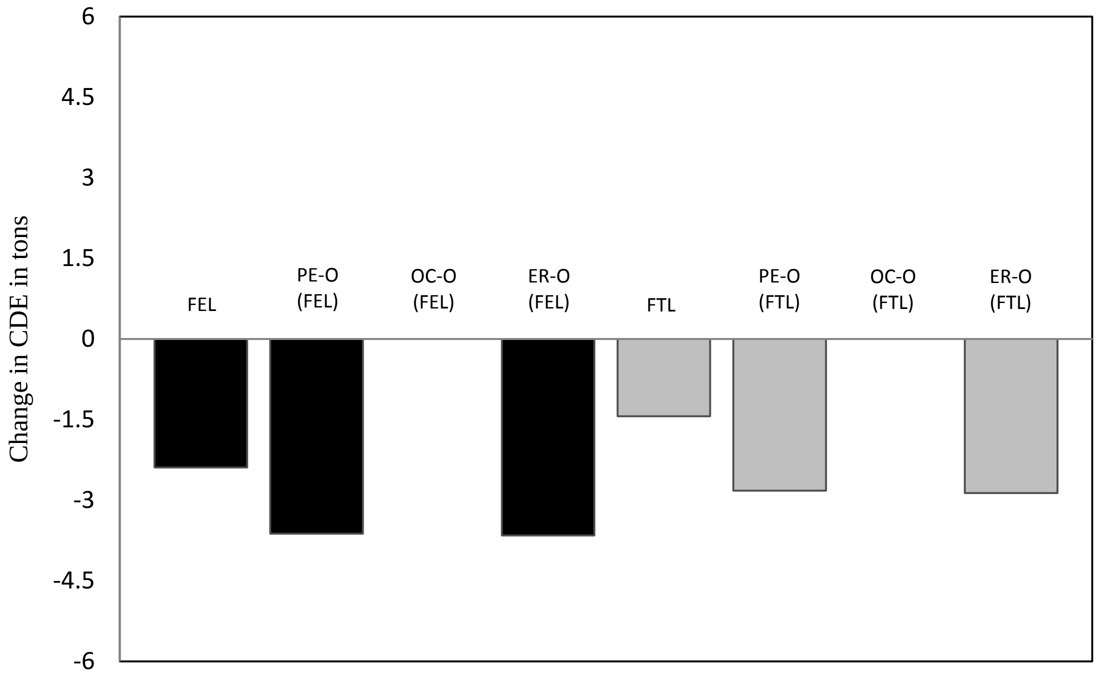

Figure 4.9. Change in CDE in tons for Miami, FL.

The change in cost of operation from the conventional case for Miami, FL is shown in Figure 4.10 . The conventional case yields a cost of operation of $4447.42 per year. In this evaluation it is immediately obvious that no simulation yields a lower cost than that of conventional operation. In fact, only CCHP-FEL and CCHP-FTL utilizing the optimization criterion of OC-O realize an operating cost equal to that of the conventional case. In this location FTL is the more economical operation strategy and again this is reflected in all optimization criteria operating under this operation strategy as opposed to those under FEL. It is important to mention here that the results for Miami are quite interesting and it is due to the fact the Miami does not have a heating load during the year.

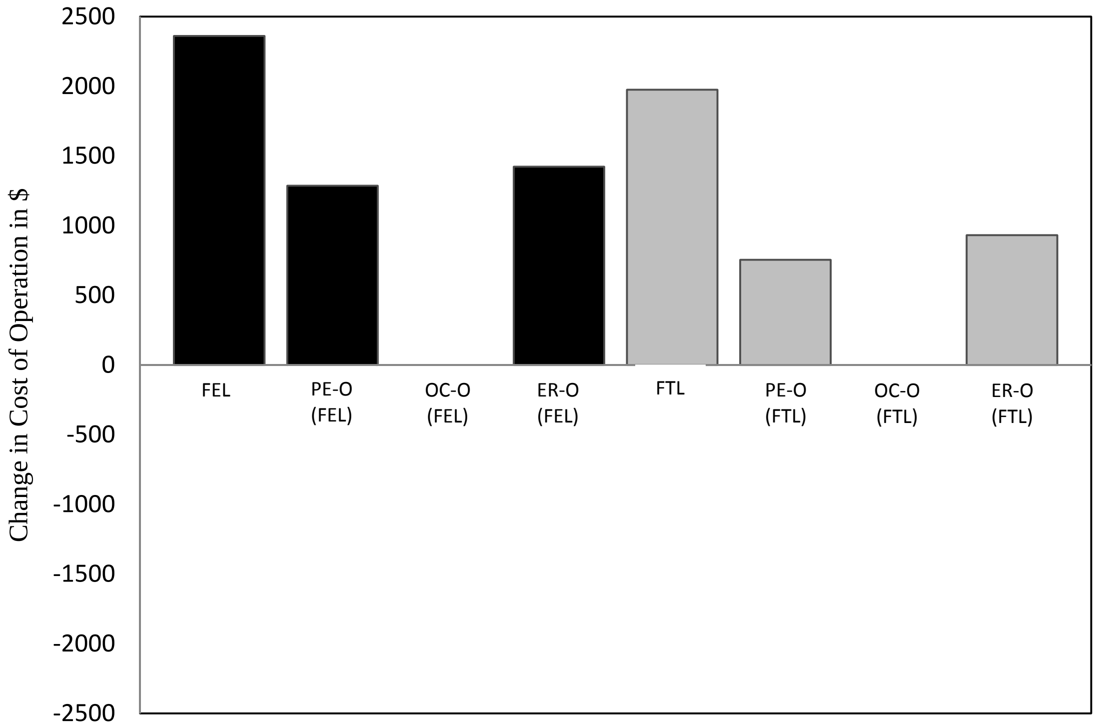

Figure 4.10. Change in Cost of Operation in $ for Miami, FL.

