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Combined Heat and Power Systems for Commercial Buildings: Investigating Cost, Emissions, and Primary Energy Reduction Based on System Components

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Combined heat and power systems for commercial buildings: investigating cost, emissions, and primary energy reduction based on system components

By

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Combined heat and power systems for commercial buildings: investigating cost, emissions, and primary energy reduction based on system components

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Combined heat and power (CHP) systems produce electricity and useful heat from fuel. When power is produced near a building which consumes power, transmission losses are averted, and heat which is a byproduct of power production may be useful to the building. That thermal energy can be used for hot water or space heating, among other applications. This dissertation focuses on CHP systems using natural gas, a common fuel, and systems serving commercial buildings in the United States.

First, the necessary price difference between purchased electricity and purchased fuel is analyzed in terms of the efficiencies of system components by comparing CHP with a conventional separate heat and power (SHP) configuration, where power is purchased from the electrical grid and heat is provided by a gas boiler. Similarly, the relationship between CDE due to electricity purchases and due to fuel purchases is analyzed as well as the relationship between primary energy conversion factors for electricity and fuel. The primary energy conversion factor indicates the quantity of source energy necessary to produce the energy purchased at the site.

Next, greenhouse gas emissions are investigated for a variety of commercial buildings using CHP or SHP. The relationship between the magnitude of the reduction in emissions and the parameters of the CHP system is explored. The cost savings and reduction in primary energy consumption are evaluated for the same buildings.

Finally, a CHP system is analyzed with the addition of a thermal energy storage (TES) component, which can store excess thermal energy and deliver it later if necessary. The potential for CHP with TES to reduce cost, emissions, and primary energy consumption is investigated for a variety of buildings. A case study is developed for one building for which TES does provide additional benefits over a CHP system alone, and the requirements for a water tank TES device are examined.

DEDICATION

To my father, who loves engineering, and to my mother, who loves teaching.

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TABLE OF CONTENTS

CHAPTER

LIST OF TABLES

LIST OF FIGURES

NOMENCLATURE

CC	capital cost
CC_{chp}	capital cost of CHP system in kW
CC_{equiv}	carbon equivalent, accounting for more than one type of emissions
$CCHP/CHCP$	combined heat, cooling and power
CE_{CH_4}	carbon equivalent emissions factor for methane
CE_{CO_2}	carbon equivalent emissions factor for carbon dioxide
CE_{NO_x}	carbon equivalent emissions factor for nitrous oxides
CHP	combined heat and power
$Cost_{chp}$	cost associated with CHP system
$Cost_e$	electricity cost per unit energy
$Cost_f$	fuel cost per unit energy
$Cost_{shp}$	cost associated with SHP system (reference case)
CR	cost ratio, $Cost_e/Cost_f$
CR_{min}	minimum CR corresponding to No Savings Case
C_{te}	coefficient to obtain recoverable thermal energy, accounting for heat loss
E_b	electricity required by the building
E_b^*	non-varying fraction of E_b considered for analysis
ECF	source-to-site energy conversion factor for electricity

EEF	electricity emissions factors, unit of pollutant per unit of electricity consumed
EER	ratio of EEF to FEF
E_{excess}	excess electricity that can be exported or stored
E_{grid}	electricity required from the grid
$Emissions_{chp}$	emissions associated with CHP system
$Emissions_{shp}$	emissions associated with SHP system
E_{pgu}	electricity output of the PGU associated with the CHP system
ER_{min}	minimum ER corresponding to equal emissions for CHP and SHP
ESS	emissions spark spread
ESS_{act}	actual emissions spark spread
ESS_{min}	minimum ESS corresponding to equal emissions for CHP and SHP
E_{useful}	electricity produced by the CHP system that is used by the building
F_b	fuel energy needed to meet the building demand Q_b
F_{boiler}	fuel used by the boiler
FCF	source-to-site energy conversion factor for electricity
F_{chp}	fuel energy used by CHP system
$\dot{F}_{chp}$	rate of fuel energy provided to the CHP system
FEF	fuel emissions factors, unit of pollutant per unit of fuel consumed
GHG	greenhouse gas
HRS	heat recovery system associated with the CHP system
LHV_{fuel}	lower heating value of fuel
m_{fuel}	mass of fuel

PBP	payback period
PBP_{CHP}	payback period for a given CHP system
PEC	primary energy consumption
PEC_{chp}	PEC associated with CHP system
PEC_{shp}	PEC associated with SHP system
PER	ratio of ECF to FCF
PER_{min}	minimum PER corresponding to equal operating costs for CHP and SHP
$PESS$	primary energy spark spread
$PESS_{act}$	actual primary energy spark spread
$PESS_{min}$	minimum PESS corresponding to equal PEC for CHP and SHP
PGU	power generation unit
PGU_{size}	size of the PGU in units of electrical power
PHR_b	power-to-heat ratio of the building demand
PHR_{chp}	power-to-heat ratio of the CHP system
$PHR_{chp(ideal)}$	power-to-heat ratio of the CHP system when $Q_{rec} = Q_{useful}$
Q_{av}	portion of Q_{pgu} that is available to the heat recovery system
Q_b	heat demand of the building
Q_b^*	non-varying fraction of Q_b considered for analysis
Q_{boiler}	heat supplied by the boiler
Q'_{boiler}	heat output from the boiler needed to meet the building's heat demand
Q_{chp}	thermal energy output provided by the CHP system to the building
Q_{excess}	excess heat produced by the CHP system beyond Q_{req}
Q_{pgu}	heat rejected from the PGU

Q_{rec}	thermal energy recovered from the CHP system as a whole
Q_{req}	heat required to meeting the building's heat demand
$Q_{storage\_new}$	thermal energy added to TES at each time step
$Q_{storage\_old}$	thermal energy present in the TES device at a given time step
Q_{useful}	heat recovered from the CHP system that is used by the building
$\dot{Q}_{useful}$	rate of useful heat provided by the CHP system
R	radius of tank
R_{boiler}	fraction of Q_b supplied by the boiler
R_e	fraction of E_b supplied by the CHP system
R_{grid}	fraction of E_b supplied by purchasing from the electrical grid
R_h	fraction of Q_b supplied by the CHP system
$R_{h(ideal)}$	R_h corresponding to $PHR_{chp(ideal)}$
$R_{h,CHP\text{-}TES}$	fraction of Q_b supplied by the CHP system with TES
R-value	thermal resistance value of insulation
SHP	separate heat and power
SS	spark spread, price difference between electricity and fuel
SS_{act}	actual SS based on price data for electricity and fuel cost
SS_{min}	calculated minimum SS corresponding to No Savings Case
T_∞	ambient temperatue
TES	thermal energy storage
TES_{cap}	capacity of the TES device, in kWh
$T_{insulation}$	insulation temperature
T_{max}	maximum allowable temperature for water tank

T_{water}	water temperature
$\dot{W}_{pgu}$	electrical power output of the PGU associated with the CHP system
VF	volume fraction of water to insulation
V_{tank}	volume of water tank
α_{water}	thermal diffusivity of insulation
α_{water}	thermal diffusivity of liquid water
η_{boiler}	thermal efficiency of the boiler
$\eta_{e,pgu}$	electric efficiency of the CHP system
$\eta_{e,pgu}$	electric efficiency of the PGU associated with the CHP system
η_{hc}	efficiency of the building's heating system, not including boiler efficiency, when either CHP or boiler are used to meet heating demand
$\eta_{hrs,chp}$	efficiency of the heat recovery system associated with the CHP system
$\eta_{hs,shp}$	efficiency of the entire SHP heating system (including boiler efficiency)
$\eta_{o,chp}$	overall efficiency of the CHP system
$\eta_{th,chp}$	ratio of useful thermal energy provided by the CHP system to fuel input
θ	nondimensional temperature relating temperature to T_{max}

CHAPTER I

INTRODUCTION

Combined heat and power (CHP), or cogeneration, is the simultaneous production of electrical and thermal energy at or near the site of use. CHP systems can reduce the primary energy needed to provide electrical power and thermal energy to a building by reducing the amount of heat rejected in power production and by reducing the transmission and distribution losses from the site of production to the site of use [1]. In this way, heat which would be waste heat at a central power plant is used to help meet the building's thermal energy needs, and the total system efficiency can reach 80% [2] (see Figure 1.1).

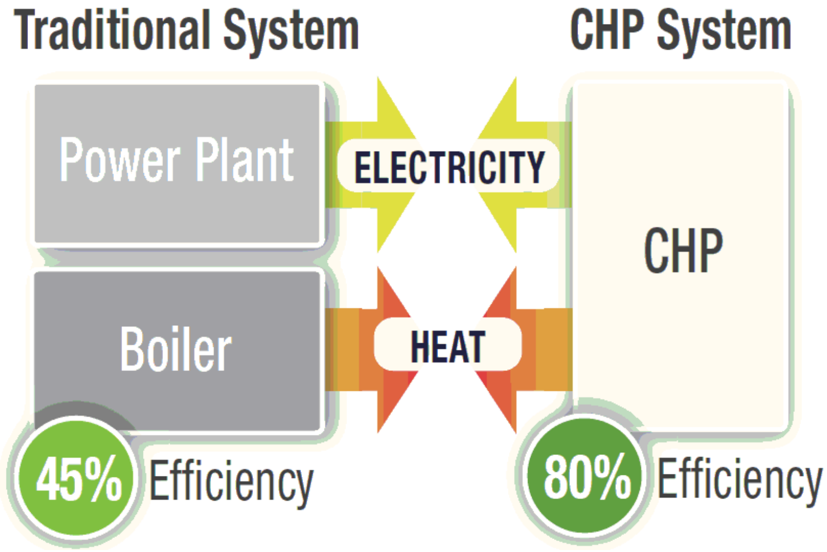

Figure 1.1 Traditional System versus CHP System [2]

A CHP system produces electricity and thermal energy from a single fuel source; while a traditional, or separate heat and power (SHP) system typically purchases electricity from the grid and provides heat with a boiler. Typical CHP components include the prime mover, the heat recovery system, and a heating system for the building, as shown in Figure 1.2.

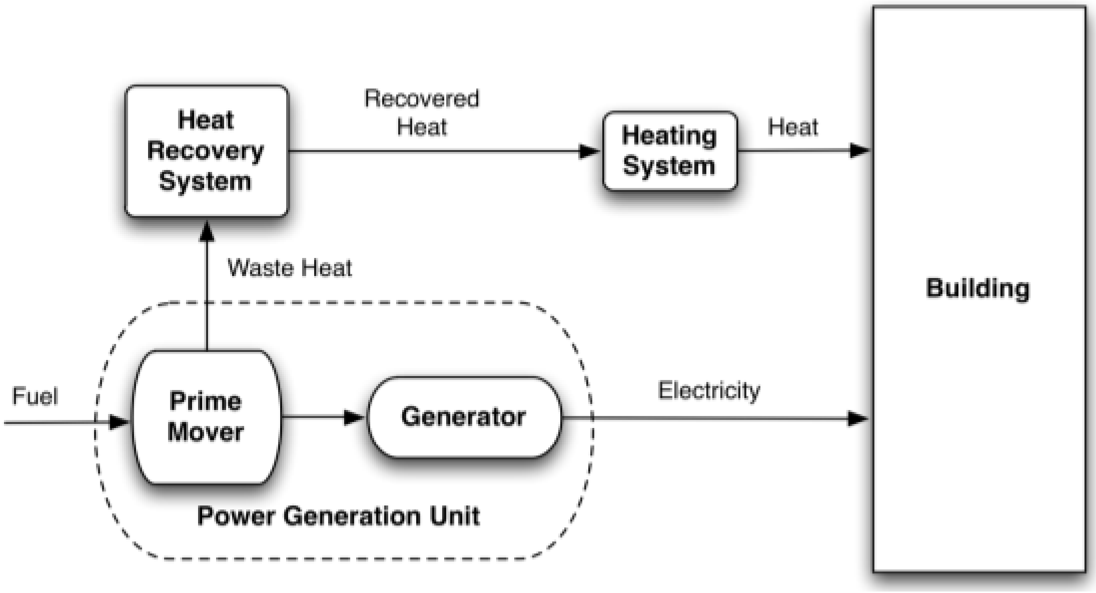

Figure 1.2 Components of a CHP system

Natural gas is a fuel commonly used for CHP installations, but any fuel may be used to provide energy to a prime mover, including coal, oil, biomass or other alternative fuels. The waste heat from the fuel combustion becomes useful thermal energy, and in the case of combined cooling, heating, and power (CCHP), or trigeneration, it may also be used for cooling.

The prime mover typically consists of a power generation unit (PGU) which produces mechanical energy that is used by a generator to produce electricity [3]. Prime movers can be combustion turbines, steam turbines, reciprocating engines, diesel engines, or any device which produces electricity and heat as a byproduct. Fuel cells which convert chemical energy to electrical energy at high temperatures and have heat available from the cells can also be used as prime movers for CHP systems [4].

Potential Benefits of Combined Heat and Power

According to the International Energy Agency (IEA) [5], CHP systems can reduce carbon dioxide emissions (CDE) and decrease the cost of power distribution and transmission. The amount of reduction in operating cost, CDE, or primary energy consumption (PEC) depends on geographic location and the operational strategy used for the system, in addition to the performance of individual CHP components [6, 7, 8].

Additionally, an economic analysis for a CHP system in a particular situation may show that it is unfavorable economically while favorable environmentally, or vice versa [1, 9, 10]. The particular benefits which are most important to the user must be determined in order to make a recommendation about whether a CHP system is appropriate for a given situation.

In addition to reductions in cost, CDE, and PEC, other benefits may be associated with the use of a CHP system: increased power reliability, improved power quality, and tax credits or other incentives [11,12, 13].

Economic Benefits

Using a CHP system in place of SHP can result in monetary savings if the cost of producing electricity and thermal energy with the CHP system is lower than the cost of purchasing electricity and producing heat with SHP. The benefits of a CHP system for use with a particular building depend strongly on the power-to-heat demand ratio of the building [14] and the price of the fuel and electricity in the location where the system is installed.

Emissions Benefits

CHP systems may reduce the amount of CDE when the emissions produced by the CHP system are lower than the emissions produced by purchased electricity and fuel that would meet the same building's energy needs [15]. CDE savings can range from 10-50%, depending on the CHP system and the type of energy production the CHP system replaces, with the greatest reduction in emissions occurring when CHP replaces electricity generation from non-renewable sources [16].

Energy Benefits

CHP systems may reduce the total amount of energy input needed to produce the electricity and heat used by a building [8, 17, 18]. It improves energy efficiency by capturing heat that would not be used by conventional utility generation, and reduces demand on the electrical grid [2]. CHP systems with natural gas engines as the prime mover can reach overall efficiencies of 70-80% [19].

Thermal Energy Storage for Use with Combined Heat and Power

Thermal energy storage (TES) refers to a device or system which can take the captured waste heat from electricity production which is above the building's current demand and store it for future retrieval.

The size of the prime mover determines the amount of thermal energy available for recovery and therefore is an important factor in not only determining the viability of a

CHP system, but also in determining the possible benefits of using thermal energy storage with that CHP system. Because thermal energy storage will ideally decrease the need for additional on-site heat production, there is potential for a CHP system with TES to reduce operational cost, PEC, and CDE more than a CHP system without TES available. When TES prevents wasting of heat, which is contrary to the purpose of CHP [20], it may eliminate the need for an auxiliary boiler in a given building.

Energy Use in Commercial Buildings and Combined Heat and Power in the U.S.

Most commercial buildings use SHP to meet the electrical and thermal demand, relying on electrical utilities for electricity and natural gas-based heating systems for space heat and hot water. The commercial sector generated less than 0.05 trillion kWh of electricity in 2011 compared with 4 trillion kWh generated by the electric power sector [21], as shown in Figure 1.3. Over all sectors, the use of CHP systems has grown in the U.S. over the last two decades, as shown in Figure 1.4, but CHP power production was only 158 billion kWh in 2011, compared to almost 3.8 trillion kWh produced by electricity-only plants [21]. Although commercial property owners are often unaware of the potential benefits from CHP systems [5], there is potential for CHP to provide economic, emissions, and energetic benefits for a range of commercial building types.

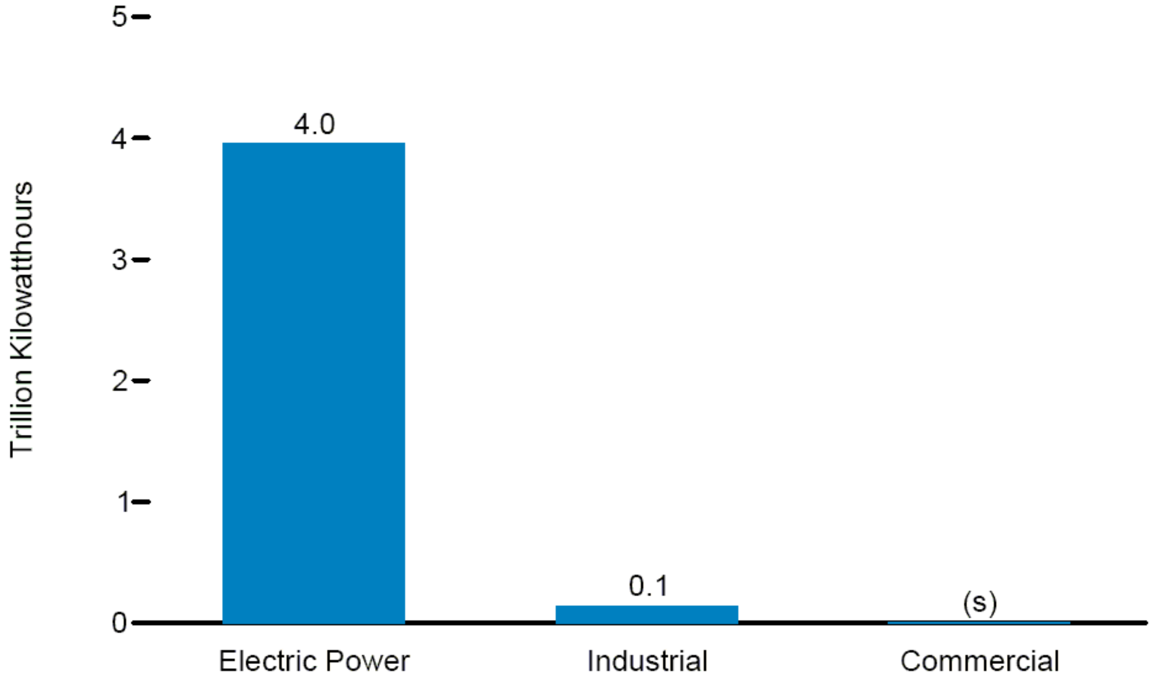

Figure 1.3 Electricity net generation by sector, 2011 [21]

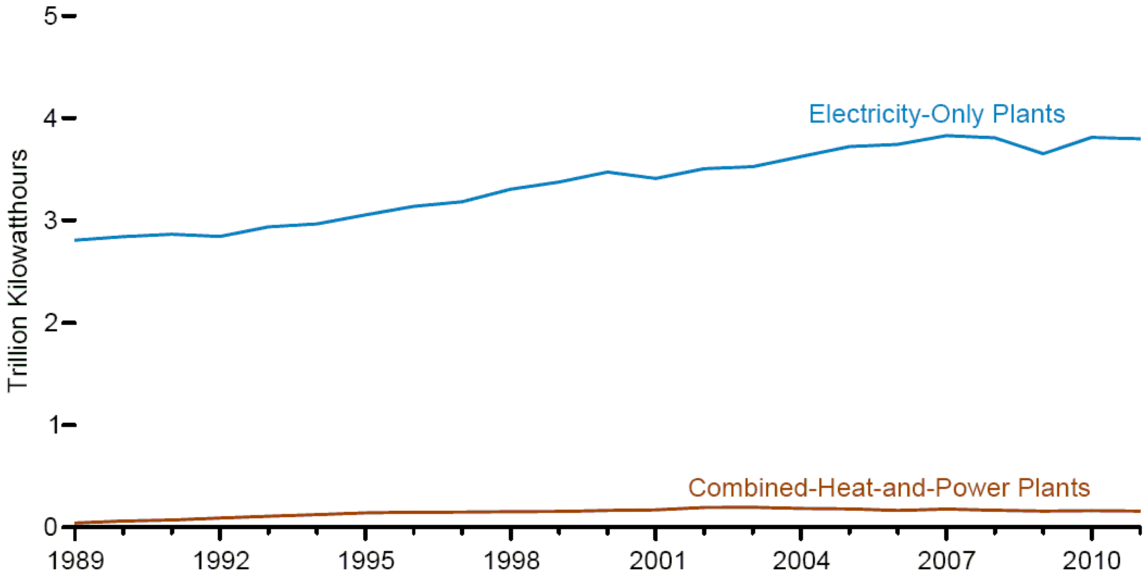

Figure 1.4 Electricity generation type, 1989-2011 [21]

Objectives

The goal of this dissertation is to identify situations in which CHP systems reduce costs, emissions, and PEC. The following objectives are addressed here in support of this aim:

- CHAPTER II consists of a literature review to address the current state of CHP systems analysis for economic, environmental, and energetic benefits, including CHP systems with TES.
- CHAPTER III provides the development of a spark spread screening parameter in terms of system component characteristics.
- CHAPTER IV provides the development of analogous emissions spark spread and primary energy spark spread.
- CHAPTER V presents an environmental evaluation of base-loaded CHP systems for different commercial building types.
- CHAPTER VI investigates the addition of TES in combination with CHP and its potential for reducing cost, CDE, and PEC for different commercial building types.

CHAPTER II

LITERATURE REVIEW

Economic Analysis

For a CHP system to be considered for any commercial installation, it must be economically viable. Overall, according to the Combined Heat and Power Partnership of the U.S. Environmental Protection Agency (EPA) [10], "When heat and power can be produced on site for less than the cost of power from a utility and fuel for heat (separate heat and power), then there is a positive payback for the project." The federal government provides tax credits and financial incentives for CHP development, although the investment tax credit for CHP is limited to 10% of expenditures on microturbines with a cap of $200/kW, or 30% of expenditures on fuel cells with a cap of $3,000/kW [13]. Additional federal, state and local incentives that exist in the U.S. can be found in the EPA's Funding Database [22]. The economic benefit of a CHP system is highly influenced by electricity tariffs, electricity buyback prices, and carbon taxes or carbon credits designated by the government [23].

The spark spread (SS), or difference between natural gas and electricity prices [7], has been used as a screening parameter for the economic feasibility of a CHP project [7, 24, 25]. Often the spark spread is discussed as a rule of thumb, or zero order indicator as to the cost saving potential of a CHP installation. The U.S. Department of Energy Midwest CHP Application Center suggests that a spark spread difference of

$0.0409/kWh ($12/MMBtu) indicates that a CHP system has the potential for a favorable payback [7]. However, this only takes into account the price difference between electricity and gas and does not consider differences in the performance characteristics of individual CHP systems. Graves et al. [26] developed a more sophisticated method that incorporates generator heat rate, thermal recovery efficiency, equipment cost, and acceptable payback period, allowing for a more accurate indicator of CHP viability.

Cardona et al. [27] expressed the minimum spark spread necessary to cover fuel costs and capital investment in a combined heat, cooling and power (CHCP) plant in terms of only fuel cost and electrical efficiency of the system. The same authors separately define a specific version of spark spread, SP_{spread}, which compares the price of purchased electricity with the cost to provide the same amount of electricity given the cost of fuel [14]. Again, this accounts for the electricity efficiency of the CHCP system but does not account for the added benefit due to heat recovery from the prime mover. Conversely, Hawkes et al. [28] define a different version of the spark spread for CHP sytems, S_{chp}, which uses system efficiencies and only accounts for the heat recovery advantage of a CHP system.

Cuttica and Haefke [7] suggest a given value for spark spread of 0.0409/kWh ($12/MMBtu) which indicates that CHP has the potential for a favorable payback period. Comparing the actual spark spread to a given cutoff value is a simple way to indicate whether CHP has the potential to reduce operating costs; however, it does not consider any conditions unique to the CHP system and the building where it will be installed. Several factors will affect the economic viability of a CHP system for a particular situation: CHP system efficiencies, prime mover size, operational strategy, power-to-heat ratio provided by the CHP and power-to-heat ratio of the building to be served by a CHP system, and overall magnitude of the energy requirements of the building [12, 29, 30]. The relationship between electrical demand and thermal demand has been emphasized by researchers [7, 14, 29, 30] as a crucial factor for the suitability of a CHP system.

Many mathematical models exist for analyzing the economic, environmental, and energy benefits of a CHP system [6, 8, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39], but SS analysis in terms of component efficiencies provides a simple method to analyze economic potential with only basic information about the CHP system and the building it serves. Smith et al. [25] have shown that the required SS may be expressed in terms of system efficiencies to produce a more accurate indicator for economic analysis, as described in CHAPTER III.

Environmental Analysis

In addition to economic concerns, the amount of harmful emissions should also be considered when determining the benefits associated with a CHP system. Meunier [16] explained the importance of CO_2 emission reduction when developing CHP systems in order to mitigate the negative impact energy production has on the climate.

A CHP project may have a social objective to meet other priorities rather than cost benefit alone. Tax legislation, environmental regulations, or public enthusiasm for energy efficient technologies may make CHP systems attractive for reasons other than cost savings. Both the European Union and United States government bodies have taken steps to analyze the benefits of CHP and the EU, in particular, has used government policy in an effort to promote CHP technology [40]. Of 21 countries studied by the IEA, 12 make greater use of CHP than the U.S. does as a percentage of overall electrical production [5]. The IEA has also identified CHP as part of a strategy to reduce greenhouse gas emissions [5]. U.S. greenhouse gas emissions are primarily energy-related CDE, and electric power production is the largest contributor to U.S. emissions [41].

Although the U.S. has not taken the governmental actions to promote CHP that are more common in Europe [40], regulating emissions and assigning a market value to harmful emissions would greatly affect the economic analysis of a CHP system [42]. If a CHP system reduces CDE but increases cost, the necessary monetary value of carbon credits can be determined which would offset the cost.

If emission allowances are regulated and assigned a market value, the emission considerations would also be part of an economic analysis [42]. Mago and Hueffed [43] evaluated a turbine driven CCHP system for large office buildings under different operating strategies and analyzed the effect of carbon credits on the system's economic performance. They reported that carbon credits can successfully yield financial reward for reducing carbon emissions. The higher the carbon credit value (in $/metric ton of carbon equivalent) the larger the cost reduction of the CCHP system operation.

Minciuc et al. [44] pointed out that efficient use of fuel by the CHP system can lead to reduced CO_2 emissions. Li et al. [31] reported that the energy savings potential of a CCHP system is also related to the system efficiencies. Mago and Luck [45] have shown that the efficiency of the power generation unit is a critical variable which influences a CHP system's potential to reduce CO_2 emissions. Therefore, a variation of the spark spread using system efficiencies which addresses CDE can also be useful for analyzing CHP systems, as described in CHAPTER IV.

Energetic Analysis

The primary benefit of a CHP system is the recovery of heat, which allows for more useful output for a given amount of fuel energy. John [46] asserted that a CHP system should only be considered if it is optimized to conserve energy. Primary energy analysis concerns source energy rather than energy used at the site (after energy losses from production and distribution have already occurred), and high PEC is associated with increased emissions [47]. Fumo et al. [17] advised that the primary energy savings of a CHP system must be considered along with the economic analysis.

"The cheapest form of energy is energy not used," according to Richard A. Muller [48], and when CHP reduces the amount of primary energy needed to produce heat and power, a number of additional benefits may follow. The energy saved with CHP can make the building eligible for LEED points [49] or an Energy Star award [50].

Li et al. [31] reported that the energy savings potential of a CCHP system is related to the system efficiencies. Therefore, variations of the spark spread which address emission of pollutants and PEC can also be useful for decision making when analyzing the potential for the use of a CHP system in a given situation.

Operation and Performance

The sizing of the CHP system, its component efficiencies, and whether it operates at a partial load are all factors affecting system performance [6, 18, 29,47, 51]. While other researchers have investigated an optimal strategy for a CHP or CCHP (combined cooling, heating, and power) system by some form of load-following [9, 39, 52] and considering partial load operation [36, 53], a CHP system in practice is often operated steadily at a given base load. In order to avoid excess electricity production, the base load is usually less than the amount of electricity demanded by the building. One simple operational strategy, thermal base-loading, involves sizing a CHP system to provide the majority of the building's thermal need and only a portion of the building's electrical need, so that the remaining electricity needed will be purchased from the grid. The system then operates at a constant base load, which ensures that the prime mover is operating at high efficiency. This type of base-loading can provide cost savings while allowing the CHP system to reach maximum efficiency because both the electrical and thermal energy produced are used by the building [10].

A CHP system is often sized to provide a base load, and additional electricity needed can be purchased from the grid [53, 54]. This alleviates the reduced efficiencies associated with partial load operation [55] and does not require knowledge of the partial load performance of the power generation unit [29, 56, 57]. Full-load operation is specifically recommended for gas turbine applications, which are commonly used for large CHP systems [24].

Thermal Energy Storage

Combined heat and power (CHP) systems can potentially reduce operational cost, emissions, and PEC associated with power production by capturing the waste heat associated with production and using it to provide space heating or hot water to a building, thereby making better use of the fuel energy [58]. One major concern for implementing CHP systems is a mismatch between the amount of electricity and heat provided by the CHP system and the amount of electrical energy and thermal energy required by the building it serves [59]. Often this is due to a low power-to-heat ratio (a ratio of the electric load to the thermal load) demanded by the building [14], so that the excess heat produced by the CHP system may not be useful to the building it serves.

Often, a CHP system operates most efficiently at a constant load; however, the electrical and thermal energy needs of a commercial building are not constant. If the heat demanded by the building varies over time, this imbalance may be alleviated when TES is available. This will allow the system to capture thermal energy when it is not being used by the building and then deliver it when the building needs more thermal energy than the CHP system provides. This can allow the CHP system to operate more profitably and for longer periods of time [60]. Thermal energy storage systems may also be integrated with district heating networks [61, 62] and used to store energy on a seasonal basis [63] in order to reduce cost, primary energy, and emissions.

A properly designed TES system will minimize energy losses and result in reduced energy consumption [64, 65], and may result in significant CDE reduction [60]. Verda and Colella [65] found that a TES system could significantly reduce the size of the additional boiler needed to meet the building's thermal energy demand with a sufficiently large TES tank, 1000 m^3 of storage volume for a CHP plant modeled in Turin, Italy.

Water storage tanks and ice storage systems are commonly studied TES devices [23, 54, 60, 66, 67]. Previous studies indicate that use of TES for excess heat produced by the CHP system can reduce the amount of additional heat required from the boiler, resulting in reduced CDE [60, 67]. It is also possible for thermal energy storage to help reduce PEC and operating cost [79]. Only a small thermal storage device is necessary to see a significant improvement over the situation where no thermal energy is stored [60].

Although an ice-based thermal energy storage system can be modeled within EnergyPlus [66], CHP systems are suited to hot thermal energy storage.

Many types of thermal energy storage are available which may store heat as sensible or latent energy [68, 69], and a water tank is a simple and commonly used form of TES. The thermal capacity of the TES device rather than the material in the tank is specified in order to make the analysis generally applicable to alternate forms of TES. The details of the TES system should be selected based on the necessary storage period and economic concerns such as projected energy prices, acceptable payback period, and costs associated with CO_2 emissions [68, 70]. The appropriate size will also depend on the characteristics of the thermal storage material and the materials used for the TES equipment [71].