4.3.3 Boston, MA

The change in PEC of each of the CCHP simulations for Boston, MA is presented in Figure 4.11. The PEC for the conventional case is 179,536 kWh per calendar year. CCHP-FTL shows a significant reduction than CCHP-FEL. The best reduction of PEC is achieved under CCHP-FTL utilizing the optimization criteria of PE-O. As with the previous simulations the best case operational strategy shows significant savings when it is used as the basis from which the individual optimization criteria operate.

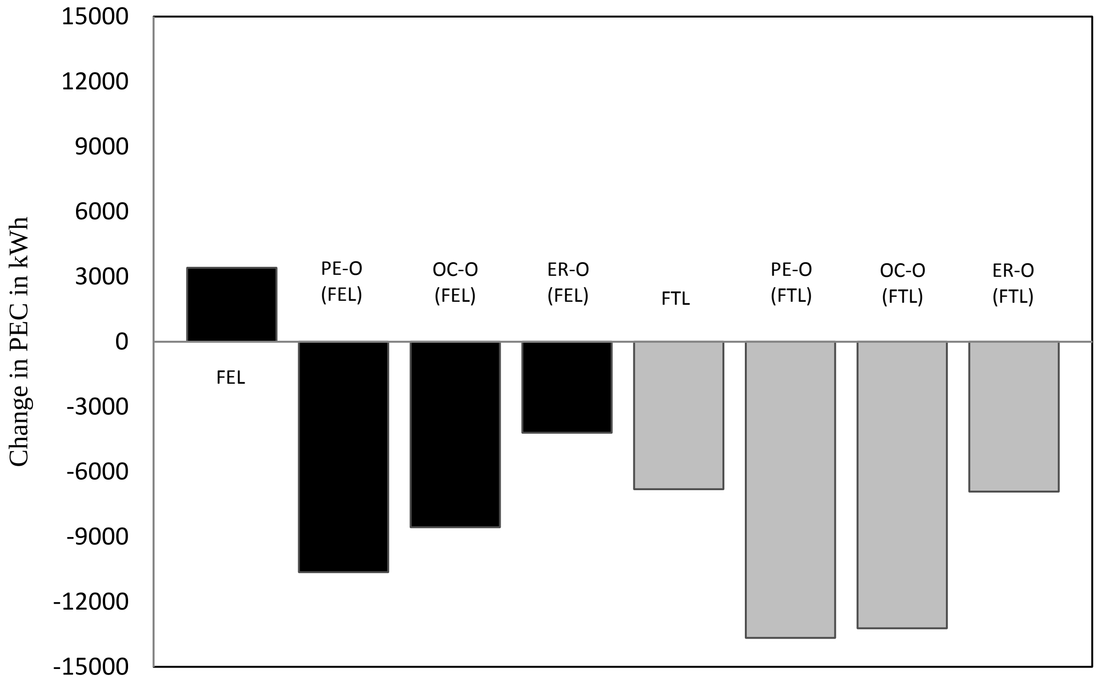

Figure 4.11. Change in PEC in kWhr for Boston, MA.

The change in CDE from the conventional case in Boston is illustrated in Figure 4.12. The conventional case yields a CDE of 26.07 tons of CO_2. Only when the CCHP system is optimized base on emissions, the CDE are lower than the CDE for the conventional case. CCHP-FTL nets a large reduction in CDE over the case of CCHP-FEL. This reduction present in FTL carries over to the optimization criteria run under FTL all yield a reduction in CDE from the same optimization criteria operated under FEL. The least possible CDE occur under ER-O under CCHP-FTL as is expected.

It is important to highlight here that once again, optimizing the CDE increases the cost of operation and PEC for both CCHP operation strategies.

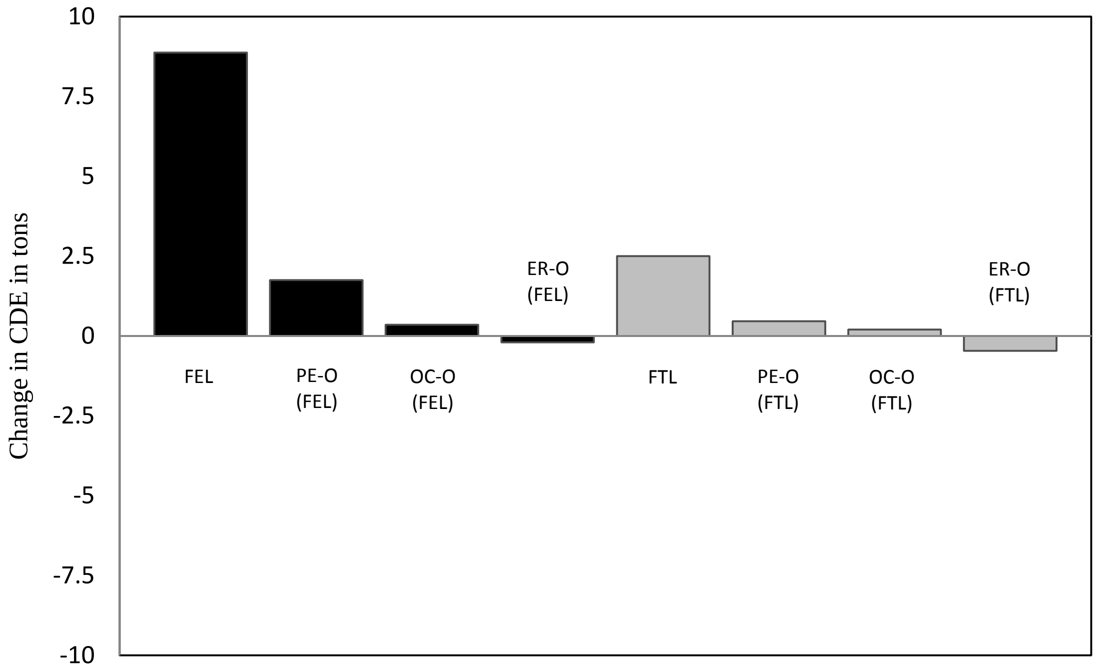

Figure 4.12. Change in CDE in tons for Boston, MA.

The change in cost of operation of each of the CCHP simulations in Boston is shown in Figure 4.13. The conventional case yields a cost of operation of $ 5,934.91. Due to this relatively high cost, all the CCHP optimized simulations are able to achieve a total operation cost lower than that of the conventional case. The optimization criteria operated under CCHP-FTL are all able to achieve higher cost savings than CCHP-FEL. As is expected, the optimization criteria of OC-O under CCHP-FTL nets the best yearly cost of $5,672.29.

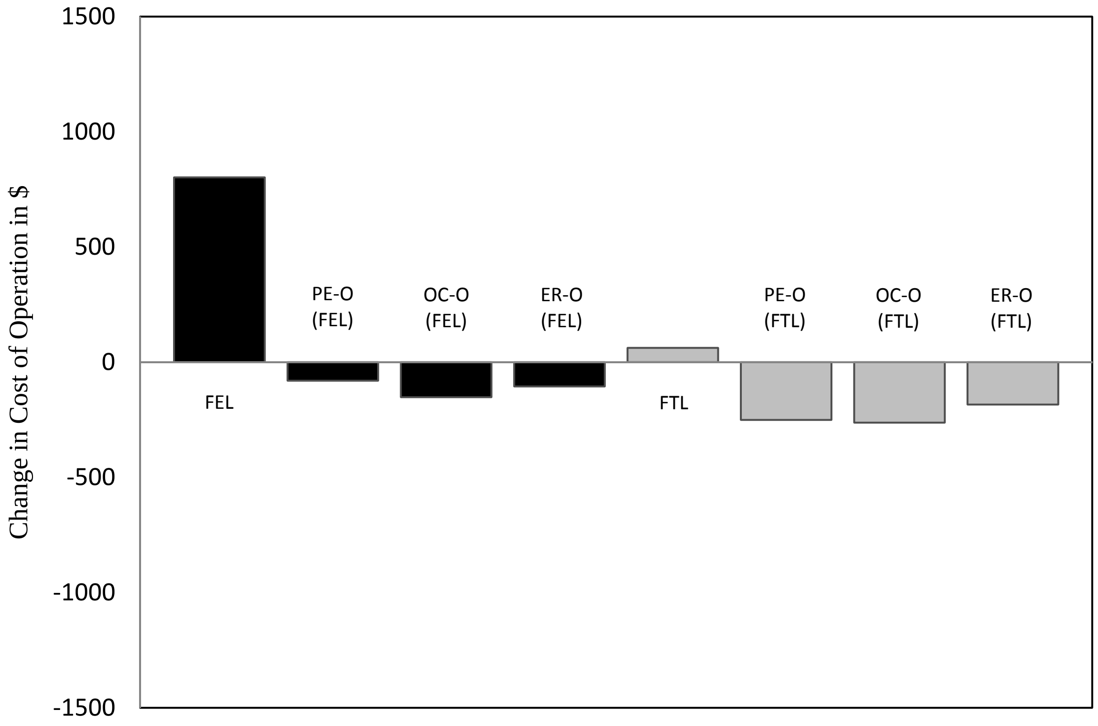

Figure 4.13. Change in Cost of Operation in $ for Boston, MA.

4.3.4 Minneapolis, MN

The changes in PEC from the conventional case for the simulations performed in Minneapolis, MN are illustrated in Figure 4.14. The conventional case yields a PEC of 202,736 kWh per calendar year. CCHP-FTL shows a slight reduction of PEC compared with CCHP-FEL. The best reduction of PEC is achieved under PE-O while the system is run under CCHP-FTL at 187,922 kWh.