CHAPTER III

SPARK SPREAD ANALYSIS BASED ON COMPONENT EFFICIENCIES

CHP systems may be considered for installation if they produce savings over conventional systems with separate heating and power. For a CHP system with a natural gas engine or microturbine as the prime mover, the difference between the price of natural gas and the price of purchased electricity, called spark spread, is an indicator as to whether a CHP system might be considered or not. For a CHP system to show an economic advantage over a conventional system, its operating costs must be lower when providing the same amount of thermal energy and electricity that would have come from conventional alternatives.

The objective of the spark spread analysis presented in this chapter is to develop a detailed model, based on the spark spread concept, that compares the electrical energy and heat energy produced by a CHP system against the same amounts of energy produced by conventional means, an SHP system. The SHP receives electricity from the grid and provides additional heat as needed with a natural gas boiler.

This chapter investigates the necessary relationship between the price of fuel and the price of electricity purchased from a utility in order for a CHP system to be economically feasible with a reasonable payback period, considering the effects of the CHP system efficiency. An expression for the spark spread based on the cost of the fuel and some of the CHP system efficiencies is presented along with an expression for the payback period for a given capital cost and spark spread. These expressions are used to determine the minimum spark spread (SS_{min}) required for a CHP system to avoid net operational losses when compared with SHP. Additionally, an expression for calculating the payback period for a CHP system based on the CHP system capital cost per unit of power output and fuel cost is presented.

Development of Minimum Spark Spread Expression

The spark spread (SS), or price difference between purchased electricity and fuel, is a simple indicator as to whether the CHP system is economically viable. The SS expressed in terms of system efficiencies will represent the minimum spark spread for a CHP system to show a potential operating cost benefit, and is designated SS_{min}. The actual spark spread, given by the price different between purchased electricity and purchased fuel at a given location and time is designated SS_{act}.

CHP System Efficiencies

Figure 3.1 illustrates the schematic of the CHP system used to develop the SS relationship. The CHP system is located near the building to provide heat and electricity. If a CHP system connects to the local electricity grid, excess electricity may be sold to the grid, or additional electricity can be bought from the grid if the CHP electricity is less than the building's electrical demand [10].

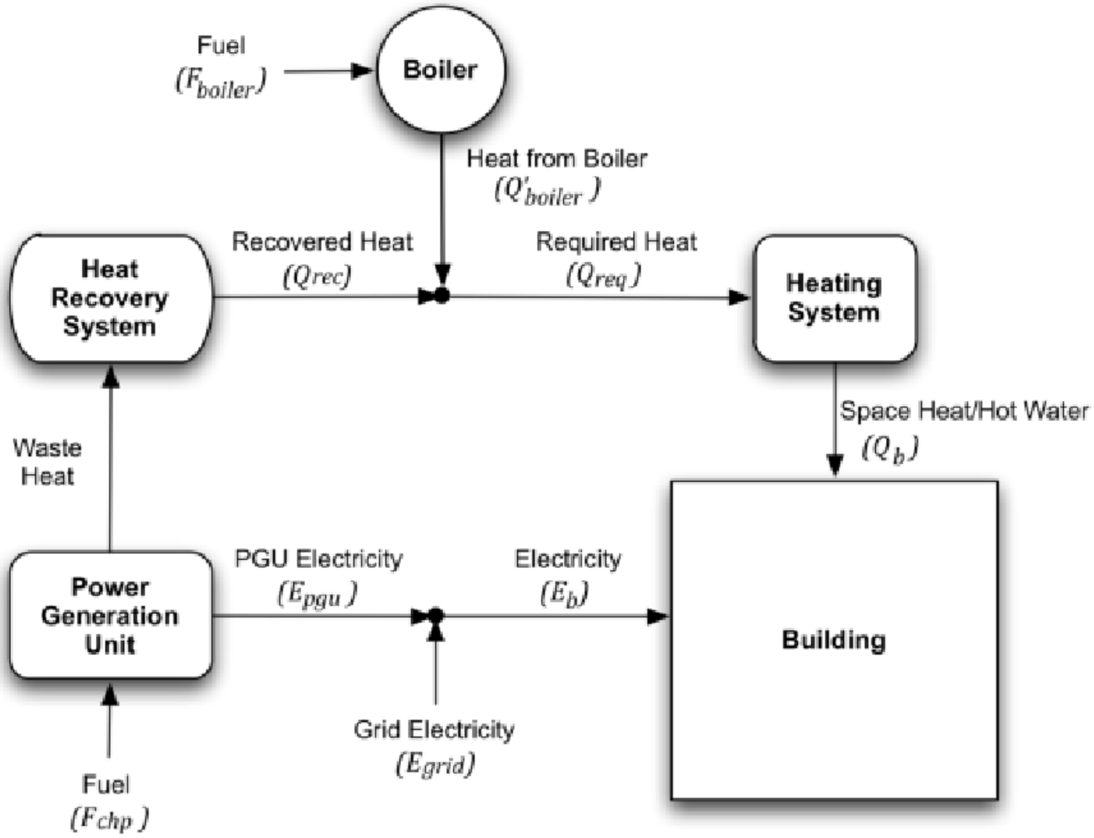

Figure 3.1 Energy flows and basic components of a CHP system

For the analysis presented in this section, all of the electricity and heat provided by the CHP is used by the building, which allows the CHP system to run at full efficiency. Fuel energy, F_{chp}, provided to the CHP system goes to the PGU, which typically consists of a prime mover and electric generator, or a fuel cell stack and power converter in the case of a fuel cell CHP system. The prime mover here is assumed to run on natural gas to simplify the comparison, since natural gas is the fuel associated with both the CHP and SHP systems.

The PGU which provides electricity, E_{pgu}, to the building and rejects heat, Q_{pgu}. Some of the heat rejected by the PGU is lost, and some heat is available, Q_{av}, that can be recovered by the equipment of the heat recovery system (HRS) to provide heat to the building, Q_{chp}.

The electric efficiency of the PGU can be expressed as the ratio of E_{pgu} output to F_{chp} input.

$$\eta_{e,pgu} = \frac{E_{pgu}}{F_{chp}} \tag{3.1}$$

The fuel thermal energy input can be expressed as:

$$F_{chp} = m_{fuel}\, LHV_{fuel} \tag{3.2}$$

where m_{fuel} is the mass of fuel used and LHV_{fuel} is the lower heating value of the fuel. The LHV of natural gas used in this dissertation is 46,400 kJ/kg [72].

The heat produced by the PGU is given by:

$$Q_{pgu} = (1-\eta_{e,pgu})F_{chp} \tag{3.3}$$

The portion of this heat that is available for the heat recovery system (HRS) can be expressed as:

$$Q_{av} = C_{te}\, Q_{pgu} \tag{3.4}$$

where C_{te} is the coefficient that accounts for thermal losses [8].

The heat recovered from the CHP system, $Q_{rec,}$ can be expressed in terms of the CHP heat recovery system efficiency, $\eta_{hrs,chp}$, as:

$$Q_{rec} = Q_{av}\eta_{hrs,chp} \tag{3.5}$$

Because this analysis assumes that all heat is used by the building, the recovered heat is the same as the heat provided by the CHP system to the building, Q_{chp}. The example models in the next section and in the chapters that follow will deal with situations where Q_{rec} is not necessarily useful to the building.

Using Equations (3.3) through (3.5), the thermal efficiency of the CHP system can be defined as:

$$\eta_{th,chp} = \frac{Q_{chp}}{F_{chp}} = \eta_{hrs,chp}\, C_{te}\,(1 - \eta_{e,pgu}) \tag{3.6}$$

The total system efficiency (overall efficiency) of the CHP system is the ratio of useful output, in the form of electricity (E_{pgu}) and heat (Q_{pgu}), to fuel energy input (F_{chp}).

$$\eta_{o,chp} = \frac{E_{pgu} + Q_{chp}}{F_{chp}} = \eta_{e,pgu} + \eta_{th,chp} \tag{3.7}$$

This efficiency is a simple, commonly used descriptor for comparing energy production with energy consumption which does not address energy quality differences between electrical and thermal output [73].

When expressed as a rate, the total CHP system efficiency includes the electrical power output, $\dot{W}_{pgu}$, from the power generation unit and the heat rate of neat useful heat delivered, $\dot{Q}_{useful}$, divided by the fuel input per unit time, $\dot{F}_{chp}$ [73].

$$\eta_{\mathrm{o,chp}} = \frac{\dot{W}_{pgu} + \dot{Q}_{useful}}{\dot{F}_{chp}} \tag{3.8}$$

Cost Ratio and Spark Spread

The difference between the cost of electricity, $Cost_e$, and the cost of fuel, $Cost_f$, is the actual spark spread and is defined as [7]:

$$SS_{act} = Cost_e - Cost_f \tag{3.9}$$

For a particular site, average cost values for electricity and fuel can be determined by simply dividing the total cost over one year by either the total electricity use for that year or the total gas use for that year [7].

The cost to operate the CHP system is the cost of fuel multiplied by the amount of fuel used.

$$Cost_{chp} = Cost_f \; F_{chp} \tag{3.10}$$

Only the cost of purchasing fuel is taken into account here; maintenance costs are not considered.

Using Equation (3.7), F_{chp} can be expressed in terms of E_{pgu}, Q_{chp}, and $\eta_{o,chp}$ as follows:

$$Cost_{chp} = Cost_f \left(\frac{E_{pgu} + Q_{chp}}{\eta_{o,chp}} \right) \tag{3.11}$$

In order to compare the operational costs of a CHP system with a SHP system, a building that has electricity requirement E_b and heat requirement Q_b is shown in Figure 3.2 (a).

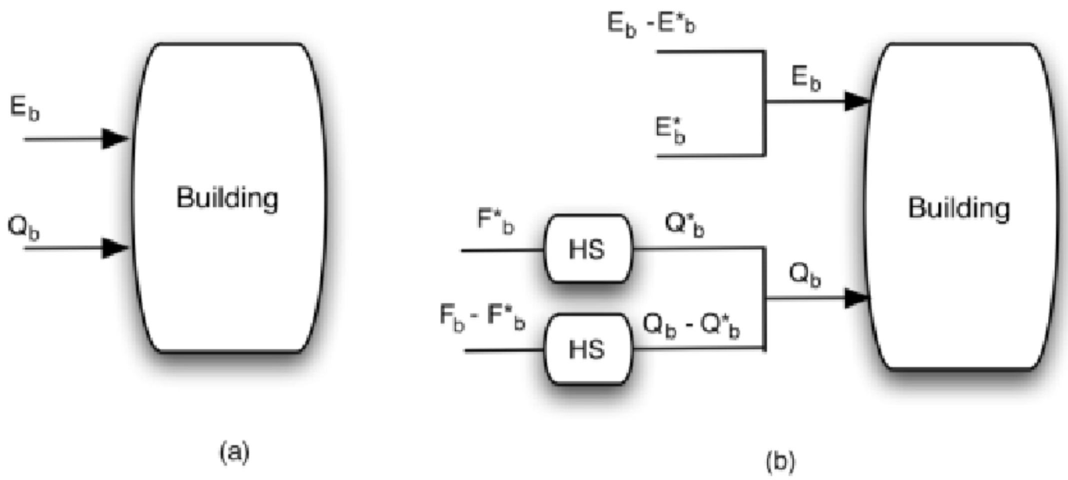

Figure 3.2 Building energy requirements: **(a)** Total **(b)** Divided into constant and varying portions of loads E_b and Q_b

As shown in Figure 3.2 (b), the building's electrical needs may be divided into two parts: some base portion of the building's electricity needs, E^*_b, will remain constant throughout the year, while the remaining portion, E_b-E^*_b, will vary with time. Likewise, a base portion of the building's thermal energy needs, Q^*_b, will remain constant, while the remaining portion, Q_b-Q^*_b, will vary with time.

The amount of fuel energy needed to satisfy the building's thermal demand without a CHP system present is given by:

$$F_b = \frac{Q_b}{\eta_{hs,shp}} \qquad 3.12$$

where $\eta_{hs,shp}$ is the efficiency of the heating system (including the building's boiler) for SHP.

It is now assumed that the CHP system provides electricity and heat in the amount of E^*_b and Q^*_b, while operating at full load and maximum efficiency. The varying electric load and the varying thermal load required above E^*_b and Q^*_b cannot, therefore, be provided by the CHP system. As shown in Figure 3.3, the CHP system provides E_{pgu} and Q_{chp} in the amount of E^*_b and Q^*_b, and the remainder is provided by grid electricity and boiler heat.

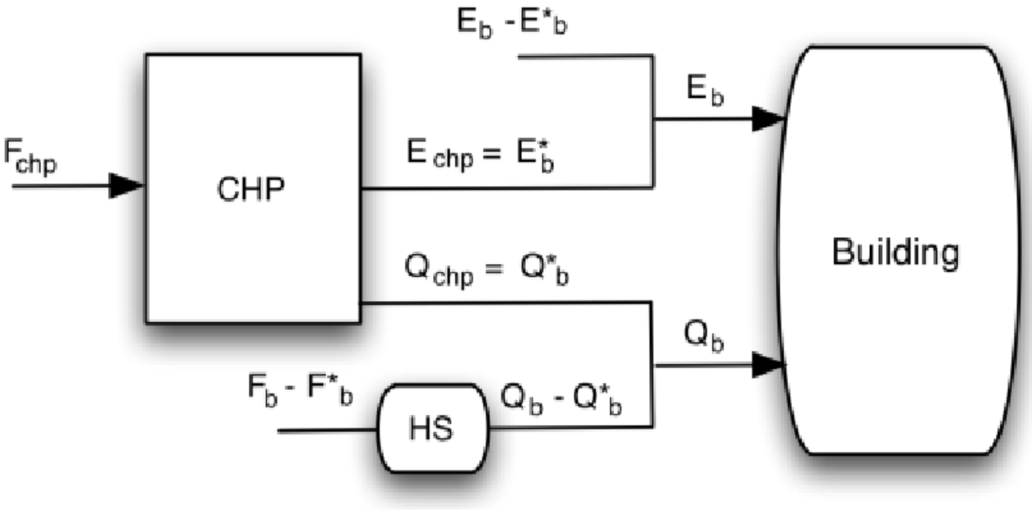

Figure 3.3 Building energy requirements with CHP system

Since the CHP system as described will provide the thermal energy in the amount of Q^*_b, Equation (3.12) is used (with $Q^*_b = Q_{chp}$) to estimate the fuel energy that a SHP system would consume in order to supply Q^*_b.

$$F^*_b = \frac{Q_{chp}}{\eta_{hs,shp}} \qquad 3.13$$

The operating cost for the CHP system in Equation (3.11) may now be written in terms of efficiencies as follows:

$$Cost_{chp} = Cost_f \left(\frac{E_{pgu}}{\eta_{o,chp}} + \frac{F^*{}_b \, \eta_{hs,shp}}{\eta_{o,chp}} \right) \qquad 3.14$$

Similarly to Equation (3.10), the cost to operate the SHP system while serving the same building is:

$$Cost_{shp} = Cost_f \ \mathrm{F}_\mathrm{b}^* + Cost_e \ \mathrm{E}_\mathrm{b}^* \qquad 3.15$$

Again, since $E^*{}_b$ and $Q^*{}_{b,}$ are defined to be the amounts of electrical and thermal energy produced by the CHP, they are E_{pgu} and Q_{chp}, respectively. Making this substitution, the fuel cost for the building with SHP may be written in terms of E_{pgu} and Q_{chp} using Equations (3.13) and (3.15).

$$Cost_{shp} = Cost_f \frac{Q_{chp}}{\eta_{hs,shp}} + Cost_e \ E_{chp} \qquad 3.16$$

If the CHP system has the potential for payback due to operating cost savings, the operating cost must be at least as low as the operating cost of an SHP system. This meaning Equation (3.17) must be satisfied.

$$Cost_{shp} - Cost_{chp} \geq 0 \qquad 3.17$$

Substituting Equations (3.14) and (3.16) into Equation (3.17):

$$Cost_f \frac{Q_{chp}}{\eta_{hs,shp}} + Cost_e \ E_{pgu} - Cost_f \left(\frac{E_{pgu}}{\eta_{o,chp}} + \frac{F_\mathrm{b}^* \, \eta_{hs,shp}}{\eta_{o,chp}} \right) \geq 0 \qquad 3.18$$

Noting that $F_\mathrm{b}^* \, \eta_{hs,shp}$ is Q_chp here, dividing by Q_{chp}, and simplifying yields:

$$Cost_f\left(\frac{1}{\eta_{hs,shp}}-\frac{E_{pgu}}{Q_{chp}\,\eta_{o,chp}}-\frac{1}{\eta_{o,chp}}\right)+Cost_e\frac{E_{chp}}{Q_{chp}}\geq 0 \qquad 3.19$$

The power-to-heat ratio PHR_{chp} is the proportion of electricity to heat energy produced by the CHP system [3]. This describes how much electricity is delivered to the building for each unit of thermal energy delivered to the building. These amounts, given the assumptions made in this section, are E_{pgu} and Q_{chp}.

$$PHR_{chp}=\frac{E_{chp}}{Q_{chp}} \qquad 3.20$$

Gathering cost-related terms on the left hand side of the inequality in Equation (3.20) and gathering efficiency terms on the right hand side yields:

$$\frac{Cost_e}{Cost_f}\geq\frac{1}{PHR_{chp}}\left(\frac{1}{\eta_o}-\frac{1}{\eta_{hs,shp}}\right)+\frac{1}{\eta_o} \qquad 3.21$$

PHR_{chp} may be expressed in terms of component efficiencies using Equations (3.1) and (3.6) as follows:

$$PHR_{chp}=\frac{\eta_{e,pgu}}{\eta_{th,chp}} \qquad 3.22$$

Recognizing that when the inequality of Equation (3.21) becomes an inequality, the operating costs for SHP and CHP are equal, Equations (3.21) and (3.22) can be used to identify a minimum value for cost ratio, below which the CHP system will cost more to operate than the SHP system.

$$CR_{min}=\frac{\eta_{o,chp}-\eta_{e,pgu}}{\eta_{e,pgu}}\left(\frac{1}{\eta_{o,chp}}-\frac{1}{\eta_{hs,shp}}\right)+\frac{1}{\eta_{0,chp}} \qquad 3.23$$

For the CHP system to have the potential for economic savings, the actual ratio of the cost of purchased electricity to the cost of purchased natural gas must be greater than the $CR_{\min}$ presented in Equation (3.23). This provides a minimum CR based on system characteristics. When the actual ratio of electricity cost to fuel cost is below this value, the CHP system will cost more to operate than SHP.

Since spark spread is defined as a difference in electricity and gas prices rather than as a ratio, Equation (3.20) can be used with the inequality of Equation (3.19).

$$Cost_f\left[\frac{1}{\eta_{hs,shp}}-\frac{1}{\eta_{o,chp}}\left(PHR_{chp}+1\right)\right]+\left(SS+Cost_f\right)PHR_{chp}\geq 0 \tag*{3.24}$$

Dividing by PHR_{chp} and simplifying:

$$SS\geq Cost_f\left[\frac{1}{PHR_{chp}}\left(\frac{1}{\eta_{o,chp}}-\frac{1}{\eta_{hs,shp}}\right)+\frac{1}{\eta_{o,chp}}-1\right] \tag*{3.25}$$

Recognizing again that the inequality represents the lower limit for CHP payback, where operating costs are equal to those of an SHP system, and using Equation (3.22), the minimum spark spread may be expressed in terms of fuel cost and component efficiencies.

$$SS_{\min}=Cost_f\left[\frac{\eta_{o,chp}-\eta_{e,pgu}}{\eta_{e,pgu}}\left(\frac{1}{\eta_{o,chp}}-\frac{1}{\eta_{hs,shp}}\right)+\frac{1}{\eta_{o,chp}}-1\right] \tag*{3.26}$$

The required *SS* can be calculated from the *CR* value when either the price of fuel, $Cost_f$, or the price of electricity $Cost_e$, is given. The relationship between these quantities is shown in Equation (3.27).

$$SS = Cost_f(CR - 1) = Cost_e\left(1 - \frac{1}{CR}\right) \tag{3.27}$$

Equation (3.27) applies to both the actual spark spread, SS_{act}, and calculated minimum spark spread, SS_{min}. For situations in which the spark spread more closely follows the price of electricity [74], it may be desirable to calculate SS_{min} in terms of $Cost_e$ as shown in Equation (3.28):

$$SS_{\min} = Cost_e\left(1 - \frac{1}{CR_{\min}}\right) \tag{3.28}$$

Analysis of Savings and Payback Using Spark Spread

Cost Savings

When the cost difference in Equation (3.17) is equal to zero, the CHP system does not show an operating cost benefit with respect to the SHP system. When the cost difference is greater than zero, the CHP system can produce E^*_b and Q^*_b with lower operating cost than the SHP system in terms of fuel and electricity purchases. This generates economic savings for CHP used in place of SHP.

Using Equations (3.6), (3.10), and (3.16) for the CHP fuel energy, total cost savings can be expressed as:

$$Cost_{shp} - Cost_{chp} = Cost_f\ Q_{chp}\left(\frac{1}{\eta_{hs,shp}} - \frac{1}{\eta_{th,chp}} + CR * PHR_{chp}\right) \tag{3.29}$$

In Equation (3.29) the only term that is not related to the performance of the CHP system and the prices of fuel and electricity is the efficiency of the SHP heating system, $\eta_{hs,shp}$. This term is important since a CHP system that is less efficient at producing useful heat energy could cost more to operate than a SHP system with a more efficient boiler, even with a larger spark spread. This situation is possible given that a typical natural gas fired boiler has about 80% efficiency [73]. On the other hand, a CHP system with $\eta_{hrs,chp}$ larger than $\eta_{hs,shp}$ for a corresponding SHP system may be economically viable with a much smaller spark spread than would otherwise be expected.

Payback Period

The yearly savings can be determined when Q_{chp} is the amount of energy produced in one year, which is also the yearly demand from the building (Q^*_b) that the CHP system satisfies.

For any given capital cost (*CC*) associated with the CHP system, a simple payback period (*PBP*), in years, can be determined using the yearly savings obtained from Equation (3.29) as follows:

$$PBP = \frac{CC}{Cost_{shp} - Cost_{chp}} \qquad 3.30$$

Likewise, when an acceptable payback period has been previously determined, the maximum allowable capital cost can be found. Figure 3.4 shows the CC as a function of the spark spread for different PBP. The results presented in this figure were obtained using $Cost_f$ = \$0.033/kWh, Q_{chp} = 175 MWh (or = $\dot{Q}_{chp}$ =20 kW), η_o = 0.75, PHR_{chp} = 0.5, and $\eta_{hs,shp}$ = 0.8. Figure 3.4 illustrates that as the spark spread increases, the allowable CC also increases because the greater difference between $Cost_e$ and $Cost_f$ leads to more savings. This figure also demonstrates that for the same *SS*, the allowable *CC* also increases with the acceptable payback period (Line A-A’ in Figure 5). On the other hand, for the same CC, the necessary SS_{min} increases when a faster payback is desired (Line B-B' in Figure 3.4). Although the magnitude of the capital cost changes with a 1, 2, or 3 year PBP, the system becomes potentially profitable at a spark spread of \$0.0165/kWh (\$4.84/MMBtu) in each case, which represents the No Savings Case ($Cost_{shp} - Cost_{chp}$ = 0). In other words, the CHP does not show an operating cost benefit. A spark spread below \$0.0165/kWh indicates that savings are not possible with a CHP system.

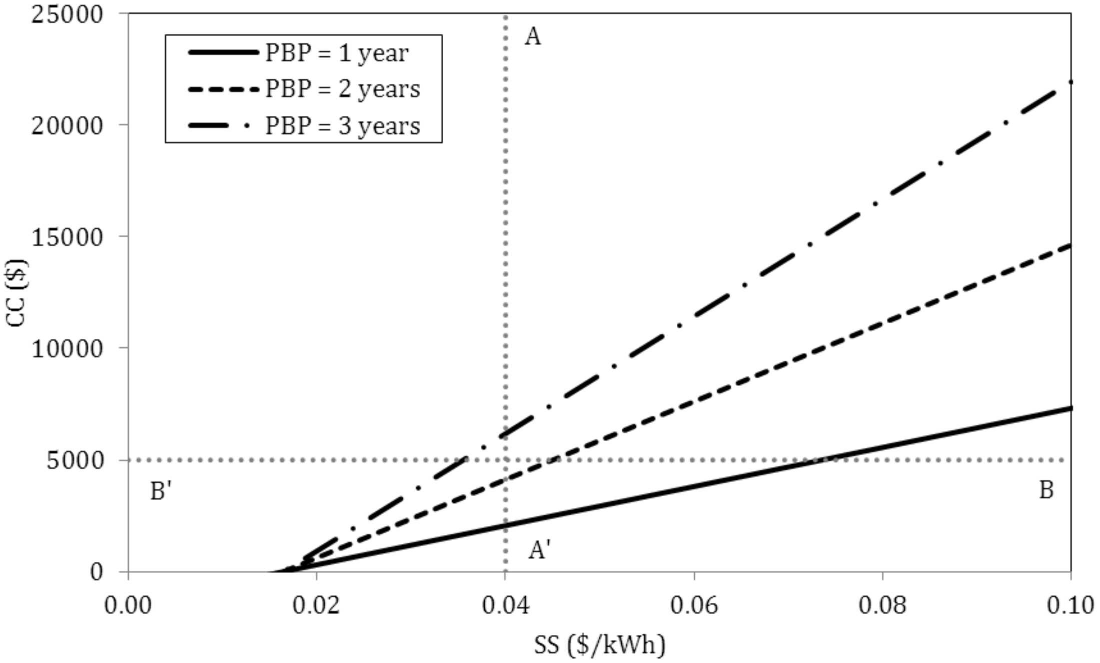

Figure 3.4 Capital Cost (CC) as a function of the Spark Spread (SS) with varying Payback Periods (PBP)

Minimum Spark Spread—Relationship to Component Efficiencies

The SS_{min} associated with the No Savings Case changes based on the component efficiencies and fuel or electricity price on which the calculations are based. Figure 3.5 shows the SS for the No-Savings Case as a function of the CHP system efficiency. Setting savings equal to zero [Equation (3.29)] allows for determining CR_{min}, and the SS can then be determined from a given $Cost_f$ or $Cost_e$. This figure was obtained using $Cost_f$ = \$0.033/kWh and $\eta_{hs,shp} = 0.7$ for different CHP system efficiency values. A spark spread greater than the value on the No Savings Case line will have a favorable payback (meaning that savings are possible), while a spark spread below this line indicates no payback potential (savings are not possible). If a CHP system could be designed such that all the fuel energy was converted to electricity and useful heat ($\eta_{0,chp}$=1), the No Savings Case would not require the price of electricity to be higher than the price of fuel (SS_{min} = 0). For all realistic cases, $\mathrm{SS}_{\mathrm{min}}$ has some positive value.

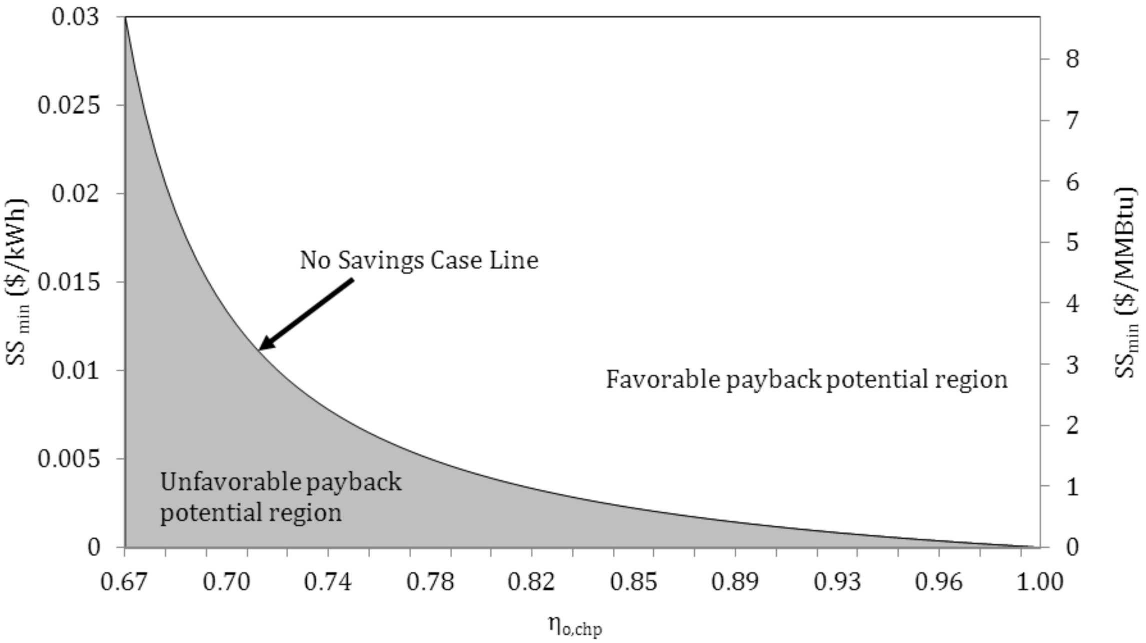

Figure 3.5 Minimum Spark Spread (SS_{min}) as a function of CHP efficiency ($\eta_{o,chp}$)

Figure 3.6 shows the SS for the No Savings Case as a function of CHP system efficiency for different $\eta_{hs,shp}$ values. Similarly to Figure 3.5, the area under each curve represents conditions where CHP is not economically viable while the area above each curve represents conditions where CHP may be economically viable. The following values were used to generate Figure 3.6: $Cost_f$ = \$0.033/kWh, $\eta_{e,pgu} = 0.25$, $C_{te} = 0.9$, and $\eta_{hrs} = 0.7$. Figure 3.6 illustrates that as $\eta_{hs,shp}$ increases with respect to $\eta_{o,chp}$ (while $\eta_{hrs,chp}$ is held constant), a CHP system becomes less likely to be profitable since a much larger SS would be necessary to produce net savings with a CHP system.