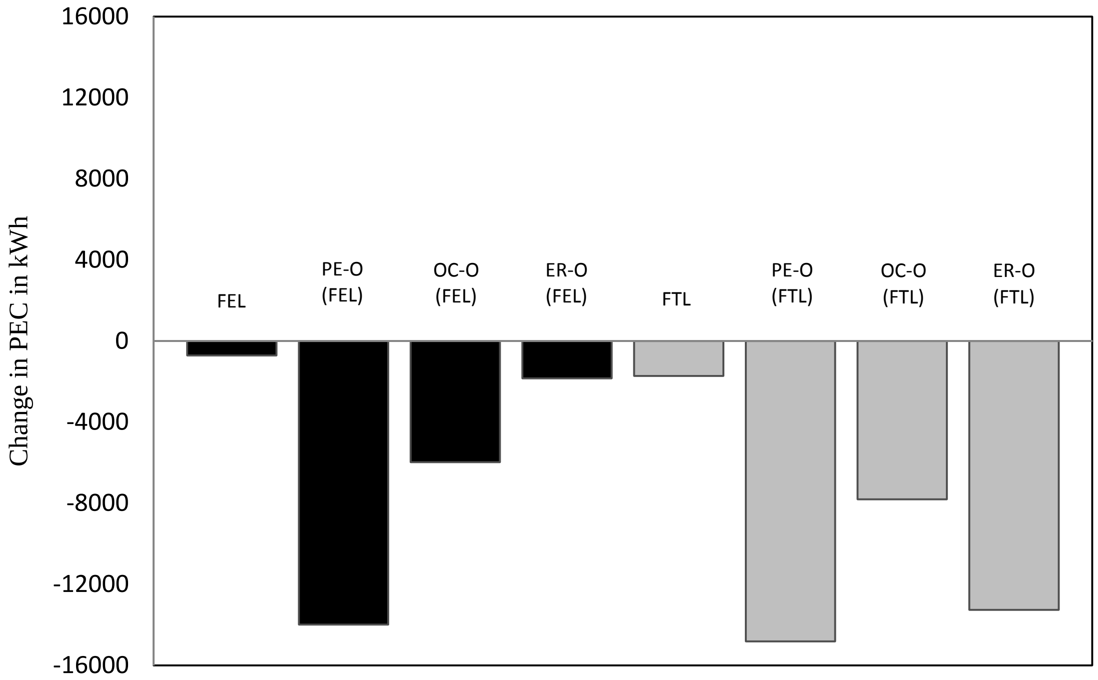

Figure 4.14. Change in PEC in kWh for Minneapolis, MN.

The changes in CDE of each of the CCHP simulations from the conventional case in Minneapolis, MN, are shown in Figure 4.15. The conventional case yields 47.38 tons of CO_2 annually. These extremely high CDE in the conventional case ensure the possibility of a good amount of emissions savings through CCHP operation. Figure 4.15 confirms this, as all CCHP optimization criteria and strategies net a reduction in emissions. The operational strategy of FEL yields the greater savings of the two operating strategies. The greatest savings are achieved under the optimization criteria of ER-O run under CCHP-FEL as expected. Under this operation the total CDE are 38.47 tons.

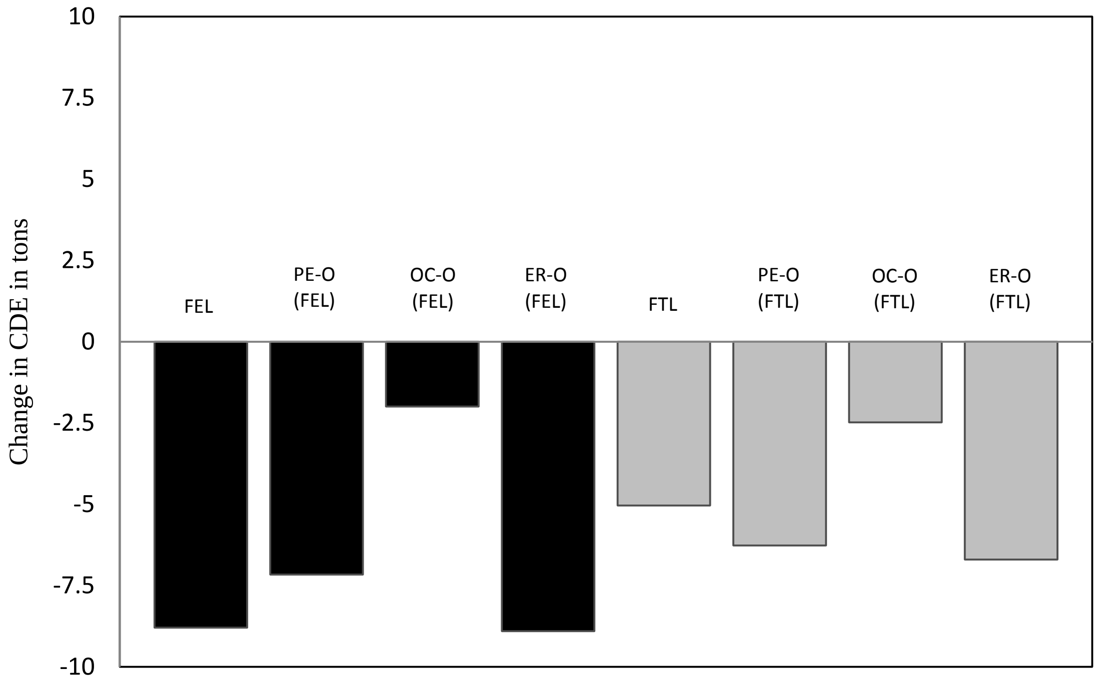

Figure 4.15. Change in CDE Emissions in tons for Minneapolis, MN.

The change in cost of operation of each of the CCHP simulations is shown in Figure 4.16. The conventional case yields a cost of operation of $ 4,990. Only the optimization criteria of OC-O under CCHP-FEL and under CCHP-FTL show a reduction in operating cost from that of the conventional cost. The operational strategy of FTL achieves a lower cost than that of FEL, at $5,806.3 to $6,570.1. As is expected, the optimization criteria of OC-O under CCHP-FTL nets the best yearly cost of $4,919.1.

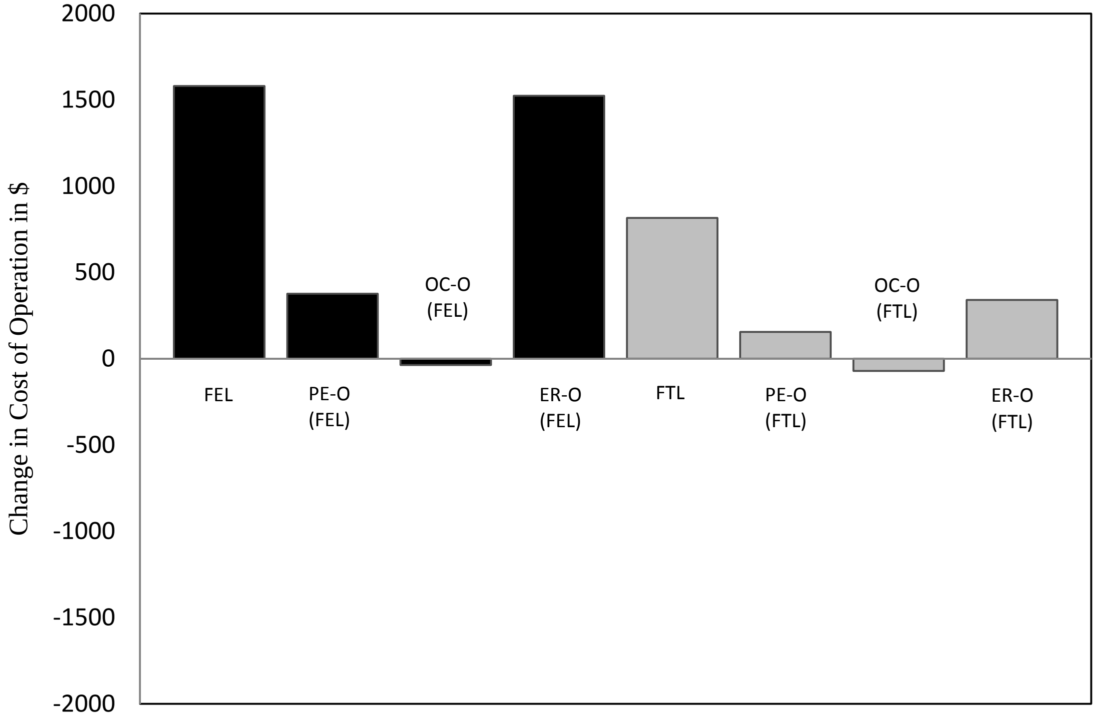

Figure 4.16. Change in Cost of Operation in $ for Minneapolis, MN.

4.3.5 San Francisco, CA

Figure 4.17 shows the change in PEC of each of the CCHP simulations for San Francisco, CA. A PEC of 151,131 kWh per year is present for the conventional case. The operational strategy of FTL shows a significant reduction from that of FEL at 142,931 kWh to 164,316 kWh. This primary energy savings is carried over into the individual operational criteria operated under CCHP-FTL as opposed to the same operational criteria operated under CCHP-FEL. The largest reduction in PEC is in the case of the optimization criteria of PE-O under CCHP-FTL. For this case the PEC totals 142,259 kWh.

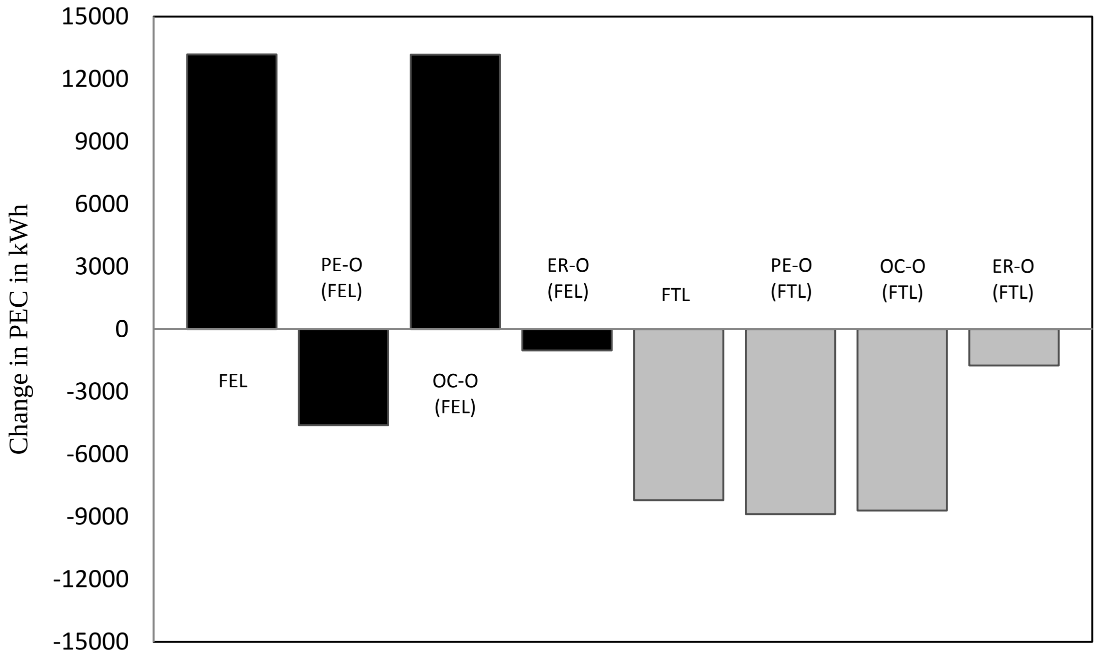

Figure 4.17. Change in PEC in kWh for San Francisco, CA.

The changes in CDE of each of the CCHP simulations performed in San Francisco, CA are shown in Figure 4.18. The conventional case yields a total of 20.24 tons of CDE annually. Only two simulations produce less CDE than the conventional case. The optimization of criteria of ER-O under CCHP-FTL and ER-O under CCHP-FEL both obtain a marginal savings. The optimization of ER-O under CCHP-FTL yields the lowest CDE at 20.14 tons annually. The operation strategy of FTL shows an improvement over FEL with CDE of 21.37 tons to 31.39 tons.