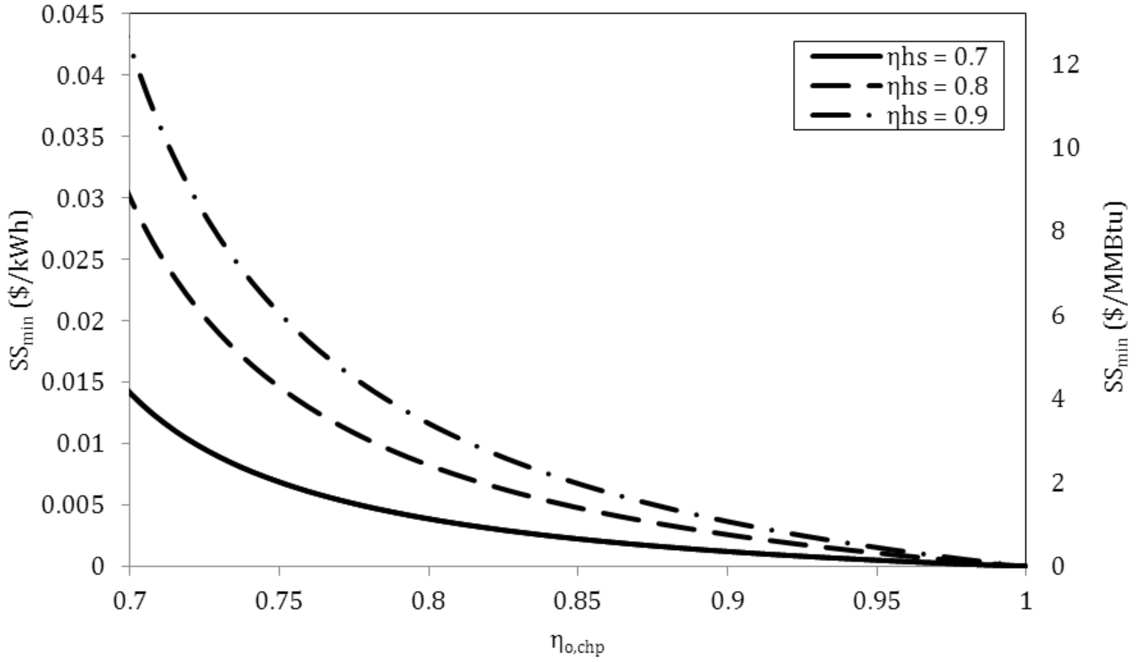

Figure 3.6 Required Spark Spread (SS_{min}) as a function of CHP system efficiency ($\eta_{o,chp}$) with varying efficiency of the SHP heating system ($\eta_{hs,shp}$)

Payback Period—Relationship to Component Efficiencies

Equations (3.29) and (3.30) can be used to express the PBP as a function of *CC, $Cost_f$, CR, PHR_{chp}, Q_{chp}*, $\eta_{hs,shp}$, and $\eta_{th,chp}$ as follows:

$$PBP = \frac{CC}{Cost_f\; Q_{chp}\left(\frac{1}{\eta_{hs,shp}} - \frac{1}{\eta_{th,chp}} + CR * PHR_{chp}\right)} \qquad 3.31$$

The power-to-heat ratio can be expressed as power over rate of heat delivery.

$$PHR_{chp} = \frac{\dot{W}_{chp}}{\dot{Q}_{chp}} \qquad 3.32$$

For an operating period (t) of 1 year, E_{pgu} is:

$$E_{pgu} = t\,\dot{W}_{chp} \qquad 3.33$$

Therefore, a new parameter called payback period for a CHP system, PBP_{CHP}, can be expressed as:

$$PBP_{chp} = \frac{CC_{chp} PHR_{chp}}{t} \frac{1}{\left(\frac{1}{\eta_{hs,shp}} - \frac{1}{\eta_{th,chp}} + CR * PHR_{chp}\right) Cost_f} \qquad 3.34$$

where CC_{CHP} is the capital cost of the CHP system per kW ($CC/\dot{W}_{CHP}$); t should be in hours if $Cost_f$ is given in \$/kWh.

Equation (3.34) can be used to determine the PBP_{CHP} when the CHP system cost per kW and some system efficiencies are known as well as the cost of fuel. All these parameters are usually known based on information from the CHP system manufacturer and the location where the system will be installed.

The SS is used as a zero order estimator for CHP systems that does not account for the cost of the equipment or time in operation, which are key factors for evaluating the economic feasibility of a CHP project. Equation (3.34) defines a parameter, PBP_{chp}, which provides information in addition to the SS_{min}, since the potential for payback is a crucial parameter considered by building owners or managers to decide about the economic feasibility of a project. Even if a required (No Savings Case) SS is calculated using the equations presented here, based on system characteristics, it only indicates whether or not savings are possible, while the PBP_{chp} provides further information about the CHP system's potential to save money over SHP over time.

Impact of Component Efficiencies on the Required Cost Ratio

Because the cost ratio is used to determine SS_{min} and PBP_{chp}, it is beneficial to understand the effects of changing component efficiencies on the required CR (CR_{min}). The calculation of SS_{min} is based on estimates of a number of variables. It is necessary to assess the likely impact of changes in some of these variables, as such changes can affect the SS calculations.

The method developed above is used while taking into account the type of building and its geographic location, and certain input parameters are varied to determine their effect on CHP efficiency and required cost ratio, CR_{min}. The CR_{min} can easily be used to calculate the required spark spread. The sensitivity of the CHP thermal efficiency, and therefore the overall efficiency and the CR_{min} is considered with respect to changes in the following variables: PGU size relative to building demand, R_e ($R_e = E_{pgu}/E_b$), PGU electric efficiency ($\eta_{e,pgu}$), and CHP heat recovery system efficiency ($\eta_{hrs,chp}$). It is assumed that the losses between the prime mover and the HRS are negligible (C_{te} in Equation (3.4) is equal to 1).

Two different building types in three U.S. locations with different climate conditions are analyzed. It is no longer assumed that all of the heat produced by the CHP system will be useful to the building. While a CHP system which produces excess electricity requires that the power be dispersed or sold, if possible, a CHP system which produces excess heat can reject this thermal energy to the atmosphere.

The heat recovered from the CHP system is entirely used by the building only when the recovered heat, Q_{rec}, is less than the required heat, Q_{req} (3.35). If the CHP system produces excess heat, only the amount needed by the building is considered to be useful heat, Q_{useful} (3.36).

$$Q_{rec} < Q_{req} \; then \;\; Q_{useful} = Q_{rec} \tag{3.35}$$

$$Q_{rec} \geq Q_{req} \; then \;\; Q_{useful} = Q_{req} \tag{3.36}$$

The thermal efficiency of the CHP system also depends on the relationship between Q_{rec} and Q_{req}.

$$Q_{rec} < Q_{req} \; then \;\; \eta_{th,chp} = \frac{Q_{rec}}{F_{chp}} = \left(1 - \eta_{e,pgu}\right)\eta_{hrs,chp} \tag{3.37}$$

$$Q_{rec} \geq Q_{req} \; then \;\; \eta_{th,chp} = \frac{Q_{req}}{F_{chp}} \tag{3.38}$$

Because CHP total system efficiency itself is a function of the PGU efficiency as well as the thermal efficiency, these two parts of the total system efficiency are also investigated separately. Since the cost of purchased electricity and fuel varies by geographic region, the required spark spread for a given system may indicate favorable economics for a CHP system in one location while the CHP system shows no potential for savings in another location. Therefore, the analysis is considered for three different U.S. locations.

The sensitivities of the $\eta_{th,chp}$, $\eta_{o,chp}$, and required CR (and thereby SS_{min}) were evaluated with respect to three system parameters: R_e, $\eta_{e,pgu}$, and $\eta_{hrs,chp}$. Two building types with different electric and thermal demand profiles were considered in three different U.S. cities with different climates. The buildings were representative building models developed by the Department of Energy [75] for a small office building and a full service restaurant, and the electrical and thermal demand amounts were taken from results of EnergyPlus 5.0 simulations. The models used as input for the building simulations were Commercial Reference Building Models (now called Commercial Prototype Building Models [76]) for existing buildings constructed after 1980. The cities chosen for the simulated locations were Houston, TX (warm climate), San Francisco, CA (temperature beach climate), and Duluth, MN (cold climate).

The yearly electrical and thermal demands as determined by EnergyPlus simulations are presented in Table 3.1 and Table 3.2 for the two building types considered in each of 3 cities. The power-to-heat ratio of the building, PHR_b, is an average PHR over the year, given as:

$$PHR_b = \frac{E_b}{Q_{req}} \qquad 3.39$$

Table 3.1 Electrical and thermal loads for a small office building in 3 cities

	E_b (GJ)	Q_{req} (GJ)	PHR_b
Houston	356.94	30.62	11.7
San Francisco	283.40	38.56	7.35
Duluth	301.30	174.10	1.73

Table 3.2 Electrical and thermal loads for a full service restaurant in 3 cities

	E_b (GJ)	Q_{req} (GJ)	PHR_b
Houston	1389.9	1208.9	1.15
San Francisco	1145.7	1429.4	0.802
Duluth	1149.5	2599.1	0.442

The sizing of the PGU relative to the building demand is considered by varying the fraction R_e from 25% to 50%. Although the electricity needs vary based on the time of year, time of day, climate, and building type, it is assumed that the PGU is sufficiently small so that the base load provided will be entirely consumed by the building. Next, the efficiency of the PGU is varied from 15% to 35% while keeping the fraction R_e constant at 0.35. Finally, the efficiency of the CHP heat recovery system is varied from 60% to 80% while keeping R_e at 0.35 and $\eta_{e,pgu}$ at 25%.

Effects of PGU Sizing

The numerical results for a small office building with varying PGU sizes as a fraction of the electrical load in Houston, San Francisco, and Duluth are presented in Table 3.3. In each case, the efficiency of the PGU is 25%.

Table 3.3 Small office building with CHP, varying PGU size

	R_e	Q_{rec} (GJ)	$Q_{rec}>Q_{req}$	Q_{useful} (GJ)	F_{chp} (GJ)	$\eta_{th,chp}$	$\eta_{o,chp}$	CR
Houston:	0.25	187	Yes	30.62	357	8.6%	33.6%	3.57
	0.30	225	Yes	30.62	428	7.1%	32.1%	3.64
	0.35	262	Yes	30.62	500	6.1%	31.1%	3.69
	0.40	300	Yes	30.62	571	5.4%	30.4%	3.73
	0.45	337	Yes	30.62	643	4.8%	29.8%	3.76
	0.50	375	Yes	30.62	714	4.3%	29.3%	3.78
San Francisco:	0.25	149	Yes	38.56	283	13.6%	38.6%	3.32
	0.30	179	Yes	38.56	340	11.3%	36.3%	3.43
	0.35	208	Yes	38.56	397	9.7%	34.7%	3.51
	0.40	268	Yes	38.56	453	8.5%	33.5%	3.58
	0.45	298	Yes	38.56	510	7.6%	32.6%	3.62
	0.50	3.82	Yes	38.56	567	6.8%	31.8%	3.66
Duluth:	0.25	158	No	158.2	301	52.5%	77.5%	1.38
	0.30	190	Yes	174.1	361	48.2%	73.2%	1.59
	0.35	222	Yes	174.1	422	41.3%	66.3%	1.94
	0.40	253	Yes	174.1	482	36.1%	61.1%	2.19
	0.45	285	Yes	174.1	542	32.1%	57.1%	2.40
	0.50	316	Yes	174.1	603	28.9%	53.9%	2.56

Office Building

The effects of the fraction R_e on CHP total efficiency and CR_{min} for the small office building are illustrated in Figure 3.7 and Figure 3.8.

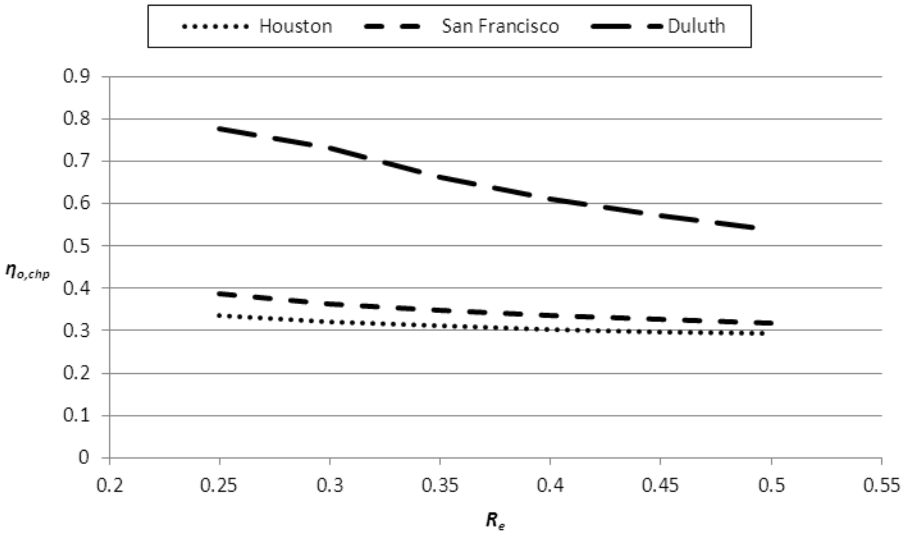

Figure 3.7 CHP efficiency for varying R_e for a small office building in 3 cities

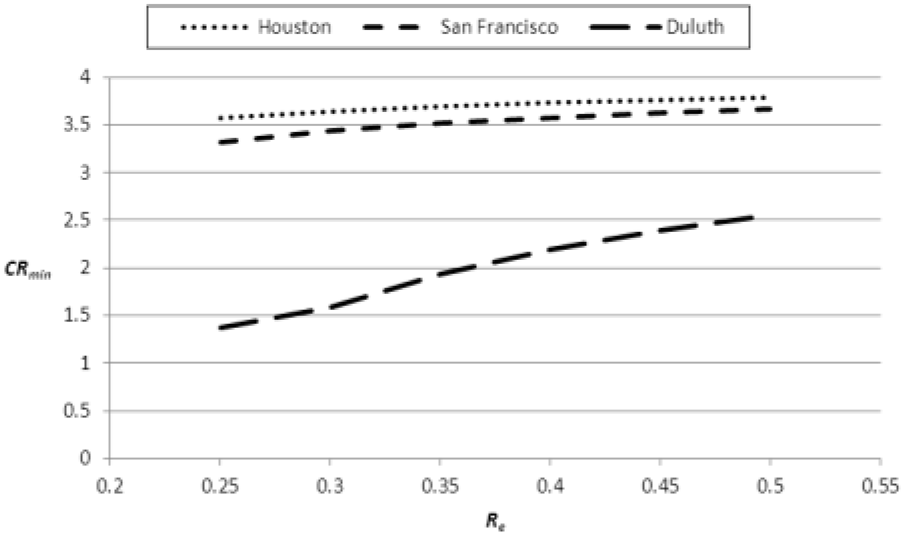

Figure 3.8 CR required for varying R_e for a small office building in 3 cities

Because the small office building requires much more electrical energy than thermal energy, the amount of heat produced by the CHP exceeds the heat required in almost every case with the PGU efficiency at 25%. The only exception is Duluth, MN, where the heating load is relatively higher and the PGU provides only 25% of E_b.

As the fraction of E_b provided by CHP increases, the amount of heat produced as a byproduct of generation also increases. Thus, less of the recovered heat is considered useful heat, and the thermal efficiency decreases. Since the efficiency of the power generation unit is taken to be constant and all the electricity produced is assumed to be used by the building, the CHP efficiency corresponds directly to the thermal efficiency. For this reason, Duluth, the city with the lowest PHR_b, has a notably higher overall efficiency and requires a lower CR, meaning a smaller difference between electricity and fuel prices is necessary to save money in Duluth. Its PHR_b corresponds more closely to the output of the CHP system and therefore the energy produced by the CHP is more likely to be used. Houston, with the lowest PHR_b, shows low overall CHP system efficiency and would require the price of electricity to be almost 4 times the price of fuel for a CHP system to have any potential to save money.

Restaurant

The results for a full service restaurant in Houston, San Francisco, and Duluth are presented in Table 3.4. In each case, the efficiency of the PGU is 25%.

Table 3.4 Full service restaurant with CHP, varying PGU size

	R_e	Q_{rec} (GJ)	$Q_{rec}>Q_{req}$	Q_{useful} (GJ)	F_{CHP} (GJ)	η_{th}	η_{CHP}	CR
Houston:	0.25	729.7	No	729.7	1390	52.5%	77.5%	1.375
	0.30	875.6	No	875.6	1668	52.5%	77.5%	1.375
	0.35	1022	No	1022	1946	52.5%	77.5%	1.375
	0.40	1168	No	1168	2224	52.5%	77.5%	1.375
	0.45	1313	Yes	1209	2502	48.3%	73.3%	1.584
	0.50	1459	Yes	1209	2780	43.5%	68.5%	1.826
San Francisco:	0.25	601.5	No	601.5	1146	52.5%	77.5%	1.375
	0.30	721.8	No	721.8	1375	52.5%	77.5%	1.375
	0.35	842.1	No	842.1	1604	52.5%	77.5%	1.375
	0.40	962.4	No	962.4	1833	52.5%	77.5%	1.375
	0.45	1083	No	1083	2062	52.5%	77.5%	1.375
	0.50	1203	No	1203	2291	52.5%	77.5%	1.375
Duluth:	0.25	603.5	No	603.5	1150	52.5%	77.5%	1.375
	0.30	724.2	No	724.2	1379	52.5%	77.5%	1.375
	0.35	844.9	No	844.9	1609	52.5%	77.5%	1.375
	0.40	965.6	No	965.6	1839	52.5%	77.5%	1.375
	0.45	1086	No	1086	2069	52.5%	77.5%	1.375
	0.50	1207	No	1207	2299	52.5%	77.5%	1.375

The effects of the fraction R_e on CHP efficiency and minimum CR for the full service restaurant are illustrated in Figure 3.9 and Figure 3.10.

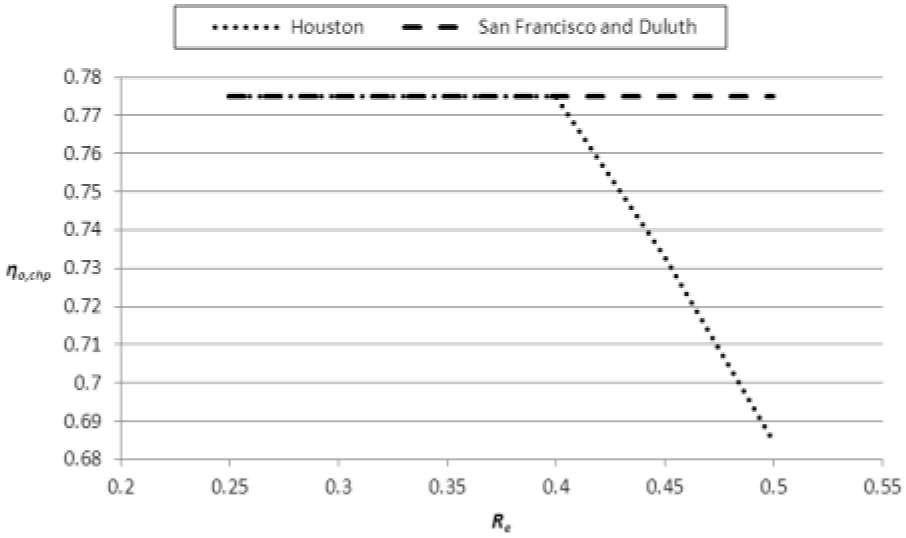

Figure 3.9 CHP efficiency for varying R_e for a full service restaurant in 3 cities

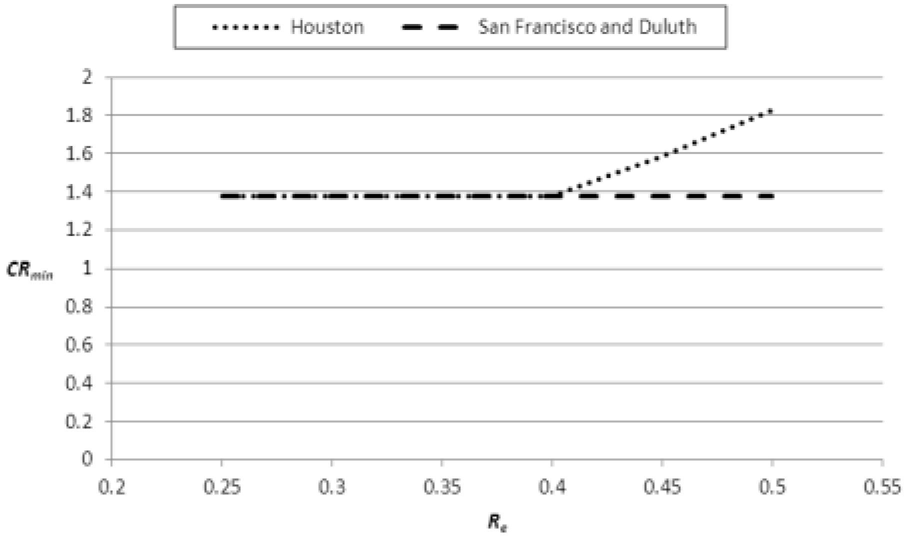

Figure 3.10 CR required for varying R_e for a full service restaurant building in 3 cities

The restaurant demands a much higher portion of its energy requirements as thermal energy than does the office building. Therefore, Q_{rec} does not exceed Q_{req} in most cases. The exceptions are in Houston, which requires the lowest heating load, with the CHP system providing a greater portion of E_b. Because $\eta_{o,chp}$ increases with increasing

$\eta_{th,chp}$, the efficiency of the CHP system reaches a maximum when $\eta_{th,chp}$ is maximum, meaning that all of Q_{rec} is useful heat. With the CHP system functioning at maximum efficiency, the required CR_{min} does not change. In the instances where Q_{rec} does exceed Q_{req}, the CR_{min} is greater because some of the thermal energy from the CHP is not used by the building, and therefore more fuel energy is wasted.

The building's PHR_b does not have an effect for smaller R_e values because the restaurant has a greater need for thermal energy and therefore all the heat produced by the CHP can be used in most cases. Therefore $\eta_{o,chp}$ and CR_{min} are calculated in the same way as the previous section, where geographic location was not taken into account. When R_e is greater than 0.4, Houston is an exception because the CHP system produces excess heat, causing $\eta_{o,chp}$ to decrease and CR_{min} to increase.

Effects of PGU Efficiency

The results for a small office building in Houston, San Francisco, and Duluth with varying efficiency of the PGU are presented in Table 3.5. In each case, R_e is held constant at 0.35.

Table 3.5 Small office building with CHP, varying PGU efficiency

	η_{pgu}	Q_{rec} (GJ)	$Q_{rec}>Q_{req}$	Q_{useful} (GJ)	F_{CHP} (GJ)	η_{th}	η_{CHP}	CR
Houston:	0.15	495.6	Yes	30.62	833	3.7%	18.7%	6.36
	0.20	349.8	Yes	30.62	625	4.9%	24.9%	4.69
	0.25	262.4	Yes	30.62	500	6.1%	31.1%	3.69
	0.30	204.1	Yes	30.62	416	7.4%	37.4%	3.03
	0.35	162.4	Yes	30.62	357	8.6%	43.6%	2.55
San Francisco:	0.15	393.5	Yes	38.56	661	5.8%	20.8%	6.18
	0.20	277.7	Yes	38.56	496	7.8%	27.8%	4.51
	0.25	208.3	Yes	38.56	397	9.7%	34.7%	3.51
	0.30	162.0	Yes	38.56	331	11.7%	41.7%	2.85
	0.35	128.9	Yes	38.56	283	13.6%	48.6%	2.37
Duluth:	0.15	418.3	Yes	174.1	703	24.8%	39.8%	4.60
	0.20	295.3	Yes	174.1	527	33.0%	53.0%	2.94
	0.25	221.5	Yes	174.1	422	41.3%	66.3%	1.94
	0.30	172.2	No	172.2	352	49.0%	79.0%	1.29
	0.35	137.1	No	137.1	301	45.5%	80.5%	1.23

Office Building

The effects of the PGU efficiency on CHP efficiency and minimum CR for the small office building are illustrated in Figure 3.11 and Figure 3.12.

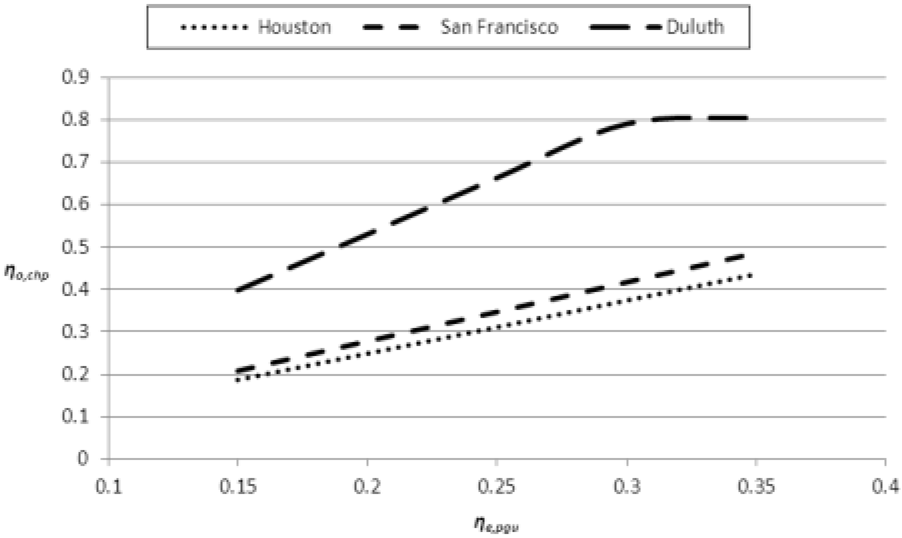

Figure 3.11 CHP efficiency for varying $\eta_{e,pgu}$ for a small office building in 3 cities

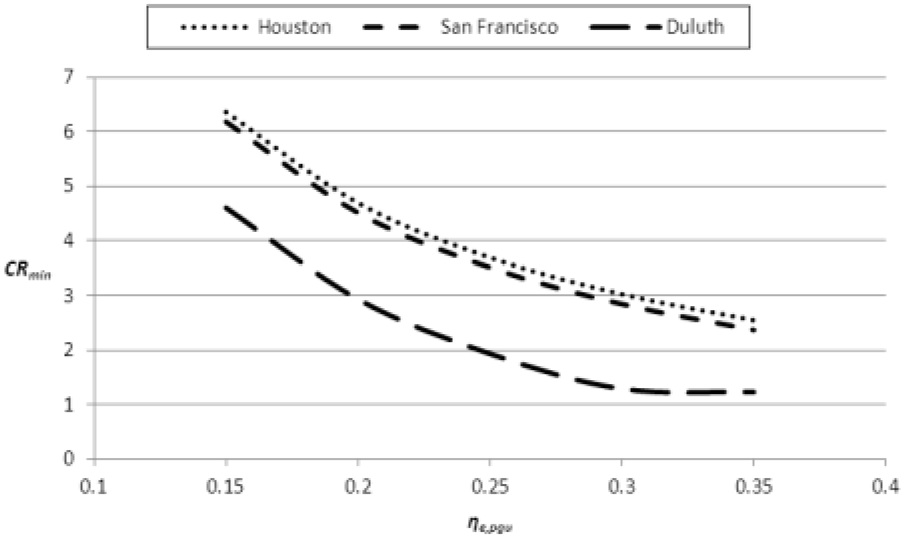

Figure 3.12 CR required for varying $\eta_{e,pgu}$ for a small office building in 3 cities

Again, the amount of heat produced by the CHP exceeds the amount of heat required in most cases with the PGU providing 35% of the load. When PGU efficiency is low and heat requirements are low, as is the case with Houston where $\eta_{e,pgu} = 0.15$, little of the excess heat is useful heat, and this results in low overall CHP efficiency and high

$\mathrm{CR}_{\mathrm{min}}$. As the PGU efficiency increases, the amount of heat produced as a byproduct of generation decreases because more fuel energy is converted to electrical energy.

When Q_{rec} is greater than Q_{req}, $\eta_{th,chp}$ increases as $\eta_{e,pgu}$ increases. However, when Q_{rec} is less than Q_{req}, as in Duluth with $\eta_{e,pgu} \geq 30\%$, $\eta_{th,chp}$ decreases with increasing $\eta_{e,pgu}$ because more fuel is being converted to electricity and less fuel energy is then used to meet the thermal energy demand.

Restaurant

The results for a full service restaurant in Houston, San Francisco, and Duluth with varying efficiency of the PGU are presented in Table 3.6. In each case, R_e is held constant at 0.35.

Table 3.6 Full service restaurant with CHP, varying PGU efficiency

	η_{pgu}	Q_{rec} (GJ)	$Q_{rec}>Q_{req}$	Q_{useful} (GJ)	F_{CHP} (GJ)	η_{th}	η_{CHP}	CR
Houston:	0.15	1930	Yes	1209	3243	37.3%	52.3%	3.56
	0.20	1362	Yes	1209	2432	49.7%	69.7%	1.89
	0.25	1022	No	1022	1946	52.5%	77.5%	1.36
	0.30	794.6	No	794.6	1622	49.0%	79.0%	1.29
	0.35	632.4	No	632.4	1390	45.5%	80.5%	1.23
San Francisco:	0.15	1591	Yes	1429	2673	53.5%	68.5%	2.21
	0.20	1123	No	1123	2005	56.0%	76.0%	1.50
	0.25	842.1	No	842.1	1604	52.5%	77.5%	1.38
	0.30	655.0	No	655.0	1337	49.0%	79.0%	1.29
	0.35	521.3	No	521.3	1146	45.5%	80.5%	1.23
Duluth:	0.15	1596	No	1596	2682	74.5%	74.5%	1.71
	0.20	1127	No	1127	2012	76.0%	76.0%	1.50
	0.25	844.9	No	844.9	1609	52.5%	77.5%	1.38
	0.30	657.1	No	657.1	1341	49.0%	79.0%	1.29
	0.35	523.0	No	523.0	1150	45.5%	80.5%	1.23

The effects of the PGU efficiency on overall CHP efficiency and CR_{min} for the full service restaurant are illustrated in Figure 3.13 and Figure 3.14.

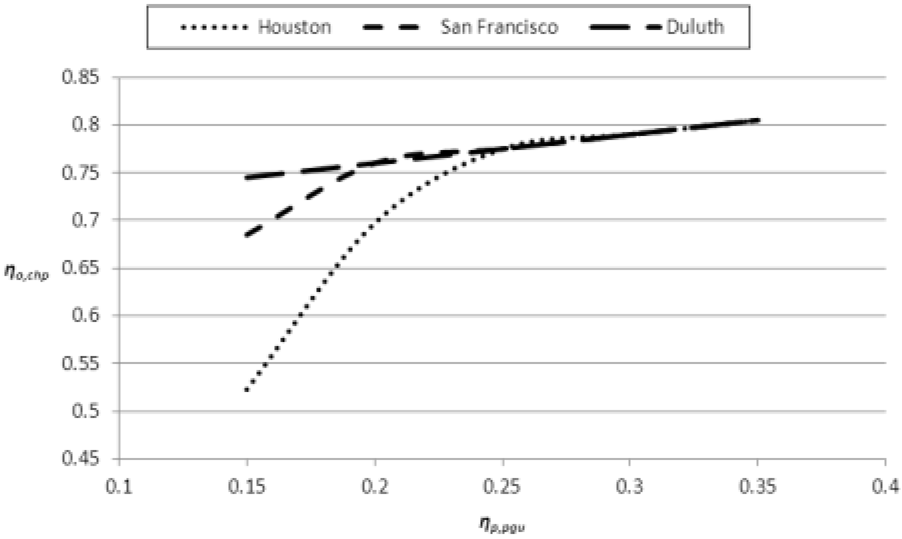

Figure 3.13 CHP efficiency for varying η_{pgu} for a full service restaurant in 3 cities

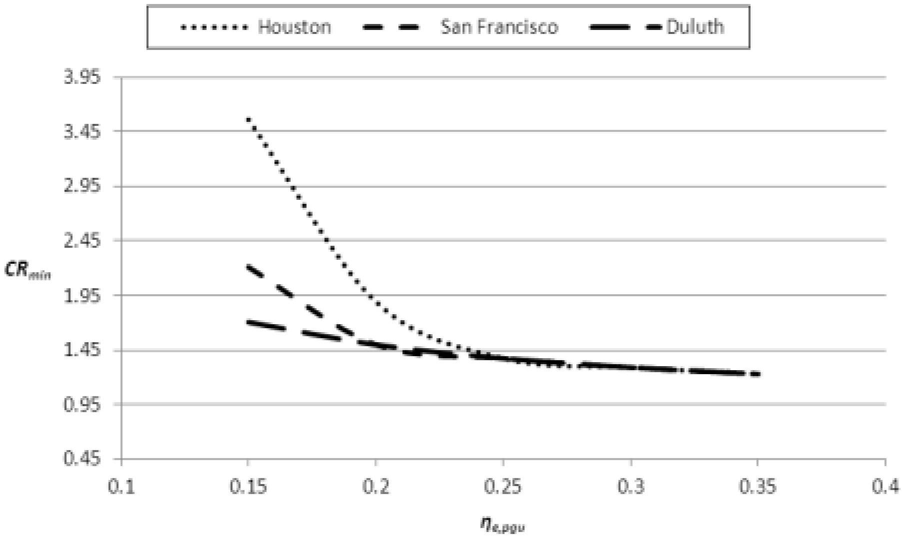

Figure 3.14 CR required for varying $\eta_{e,pgu}$ for a full service restaurant in 3 cities

Q_{rec} does not exceed Q_{req} in most cases for the restaurant, except in the warm climates with low PGU efficiency. The thermal efficiency of the CHP system reaches a maximum when $\eta_{e,pgu}$ is such that $Q_{rec} = Q_{req}$, but $\eta_{o,chp}$ continues to increase and CR_{min} continues to decrease with increasing $\eta_{e,pgu}$. In the cases when Q_{rec} does exceed Q_{req}, the CR_{min} increases dramatically when $\eta_{e,pgu}$ decreases because more of the thermal energy from the fuel is not used.