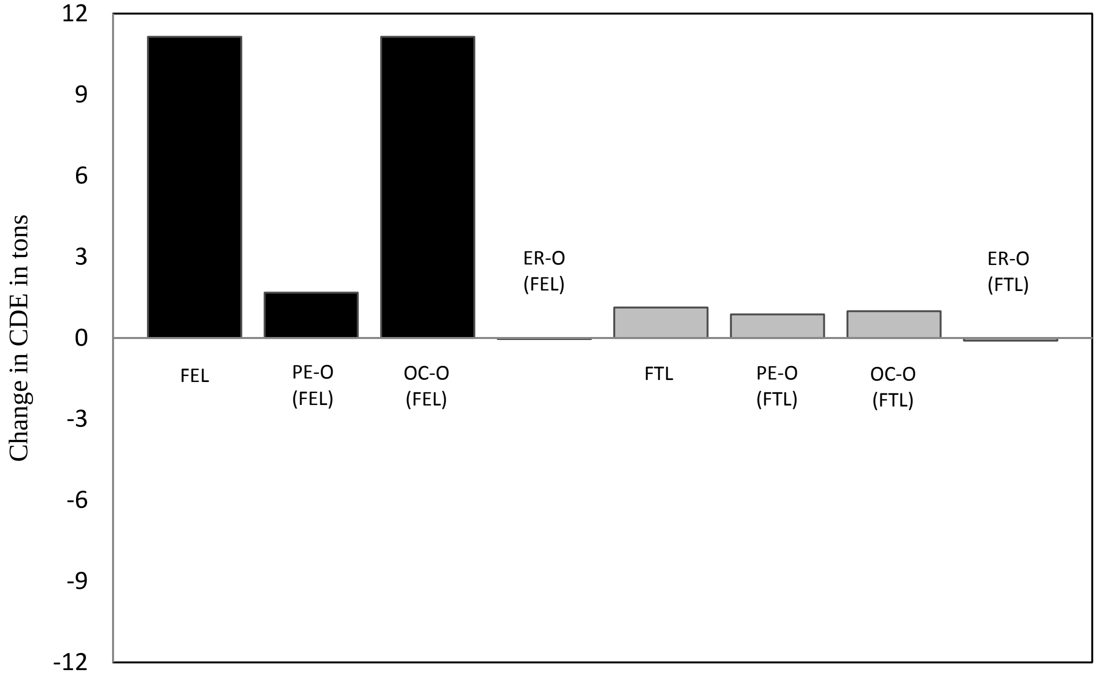

Figure 4.18. Change in CDE in tons for San Francisco, CA.

The change in cost of operation of each of the CCHP simulations in San Francisco is detailed in Figure 4.19. The conventional case yields a cost of operation of $ 5318.9. All CCHP simulations achieve cost savings over the conventional case. The operating strategy of FEL achieves a savings over its counterpart of FTL at $4,337.15 to $4,687.41. This is evident in all of the optimization criteria under CCHP-FEL as they are more cost effective than their counterparts under CCHP-FTL. As is expected, the optimization criteria of OC-O under CCHP-FEL yields the lowest yearly cost at $4,337.09.

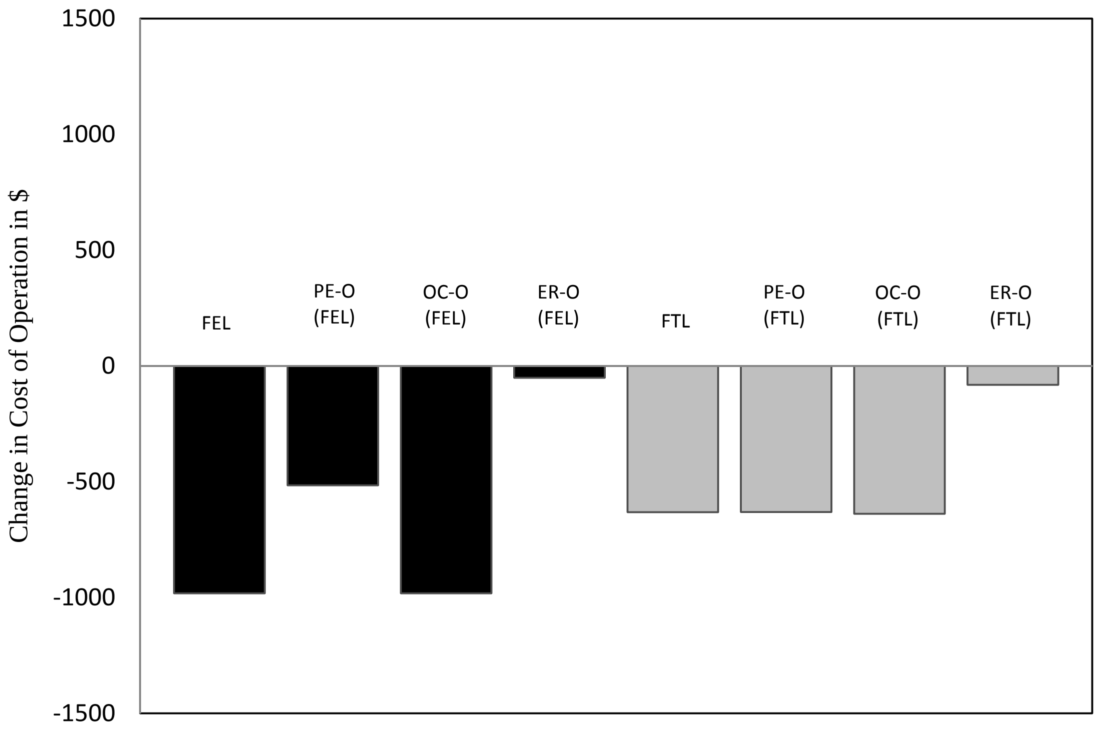

Figure 4.19. Cost of Operation in $ for San Francisco, CA.

CHAPTER 5

CONCLUSIONS

This thesis presented an analysis and optimization of CCHP systems operated FEL and FTL. The system was optimized based on different optimization criterion: energy savings, operation cost reduction or minimum environmental impact. CCHP systems operation was simulated for five varying geographical climate zones. The locations selected include Columbus, Miami, Boston, Minneapolis, and San Francisco. The resultant quantities of PEC, CDE, and cost of operation for each location under each optimization criteria and operational strategy are then compared to the conventional case for each specific location.

For the simulations performed at Columbus, MS significant savings were attained in most cases. The simulation results for PEC yielded a reduction from the case of conventional operation for all cases except for CCHP-FEL. The best case reduction was obtained for the optimization criteria of PE-O under CCHP-FTL where PEC was reduced from 183,257 kWh in the case of conventional operation to 173,063 kWh. For CDE in Columbus, MS a reduction from the conventional case was attained in every simulation with a best case reduction while utilizing the optimization criteria of ER-O under CCHP-FEL where CDE emissions were reduced from 39.05 tons to 35.4 tons. The cost of operation had more mixed results as five out of the eight simulations did not yield a savings. The best case reduction was present while utilizing the optimization criteria of OC-O operating under CCHP-FTL where operation costs were reduced from $4315 to $4193. From these results it can be seen that a CCHP system has the potential to provide a great benefit to a facility located in Columbus, MS as several of the simulations were able to yield a reduction in all three parameters investigated.

For the simulations performed for Miami, FL there were slightly different results from those of Columbus, MS. The vastly different thermal loadings of a facility in Miami, FL as well as the differing costs of electricity and natural gas caused favorable results to be slightly less easily attained. For PEC all simulations except for the OC-O simulations were able to attain a reduction. The optimization criteria of PE-O operating under CCHP-FEL was able to reduce the PEC from 195,628 kWh to 181,692 kWh. Once again, a reduction in CDE is attainable in all but the OC-O simulations. The optimization criteria of ER-O operating under CCHP-FTL, yields the largest reduction from 38.8 tons to 35.1 tons. When comparing cost of conventional operation with that of the CCHP simulations, there is no benefit obtainable. The optimization criteria of OC-O operating under CCHP-FTL and OC-O operating under CCHP-FEL both yield the exact same cost as that of conventional operation, $4447. This is due to the higher relative cost of natural gas and lower relative cost of conventional electricity in this location. Despite the inability of a CCHP system to reduce cost there are still multiple simulations that would allow for both a reduction in PEC and CDE without increasing the cost of operation.

In the location of Boston, MA there are further mixed results when comparing the CCHP simulations to that of the conventional operation case. PEC is for the most part reducible as all simulations but CCHP-FEL yield a reduction. The optimization criteria of PE-O operating under CCHP-FTL yields the largest reduction from conventional operation at 165,867 kWh from 179,536 kWh. The CDE results are slightly less favorable with only the ER-O simulations yielding a reduction from conventional operation. The largest reduction occurred under the optimization criteria of ER-O operating under CCHP-FTL as a reduction from the conventional emissions of 26.07 tons to 25.61 tons was obtained. The cost of operation was more favorable in Boston, MA as all simulations but simple CCHP-FEL and CCHP-FTL were able to yield a reduction in operating cost. The largest reduction occurred utilizing the optimization criteria of OC-O operating under CCHP-FTL when cost was reduced from $5934.91 to $5672.29. These results are largely due to the differing prices of electricity and LNG in Boston, MA as well as the cleaner conventional electricity system. A facility in Boston, MA could benefit from CCHP operation in every facet of this analysis under several of the different CCHP simulations.

For Minneapolis, MN, there are once again some significant reductions that are evident from CCHP simulation. The PEC is reduced from conventional operation in every simulation with a best case reduction obtained utilizing the optimization criteria of PE-O operating under CCHP-FTL when PEC is reduced from 202,736 kWh to 187,922 kWh. The CDE were also reduced in every simulation with the largest reduction being obtained utilizing the optimization criteria of ER-O operating under CCHP-FEL when emissions are reduced from 47.4 tons to 38.5 tons. Only under the OC-O simulations, the cost of operation was able to be reduced from that of the conventional case.. These results were due in large part to a relatively dirty conventional electricity system and a low price of conventional electricity, but even with these conditions a CCHP system could still be operated in order to reduce consumption of all three quantities investigated at the same time.

In the simulations performed for San Francisco, CA there are once again mixed results for the simulations. PEC is reduced in all but the simple case of CCHP-FEL and the utilization of the optimization criteria of OC-O operating under CCHP-FEL. The largest reduction occurs utilizing the optimization criteria of PE-O operating under CCHP-FTL. CDE are only reduced when using the emission optimization criteria. The largest reduction was obtained utilizing the optimization criteria operating under CCHP-FTL at 20.14 tons from 20.24 tons. The cost of operation was reduced in all cases of CCHP operation. The best case was that of the utilization of the optimization criteria of OC-O operating under CCHP-FEL, where the cost of operation is reduced from $5318.89 to $4337.09. Once again there were two simulations which yield a reduction of all three quantities and as such CCHP is a potential benefit for operation in San Francisco, CA.