Effects of Heat Recovery System Efficiency

The results for a small office building in Houston, San Francisco, and Duluth with varying efficiency of the PGU are presented in Table 3.7. In each case, $\eta_{e,pgu}$ is 0.25 and R_e is 0.35.

Table 3.7 Small office building with CHP, varying CHP heat recovery efficiency

	η_{chr}	Q_{rec} (GJ)	$Q_{rec}>Q_{req}$	Q_{useful} (GJ)	F_{CHP} (GJ)	η_{th}	η_{CHP}	CR
Houston:	0.6	224.9	Yes	30.62	499.7	6.1%	31.1%	3.69
	0.65	243.6	Yes	30.62	499.7	6.1%	31.1%	3.69
	0.70	262.4	Yes	30.62	499.7	6.1%	31.1%	3.69
	0.75	281.1	Yes	30.62	499.7	6.1%	31.1%	3.69
	0.80	299.8	Yes	30.62	499.7	6.1%	31.1%	3.69
San Francisco:	0.6	178.5	Yes	38.56	396.8	9.7%	34.7%	3.51
	0.65	193.4	Yes	38.56	396.8	9.7%	34.7%	3.51
	0.70	208.3	Yes	38.56	396.8	9.7%	34.7%	3.51
	0.75	223.2	Yes	38.56	396.8	9.7%	34.7%	3.51
	0.80	238.1	Yes	38.56	396.8	9.7%	34.7%	3.51
Duluth:	0.6	189.8	Yes	174.1	421.8	41.3%	66.3%	1.94
	0.65	205.6	Yes	174.1	421.8	41.3%	66.3%	1.94
	0.70	221.5	Yes	174.1	421.8	41.3%	66.3%	1.94
	0.75	237.3	Yes	174.1	421.8	41.3%	66.3%	1.94
	0.80	253.1	Yes	174.1	421.8	41.3%	66.3%	1.94

Office Building

The effects of the CHP heat recovery system efficiency on CHP overall efficiency and CR_{min} for the small office building are illustrated in Figure 3.15 and Figure 3.16.

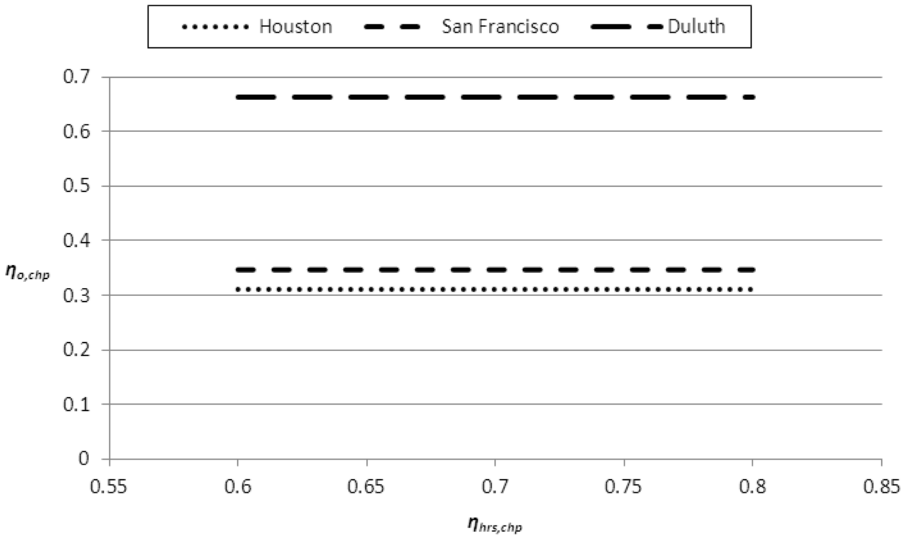

Figure 3.15 CHP efficiency for varying $\eta_{hrs,chp}$ for a small office building in 3 cities

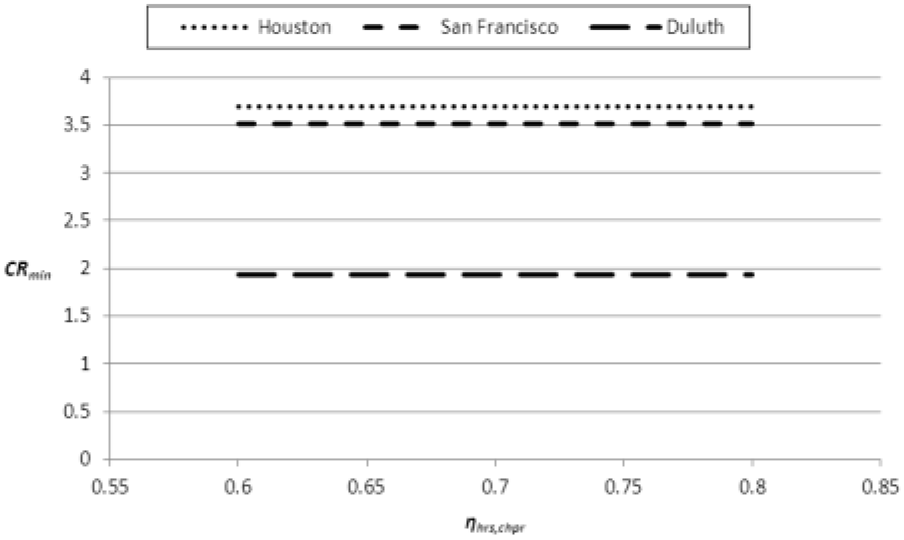

Figure 3.16 CR required for varying $\eta_{hrs,chp}$ for a small office building in 3 cities

The amount of heat produced by the CHP exceeds the amount of heat required in each case above for the small office building. As the efficiency of the CHP's heat recovery system increases, the amount of heat recovered increases, but since this heat is in excess of the thermal demand, values for $\eta_{th,chp}$, $\eta_{o,chp}$, and CR_{min} remain the same (Q_{useful} remains constant).

The results for a small office building in Houston, San Francisco, and Duluth with varying efficiency of the PGU are presented in Table 3.8. In each case, $\eta_{e,pgu}$ is 0.25 and R_e is 0.35.

Table 3.8 Full service restaurant with CHP, varying CHP heat recovery efficiency

	η_{chr}	Q_{rec} (GJ)	$Q_{rec}>Q_{req}$	Q_{useful} (GJ)	F_{CHP} (GJ)	η_{th}	η_{CHP}	CR
Houston:	0.6	875.6	No	875.6	1946	45.0%	70.0%	1.75
	0.65	948.6	No	948.6	1946	48.8%	73.8%	1.56
	0.70	1022	No	1022	1946	52.5%	77.5%	1.38
	0.75	1095	No	1095	1946	56.3%	81.3%	1.19
	0.80	1168	No	1168	1946	60.0%	85.0%	1.00
San Francisco:	0.6	721.8	No	721.8	1604	45.0%	70.0%	1.75
	0.65	781.9	No	781.9	1604	48.8%	73.8%	1.56
	0.70	842.1	No	842.1	1604	52.5%	77.5%	1.38
	0.75	902.2	No	902.2	1604	56.3%	81.3%	1.19
	0.80	962.4	No	962.4	1604	60.0%	85.0%	1.00
Duluth:	0.6	724.4	No	724.4	1609	45.0%	70.0%	1.75
	0.65	784.6	No	784.6	1609	48.8%	73.8%	1.56
	0.70	844.9	No	844.9	1609	52.5%	77.5%	1.38
	0.75	905.3	No	905.3	1609	56.3%	81.3%	1.19
	0.80	965.6	No	965.6	1609	60.0%	85.0%	1.00

Restaurant

The effects of the CHP heat recovery system efficiency on CHP overall efficiency and minimum *CR* for the full service restaurant are illustrated in Figure 3.17 and Figure 3.18.

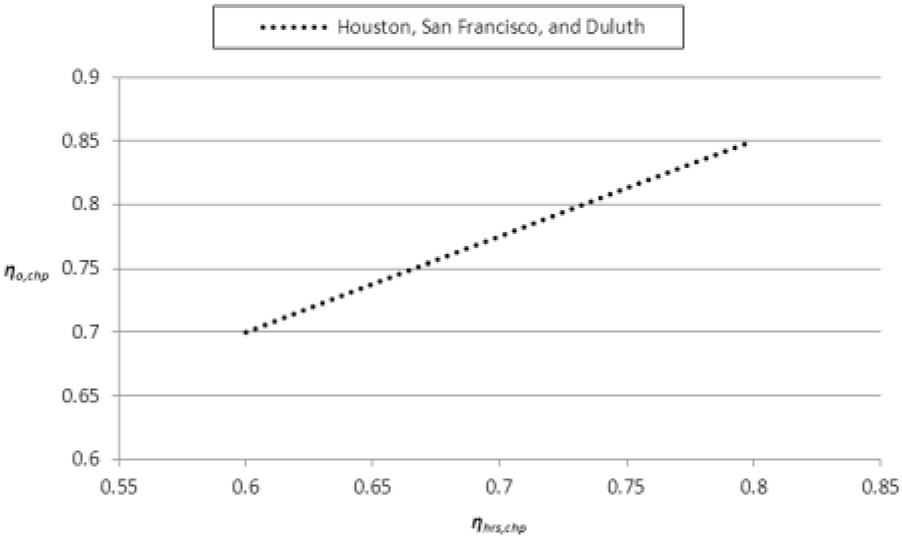

Figure 3.17 CHP efficiency for varying $\eta_{e,pgu}$ for a full service restaurant in 3 cities

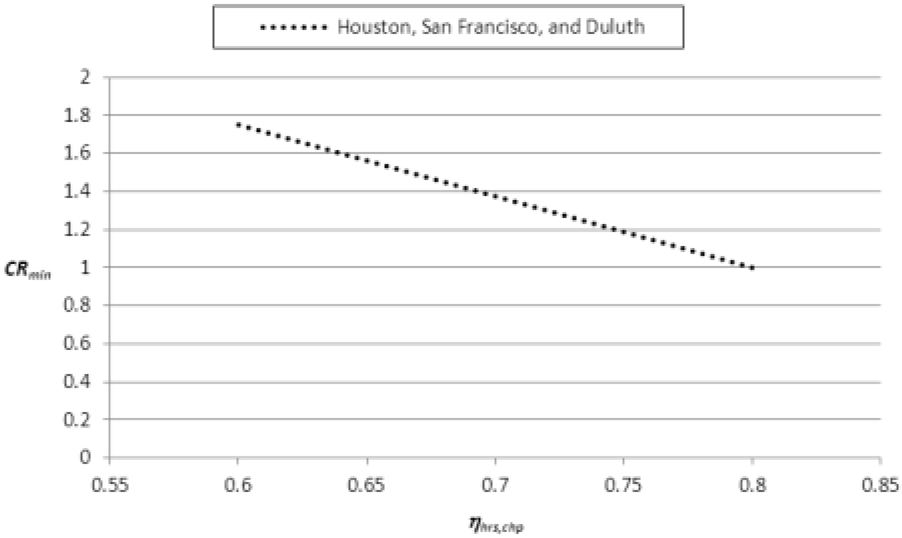

Figure 3.18 CR required for varying $\eta_{e,pgu}$ for a full service resturant in 3 cities

For the restaurant, which has a lower PHR_b, the amount of heat recovered is never in excess of the heating demand. As the efficiency of the CHP's heat recovery system increases, the amount of heat recovered increases and therefore $\eta_{th,chp}$ increases. Correspondingly, $\eta_{o,chp}$ increases and CR_{min} becomes less with increasing Q_{rec}.

Cost Spark Spread: Summary and Conclusions

Mathematical Models

A detailed model, based on the spark spread, that compares the electrical energy and heat energy produced by a CHP system against the same amounts of energy produced by a traditional, or separate heating and power (SHP) system is presented in this chapter. It was assumed that the CHP system operates at full load and full efficiency and that the building uses all energy produced by the CHP system. The energy consumption amounts which were not met by the CHP system are the same for both systems (CHP and SHP) so they do not contribute to the comparison.

An expression for the spark spread based on the cost of the fuel and some CHP system efficiencies, as well as an expression for the payback period with a given capital cost and spark spread, is presented in this chapter. The ratio of electricity cost to fuel cost was found to be a contributing parameter for both. The developed expressions can be used to determine the required spark spread, $\mathrm{SS}_{\mathrm{min}}$, which gives a baseline above which a CHP system could produce net operational savings over the SHP. $\mathrm{SS}_{\mathrm{min}}$ is expressed in terms of the performance of system components.

Although a spark spread of \$0.0409/kWh is typically used to indicate the potential for favorable payback of a CHP system, the analysis presented in this chapter shows that the required spark spread depends on the components, the desired payback period or capital cost, and the magnitude of the price of fuel, or of the price of electricity. A CHP system may be economically viable with a spark spread much less than \$0.0409/kWh in some cases, and in others a spark spread even greater than \$0.0409/kWh may not result in a favorable payback. The required SS (No Savings Case) strongly depends on the efficiency of the SHP heating system, the efficiency of the CHP system, and the relationship between electricity output and heat output (or, PGU efficiency relative to CHP thermal efficiency). Larger spark spreads are necessary in order to guarantee: shorter payback periods, lower CHP efficiencies, higher SHP heating system efficiencies, and higher fuel prices.

The introduced PBP_{CHP} is a simple indicator of the economic viability of a CHP system which takes into account the CHP and SHP thermal efficiencies, power-to-heat ratio of the CHP system, capital cost of the CHP system, and the cost of fuel and its relationship to the cost of electricity. Rather than specifying a spark spread which may or may not be met in order to indicate economic viability of a CHP system, the PBP_{CHP} indicates if net savings over an SHP system could be achieved.

Computational Examples

The analysis leading to SS_{min} made the assumption that all electricity and thermal energy produced by the CHP would be used by the building. Varying levels of electrical and thermal demand would not affect this analysis and for this reason, different building types and locations were not considered.

For cases where $Q_{rec} < Q_{req}$, the recovered heat is entirely used and the results obtained are identical to those from the earlier model. Under those conditions, the sizing of the PGU with respect to the building demand has no effect on overall CHP efficiency or on the *CR* or *SS* required. Increasing $\eta_{e,pgu}$ or increasing $\eta_{hrs,chp}$ in this case results in a linear increase in $\eta_{o,chp}$ and a linear decrease in CR_{min}.

Since an installed system may produce excess energy, the case where excess heat production occurs was considered. This analysis shows for cases where $Q_{rec} \geq Q_{req}$, the needs of the building and the sizing of the CHP system play an important role in the system efficiencies (and therefore SS_{min} and CR_{min}) because some of the energy produced may not be useful to the building under analysis.

When excess heat is recovered from the CHP system, a smaller PGU size will result in larger $\eta_{o,chp}$ and smaller required CR. The effect of PGU sizing on $\eta_{o,chp}$ and *CR* is more pronounced at low R_e. The overall CHP efficiency decreases quickly when the power-to-heat ratio provided by the CHP system decreases below the PHR_b for that particular location and building type. Increasing $\eta_{e,pgu}$ in this case results in a steep linear increase in $\eta_{o,chp}$ until the point where $Q_{rec}=Q_{req}$, where the increase becomes less steep. This also results in a decrease in required CR, with a much more pronounced effect in Houston, a hot climate. Increasing $\eta_{hrs,chp}$ in this case does not affect $\eta_{o,chp}$ or the required CR because the heat produced is more than enough to meet the building's thermal energy requirement.

Comparing results between the three cities, it is obvious in each case that Duluth, which has much colder weather, produces much higher CHP efficiencies because the heat recovered is all, or mostly, useful heat. The restaurant shows much more favorable results because the disparity between the power and heat provided by the CHP system and the PHR_b of the building is much smaller than for the office building.

The electrical load is relatively much larger than the thermal load in the warmer climates, resulting in a larger Q_{rec} because the recovered heat is directly proportional to the amount of electricity produced when $\eta_{e,pgu}$ is assumed constant. However, in a warmer climate zone, less space heating is needed throughout the year and therefore the amount of heat recovered becomes much more likely to exceed the amount of heat that can be used. For the office building, which has a large PHR_b, the CR_{min} required for a CHP system to show a potential cost benefit is prohibitively high for Houston and San Francisco.

Because CHP replaces purchased electricity with electricity generated from fuel on-site, the larger the ratio of $Cost_e$ to $Cost_f$, the more advantageous a CHP system becomes over an SHP system. $\mathrm{CR}_{\mathrm{min}}$ is closely linked with $\eta_{o,chp}$, with highly efficient CHP systems having a lower $\mathrm{CR}_{\mathrm{min}}$, indicating more potential for cost benefit.

While the results shown consider the energy needs of a building over the entire year at once, the analysis could be conducted in the same way on a monthly basis, since climate conditions change throughout the year, or on an hourly basis if this level of data is available for the building under study.

In general, the full service restaurant model is more suitable for CHP due to its high thermal demand, which corresponds to lower PHR_b values and allows for more of the heat available from the CHP system to be used by the building.

Duluth, the coldest climate used for this analysis, showed the most potential for cost savings with a CHP system. The buildings located in Duluth need more heat than those in milder climates, and therefore the power-to-heat ratio provided by the CHP system is closer to PHR_b. This method may be used to analyze a wider variety of building types in any climate zone of interest.

CHAPTER IV

EMISSIONS SPARK SPREAD AND PRIMARY ENERGY SPARK SPREAD

Costs, CDE, and PEC for CHP and SHP systems will vary with the location where the system is installed. The amount of harmful emissions associated with purchased electricity varies with the fuel mix used by the utility which produces that power [77]. The energy consumed at the site is also related to the energy consumed at the utility by a local source-site ratio [8].

This chapter presents an emissions spark spread (ESS) and a primary energy spark spread (PESS) as environmental and energy screening parameters for CHP systems. The objective of this work is to provide simple screening tools, using the method shown in CHAPTER III, which indicate CHP's potential to reduce CDE and to reduce PEC. Then, factors are investigated which influence the amount of emissions and energy reduction possible with a CHP system rather than a conventional SHP system.

In addition to the SS, its variations which address CDE and PEC for different locations are needed if environmental and energetic considerations are important to determine the feasibility of a CHP system. The ESS and PESS are compared for cities in 16 climate zones, which represent divisions of the 8 basic U.S. climate zones shown in Figure 4.1.

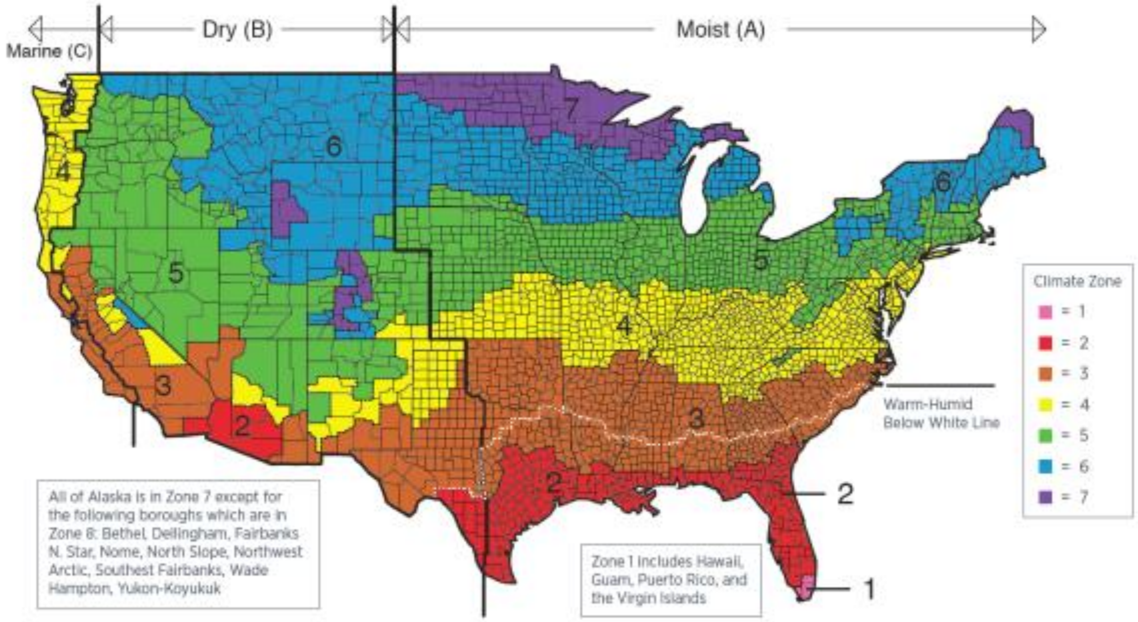

Figure 4.1 U.S. climate zones [93].

Development of New Spark Spread Expressions for Emissions and Energy

Emissions Spark Spread

Emissions Spark Spread can be defined as:

$$ESS = EEF - FEF \qquad 4.1$$

where *EEF* is the electricity emissions factor and *FEF* is the fuel emissions factor. Fumo et al. [9] define EEF as “the quantity of emission of a pollutant associated with the site electric energy consumed” and FEF as “the quantity of emission of a pollutant associated with the site fuel energy consumed”. This is a global assessment of pollutant which does not take into account the local impact of pollutants emitted from a CHP system, which is a traditional method of comparing CHP and SHP [36].

The CDE from the CHP system operation as a function of the quantity of fuel consumed can be expressed as:

$$Emissions_{chp} = F_{chp}\ FEF \tag{4.2}$$

This is analogous to Equation (3.10).

Similarly, the CDE from the SHP system operation of the reference building as a function of the quantities of fuel and electricity consumed at the site is:

$$Emissions_{shp} = E_b^* EEF + F_b^* FEF \tag{4.3}$$

This is analogous to Equation (3.15). Because only the constant portion of electrical and thermal energy than the CHP system can provide is considered in this comparison, here $E_b = E_{pgu}$ as in CHAPTER III, and F_b can also be defined in terms of the heat provided by the CHP system if it is assumed that all of this heat is used by the building.

$$Emissions_{shp} = E_{chp} EEF + \frac{Q_{chp}}{\eta_{hs,shp}} FEF \tag{4.4}$$

A favorable CDE potential, similar to a favorable payback potential, is the opportunity for a CHP system to reduce emission over time (rather than reducing monetary expenditures). For the CHP system to have a favorable CDE potential, the total emissions resulting from the CHP system operation must not be larger than that resulting from the operation of the SHP system; otherwise the CHP systems produces more CDE than the reference system.

$$Emissions_{shp} - Emissions_{chp} \geq 0 \tag{4.5}$$

Using the analysis method of CHAPTER III, Equation (3.23) can be modified to account for emissions by changing CR_{min} to a minimum emissions ratio, ER_{min}, which represents the ratio of CDE associated with conventional electricity production to CDE associated with on-site fuel use. The emissions ratio can be solved for in the same manner as CR_{min}, where the resulting ER_{min} corresponds to the break-even conditions, which exist when the CHP system and SHP system produce equal amounts of emissions [78]:

$$ER_{\min} = \frac{1}{PHR_{chp}}\left(\frac{1}{\eta_{o,chp}} - \frac{1}{\eta_{hs,shp}}\right) + \frac{1}{\eta_{o,chp}} \tag{4.6}$$

For a CHP system the potential to reduce CDE, *ESS* should satisfy the inequality:

$$ESS_{\backslash} \geq FEF\,(ER_{\min} - 1) \tag{4.7}$$

where ESS is the difference in EEF and FEF values obtained for a given situation. EEF values for purchased electricity will vary based on the fuel mix used to generate that electricity in the eGRID subregion corresponding to the building's location [79, 80]. FEF values account for direct greenhouse gas emissions and are unique to the fuel used according to its heating value and carbon content [79, 81].

The ESS_{act} values for the different climate conditions are presented in Table 4.1. This table was calculated using a nationwide average *FEF* value of 181 kg CO_2/MWh given by the EPA [79] for natural gas.

Table 4.1 ESS for the 16 U.S. cities evaluated in this investigation

Climate Zone	City	EEF (kg/MWh)*	ESS_{act} (kg/MWh) Eq. (B6)
1A	Miami, FL	598	417
2A	Houston, TX	601	420
2B	Phoenix, AZ	595	414
3A	Atlanta, GA	676	495
3B-Coast	Los Angeles, CA	328	147
3B	Las Vegas, NV	595	414
3C	San Francisco, CA	328	147
4A	Baltimore, MD	517	336
4B	Albuquerque, NM	596	414
4C	Seattle, WA	409	228
5A	Chicago, IL	698	517
5B	Boulder, CO	854	673
6A	Minneapolis, MN	826	645
6B	Helena, MT	409	228
7A	Duluth, MN	826	645
8A	Fairbanks, AK	559	378

**Values taken in October 2010*

Primary Energy Spark Spread

Primary Energy Spark Spread, PESS, can be defined similarly to ESS as

$$PESS = ECF - FCF \tag{4.8}$$

where *ECF* is the electricity conversion factor and *FCF* is the fuel energy conversion factor. Fumo et al. [8] define ECF as “the factor used to express site electric energy in terms of total equivalent primary source energy” and FCF as “the factor used to express site fuel energy in terms of total equivalent primary source energy.” These factors account for losses that occur in producing and transporting energy in the form of either electricity or fuel.

Likewise, the primary energy used by the CHP system must be at least as low as the primary energy used by an SHP system; otherwise the CHP systems consumes more primary energy than the reference system.

$$PEC_{shp} - PEC_{chp} \geq 0 \tag{4.9}$$

The primary energy ratio can be solved for in the same manner as CR_{min} and ER_{min}, where the resulting PER_{min} corresponds to the break-even conditions, where the the CHP system and the SHP system are responsible for the consumption of equal amounts of primary energy:

$$PER_{\min} = \frac{1}{PHR_{chp}}\left(\frac{1}{\eta_{o,chp}} - \frac{1}{\eta_{hs,shp}}\right) + \frac{1}{\eta_{o,chp}} \tag{4.10}$$

For a CHP system to have the potential to reduce PEC, *PESS* should satisfy the inequality:

$$PESS \geq FCF(PER_{\min} - 1) \tag{4.11}$$

where PESS is the difference in ECF and FCF values obtained for a given situation. ECF values for purchased electricity account for losses associated with the conversion of a fuel to electricity, and transmission and distribution losses on the way to the site, and will also vary based on the fuel mixed used for electrical generation in the region [80, 82]. FCF values for natural gas account for pipeline transmission and distribution losses on the way to the site. The FCF value, provided by the EPA [83], is unique to the fuel used and will vary slightly over time. *PER*, again, represents the ratio of the source-to-site conversion factor for electricity, ECF, to the source-to-site conversion factor for fuel, FCF.

The PESS values for the different climate conditions are presented in Table 4.2. This table was calculated using the *FCF* nationwide average value of 1.047 given by the EPA [83] for natural gas.

Table 4.2 PESS for the 16 U.S. cities investigated in this evaluation

Climate Zone	City	ECF	$PESS_{act}$– Eq. (4.8)
1A	Miami, FL	3.7	2.65
2A	Houston, TX	3.7	2.65
2B	Phoenix, AZ	2.9	1.85
3A	Atlanta, GA	3.4	2.35
3B-Coast	Los Angeles, CA	2.2	1.15
3B	Las Vegas, NV	3.1	2.05
3C	San Francisco, CA	2.2	1.15
4A	Baltimore, MD	3.5	2.45
4B	Albuquerque, NM	3.7	2.65
4C	Seattle, WA	1.5	0.453
5A	Chicago, IL	3.6	2.55
5B	Boulder, CO	3.4	2.35
6A	Minneapolis, MN	3.5	2.45
6B	Helena, MT	2	0.95
7A	Duluth, MN	3.5	2.45
8A	Fairbanks, AK	2.7	1.65

Results and Discussion of the Emissions Spark Spread and Primary Energy Spark Spread

To illustrate the use of ESS and PESS, three cases were analyzed for different overall CHP total system efficiencies (60%, 70%, and 80%) as presented in Table 4.3. These CHP system efficiencies were selected to represent a range of efficiencies that could be achieved using the same prime mover ($\eta_{e,pgu}$ = constant) with varying amounts of useful thermal energy ($\eta_{th,chp}$ ranging from 0.35 to 0.55).

Table 4.3 System parameters for the three cases analyzed in this investigation

Parameter	Case A	Case B	Case C
$\eta_{o,chp}$	0.6	0.7	0.8
$\eta_{e,pgu}$	0.25	0.25	0.25
$\eta_{th,chp}$	0.35	0.45	0.55
PHR_{chp}	0.71	0.56	0.45
$\eta_{hs,shp}$	0.8	0.8	0.8

Using Equation (4.7) and Equation (4.11) the minimum *ESS* and minimum *PESS* for the three analyzed cases can be determined. These values are presented in Table 4.4.

Table 4.4 $\mathrm{ESS}_{\mathrm{min}}$ and $\mathrm{PESS}_{\mathrm{min}}$ for the three cases analyzed in this investigation

Parameter	Case A	Case B	Case C
ESS_{min} (kg/MWh)	226.3	135.8	45.8
$PESS_{min}$ (unitless, or MWh/MWh)	1.309	0.785	0.262

The ESS_{act} may be calculated using the *FEF* (181 kg/MWh) and the *EEF* for the location of interest, given in Table 4.1. Similarly, the $PESS_{act}$ may be calculated using the *FCF* (1.047) and the *ECF* for the location of interest given in Table 4.2. After the actual *ESS* is known, the ratio of *ESS* to ESS_{min} can be calculated to illustrate the potential environmental advantage of the CHP system. When this ratio is greater than 1, the CHP system shows potential to reduce CDE compared to the SHP system, but when the ratio is less than 1, the CHP system will cause more CDE. The higher the ratio ESS/ESS_{min}, the greater the potential for a CHP system to reduce CDE in that climate zone, using the nationwide average fuel emissions factor. Similarly, the ratio of *PESS* to $PESS_{min}$ can be calculated to illustrate the advantage of the CHP system in terms of primary energy. When this ratio is greater than 1, the CHP system shows potential to reduce PEC compared to the SHP system, but when the ratio is less than 1, the CHP system will consume more primary energy. The higher this ratio is, the greater the potential for a CHP system to reduce PEC in that climate zone, using the nationwide average fuel conversion factor.

Table 4.5 presents the EES_{act}/ESS_{min} for the evaluated cities for the three different cases analyzed. In addition, the ESS_{act}/ESS_{min} ratios are presented in Figure 4.2 to allow for visual comparison between the cities. The CHP system shows potential to reduce CDE in all the evaluated cities for all cases except for Case A in the cities of Los Angeles and San Francisco. For Case A, these two cities give a ratio smaller than 1, which means that for this case, a CHP system is not favorable in terms of emissions. The ratio for these two cities is close to 1 for Case B. Therefore, it can be concluded that for the evaluated cases, a CHP system has to operate with an efficiency above 70% to be able to reduce CDE with respect to the reference case. The largest reductions would take place in Boulder, Minneapolis, and Duluth. The least improvement would take place Los Angeles and San Francisco due to the relatively clean production of electricity in California.

Table 4.5 ESS_{act}/ESS_{min} Ratios for 16 U.S. Cities Analyzed in This Investigation

Climate Zone	City	ESS_{act}/ESS_{min} (Case A)	ESS_{act}/ESS_{min} (Case B)	ESS_{act}/ESS_{min} (Case C)
1A	Miami, FL	1.84	3.07	9.22
2A	Houston, TX	1.86	3.09	9.28
2B	Phoenix, AZ	1.83	3.05	9.15
3A	Atlanta, GA	2.19	3.65	10.94
3B-Coast	Los Angeles, CA	0.65	1.08	3.25
3B	Las Vegas, NV	1.83	3.05	9.15
3C	San Francisco, CA	0.65	1.08	3.25
4A	Baltimore, MD	1.49	2.48	7.43
4B	Albuquerque, NM	1.83	3.05	9.15
4C	Seattle, WA	1.01	1.68	5.04
5A	Chicago, IL	2.29	3.81	11.43
5B	Boulder, CO	2.97	4.96	14.87
6A	Minneapolis, MN	2.85	4.75	14.25
6B	Helena, MT	1.01	1.68	5.04
7A	Duluth, MN	2.85	4.75	14.25
8A	Fairbanks, AK	1.67	2.78	8.35

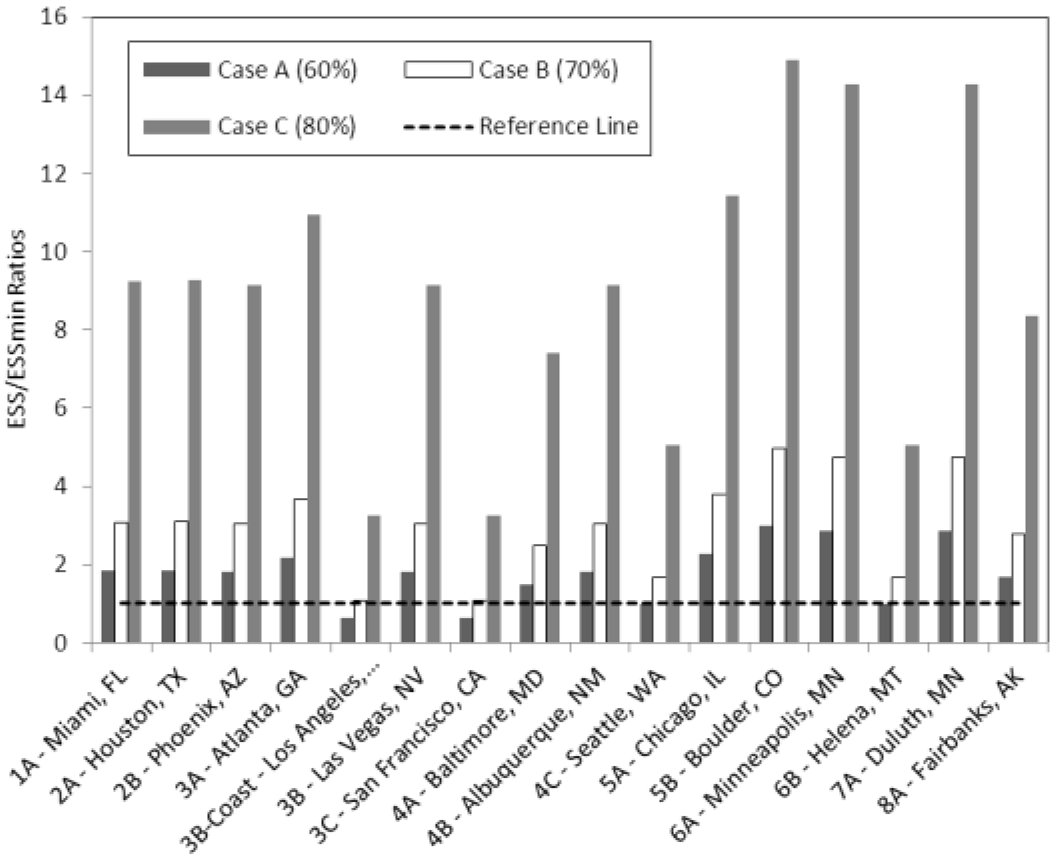

Figure 4.2 ESS/ESS_{min} ratios for 16 U.S. cities analyzed in this investigation

Since *ESS* is the difference between the local electricity emissions factor and a nationwide average fuel emissions factor, the characteristics of the fuel mix in the local region are a critical factor for determining whether a CHP system can reduce emissions in that location. The fuel mix used to produce electricity determines the amount of CO_2 to be released as a result of electricity production. The amount of carbon in the fuel mix has a high impact on the CDE for that region. For example, Boulder, Minneapolis, and Duluth have the highest *EEF*s, from 826 to 854 kg CO_2/MWh [77]. Therefore, the high level of pollutants caused by conventional electricity production in these areas makes the use of a CHP system especially attractive. On the other hand, Los Angeles and San

Francisco have a relatively low *EEF* of 328 kg CO_2/MWh, and therefore the use of a CHP system is not beneficial for some cases.

Some cities, such as Los Angeles and San Francisco, above, receive electricity that comes from a similar fuel mix. For example, based on the EPA Power Profiler data [77], Los Angeles and San Francisco are located in the same subregion [80] used for the EPA's emissions finding tool, which gives both cities the same *EEF*, and therefore the same ESS_{act} to ESS_{min} ratio in this analysis. Also, some cities within a given climate zone might purchase electricity from different sources using varying amounts of high-pollution or low-pollution fuels, in which case ESS_{act}/ESS_{min} could vary even with similar climate conditions. For example, Boulder, Minneapolis, and Duluth have the highest *EEF*s, while Helena, with a similarly cold climate, has a lower *EEF* (409 CO_2/MWh) [77]. Therefore, there is not as much potential for a CHP system to reduce CDE in Helena.

Table 4.6 presents $PESS_{act}/PESS_{min}$ for the evaluated cities for the three different cases analyzed, and Figure 4.3 prevents this information graphically. Results indicate that a CHP system shows potential to reduce PEC in all the cities except in Seattle, Helena, San Francisco, and Los Angeles for Case A. For Case A, the cities mentioned above give a ratio smaller than 1, which means that for this case, a CHP system is not favorable in terms of primary energy reduction. For Case B, Seattle is the only city that shows unfavorable potential, while for Case C the use of a CHP system seems favorable to reduce the primary energy. The largest reductions would take place in Miami, Houston, and Albuquerque. The smallest improvement would take place in Seattle. The PESS is the difference between the local energy conversion factor and a nationwide average fuel energy conversion factor, and therefore the amount of primary energy used to produce the electricity purchased on-site will determine how much a CHP system can reduce PEC in that area. Based on the ECF state-by-state chart [8], Los Angeles and San Francisco again have the same ECF which is used in this analysis, and therefore the same PESS to $PESS_{min}$ ratio. Likewise, if different cities have different electricity conversion factors, $PESS/PESS_{min}$ could vary even with similar climate conditions. For example, Houston shows a much greater potential for reducing primary energy than does Phoenix, even though both cities are located in warm climates.

Table 4.6 PESS/ $PESS_{min}$ ratios for 16 U.S. cities analyzed in this investigation

Climate Zone	City	$PESS/PESS_{min}$ (Case A)	$PESS/PESS_{min}$ (Case B)	$PESS/PESS_{min}$ (Case C)
1A	Miami, FL	2.02	3.37	10.12
2A	Houston, TX	2.02	3.37	10.12
2B	Phoenix, AZ	1.41	2.36	7.07
3A	Atlanta, GA	1.80	2.99	8.98
3B-Coast	Los Angeles, CA	0.88	1.46	4.39
3B	Las Vegas, NV	1.57	2.61	7.83
3C	San Francisco, CA	0.88	1.46	4.39
4A	Baltimore, MD	1.87	3.12	9.36
4B	Albuquerque, NM	2.02	3.37	10.12
4C	Seattle, WA	0.35	0.58	1.73
5A	Chicago, IL	1.95	3.25	9.74
5B	Boulder, CO	1.80	2.99	8.98
6A	Minneapolis, MN	1.87	3.12	9.36
6B	Helena, MT	0.73	1.21	3.63
7A	Duluth, MN	1.87	3.12	9.36
8A	Fairbanks, AK	1.26	2.10	6.30

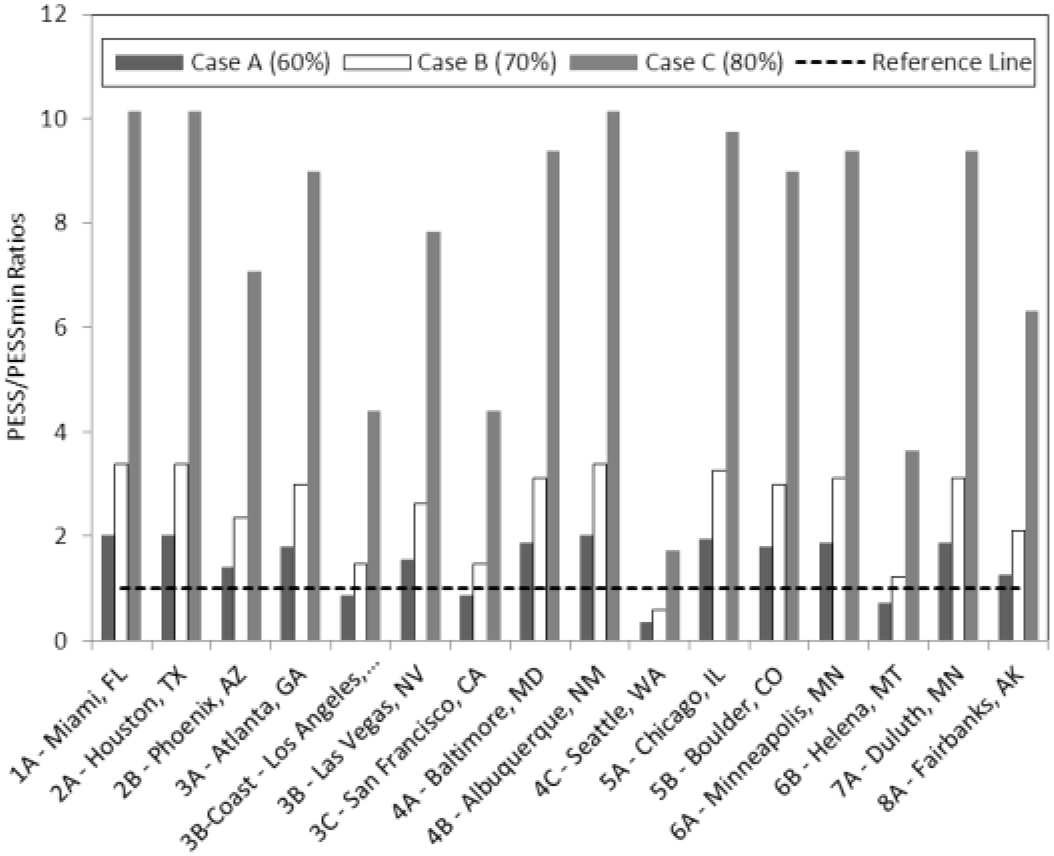

Figure 4.3 PESS/ ratios for 16 U.S. cities analyzed in this investigation

Emissions and Primary Energy Spark Spread: Summary and Conclusions

Spark spread has been used to indicate whether a CHP system shows potential to reduce costs compared to an SHP system. This chapter introduced an emissions spark spread and primary energy spark spread as screening parameters for indicating whether a CHP system shows potential to reduce harmful emissions and PEC, using the steps developed in CHAPTER III. ESS_{min} and $PESS_{min}$ were determined to show at what point a CHP system and SHP system would have similar results for emissions and PEC. When ESS_{act} and $PESS_{act}$ are computed using recent, local data to be greater than ESS_{min} and

$PESS_{min}$, the CHP system shows a potential benefit in terms of emissions reduction or lowered energy consumption, and the magnitude of this benefit may be gauged with the ratios ESS_{act}/ESS_{min} and $PESS_{act}/PESS_{min}$.

Low ESS_{act}/ESS_{min} ratios (Table 4.5) correspond to low EEFs (Table 4.1). For example, Helena does not show favorable emissions potential for CHP system applications in the way that the other colder climate cities do, resulting from Helena's much lower EEF of 409 kg/MWh. Helena receives almost half of its electricity from hydropower sources and uses less coal, oil, and natural gas than the national average. Therefore, since the electricity purchased by an SHP system causes less CO_2 emissions in Helena than it does in Boulder, replacing SHP with CHP in this location would not cause the same amount of reduced emissions.

Low $PESS_{act}/PESS_{min}$ ratios (Table 4.6) correspond to low ECFs (Table 4.2). The state of Washington has a low ECF of 1.5, meaning that a certain amount of electricity purchased from the grid in Seattle would not require as much primary energy as the same amount purchased in any of the other cities investigated. A CHP system in Seattle would use more primary energy than an SHP system, if both systems have the same characteristics as defined above.

If the emissions factors for electricity and fuels as well as the site-to-source conversion factors are known, the ratios ESS_{act}/ESS_{min} and $PESS_{act}/PESS_{min}$ can be can be applied to any location to evaluate the potential of CHP systems for providing environmental and economic benefits. This screening tool may indicate whether a more thorough analysis is of interest. The two new screening parameters provided in this chapter indicate a CHP systems' potential to reduce CDE or to reduce PEC, which can then be used in conjunction with the cost spark spread to inform energy policy and to evaluate appropriate incentives for CHP systems installations based on the desired reduction in economic costs, harmful emissions, and energy consumption.

CHAPTER V

REDUCING EMISSIONS OF THREE GREENHOUSE GASES FOR DIFFERENT BUILDING TYPES USING BASE LOADED CHP SYSTEMS

Under the right conditions, a CHP system can reduce the harmful emissions resulting from power production, causing less greenhouse gases to be released than with a reference system where power comes from the electricity grid. Different building types may be more or less likely to save emissions with CHP systems based on the electrical and thermal needs of the building. In this chapter, CHP systems are evaluated with seven different types of buildings located in Chicago, Illinois for their potential to reduce CO_2, NO_x, and CH_4 emissions. The CHP system modeled in this chapter is sized to provide 30% of the average hourly electricity needs of each building. The total carbon equivalent emissions, PEC, and operational cost of a CHP system are presented along with those of a reference system. In addition, the CHP system efficiency is analyzed with respect to the fraction of the thermal load that is satisfied by the CHP system (R_h).

Model Development

Chicago Building Models

For the building models presented here, the CHP system is sized such that it provides a constant base load equal to the minimum electricity required by the building. The overall energy flows for the model CHP system are shown in Figure 3.1.

For this reason, several model buildings representing a wide variety of building types in the commercial sector are investigated in this chapter. The reduction of emissions is considered as a result of using a CHP system in place of a conventional SHP system where electricity is purchased from the grid. Similarly, the operational cost and PEC using a CHP system for each building is considered against that of the reference case.

The buildings analyzed are located in Chicago, IL. The city of Chicago has set aggressive goals for reducing greenhouse gas emissions and has identified building energy usage as the primary contributor to greenhouse gas emissions, and therefore the primary target for emissions reduction [84]. The best candidates for reduced emissions and energy consumption with CHP can be identified by analyzing different building types. In order to incorporate NO_x and CH_4 emissions in addition to CO_2 emissions, the carbon equivalent parameter is used to assess the overall global warming potential of the emissions associated with a particular case. This value correlates the radiative forcing ability of a certain gas relative to that of CO_2 [79], where radiative forcing is used to quantify the strength of a given agent toward causing climate change [85].

The operational cost analysis for each building determines whether monetary savings are indicated, and when the CHP system would cost more than the reference case, the monetary value of carbon credits necessary to make up for the additional cost is calculated.

CHP System Model

This section presents the equations used to model the base-loaded CHP system. A schematic of the CHP system is shown in Figure 3.1. The electric energy that is to be supplied by the power generation unit (PGU) of the CHP system, i.e., the amount of base load, is assumed to be a fraction of the hourly electricity, R_e, needs of the building as follows:

$$E_{pgu} = R_e E_b \tag{5.1}$$

where E_b here represents the hourly electricity needs of the building, including electric equipment, lights, and electricity used for cooling.

The CHP system fuel energy consumption can be estimated as

$$F_{chp} = \frac{E_{pgu}}{\eta_{e,pgu}} \tag{5.2}$$

Since the PGU operates at constant load, the efficiency of the PGU is again assumed to be constant.

The heat recovered from the PGU can be expressed using Equations (3.3, 3.4, and 3.5) as

$$Q_{rec} = C_{te}\left(F_{chp} - E_{pgu}\right)\eta_{hrs,chp} \tag{5.3}$$

The heat required from the CHP system in order to meet the building's heating requirement (Q_b) is

$$Q_{req} = \frac{Q_b}{\eta_{hc}} \tag{5.4}$$

where η_{hc} is the efficiency of building heating system when the CHP system and/or boiler are used to meet the building's heating load. The required heat and the energy flows which are required to meet this demand are illustrated in Figure 5.1.

If the recovered heat given by Equation (5.3) is sufficient to satisfy the thermal load, Q_{useful} again represents only the portion of the recovered heat that is used to satisfy the thermal demand of the building, as shown in Equations (3.35) and (3.36) and Figure 5.1.

If the recovered heat is not sufficient to satisfy the thermal load, additional heat in the amount $Q_b^{'}$ is supplied by the boiler to meet Q_{req} as follows:

$$Q_{req} = Q_{useful} + Q_{boiler}^{'} \qquad 5.5$$

where $Q_{boiler}^{'}$ is the additional heat needed from the boiler to satisfy the building's heat requirement, and is therefore 0 when $Q_{rec} \geq Q_{req}$.

The total thermal load of the building can be expressed in terms of the heat supplied by the CHP system, Q_{chp}, and the heat supplied by the boiler, Q_{boiler}, as follows:

$$Q_b = Q_{chp} + Q_{boiler} \qquad 5.6$$

where Q_{chp} and Q_{boiler} can be determined as:

$$Q_{chp} = \frac{Q_{useful}}{\eta_{hc}} \qquad 5.7$$

$$Q_{boiler} = \frac{Q_{boiler}^{'}}{\eta_{hc}} \qquad 5.8$$

If the boiler provides heat to the building, the boiler fuel energy can be determined as

$$F_{boiler} = \frac{Q_{boiler}^{'}}{\eta_{boiler}} \qquad 5.9$$

where η_{boiler} is the boiler efficiency. The boiler and its energy flows are also shown in Figure 5.1.

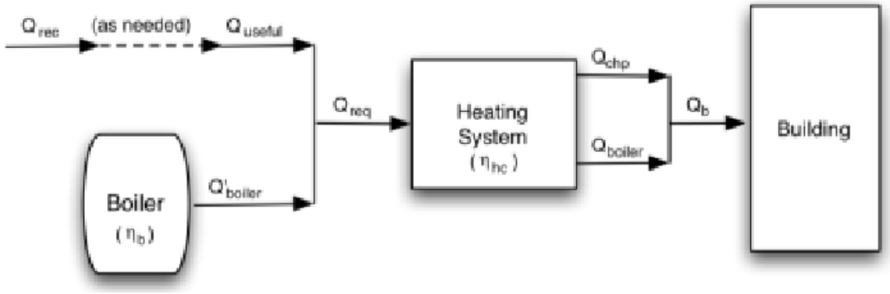

Figure 5.1 Heat flows toward meeting the building's heat demand

Depending of the size of the PGU of the CHP system, the amount of electricity produced may not match the electricity required by the building (E_b). Therefore

$$\text{If } E_b > E_{pgu} \quad \text{then} \quad E_{grid} = E_b - E_{pgu} \qquad 5.10$$

$$\text{If } E_b < E_{pgu} \quad \text{then} \quad E_{excess} = E_{pgu} - E_b \qquad 5.11$$

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.

The total fuel consumption and electricity consumption registered at the fuel meter and electric meter, respectively, can be estimated as

$$F_m = F_{chp} + F_{boiler} \qquad 5.12$$

$$E_m = E_{grid} \qquad 5.13$$

The relative contribution of the CHP system to satisfy the electric and thermal building loads can be defined as:

$$R_e + R_{grid} = 1 \rightarrow \frac{E_{pgu}}{E_b} + \frac{E_{grid}}{E_b} = 1 \qquad 5.14$$

$$R_h + R_{boiler} = 1 \rightarrow \frac{Q_{chp}}{Q_b} + \frac{Q_{grid}}{Q_b} = 1 \qquad 5.15$$

where R_e represents the fraction of the total electric load that is supplied by the CHP system, R_{grid} represents the fraction of the electric load that must be imported from the grid, R_h is the fraction of the thermal load supplied by the CHP system and R_{boiler} represents the fraction of the thermal load supplied by the boiler.

The ratio of R_e to R_h can be expressed as

$$\frac{R_e}{R_h} = \frac{PHR_{chp}}{PHR_b} \qquad 5.16$$

where PHR_{CHP}, as before, is the power-to-heat ratio of the CHP system and PHR_b is the power-to-heat ratio of the building demand. These parameters can be determined as:

$$PHR_b = \frac{E_b}{Q_b} \qquad 5.17$$

$$PHR_{chp} = \frac{E_{pgu}}{Q_{chp}} \qquad 5.18$$

If all the heat recovered is used by the building $\left(Q_{useful} = Q_{rec}\right)$, the ideal power-to-heat ratio for the CHP system, $PHR_{CHP,ideal}$, can be expressed using Equations (5.2) and (5.3) as

$$PHR_{CHP,ideal} = \frac{\eta_{e,pgu}}{C_{te}\eta_{hrs,chp}\eta_{hc}\left(1-\eta_{e,pgu}\right)} \qquad 5.19$$

Therefore, for a fixed value of R_e, which occurs with constant base load operation, and a known value of PHR_b based on the needs of a specific building, the

$R_{h(ideal)}$ that must be obtained from the CHP system can be calculated using Equation (5.16) as

$$R_{h(ideal)} = R_e \frac{PHR_b}{PHR_{CHP,ideal}} \tag{5.20}$$

The CHP system efficiency is expressed as

$$\eta_{o,chp} = \eta_{e,chp} + \eta_{th,chp} \tag{5.21}$$

The electric efficiency can be determined as:

$$\eta_{e,chp} = \frac{E_{useful}}{F_{pgu}} \tag{5.22}$$

where E_{useful} is the portion of the electricity produced by the PGU that is used by the building. Since the system is base-loaded and sized to satisfy the minimum electricity requirement of the building, here $E_{useful} = E_{pgu}$ and $\eta_{e,chp} = \eta_{e,pgu}$.

The thermal efficiency can be determined as described previously:

$$\eta_{th,chp} = \frac{Q_{useful}}{F_{pgu}} \tag{5.23}$$

Emissions, Primary Energy, and Operational Cost Analysis

Emissions

The difference in emissions from using the CHP system versus using the reference system (which was forced to be positive in Equation (4.5)) is

$$\Delta Emissions = Emissions_{shp} - Emissions_{CHP} \tag{5.24}$$

where $Emissions_{shp}$ are the emissions from the reference case using the SHP system and $Emissions_{chp}$ are the emissions due to CHP system operation and can be calculated as

$$Emissions_{shp} = E_b EEF + F_b FEF \quad 5.25$$

$$Emissions_{chp} = E_m EEF + F_m FEF \quad 5.26$$

where EEF and FEF are the emission conversion factors for delivered electricity and natural gas fuel, respectively. Equations (5.25) and (5.26) include terms in addition to the expressions previously developed in CHAPTER IV because the entire building demand is taken into account, rather than only the amount provided by the CHP system. The amount of CO_2, NO_x, and CH_4 emissions can be determined using Equations (5.25) and (5.26) by using the emission conversion factors for CO_2, NO_x, and CH_4, respectively. These emission conversion factors depend on the location where the facility is installed and on the fuel mix used to generate electricity in that location. The two alternative scenarios for providing electricity and heat to the building are illustrated in Figure 5.2. The emissions caused by the SHP system, shown on the left, result from the production and distribution of power plant electricity and the use of a boiler to provide heat. The emissions caused by the use of a base loaded CHP system, shown on the right, result from the CHP system operation as well as from supplemental power plant electricity and boiler heat. The emissions associated with the CHP system can be evaluated against the emissions associated with the reference case by comparing Equations (5.25) and (5.26).

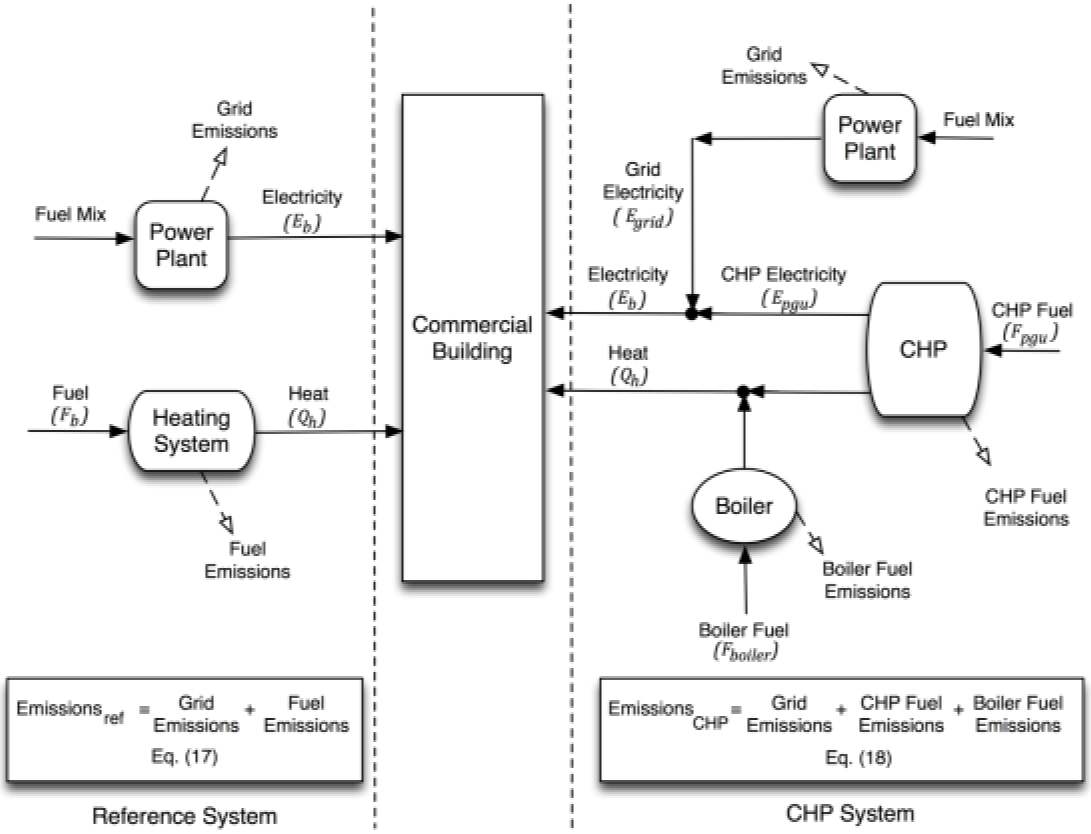

Figure 5.2 Emissions obtained from the reference system and the CHP system

The carbon equivalent, a parameter used by the U.S. Environmental Protection Agency [79] and the U.S. Energy Information Administration [86] to compare the emission from various greenhouse gases based upon their global warming potential (GWP), can be determined as:

$$CC_{equivalent} = Emissions_{CO_2}CE_{CO_2} + Emissions_{NO_x}CE_{NO_x} + Emissions_{CH_4}CE_{CH_4} \quad 5.27$$

where CE_{CO_2}, CE_{NO_x}, and CE_{CH_4} are the total carbon equivalent emissions factors for carbon dioxide (CO_2), nitrous oxides (NO_x), and methane (CH_4), respectively. These three gases can be produced by all fuel types [87] and make up three of the four principal greenhouse gases, along with halocarbons, which are associated with refrigeration agents rather than fuels [85]. This chapter only accounts for CO_2, NO_x, and CH_4 in the carbon equivalent calculations, but if other greenhouse gases are produced at the site they may be treated in the same manner.

Primary Energy and Cost

In addition to the emissions reduction, other parameters such as the PEC and operational cost can be evaluated to determine the performance of a CHP system. The PEC of the building operating the CHP system is calculated in the following manner:

$$PEC_{chp} = E_m ECF + F_m FCF \quad 5.28$$

where ECF and FCF are the primary energy conversion factors for electricity and fuel, respectively.

The variation of the PEC of the CHP system with respect to the reference case can be expressed as

$$\Delta PEC = PEC_{shp} - PEC_{chp} \quad 5.29$$

where PEC_{shpf} is the PEC of the reference building and can be determined using Equation (5.28) by changing E_m and F_m to E_b and F_b, respectively.

Finally, the CHP system operational cost can be determined as follows

$$Cost_{chp} = E_m Cost_e + F_m Cost_f \quad 5.30$$

where $Cost_e$ and $Cost_f$ are the cost of electricity and fuel, respectively.

The variation of the operational cost of the CHP system with respect to the reference case can be expressed as

$$\Delta Cost = Cost_{shp} - Cost_{CHP} \quad 5.31$$

where $Cost_{shp}$ is the operational cost of the reference building and can be determined using Equation (5.30) by changing E_m and F_m to E_b and F_b, respectively.

Results and Discussion

Representative prototype building models developed by the Department of Energy [75] were used to apply the model developed in the previous section. These models were simulated over a year using EnergyPlus [88] software using the weather data of Chicago, IL, and the output from the simulations, in the form of electric and thermal building loads, were used as inputs to the model presented in the Model Development. Table 5.1 presents the different buildings selected, including the total floor area, and the results obtained from the simulations, as well as the calculated PHR_b. The size of the selected buildings ranges from 511.15 m^2 (full service restaurant) to 22,422.2 m^2 (hospital). Table 5.2 presents the electric and gas utility rates used in this chapter, which are average annual rates, as well as the primary energy conversion factors for the city of Chicago obtained from [89]. Although the electric and gas utility rates may vary for different building applications, average rates were considered in order to make a fair economic comparison among the different building types. Table 5.3 presents the CO_2, NO_x, and CH_4 emission conversion factors for electricity and natural gas [88] while Table 5.4 presents the carbon equivalent conversion factors for the city of Chicago [87].