While these results were positive for the application of CCHP to a wide range of locations and climates within the United States, there is the matter of prime mover variable efficiency to consider. A model that takes into consideration the variance of thermal efficiencies of the prime mover would be much more accurate and would lead to more useful results. This can be seen from the results of a case study of a diesel engine powered CCHP system with and without variance in the prime mover thermal efficiency. In general, if CCHP systems increase the cost of operation, as long as energy savings and reduction of emissions are guaranteed, the implementation of these systems should be considered. The selection of the optimization criterion depends on the main goal of the CCHP system and it has to be carefully analyzed to determine the effect on the other parameters.

REFERENCES

Absorption Chillers. Advanced Design Guideline, New Buildings Institute, 1998.

Cardona, E. and Piacentino, A., A Validation Methodology for a Combined Heating Cooling and Power (CHCP) Pilot Plant. *Journal of Energy Resources Technology*, 2004, 126, pp. 285-292.

Cardona, E. and Piacentino, A. “Matching economical, energetic, and environmental benefits: an analysis for hybrid CCHP-heat pump systems.” *Energy*, 31, 4, March 2006, pp. 490-515.

Cardona, E. and Piacentino, A., A Methodology for Sizing a Trigeneration Plant in Mediterranean Areas. *Applied Thermal Engineering*, 2003, 23, pp. 1665-1680.

Chicco, G. and Mancarella, P., From Cogeneration to Trigeneration: Profitable Alternatives in a Competitive Market. *IEEE Transactions on Energy*, 2006, 21, pp. 265-272.

Chicco G. and Pierluigi, M. "Assessment of the greenhouse gas emissions from cogeneration and trigeneration systems. Part I: Models and indicators." Energy, 2008, Vol. 33, Issue 3, pp. 410-417.

Chicco G. and Pierluigi, M. "Assessment of the greenhouse gas emissions from cogeneration and trigeneration systems. Part II: Analysis techniques and application cases," Energy, 2008, Vol. 33, Issue 3, pp. 418-430.

Chicco G. and Pierluigi, M. "Distributed multi-generation: A comprehensive view." Renewable and Sustainable Energy Reviews, Vol. 13, Issue 3, April 2009, pp. 535-551.

EnergyPlus. Energy Simulation Software, Available at: http://www.eere.energy.gov/buildings/energyplus/

Fumo, N., Mago, P.J., and Chamra, L.M., “Cooling, Heating, and Power Energy Performance for System Feasibility.” IMechE *Journal of Power and Energy*, Vol. 222, No. 5, 2008, pp. 347-354.

Hambley, A. R., Electrical Engineering: Principles and Applications. 3rd ed. Upper Saddle River, NJ: 2005.

Jalalzadeh-Azar, A., A Comparison of Electrical and Thermal Load Following CHP Systems. *ASHRAE Transactions*, 2004, 110, pp. 85-94.

Kakac, S. and Liu, H. Heat Exchangers: Selection, Rating, and Thermal Design. 2nd ed. Boca Raton, FL: CRC Press, 2002.

Li, H., et al., Energy Utilization Evaluation of CHP Systems. *Energy and Buildings*, 2006, 38, pp. 253-257.

Mago, P.J., Fumo, N., and Chamra, L.M., "Performance Analysis of CCHP and CHP Systems Operating Following the Thermal and Electric Load." *International Journal of Energy Research*, *DOI:10.1002/er.1526.*

Mago, P.J, Chamra, L.M., and Ramsay, J. "CHP System Hybrid Electric-Thermal Load Following Operation." IMechE *Journal of Power and Energy*, *Under Review.*

Mago, P.J., Fumo, N., and Chamra, L.M. "Methodology to Perform a Non-conventional Evaluation of Cooling, Heating, and Power Systems," Journal of Power and Energy, 2007, 222, pp. 1075-1087.

Mollersten K., Yan J., and Westermark M. "Potential and cost-effectiveness of CO2 reductions through energy measures in Swedish pulp and paper mills." Energy, 2003, 28, 7, pp. 691-710.

Moran, A., Mago, P.J., and Chamra, L.M., "Thermoeconomic Modeling of Micro-CHP (Micro-Cooling, Heating, and Power) for Small Commercial Applications." *International Journal of Energy Research*, Vol. 32, No. 9, July 2008, pp. 808-823.

"Propane Technology Review." April 2006. <http://www.afdc.energy.gov>

Pullkrabek, W.W. Engineering fundamentals of the Internal Combustion Engine. 2nd ed. Upper Saddle River, NJ: Prentice-Hall, 2004.

Shipley, A., et al., "Combined Heat and Power: Effective Energy Solutions for a Sustainable Future." Available online at *http://www.osti.gov/bridge*

Sonntag, R. E., Borgnakke, C., and Van Wylen, G.J. Fundamentals of Thermodynamics. 6th ed. Hoboken, NJ: John Wiley & Sons, 2003.

Sun, Z., et al., Energetic Efficiency of a Gas-Engine-Driven Cooling and Heating System. *Applied Thermal Engineering*, 2004, 24, pp. 941-947.

U.S. Department of Energy, Energy Information Administration, *Glossary*. http://www.eia.doe.gov. Jan. 10, 2007.

U.S. Department of Energy, Environmental Protection Agency, Energy Star Program, *Target Finder. Available at http://energystar.gov/*

Wahlund, B., Yan J., and Westermark, M. "Increasing biomass utilization in energy systems: A comparative study of CO2 reduction and cost for different bioenergy processing options," Biomass and Bioenergy, 2004, 26, 6, pp. 531-544.

Zogg et al., Using CHP Systems in Commercial Buildings. *Ashrae Journal*, 2005, pp. 33-36.

http://www.cogenerationtechnologies.com