Table 5.1 Building information and utility costs for the evaluated buildings in Chicago, IL [88]

	Full Service Restaurant	Large Hotel	Primary School	Outpatient	Supermarket	Small Hotel	Hospital	Small Office
Total Area (m^2)	511.2	11,345.3	6,871.0	3,804.0	4,180.8	4,013.6	22,422.2	511.2
Total Electricity (GJ)	1,126.2	9,934.7	3,078.3	4,880.2	5,929.2	2,104.5	33,202.4	233.2
Total Gas (GJ)	1,972.4	11,530.1	2,084.9	3,275.1	3,435.7	1,080.4	16,936.4	81.8
Thermal Load (GJ)	1577.9	13549.1	9224.1	4197.1	1667.9	2748.6	864.3	2620.1
Building Power to heat ratio (PHR_b)	0.71	2.45	1.08	5.10	1.85	2.16	2.43	1.86

Table 5.2 Primary energy conversion factors and cost for electricity and natural gas for the city of Chicago [89]

	Electricity	Natural Gas
Primary Energy Conversion Factor *	3.546	1.092
Cost ($/kWh) *	0.086	0.031

* *Values taken in August 2011*

Table 5.3 CO_2, NO_x, and CH_4 emission conversion factors for electricity and natural gas for the city of Chicago [89]

	Electricity	Natural Gas
CO_2 Conversion Factor (g/MJ)	341.7	52.1
NO_x Conversion Factor (g/MJ)	0.622	0.0473
CH_4 Conversion Factor (g/MJ)	0.7472	0.00106

Table 5.4 Total carbon equivalent conversion factors for CO_2, NO_x, and CH_4 [87]

	Factor
CE CO_2 (kg C/kg CO_2)	0.2727
CE NO_x (kg C/kg NO_x)	80.7272
CE CH_4 (kg C/kg CH_4)	6.2727

To compare the performance of the CHP system it was assumed that the fraction of electricity produce by the CHP to the total building electricity (R_e) was the same for all the evaluated buildings (0.3). Table 5.5 shows the size of the PGU used to simulate each building, representing 30% of the average electricity needed by the building in an hour. The size of the PGU in relation to the building's electrical needs is held constant across all building types, which allows the influence of other parameters on the overall CHP system performance to be determined while the relative size of the PGU is consistent for all cases. For only two of the buildings the sizes selected generate a slight amount of excess electricity, and that is to be neglected from the analysis. Table 5.6 presents the CHP system parameters used in this chapter.

Table 5.5 PGU size used to simulate the evaluated buildings for $R_e = 0.3$

Building	PGU Size (kW)
Full Service Restaurant	11
Large Hotel	96
Primary School	30
Outpatient	47
Supermarket	60
Small Hotel	60
Hospitals	316

Table 5.6 CHP system parameters

Parameter	Value
PGU Efficiency, $\eta_{e,pgu}$	0.25
Factor that accounts for energy losses, ξ	0.95
Boiler efficiency, η_{boiler}	0.8
Heat recovery system efficiency, $\eta_{hrs,chp}$	0.8
Building Heating System efficiency, η_{hc}	0.8

Figure 5.3 illustrates a comparison of the CO_2, NO_x, and CH_4 emissions of the building served by an SHP system and the building using a CHP system. The value of R_h for each building, corresponding to R_e=0.3, is presented in the x-axis. Therefore, it can be seem that the value of R_h is different for all the evaluated buildings. In general it can be seen that the use of a CHP system reduces the CO_2, NO_x, and CH_4 emissions for all the evaluated buildings. In addition, it can be observed that the higher the R_h value the higher the reduction of emissions from the CHP system. This can be explained since higher R_h values mean that the CHP system is providing most of the thermal load using the recovered heat, thereby reducing the amount of fuel that otherwise would be used to satisfy the thermal demand of the building. The building that shows the highest reduction of CO_2, NO_x, and CH_4 emissions is the outpatient building: 19%, 24%, and 30%, respectively. The outpatient facility has the highest R_h (0.89). On the other hand, the

building that shows the least reduction of CO_2, NO_x, and CH_4 emissions is the restaurant: 13%, 20%, and 30%, respectively, and the restaurant has the lowest R_h (0.33). This means that only 33% of the building's thermal demand is satisfied by the CHP system.

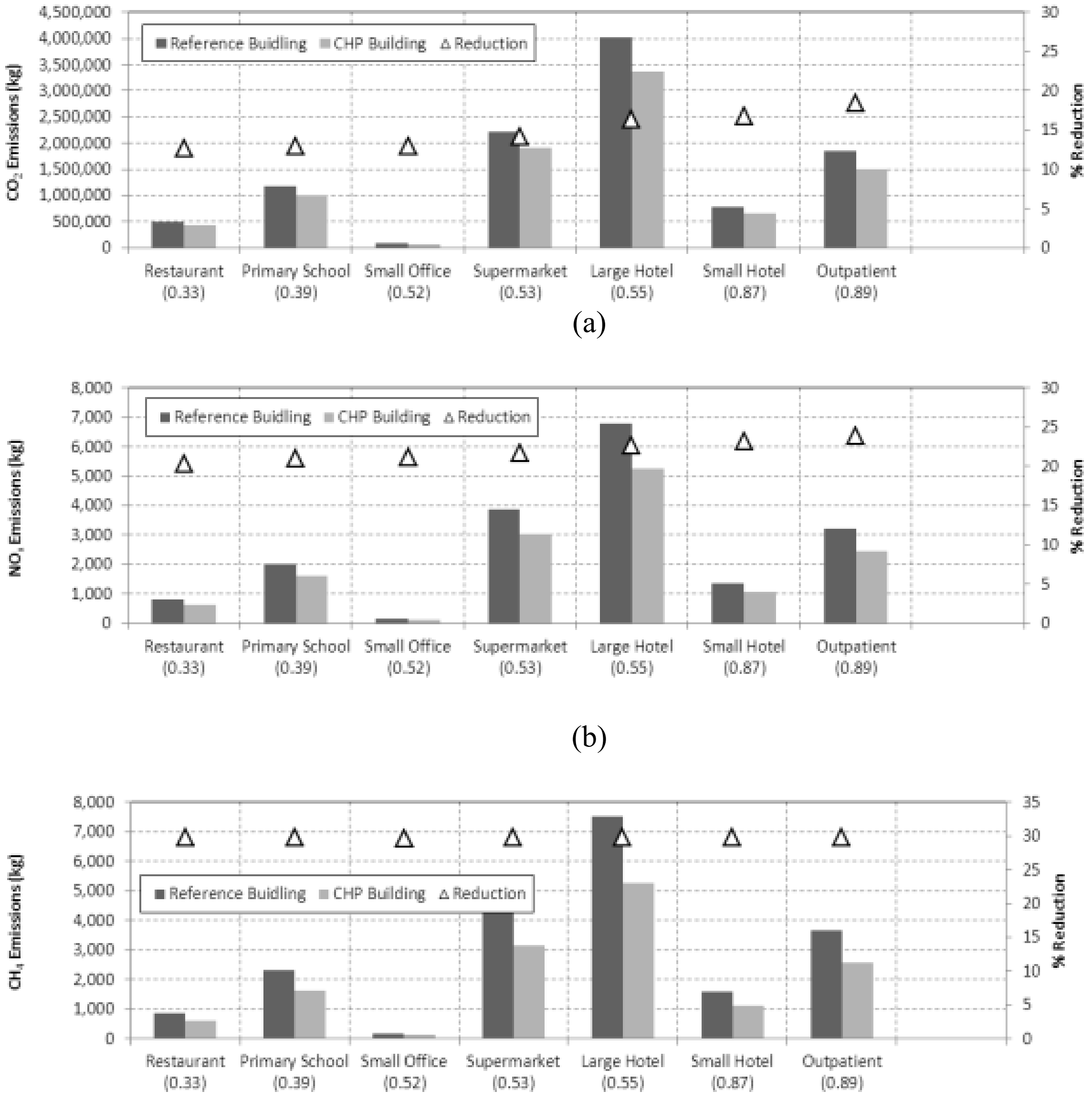

Figure 5.3 Comparison of the CO_2, NO_x, and CH_4 emissions of the reference building with the CHP building

Figure 5.4 shows the carbon equivalent for the reference buildings and the buildings using a CHP system as well as the reduction in emitted carbon obtained with the use of the CHP system. For all of the buildings, the use of a CHP system reduces emissions, similar to the results presented in Figure 5.3. Also, the trend regarding the R_h value is the same as before. Higher values of R_h provide more reduction of emissions for the evaluated buildings. The maximum reduction in kg C was obtained for the large hotel (318,713 kg) while the minimum reduction was obtained for the small office (5,855 kg). On the other hand, the maximum and minimum reductions in percentage points were achieved for the outpatient building (20.6%) and the restaurant (15.6%), respectively. Figure 5.3 and Figure 5.4 illustrate the environmental benefits of the use of CHP systems in different commercial buildings since for the selected location the use of the CHP system always reduced emissions under the stated conditions.

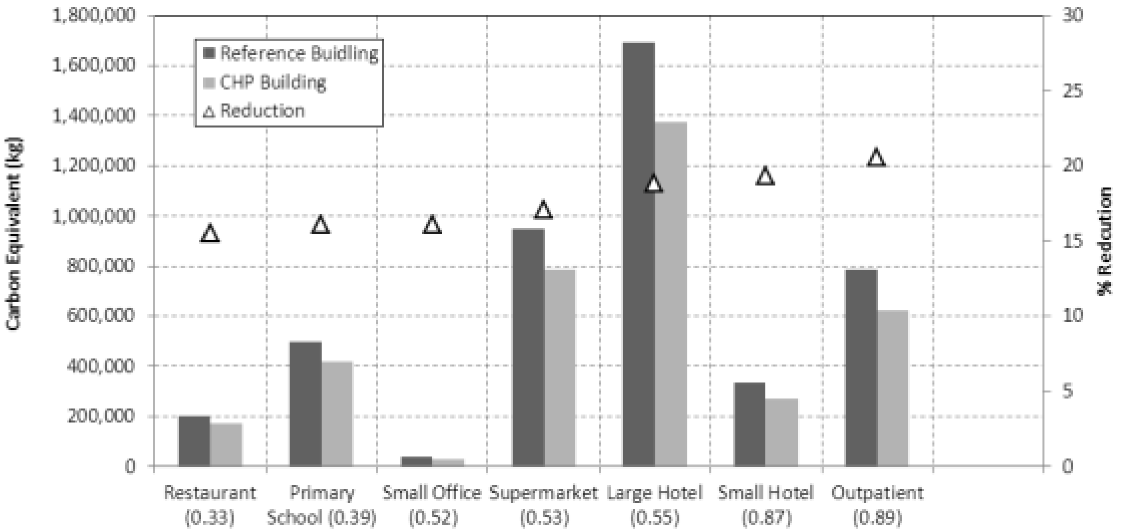

Figure 5.4 Comparison of the carbon equivalent of the reference building with the carbon equivalent of the CHP building and the reduction obtained with the CHP application

Now that the benefits of the use of CHP systems in terms of reducing emissions associated with GWP have been established, it is useful to evaluate other parameters such as PEC and operational cost. Figure 5.5 shows the PEC of the reference buildings and the buildings using a CHP system as well as the variation of the PEC with the use of the CHP system from the reference case. In this figure, positive values mean that the CHP system reduces the PEC and negative values means that the CHP system increases the PEC. This figure illustrates that the use of a CHP system reduces the PEC for all buildings examined except for the primary school and the small office buildings. The maximum PEC reduction was obtained for the outpatient building, corresponding to the highest R_h value (8.8%). For the primary school and the small office building the PEC was increased by 1.5% and 2.6%, respectively. Higher R_h values tend to reduce PEC as opposed to lower R_h values that lead to similar or higher PEC than the reference case.

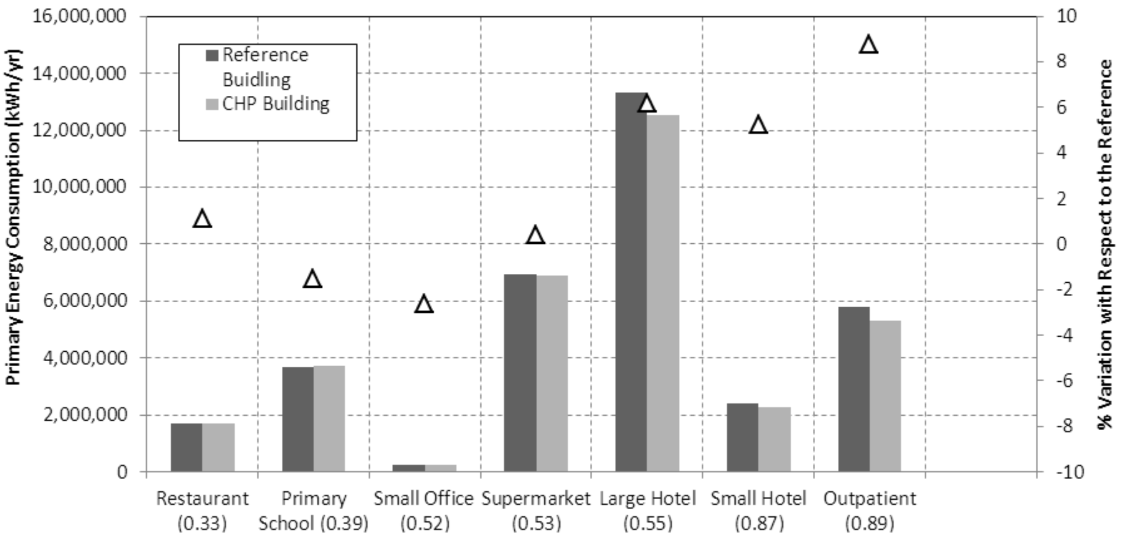

Figure 5.5 Comparison of the PEC of the reference building with the PEC of the CHP building and the variation from the reference obtained with the CHP application

Figure 5.6 shows the operational cost of the reference buildings and the buildings using a CHP system as well as the variation of the operational cost with the use of the CHP system from the reference case. Similarly to Figure 5.5, positive values mean that the CHP system reduces the operational cost and negative values means that the CHP system increases the operational cost. The use of a CHP system increases the operational cost in four buildings: full service restaurant, primary school, small office, and supermarket. For the restaurant and supermarket buildings, operational cost increased even though PEC was reduced with CHP. The maximum percentage increase of operational cost occurred for the small office building, 7.7%. On the other hand, the maximum reduction of operational cost was achieved for the outpatient building, 5.7%. The trends shown in this figure imply that higher R_h values tend to provide operational cost savings from the CHP operation. The values presented in Figure 5.6 represent only the operational cost due to fuel and electricity purchases, and for a complete economic analysis the capital cost and maintenance cost must be considered.

Figure 5.5 and Figure 5.6 illustrate that in addition to the environmental benefits obtained from the use of CHP systems for these building types in Chicago, other benefits such as reduced PEC and reduced operational cost could be achieved.

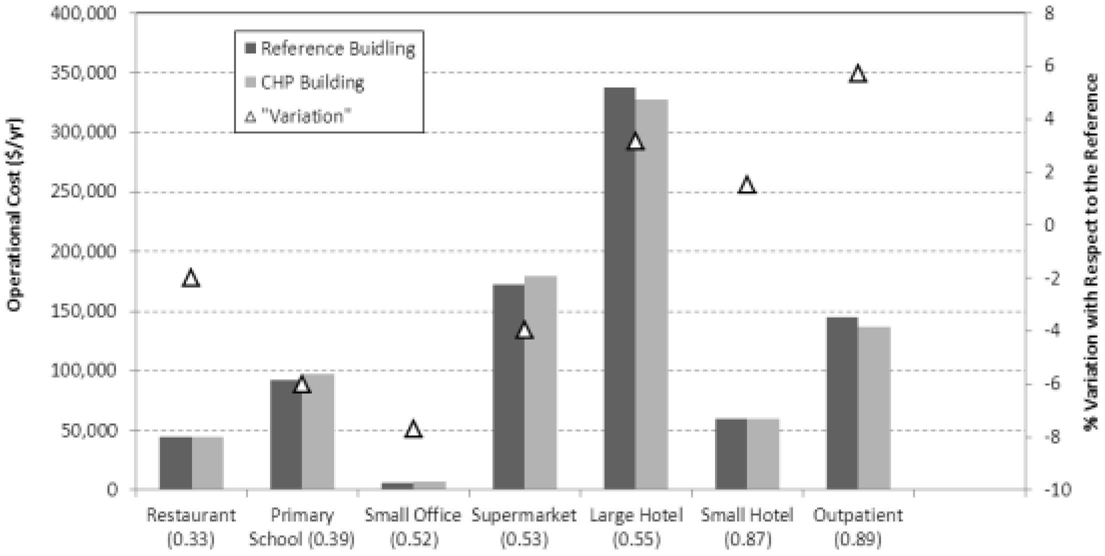

Figure 5.6 Comparison of the operational cost of the reference building with the operational cost of the CHP building and the variation from the reference obtained with the CHP application

Figure 5.7 presents the variation of the carbon equivalent, operational cost, and PEC for all the evaluated buildings. From this figure it can be seen that three of the seven buildings show reduction of the three parameters when a CHP system is used. These buildings are: large hotel, small hotel, and outpatient. On the other hand, the remaining buildings show an increase of the operational cost and/or the PEC.

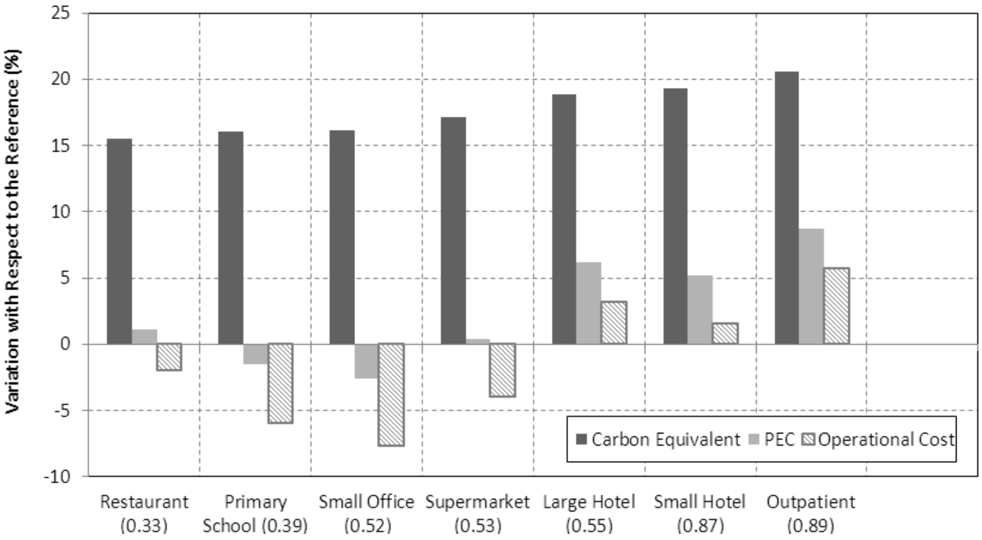

Figure 5.7 Variation of the carbon equivalent, PEC, and cost of the CHP building with respect to the reference case

The outpatient building is the one that has the highest R_h and it is the one that shows the best performance in terms of emissions, operational cost, and PEC. Therefore, it seems that selecting CHP equipment to provide high R_h values is beneficial for the performance of the CHP system relative to the SHP system. As mentioned before, the total emissions are reduced for all the buildings with the use of CHP systems. If carbon credits are available to provide financial reimbursement for the reduction in greenhouse gas emissions, the higher operational cost of some of the buildings could be offset and thereby become economically attractive. For example, the use of a CHP system at a primary school reduces the CO_2 emissions by 151,162 kg/yr while increasing the operational cost by \$5,538/yr. Therefore a minimum carbon credit of approximately \$27.3/kg of CO_2 is required to offset the different in the operational cost. The approximate carbon credits needed for the restaurant, small office, and supermarket are \$70.5/kg, \$27.3/kg, and \$46.2/kg, respectively. It is important to mention here that the operational cost may be improved for some of the evaluated buildings, i.e., small office, primary school, by reducing the operation hours of the CHP system to correspond with periods of high heating demand, which effectively increases the R_h value for the operational periods. However, this may reduce the environmental benefits that can be obtained from around the clock operation of the CHP system.

Figure 5.8 shows the CHP efficiency, percent of the recovered heat not used, actual R_h, $R_{h\ (ideal)}$, and the ratio of R_h to $R_{h\ (ideal)}$. The value of the ratio $R_h/R_{h\ (ideal)}$ for each building, corresponding to $R_e = 0.3$, is also presented along the x-axis in parentheses. This figure illustrates that for a fixed value of R_e (0.3) the value of R_h changes depending on the PHR_b. In addition, in the ideal case where all the electricity and heat generated by the CHP system were used, the PHR_{chp} would have been constant for all the buildings. However, as can be observed in Figure 5.8, for all the buildings, there is some percentage of the recovered heat that is not used by the building and has to be discharged. This figure also shows the $R_{h\ (ideal)}$ that represents the value of R_h that the CHP system has to supply to guarantee that all the heat recovered is being used. This value may be higher than 1, which simply means that the CHP system has to supply all the heat to satisfy the thermal load of the facility. Figure 5.8 illustrates that the higher the CHP efficiency, the lower the percentage of recovered heat that is not used. On the other hand, the higher the percentage of unused recovered heat the higher the difference between R_h and $R_{h\ (ideal)}$. From these results it can be concluded that the higher the ratio between R_h and $R_{h\ (ideal)}$ the higher the overall efficiency of the CHP system and the lower the amount of unused recovered heat.

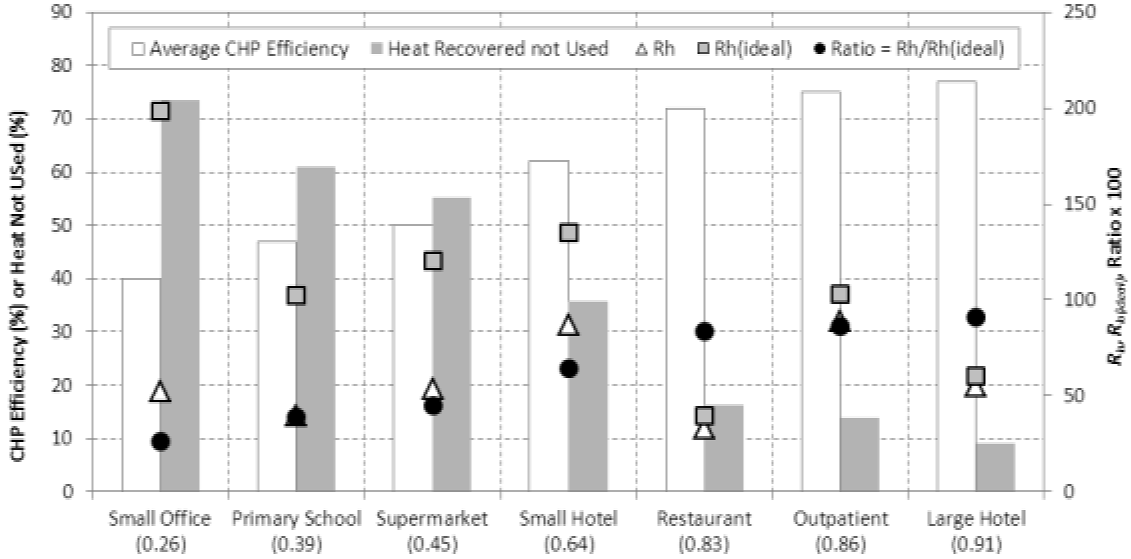

Figure 5.8 CHP efficiency, percent of the recovered heat not used, actual R_h, $R_{h\,(ideal)}$, and the ratio of R_h to $R_{h\,(ideal)}$

Summary and Conclusions

This chapter presented a model to evaluate the potential emission reductions from the use of CHP systems. The model was applied to seven different commercial buildings that were simulated in the city of Chicago. Results indicated that the use of a CHP system always reduced emissions of CO_2, NO_x, and CH_4, as well as the carbon equivalent for all buildings studied. The building that shows the highest reduction of CO_2, NO_x, and CH_4 emissions is the outpatient building: 19%, 24%, and 30%, respectively, and it has the highest R_h (0.89). Additional parameters such as PEC and operational cost were also evaluated and compared with the reference building performance. Only two of the seven buildings showed an increase of the PEC when a CHP system is used (primary school and small office), while the remaining five showed a reduction of the PEC with respect to the reference building. Four of the seven buildings present an operational cost higher than the reference buildings (full service restaurant, primary school, small office and supermarket). In general it is beneficial to have high R_h values, or to guarantee that the CHP provides a significant portion of the thermal demand of the facility, since this will provide reduced emissions, cost, and PEC due to the CHP system operation. In addition, the R_h value should be designed to be close to the $R_{h(ideal)}$ since this guarantees higher CHP system efficiencies. The results presented in this chapter reflect the need for effective policies and incentives to make the use of CHP systems more attractive from the economic point of view, if reduced emissions and energy consumption are paramount concerns. For the buildings analyzed in this chapter for the city of Chicago, the use of CHP systems always reduce the emissions of CO_2, NO_x, and CH_4, as well as the carbon equivalent. However, for some buildings the cost and/or PEC are higher that the reference building. If additional benefits such as power quality and power reliability were factored into an economic analysis, the use of a CHP system could also be more feasible and attractive economically.

CHAPTER VI

THERMAL ENERGY STORAGE WITH CHP—EFFECTS ON COST, PRIMARY ENERGY CONSUMPTION, AND CARBON DIOXIDE EMISSIONS

As demonstrated by CHAPTER III through CHAPTER V, CHP systems can result in lower operational cost, PEC, and CDE when compared to separate heat and power systems, the standard alternative of purchasing electricity from the grid and supplying heat from a boiler. However, the potential for these benefits is closely linked to the relationship between PHR_{chp} and PHR_b, as well as the proportion of the building's heat demand that is met by the CHP system, as discussed in the previous chapters. Thermal energy storage (TES) has been proposed to store excess thermal energy produced by a CHP system when it is not needed by the building and deliver it at a later time when the building's demand increases, alleviating some of the load imbalance.

The benefits obtained by using a CHP system also vary with the size of the prime mover, with larger PGUs being useful when the building has a higher thermal load [45]. Variations in the electrical and thermal load of a building can make proper sizing and choice of operational strategy for a CHP system into complex tasks, especially if economic, environmental, and energetic concerns are all factored into the analysis [37].

In the models presented in this chapter, the CHP system is base-loaded, providing a constant power-to-heat ratio, as in the previous analyses. The power-to-heat ratio demanded by the building depends on the location and the needs of the building, which vary throughout the day and throughout the year. At times when the CHP system does not provide the electricity needed by the building, electricity is purchased from the grid, and when the CHP system does not provide the heat needed by the building, heat is generated with a supplemental boiler.

Thermal energy storage (TES) is an option introduced in this chapter which can help to address the building's load variation by storing excess heat when the building needs less heat than the Q_{rec}. Then, excess thermal energy can then be used later when the building needs more heat than Q_{rec}, supplanting some of the thermal energy which would otherwise be produced by the building's boiler. According to Hyman [20], hot water TES can allow a CHP system to operate at a higher load (or, therefore, larger PGU size) than would otherwise be beneficial. This possibility is investigated in the first part of this chapter.

The potential for a CHP system with TES to reduce cost, PEC, and emissions is investigated in this chapter, and compared with both a CHP system with and without TES and with the standard reference case SHP system. This proposed model is evaluated for three different commercial building types in three different U.S. climate zones. The size of the power generation unit (PGU) is varied and the effect of the correspondingly smaller or larger base load on the cost, PEC, and emissions savings is analyzed. The need for a supplemental boiler to provide additional heat is also examined in each case with the thermal storage option.

Next, a CHP system is investigated with and without a thermal energy storage option for eight different commercial building types located in Chicago, IL. The building's electrical and thermal loads are simulated on an hourly basis over one year and a CHP system is modeled operating at a constant baseload. The CHP system alone is compared with a CHP system which incorporates TES in varying amounts, up to the maximum thermal energy required by the building in an hour.

Methodology for Varying Location and PGU Size Study

A CHP system without thermal energy storage and a CHP system with thermal storage (CHP-TES) are compared against the reference case, in which electricity is purchased from the grid to meet the building's electrical needs and heat is obtained from a boiler to meet the building's thermal needs. The increase or decrease in operational cost, PEC, and emissions with respect to the reference case is presented for three different building types in three different locations. The buildings analyzed are the building models used in previous chapters which were created to represent typical commercial buildings in the U.S. [75], and they are simulated with EnergyPlus software [88]. The three buildings considered are a small office, a full service restaurant, and a hospital. Each building is simulated in Houston, TX, a warm climate, San Francisco, CA, a mild climate, and Duluth, MN, a cold climate.

Figure 6.1 illustrates the CHP system while Figure 6.2 illustrates the CHP-TES system.

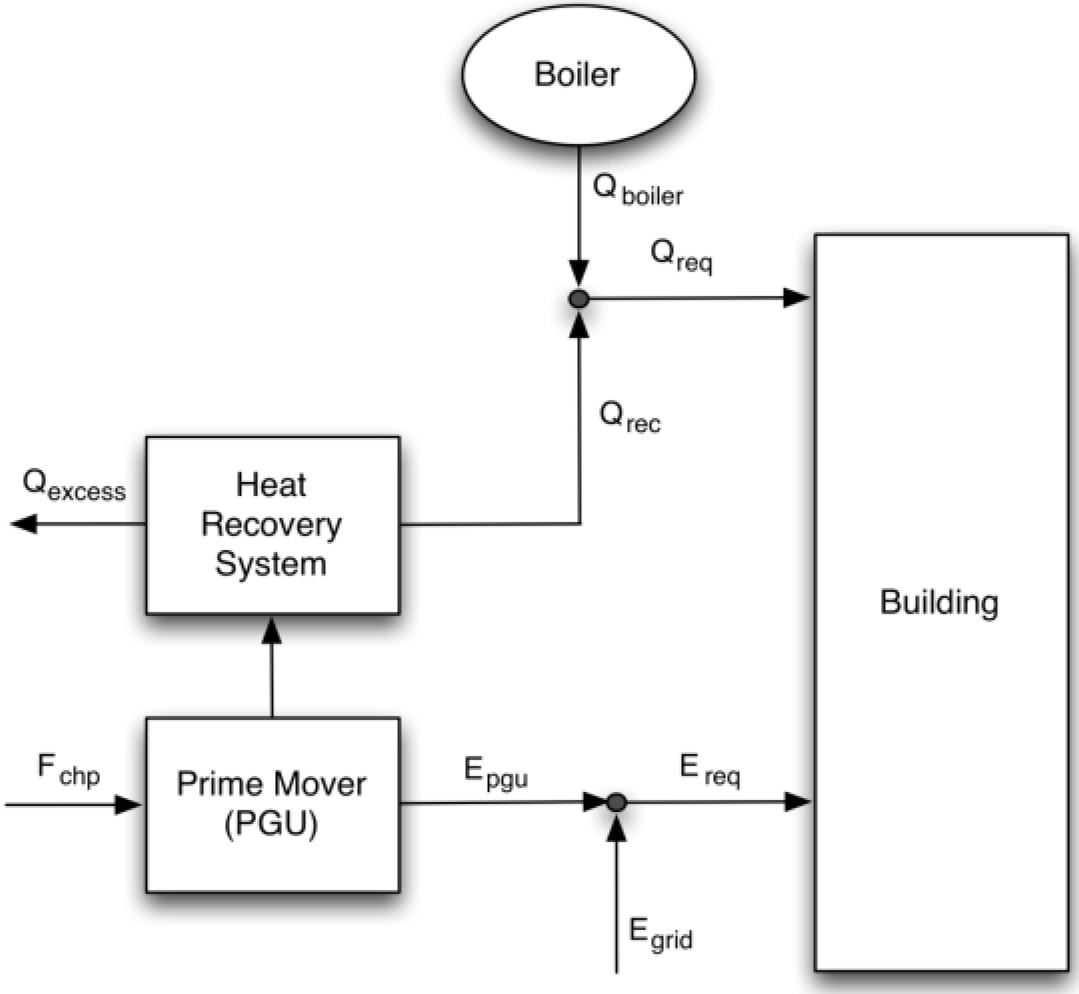

Figure 6.1 CHP system schematic

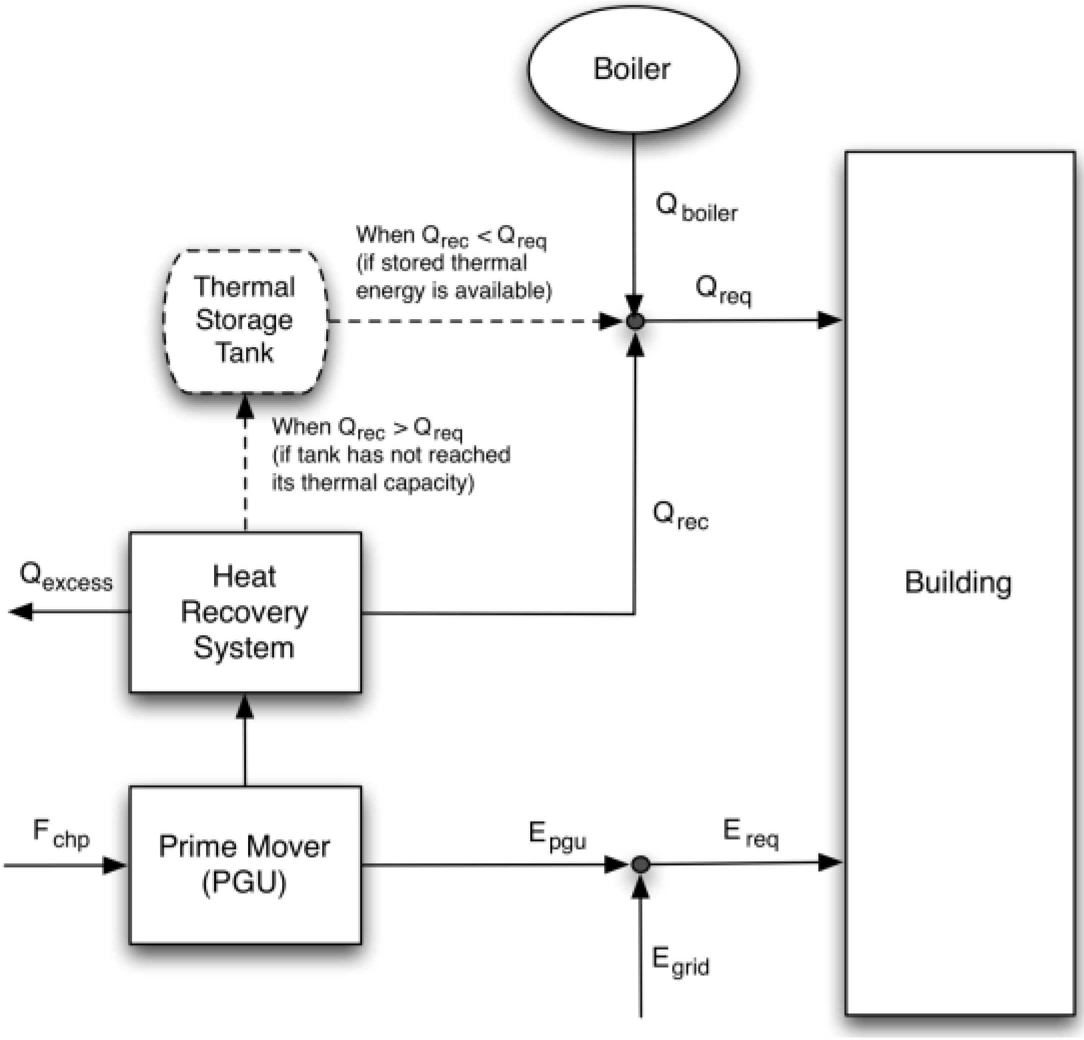

Figure 6.2 CHP-TES system schematic

The CHP system in all cases operates at a constant base load. The size of the PGU is varied for each building type and location. The smallest PGU size provides between 11% and 16% of the building's average hourly electrical demand (R_e averages from 0.11 to 0.16), while the largest size provides between 66% and 86% of the average hourly electrical demand (R_e average from 0.66 to 0.86). The electrical and thermal energy demands of each building are presented with the Results for Varying Location and PGU

Size Study. Because the electricity needed by the building will vary over the course of days, weeks, or months, a larger PGU may sometimes produce excess electricity.

The electricity produced each hour by the PGU is given by:

$$E_{pgu} = PGUsize * hr * 3.6 \times 10^6 \tag{6.1}$$

where $PGUsize$ is in kW and E_{pgu} is in J.

The fuel energy used by the PGU of the CHP system is given by:

$$F_{chp} = \frac{E_{pgu}}{\eta_{e,pgu}} \tag{6.2}$$

where $\eta_{e,pgu}$ is, again, considered to be constant because the PGU operates at constant base load.

The heat recovered from the CHP system is the same as Equation (5.3):

$$Q_{rec} = (F_{chp} - E_{pgu}) C_{te} \eta_{hrs,chp} \tag{6.3}$$

where C_{te} accounts for energy losses before the HRS.

The heat required by the building is determined using the EnergyPlus simulation output for natural gas used for heating and natural gas used for hot water. When more heat is recovered during an hour than the building requires, that heat is considered excess or waste heat for a typical CHP system. For a CHP-TES system, that additional heat is stored as thermal energy until a maximum thermal capacity is reached, as described by Equations (6.4) through (6.7).

$$Q_{storage\_new} = (Q_{rec} + Q_{storage\_old}) - Q_{req} \text{ if } (Q_{rec} + Q_{storage\_old}) > Q_{req} \quad 6.4$$

$$Q_{storage\_new} = 0 \text{ otherwise} \quad 6.5$$

$$Q_{storage\_old} = Q_{storage\_old} + Q_{storage\_new} \text{ if } Q_{storage\_old} = Q_{storage\_old} + Q_{storage\_new} \quad 6.6$$

$$Q_{storage\_old} = TS_{cap} \text{ otherwise} \quad 6.7$$

where $Q_{storage\_new}$ is the thermal energy added to thermal storage at each time step, $Q_{storage\_old}$ is the thermal energy present in the TES device, and Q_{req} is the thermal energy needed to meet the building's energy requirement.

When, at a later time step, the heat recovered is less than the building requires, the stored thermal energy is used toward meeting the building's thermal requirement. If the heat recovered combined with the heat available in thermal storage is greater than the heat required for every time step, then the building's boiler is not needed.

$$Q'_{boiler} = Q_{req} - (Q_{storage\_old} + Q_{rec}) \text{ if } (Q_{storage\_old} + Q_{rec}) < Q_{req} \quad 6.8$$

$$Q'_{boiler} = 0 \text{ otherwise} \quad 6.9$$

where Q'_{boiler} is the amount of heat required from the boiler to be delivered to the building's heating system, as shown in the section CHP System Model of the previous chapter.

If additional heat is required beyond the heat recovered (for CHP) or the heat recovered and the thermal energy in storage (for CHP-TES), then a natural gas boiler will be used to provide the required heat. The fuel consumed by this boiler is given by Equation (5.9) as $F_{boiler} = \frac{Q'_{boiler}}{\eta_{boiler}}$.

When additional electricity is required beyond the electricity produced by the PGU, electricity will be purchased from the electrical grid in the amount of E_{grid} as shown in Equation (6.10).

$$E_{grid} = E_b - E_{pgu} \qquad 6.10$$

Cost

SHP

To provide a baseline for comparison, the operating cost of the reference case where no CHP system is present is calculated as

$$Cost_{shp} = E_{req} Cost_e + F_{boiler} Cost_f \qquad 6.11$$

where E_{req} represents the electricity required by the building, $Cost_e$ is the cost of electricity purchased from the grid, F_{boiler} is the fuel energy consumed by the boiler [Equation (5.9)] and $Cost_f$ is the cost of the fuel based on energy content. This calculated cost does not take into account any maintenance or other equipment costs for the building's equipment.

CHP

The cost to operate the CHP system is calculated as

$$Cost_{chp} = E_{grid} Cost_e + (F_{pgu} + F_{boiler}) Cost_f \qquad 6.12$$

where E_{grid} represents any additional electricity that must be purchased from the grid [Equation (6.10)] and F_{boiler} is related to Q'_{boiler} by Equation (5.9).

CHP-TES

The cost to operate the CHP system with thermal storage (CHP-TES) is calculated as in Equation (6.12). However, Q'_{boiler} may be reduced based on the contribution from the TES device.

The storage device is considered to be discharged (no thermal energy available from storage) at the beginning of the simulation and the storage modeling is handled as in Equations (6.4) through (6.7).

If the amount of heat recovered from the CHP system is less than the heat required by the building ($Q_{rec}<Q_{req}$), then thermal energy will be taken from the TES device as long as thermal energy is available:

$$Q_{storage\text{-}new} = Q_{storage\text{-}old} + Q_{rec} - Q_{req} \quad if\ Q_{storage\text{-}old} \geq Q_{rec} - Q_{req} \qquad 6.13$$

$$Q_{storage\text{-}new} = 0 \ \ otherwise \qquad 6.14$$

Note that if the amount of heat recovered from the CHP system is the same as the heat required by the building ($Q_{rec}=Q_{req}$), then no thermal energy will be transferred to or from the TES device:

$$Q_{storage\text{-}new} = Q_{storage\text{-}old} \qquad 6.15$$

Equations (6.13) through (6.15) do not take into account any heat losses from the associated with the TES device and there are no limitations placed on the amount of heat which can be transferred in a given time period. In an actual system, the limitations of the heat exchangers and the insulation of the device must be considered.

The amount of heat transferred from TES to the building in a time step, Q_{TES}, is:

$$Q_{TES} = Q_{storage\text{-}old} - Q_{storage\text{-}new} \quad if\ Q_{storage\text{-}old} - Q_{storage\text{-}new} > 0 \tag{6.16}$$

$$Q_{TES} = 0 \ \ otherwise \tag{6.17}$$

The fraction of the thermal demand that is satisfied by the CHP system with TES is:

$$R_{h,CHP-TES} = \frac{Q_{rec} + Q_{TES}}{Q_{req}} \quad if\ (Q_{rec} + Q_{TS}) \le Q_{req} \tag{6.18}$$

$$R_{h,CHP-TES} = 1 \ \ otherwise \tag{6.19}$$

The heat provided from the supplemental boiler is now:

$$Q_{boiler} = Q_{req} - Q_{rec} - Q_{TES} \quad if\ Q_{req} - Q_{rec} - Q_{TES} > 0 \tag{6.20}$$

$$Q_{boiler} = 0 \ \ otherwise \tag{6.21}$$

The fuel energy consumed by the boiler can be calculated using Equation (6.2) again, and then the cost to operate the CHP system and the cost to operate the CHP-TES system are compared with the cost of the reference case. This operating cost analysis does not include capital costs or any costs other than supplying the necessary fuel for the PGU and the boiler and purchasing electricity from the grid. The addition of TES to a CHP system will require additional capital and maintenance expenses, which must be weighed against any possible reductions in the size requirement of the supplemental boiler along with any possible reductions in operating costs for the system as a result of TES installation.

The values used for $Cost_e$ and $Cost_f$ for this section are given in Table 6.1 below.

Table 6.1 Cost of electricity [90] and natural gas [91]

	Electricity (\$/kWh)	Natural Gas (\$/MMBtu)
Houston	0.0875	7.822
San Francisco	0.1215	8.218
Duluth	0.0834	7.525

Primary Energy

The PEC of the SHP system case is calculated as

$$PEC_{shp} = E_{req} ECF + F_{boilerf} FCF \qquad 6.22$$

where ECF and FCF again represent the primary energy conversion factors for electricity and natural gas, respectively. The values used are given in Table 6.2 below.

Table 6.2 Site-to-primary energy conversion factors [88]

	Electricity, *ECF*	Natural Gas, *FCF*
Houston	3.632	1.092
San Francisco	3.095	1.092
Duluth	3.437	1.092

Next, the PEC of the CHP system is calculated.

$$PEC_{CHP} = E_{grid} ECF + (F_{pgu} + F_{boiler}) FCF \qquad 6.23$$

where F_{boiler} is determined according to Equation (5.9) for CHP and Equations (5.9), (6.20) and (6.21) for CHP-TES.

Finally, the PEC of the CHP system and the PEC of the CHP-TES system are compared with the PEC of the reference case.

Carbon Dioxide Emissions

The CDE for the SHP system case is calculated.

$$CDE_{shp} = E_{req}CF_{CDE,e} + F_{boiler}CF_{CDE,f} \qquad 6.24$$

where $CF_{CDE,e}$ and $CF_{CDE,f}$ represent the emission conversion factors for electricity and natural gas, respectively. The values used are given in Table 6.3 below.

Table 6.3 CDE conversion factors [79]

	Electricity, $CF_{CDE,e}$ (ton/yr-kWh)	Natural Gas, $CF_{CDE,f}$ (ton/yr-kWh)
Houston	0.0006263	0.0001996
San Francisco	0.0003405	0.0001996
Duluth	0.0008613	0.0001996

Next, the CDE of the CHP system is calculated.

$$CDE_{CHP} = E_{grid}CF_{CDE,e} + (F_{pgu} + F_{boiler})CF_{CDE,f} \qquad 6.25$$

where F_{boiler} is again determined according to Equation (5.9) for CHP and Equations (5.9), (6.20) and (6.21) for CHP-TES.

Finally, the CDE of the CHP system and the CDE of the CHP-TES system are compared with the CDE of the reference case.

Assumed Parameters for CHP System

The basic characteristics of the CHP system, such as the efficiency of the PGU, are assumed to be constant in order to allow for comparison between the nine different situations. The values for these parameters are given in Table 6.4.

Table 6.4 CHP system parameters

Parameter	Value
$\eta_{e,pgu}$	0.3
C_{te}	0.95
η_{rec}, η_{boiler}	0.8
TES_{cap}	220 kWh

The water tank size is sufficiently large so that the changes in cost, PEC, and CDE will not be highly sensitive to the tank size. If a thermal storage device is chosen in practice, it may be sized as described by Ren et al. [23].

Results for Varying Location and PGU Size Study

The operational cost, PEC, and CDE was computed in each case for the reference case, a CHP system, and a CHP-TES system. The variation of the CHP system from the reference case with and without TES is plotted for each building type and city. Additionally, the possibility for CHP-TES to eliminate the need for a supplemental boiler was investigated.

Small Office Building

The energy requirements obtained from EnergyPlus for a small office building in each of the three locations are presented in Table 6.5, where $E_{req,ave}$ represents the average electricity needed by the building in an hour, $E_{req,min}$ represents the minimum electricity needed in an hour, $Q_{req,ave}$ represents the average thermal energy needed by the building in an hour, and PHR_b is the ratio of $E_{req,ave}$ to $Q_{req,ave}$.

Table 6.5 Small office building energy requirements [88]

	$E_{req,ave}$ (MJ)	$E_{req,min}$ (MJ)	$Q_{req,ave}$ (MJ)	PHR_b
Houston	40.75	7.73	4.37	9.33
San Francisco	32.35	7.73	5.50	5.88
Duluth	34.40	7.73	61.89	0.56

Houston

The relative results for a small office building with varying PGU sizes in Houston are presented in Figure 6.3.

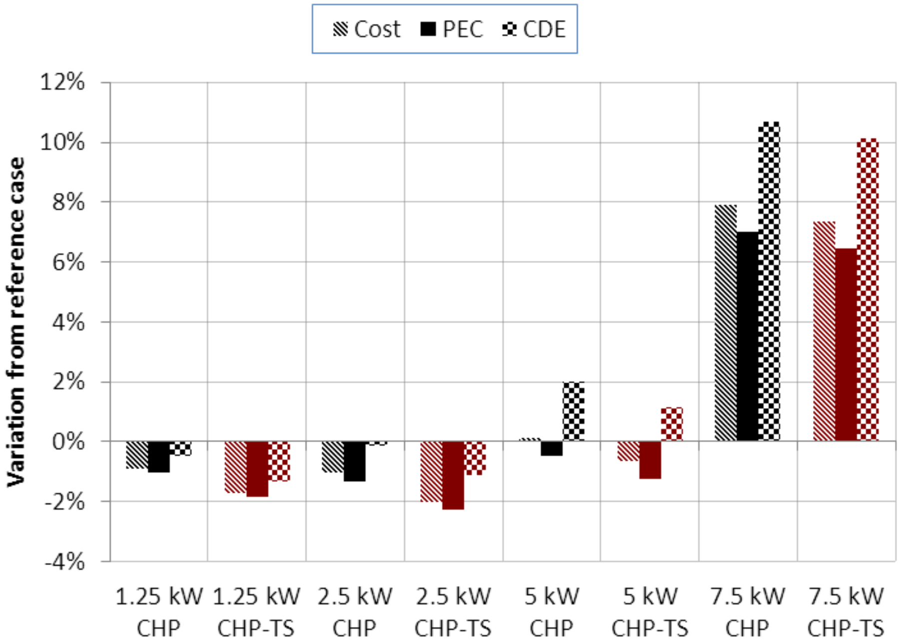

Figure 6.3 Variation of cost, PEC, and CDE from reference case for CHP and CHP-TES with varying PGU size for a small office building in Houston

For the 1.25 kW and 2.5 kW engines, the cost, PEC, and CDE are all reduced for the small office in Houston. In both cases, TES provides additional savings in cost, PEC, and CDE. For example, the 2.5 kW CHP-TES system provides an additional 0.9%, 1.0%, and 0.95% decrease from the reference case for cost, PEC, and CDE as compared with CHP with no TES available. For the 5 kW size, the CHP system reduces PEC but causes increased cost and CDE over the reference case. Adding thermal storage to the 5 kW CHP system will allow the CHP system to reduce cost over the reference system, and it will reduce the amount of CDE. Increasing the PGU size over 5 kW causes the CHP to increase cost, PEC, and CDE over the reference case. As shown for the 7.5 kW case, even the CHP-TES system, which has slightly lower cost, PEC, and CDE, is significantly higher than the reference case and therefore is not a viable option at this size. A larger PGU size results in more excess heat that is not used by the building due to the high PHR_b in Houston [92].

San Francisco

The relative results for a small office building with varying PGU sizes in San Francisco are presented in Figure 6.4.

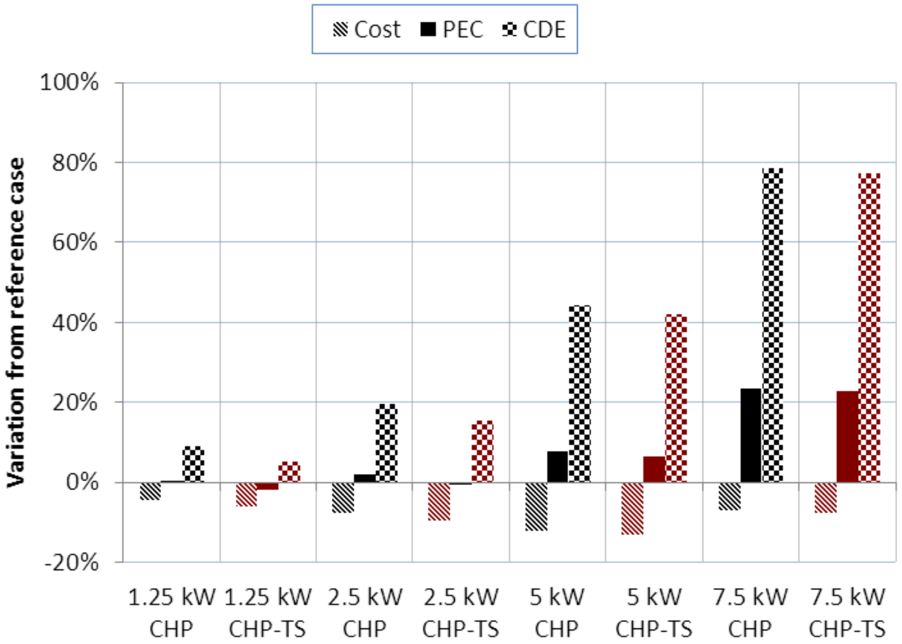

Figure 6.4 Variation of cost, PEC, and CDE from reference case for CHP and CHP-TES with varying PGU size for a small office building in San Francisco

Regardless of the PGU size, the CHP and CHP-TES systems cause an increase in CDE in San Francisco. This is due to the low $CF_{CDE,e}$ for electricity purchased in California. Because of the fuel mix in this region, purchased electricity is associated with much less CDE than purchased natural gas. Adding thermal storage does help to reduce the CDE for a given engine size due to better usage of the fuel energy input to the CHP-TES system. For example, for the 2.5 kW size, the CHP-TES system produces 3.3% less CDE than the CHP system. For the 2.5 kW CHP-TES system, the thermal storage provides an additional 1.7% decrease from the reference case in cost. The most reduction in cost over the reference case took place with a 5 kW engine size. Smaller and larger sizes did not reduce cost as effectively, although the cost was reduced for all cases here. PEC can be reduced only with a very small engine (1.25 kW) used with a CHP-TES system. For this case, the CHP-TES system consumes 2.5% less primary energy than the CHP system, causing a 0.7% decrease in PEC from the reference case. In all other cases PEC was increased over the reference case. The value for $CF_{PEC,e}$ is also significantly lower in California than for the other locations considered.

Duluth

The relative results for a small office building with varying PGU sizes in Duluth are presented in Figure 6.5.

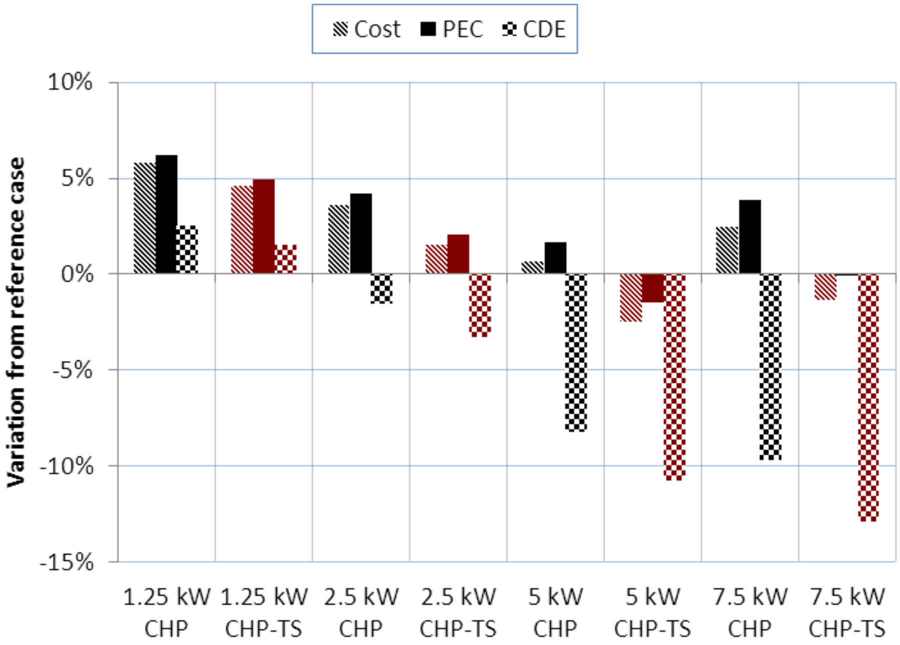

Figure 6.5 Variation of cost, PEC, and CDE from reference case for CHP and CHP-TES with varying PGU size for a small office building in Duluth

For a small office building in Duluth, for most cases cost and PEC increased with the use of a CHP system. However, the 5 kW size with TES shows improved performance over the reference case, decreasing cost, PEC, and CDE. In this case, the thermal storage provides an additional 3.1%, 3.2%, and 2.6% decrease from the reference case for cost, PEC, and CDE as compared with CHP with no thermal storage. All engine sizes studied which were larger than 1.25 kW did cause reduced CDE. Duluth shows more favorable results with larger PGU sizes because it requires large amounts of heat for a significant portion of the year. Again, adding thermal storage to the CHP system at a given size causes less cost, PEC, and CDE than a CHP system without TES.

Supplemental Heat

The effect of TES on the small office building's requirement for supplemental heat is shown in Table 6.6.

Table 6.6 Requirement for a supplemental boiler with CHP-TES system for a small office building

PGU Size	Houston	San Francisco	Duluth
1.25 kW	Yes	Yes – Reduced	Yes
2.5 kW	Yes	Yes – Reduced	Yes
5 kW	Yes	No	Yes
7.5 kW	No	No	Yes

In Houston, only the 7.5 kW size was able to produce enough heat in order to eliminate the need for a supplemental boiler when thermal storage is used. However, given the increases in cost, PEC, and CDE associated with this size at this location, it is not a feasible option. In San Francisco, the 5 kW and 7 kW sizes produce enough heat in order to operate the system without a supplemental boiler, but the increases in PEC and CDE make this an unfavorable choice. The 1.25 and 2.5 kW sizes in San Francisco would reduce the size of the boiler required to meet the building's needs. In Duluth, due to the cold climate, a supplemental boiler is needed in each case. Overall, the CHP-TES does not eliminate the need for a boiler at any reasonable operating conditions for a small office building.

Restaurant

The energy requirements obtained from EnergyPlus for a restaurant building in each of the three locations are presented in Table 6.7.

Table 6.7 Full service restaurant building energy requirements [88]

	$E_{req,ave}$ (MJ)	$E_{req,min}$ (MJ)	$Q_{req,ave}$ (MJ)	PHR_b
Houston	158.7	56.7	58.2	2.73
San Francisco	130.8	56.9	89.7	1.46
Duluth	131.2	56.5	256.6	0.51

Houston

The relative results for a full service restaurant with varying PGU sizes in Houston are presented in Figure 6.6.

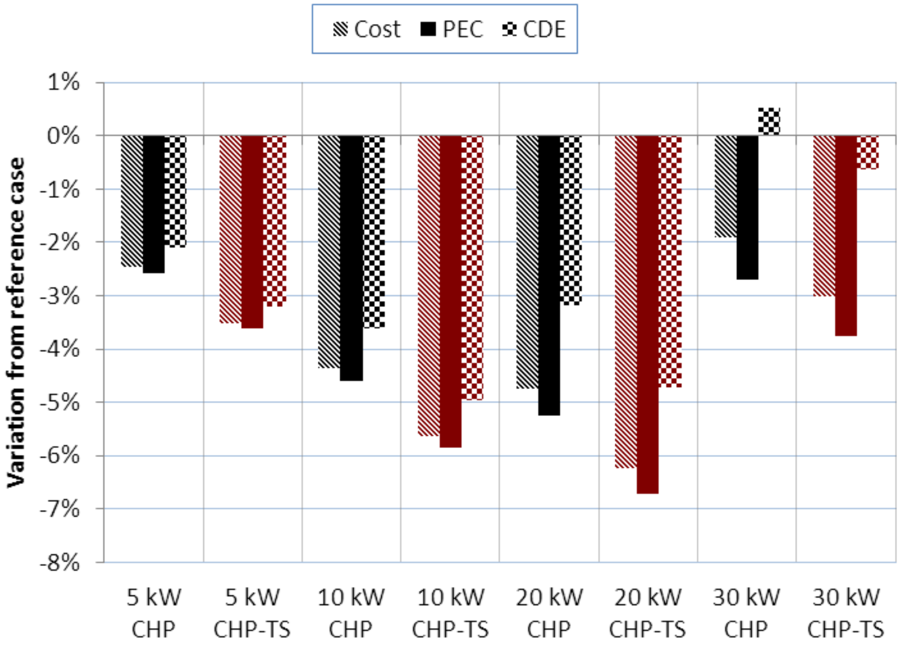

Figure 6.6 Variation of cost, PEC, and CDE from reference case for CHP and CHP-TES with varying PGU size for a full service restaurant in Houston

Although Houston has a higher PHR_b than San Francisco or Duluth, the PHR_b for the restaurant is much lower than for the office building due to higher thermal demand. Because of this, results for a restaurant building with CHP are much more favorable than the results for a small office building with CHP due to the differences in electrical and thermal demand, as shown by Smith et al. [92]. Cost and PEC are reduced for every case shown, and CDE is reduced for all cases except for the 30 kW CHP system. As with the small office building, adding thermal storage does reduce Cost, PEC, and CDE more than the CHP system without TES. The 20 kW CHP-TES system with thermal storage provides an additional 1.5%, 1.4%, and 1.5% decrease from the reference case for cost, PEC, and CDE as compared with CHP with no TES available. The largest reductions in

Cost and PEC correspond to a PGU size of 20 kW and a CHP-TES system. The most reduction in CDE occurs when the PGU size is 10 kW with a CHP-TES system.

San Francisco

The relative results for a full service restaurant with varying PGU sizes in San Francisco are presented in Figure 6.7.

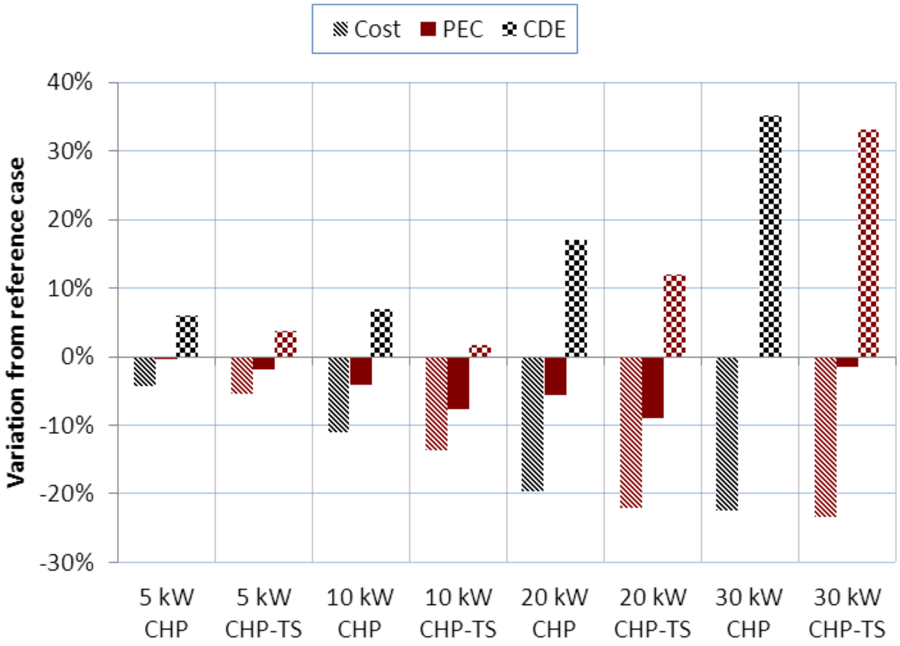

Figure 6.7 Variation of cost, PEC, and CDE from reference case for CHP and CHP-TES with varying PGU size for a full service restaurant in San Francisco

As before, the CDE is increased for each case regardless of the PGU size for San Francisco, due to the low $CF_{CDE,e}$. The 10 kW engine size with TES shows the least increase in CDE over the reference case. The most reduction in cost over the reference case took place with a 30 kW CHP-TES system, while the largest reduction in PEC took place with a 20 kW CHP-TES system. For the 20 kW CHP-TES system, the thermal storage provides an additional 2.4% and 3.4% decrease from the reference case for cost and PEC as compared with CHP with no thermal storage. The CHP-TES system also increases CDE over the reference case by 5.0% less than the CHP system. The smaller PGU sizes did not reduce cost and PEC as effectively, although the increased emissions for the 5 kW and 10 kW sizes were not as pronounced as for the larger PGU sizes.

Duluth

The relative results for a full service restaurant with varying PGU sizes in Duluth are presented in Figure 6.8.

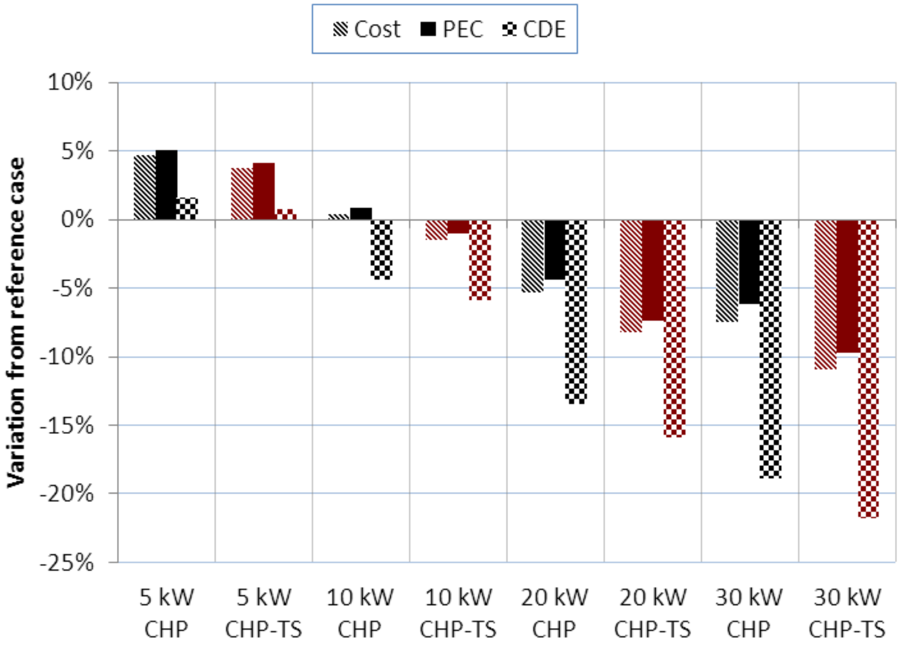

Figure 6.8 Variation of cost, PEC, and CDE from reference case for CHP and CHP-TES with varying PGU size for a full service restaurant in Duluth

In Duluth, larger engine sizes resulted in decreased cost, PEC, and CDE. Due to the cold climate and the lower PHR_b resulting from higher relative thermal demand of the restaurant building, the extra heat produced by a larger engine becomes useful to the building. Adding thermal storage at a given engine size continues to improve cost, PEC, and CDE. While the 5 kW CHP and CHP-TES systems showed unfavorable results, the 30 kW size with TES showed over a 20% reduction in CDE over the reference case, which is 3.0% less than the reduction in CDE without TES. The 30 kW CHP-TES system also increased cost and PEC by about 10%, which is an additional decrease of 3.4% and 3.6%, respectively, as compared with CHP without TES.

Supplemental Heat

The effect of TES on the restaurant building's requirement for supplemental heat is shown in Table 6.8.

Table 6.8 Requirement for a supplemental boiler with CHP-TES system for a full service restaurant

PGU Size	Houston	San Francisco	Duluth
5 kW	Yes – Reduced	Yes	Yes
10 kW	Yes – Reduced	Yes	Yes
20 kW	Yes – Reduced	Yes	Yes
30 kW	Yes – Reduced	Yes – Reduced	Yes

Due to the thermal needs of the restaurant building, the CHP-TES does not provide enough heat to cover the building's heat requirement, and a supplemental boiler will still be required in every case. However, for each size considered in Houston, the size of the boiler required to meet the restaurant's thermal energy needs would be smaller with CHP-TES than with CHP alone. In San Francisco, the 30 kW size would reduce the required boiler size, but for the smaller sizes the PGU does not produce enough excess heat to significantly reduce the maximum thermal energy needed from the boiler.

Hospital

The energy requirements obtained from EnergyPlus for a hospital building in each of the three locations are presented in Table 6.9.

Table 6.9 Hospital building energy requirements [88]

	$E_{req,ave}$ (MJ)	$E_{req,min}$ (MJ)	$Q_{req,ave}$ (MJ)	PHR_b
Houston	5458	2840	1607	3.40
San Francisco	4636	3270	1887	2.46
Duluth	4417	2025	2302	1.92

Houston

The relative results for a hospital with varying PGU sizes in Houston are presented in Figure 6.9.

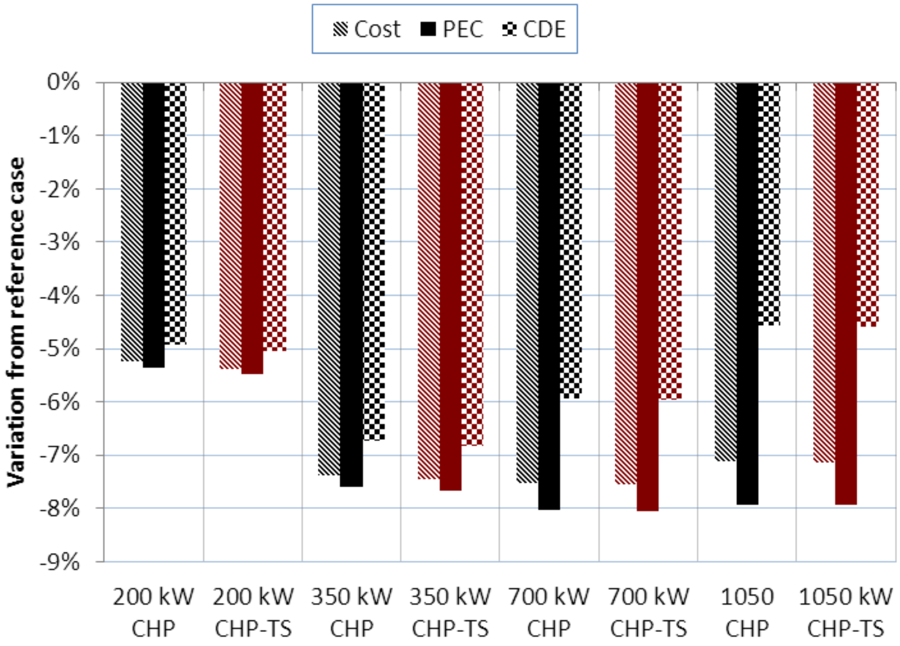

Figure 6.9 Variation of Cost, PEC, and CDE from reference case for CHP and CHP-TES with varying PGU size for a hospital in Houston

The systems show highly favorable outcomes in each case for the hospital in Houston. Cost, PEC, and CDE are significantly reduced for every case shown, with the 700 kW size showing the best results. However, thermal storage provides very little advantage in this situation because the amount of heat recovered from the CHP system at each time step is usually larger than the heat required by the building. Therefore, heat may be stored but is rarely needed in order to meet the thermal energy requirements of the building. For the 700 kW size, there is not a significant difference between the cost, PEC, and CDE of the CHP-TES and CHP systems.

San Francisco

The relative results for a hospital with varying PGU sizes in San Francisco are presented in Figure 6.10.

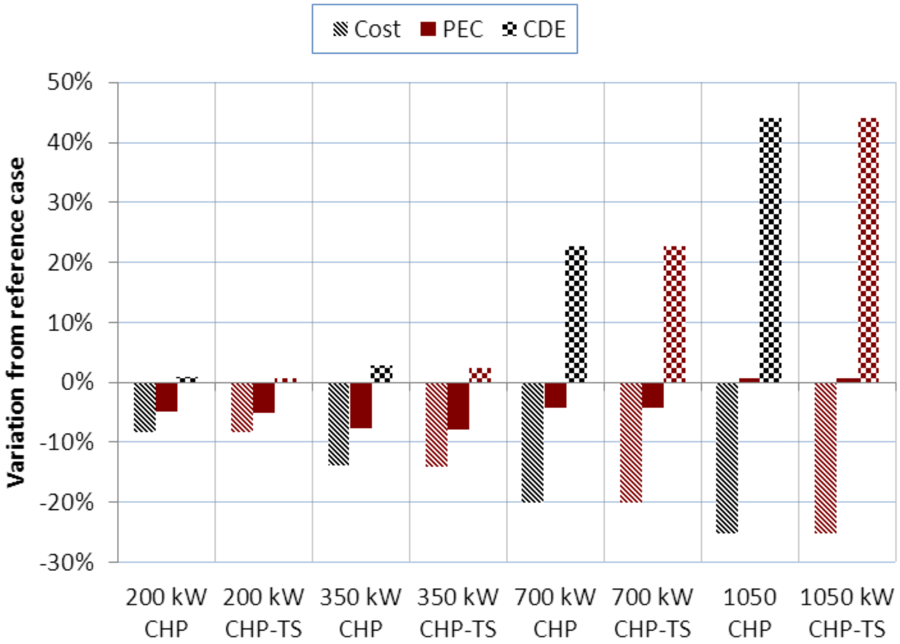

Figure 6.10 Variation of Cost, PEC, and CDE from reference case for CHP and CHP-TES with varying PGU size for a hospital in San Francisco

Again, adding thermal storage to the CHP system with the sizes chosen does not provide any significant additional benefit, for the same reasons as above. For the San Francisco location, CDE is increases in each situation, as was shown previously for the small office and restaurant buildings in San Francisco. For the 200 kW size, the increase in CDE is small and both cost and PEC are reduced from the reference case. As the PGU size increases, the cost and PEC become more favorable, but CDE continues to increase over the reference case. With the 1050 kW size, cost is reduced by over 20%, but PEC increases slightly and CDE increases dramatically, over 40% more than the reference case. No highly favorable options exist for the hospital in San Francisco.

Duluth

The relative results for a hospital with varying PGU sizes in Duluth are presented in Figure 6.11.

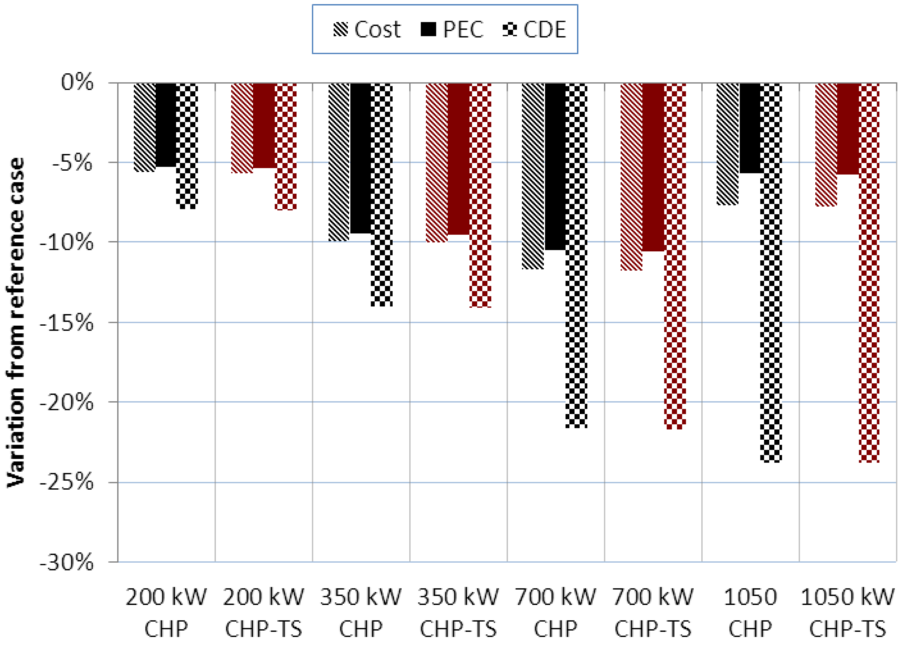

Figure 6.11 Variation of Cost, PEC, and CDE from reference case for CHP and CHP-TES with varying PGU size for a hospital in Duluth

Thermal energy storage still does not provide an additional benefit. The CHP system does show favorable results overall in each case, reducing cost, PEC, and CDE. The 700 kW size shows the largest reduction in cost and PEC, while the 1050 kW size shows the greatest reduction in CDE.

Supplemental Heat

The effect of TES on the hospital building’s requirement for supplemental heat is shown in Table 6.10.

Table 6.10 Requirement for a supplemental boiler with CHP-TS for a hospital

PGU Size	Houston	San Francisco	Duluth
200 kW	Yes	Yes	Yes
350 kW	Yes	Yes	Yes
700 kW	No	No	Yes
1050 kW	No	No	Yes

For the 700 kW and 1050 kW sizes, TES was able to eliminate the need for a supplemental boiler in Houston and San Francisco. However, a 1050 kW CHP would not need supplemental heat, either, due to the large amount of heat recovered. Duluth's cold climate still requires the building to have a boiler in every case. The options for San Francisco are still unfavorable due to the increase in PEC. If the 1050 kW size was chosen for Houston, it would result in excess electricity production of $2.68*10^{11}$ kWh, so without a favorable option to sell electricity back to the grid, the 700 kW size would be more beneficial. In each case where the supplemental boiler was required, the size remains the same whether CHP-TES or CHP alone is used.

From the results presented in Figure 6.3 to Figure 6.11, it can be concluded that in general, the most beneficial size for a CHP application depends on whether the cost, PEC, or CDE should be optimized. The lowest cost, the lowest PEC, and the lowest CDE usually correspond to different PGU sizes. However, in many cases all three parameters were reduced with a given size, indicating an advantage for CHP over the reference system. It should also be noted that the CHP and CHP-TES systems were assumed to operate around the clock at constant load. A customized operational strategy could provide additional cost, PEC, and CDE savings, and might make some of the less favorable options more attractive.

Conclusions from varying location and PGU size study

The potential for a CHP-TES to reduce cost, PEC, and emissions was investigated, and compared with both a CHP system without thermal storage and with the standard reference case. The addition of a thermal storage option to a CHP system did reduce the cost, PEC, and CDE over the CHP system alone for a given PGU size, but did not significantly change the optimum PGU size. For the small office building, a PGU size relatively small to the building's electrical demand showed more favorable results in general, and a CHP-TES system decreased cost, PEC, and CDE from 1% to 3% more than a CHP system alone. For the full service restaurant building, the decrease in cost, PEC, and CDE was from 1.5% to 5% more with CHP-TS as compared with CHP. For the hospital building, CHP-TES was not beneficial compared with CHP for the given situation, although a larger PGU size showed increasingly favorable results. The cost, PEC, and CDE were greatly decreased for the hospital with the exception of CDE in San Francisco. CDE in San Francisco were always shown to be unfavorable due to the low $CF_{PEC,e}$ in California, resulting from the relatively low emissions of the electricity generated for purchase in this region.

The addition of TES generally did not eliminate the need for supplemental heating in the form of a boiler in order to meet the thermal demand of the building, although in some situations the size of the boiler may be reduced due to TES. In Duluth, the coldest climate studied, a boiler was always necessary in order to meet the heating demands of each building type. The restaurant building, which also has a high thermal demand, will always require a boiler as well. For the small office building and the hospital, it may be possible to eliminate the need for a boiler in Houston and San Francisco with a larger

PGU size. However, in San Francisco, this comes at the cost of greatly increased CDE. The small office building with CHP-TES in Houston is unfavorable on all three parameters. The hospital with CHP-TES produces a large amount of excess electricity with the largest engine size, so only the hospital in Houston with a 750 kW PGU size is recommended for reducing cost, PEC, and CDE while eliminating the need for a boiler.

Because the cost calculations for both the CHP and CHP-TES systems only include the cost of purchasing fuel and electricity, capital costs and additional operation and maintenance costs should be considered before making a financial decision about whether CHP and CHP-TES systems can reduce cost.

Methodology for Varying Building Type and TES Size Study

This section investigates the benefits of the TES option combined with a CHP system for eight different commercial building types located in Chicago, IL. Chicago is located in a cold climate region (between 5,400 and 9,000 heating degree days on a 65°F basis) [93]. The buildings were modeled using EnergyPlus simulation software [88] and the same commercial building models developed by the DOE [75]. A CHP system size that leads to benefits for the building in terms of reducing operational cost, PEC, and CDE is determined. Then the amount of TES that is beneficial to the particular building is investigated, along with the effects of the TES option on cost, PEC, CDE, and optimal boiler size and power generation unit (PGU). This section presents the methodology used to evaluate the benefits of thermal energy storage in combination with a CHP system for different commercial building types.

Chicago Building Models

Eight commercial building types with varying characteristics were selected for the investigation using building models [75] designed to be representative of typical U.S. buildings constructed after 1980. More information about these hypothetical buildings is provided in Table 6.11. The reference building files are provided as input for EnergyPlus [88] and the building's performance is simulated. The results of the simulations are used to provide each building's hourly demand for electricity and heat over one year. Next, the operational cost, PEC, and CDE associated with purchasing electricity from the grid and providing heat with an auxiliary boiler are computed for the reference case, for the CHP system, and for the CHP system with thermal energy storage (CHP-TES).

Table 6.11 Building model basic characteristics by building type [75]

Building Type	Area (m^2)	Volume (m^3)	Occupancy* (m^2/person)
Full Service Restaurant	511	1,558	1.4
Hospital	2,595	88,863	18.6
Large Hotel	11,345	35,185	[1.5 guests/room, 65% occupancy rate]
Outpatient Building	3,804	11,932	4.7
Primary School	6,871	27,484	4
Small Hotel	4,014	13,204	[1.5 guests/room, 65% occupancy rate]
Small Office	511	2,279	18.6
Supermarket	4,181	25,486	11.6

*Occupancy is provided for the main area or most common type of room for a given building type. Exact occupancies used in simulation vary with time/location and may be found in the EnergyPlus input file. See Deru et al. p. 18 for occupancy information.

CHP System Model

The CHP system considered for each building is shown in Figure 6.1. Electricity is generated by a prime mover, which is again assumed to be a PGU fueled by natural gas. Electricity in the amount of E_{pgu} is provided to the building, where E_{pgu} is given by

Equation (6.1). The fuel energy used by the PGU in an hour is given by Equation (5.2) and the heat recovered by the CHP system in an hour is given by Equation (5.3).

The fraction of the thermal demand that is satisfied by the CHP system [58] is given by:

$$R_{h,CHP} = \frac{Q_{rec}}{Q_{req}} \quad if\ Q_{rec} \leq Q_{req} \tag{6.26}$$

$$R_{h,CHP} = 1 \ \ otherwise \tag{6.27}$$

where Q_{req} is the thermal energy required by the building.

The CHP system is assumed to operate at a constant baseload. This allows the PGU to operate with a maximum, constant efficiency [54]. Table 6.12 presents the constant values which are used for the system parameters in the above equations.

Table 6.12 CHP system parameters

Parameter	Value
$\eta_{e,pgu}$	0.3
ξ	0.95
$\eta_{hrs,chp}$	0.8

If E_{pgu} does not meet the building's electricity requirement, E_{req}, then additional electricity is purchased from the grid, E_{grid}, as give by Equation (6.10). Some of the heat produced by the PGU is then captured by the heat recovery system (HRS) and thermal energy, Q_{rec}, is available to the building. If the heat produced exceeds Q_{req}, then excess heat is produced, Q_{excess}. If Q_{rec} is less than Q_{req}, additional heat is provided by a supplemental boiler, Q'_{boiler}.

$$Q'_{boiler} = Q_{req} - Q_{rec} \quad if\ Q_{rec} < Q_{req} \tag{6.28}$$

$$Q'_{boiler} = 0 \ \ otherwise \tag{6.29}$$

CHP-TES System Model

Next, the CHP system is investigated with a thermal storage option as shown in Figure 6.2. In this situation, when the CHP system produces excess heat, it may be stored in the TES device until the device reaches its capacity. When the heat produced is insufficient to meet Q_{req}, the stored thermal energy may be used to meet the building's energy needs. The boiler is only used if the amount of thermal energy required is greater than the amount produced by the CHP and the amount stored in the TES device combined. Equations (6.4) through (6.7) describe the implementation of these conditions. It is assumed that the TES system does not experience thermal losses and that it can deliver the thermal energy as needed.

The system is modeled to investigate whether CHP-TES provides additional cost, PEC, and CDE reductions over the use of a CHP system alone, and whether increasing the size of the TES device provides additional benefits. Then it is considered whether CHP-TES can reduce the required boiler size.

The economic analysis is performed as in the Cost section above (from previous study with varying location and PGU size); the energy analysis is performed as in the Primary Energy section above; and the emissions analysis is performed as in the Carbon Dioxide Emissions section above.

Results from Chicago study

The thermal and electric requirements, Q_{req} and $E_{req,}$ respectively, need to be known to apply the methodology presented in the previous section. These two parameters are determined from the results of the EnergyPlus simulation. They will vary from timestep to timestep and will vary among the different building types. The total yearly electrical and thermal energy requirements as well as the power-to-heat ratio for each of the evaluated buildings are presented in Table 6.13. In addition, the cost of electricity and natural gas as well as primary energy and emission conversion factors for electricity and natural gas must to be known. The values used in this investigation are presented in Table 6.14.

Table 6.13 Yearly energy requirements [88] and power-to-heat ratios by building type

Building Type	E_{req}	Q_{req}	PHR_b
Full Service Restaurant	1,205 GJ	1,512 GJ	0.80
Hospital	42,674 GJ	17,681 GJ	2.41
Large Hotel	16,049 GJ	13,724 GJ	1.17
Outpatient Building	5,708 GJ	4,682 GJ	1.22
Primary School	3,771 GJ	2,873 GJ	1.31
Small Hotel	2,748 GJ	1,160 GJ	2.37
Small Office	312 GJ	138 GJ	2.27
Supermarket	7,295 GJ	4,877 GJ	1.50

Table 6.14 Cost, emissions conversion factors, and primary energy conversion factors for Chicago

Electricity or Natural Gas Factor	Value
$Cost_e$ [90]	\$0.0867/kWh
$Cost_f$ [91]	\$0.028/kWh
ECF [88]	3.546
FCF [88]	1.092
$CF_{CDE,e}$ [88]	0.0007689 ton/kWh
$CF_{CDE,f}$ [88]	0.0001996 ton/kWh

PGU Size Selection

In order to investigate the benefits of TES combined with a CHP system, it is important to determine that the CHP system can potentially benefit the building in terms of cost, PEC, and CDE. The option to sell or export electricity is not considered in this investigation. To define the size of the PGU to be used in the analyses, the size of the PGU was varied from a small size corresponding to half of the minimum hourly electricity required by the building to a large size which would produce twice the average hourly electricity required by the building. For every evaluated building, it was found that a PGU size corresponding to half the average hourly electricity would reduce cost, PEC, and CDE with respect to the reference case. Therefore, the PGU size was held at 50% of E_{ave} in all cases to provide consistency in the comparison among building types. Table 6.15 presents the average hourly electrical demand, the PGU size which provides 50% of this amount of energy over an hour (average $R_e = 0.5$), and the thermal energy which can be recovered from this PGU in one hour given the assumed efficiencies in Table 6.12.

Table 6.15 PGU sizing based on average electrical demand of the building

Building Type	E_{ave}	PGU size	Q_{rec}
Full Service Restaurant	138 MJ	19 kW	1213 MJ
Hospital	4871 MJ	675 kW	4309 MJ
Large Hotel	1832 MJ	255 kW	1628 MJ
Outpatient Building	652 MJ	90 kW	575 MJ
Primary School	431 MJ	60 kW	383 MJ
Small Hotel	314 MJ	44 kW	132 MJ
Small Office	36 MJ	5 kW	32 MJ
Supermarket	833 MJ	115 kW	557 MJ

TES Capacity and Necessary Boiler Size Analysis

The CHP and CHP-TES systems were simulated using the PGU sizes given in Table 6.15 which were determined to be potentially beneficial by the previous calculations. The size of the TES device was varied according to the maximum thermal energy required by the building in one hour, Q_{max}. The thermal capacity is the only parameter of interest for the TES study, and therefore the analysis could apply to different forms of TES. A range of TES sizes from $0.25Q_{max}$ to Q_{max} were simulated, and the cost, PEC, and CDE were calculated. Table 6.16 presents the storage capacities that were evaluated. If the storage device was found to provide additional benefits in terms of cost, PEC, or CDE reduction, each value for TES_{cap} was examined in order to determine whether it could reduce the size of the boiler needed to satisfy the thermal load of the building. In other words, because the TES device can provide some of the heating load, if the maximum thermal energy required from the boiler is reduced due to the addition of TES, then the boiler size necessary to meet the building's thermal needs may become smaller.

Table 6.16 Sizing of thermal store based on maximum thermal demand of the building

Building Type	$TES_{cap} = 0.25Q_{max}$	$TES_{cap} = 0.50Q_{max}$	$TES_{cap} = 0.75Q_{max}$	$TES_{cap} = Q_{max}$
Full Service Restaurant	52.5 kWh	105 kWh	157.5 kWh	210 kWh
Hospital	172 kWh	344 kWh	516 kWh	688 kWh
Large Hotel	340 kWh	680 kWh	1020 kWh	1360 kWh
Outpatient Building	57 kWh	114 kWh	171 kWh	228 kWh
Primary School	232 kWh	464 kWh	696 kWh	928 kWh
Small Hotel	19 kWh	38 kWh	57 kWh	76 kWh
Small Office	12.5 kWh	25 kWh	37.5 kWh	50 kWh
Supermarket	301 kWh	602 kWh	903 kWh	1204 kWh

Building Analysis

Full Service Restaurant

Figure 6.12 presents the reductions in cost, PEC, and CDE with respect to the reference case obtained with a CHP system and CHP-TES systems with varying thermal storage capacities for the restaurant building. The restaurant has the smallest PHR_b over the year compared with the other seven buildings studied, with a value of 0.80. This indicates that more of the energy required by the building is in the form of thermal energy. For this case, the CHP-TES system does reduce cost, PEC, and CDE more than a CHP system alone. Therefore, results confirm that it is generally beneficial to have high relative thermal demand for the operation of the CHP and the CHP-TES systems to be favorable in terms of cost, PEC, and CDE.

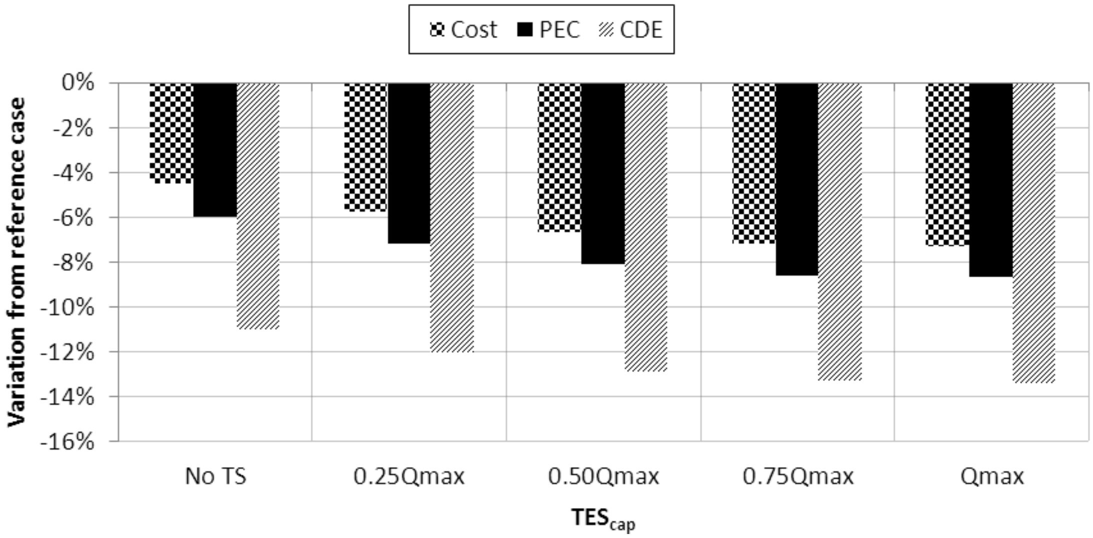

Figure 6.12 Variation of Cost, PEC, and CDE from reference case for CHP without TES and CHP-TS with varying TES_{cap} for a full service restaurant

The fraction of the thermal load satisfied by the CHP system is, on average, 0.743. As the size of the TES device increases, the reductions on cost, PEC, and CDE become more favorable. However, once TES_{cap} is about 75% of Q_{max}, the gains resulting from additional thermal storage capacity are very small, as illustrated in Figure 6.13. This figure shows the primary energy which is saved by using a CHP-TS system versus the reference case over a wide range of TES_{cap}. Although each building has a unique curve, and the magnitude of primary energy saved is different for each building, all building types studied have little or no improvement in energy savings when TES_{cap} is increased past Q_{max}.

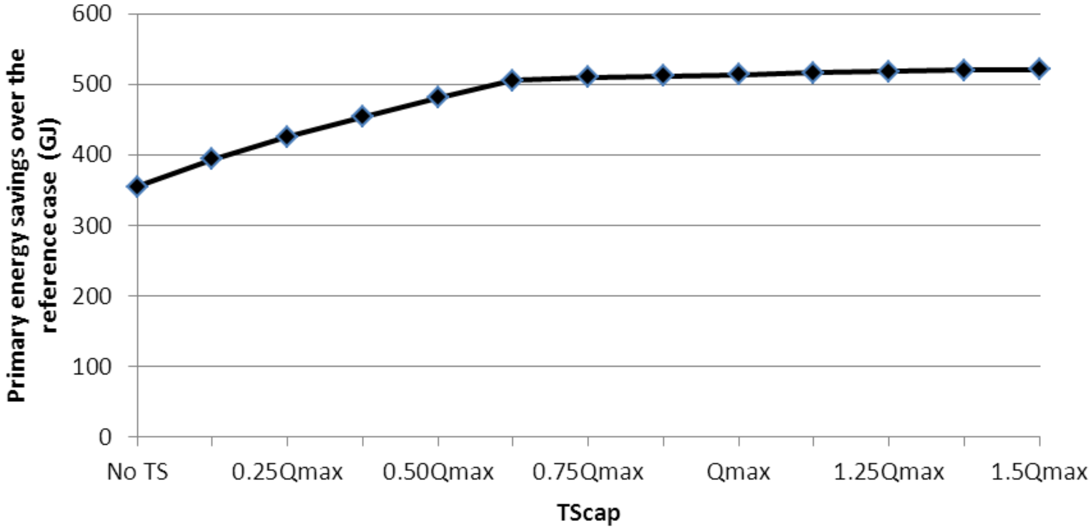

Figure 6.13 Primary energy savings over the reference case with varying TES_{cap} for a full service restaurant with CHP and CHP-TES

The fraction of the thermal load satisfied by the CHP system with the TES size corresponding to 100% of Q_{max} is, on average, 0.786. Therefore, the maximum improvement shown in R_h value from $R_{h,CHP}$ to $R_{h,CHP\text{-}TS}$ is 5.7%. The R_h values for CHP and CHP-TES are presented in Figure 6.14. For this case, the required boiler size for each case remains the same, at 211 kWh, indicating that the maximum hourly thermal load which must be met by the boiler is not reduced by the addition of TES.

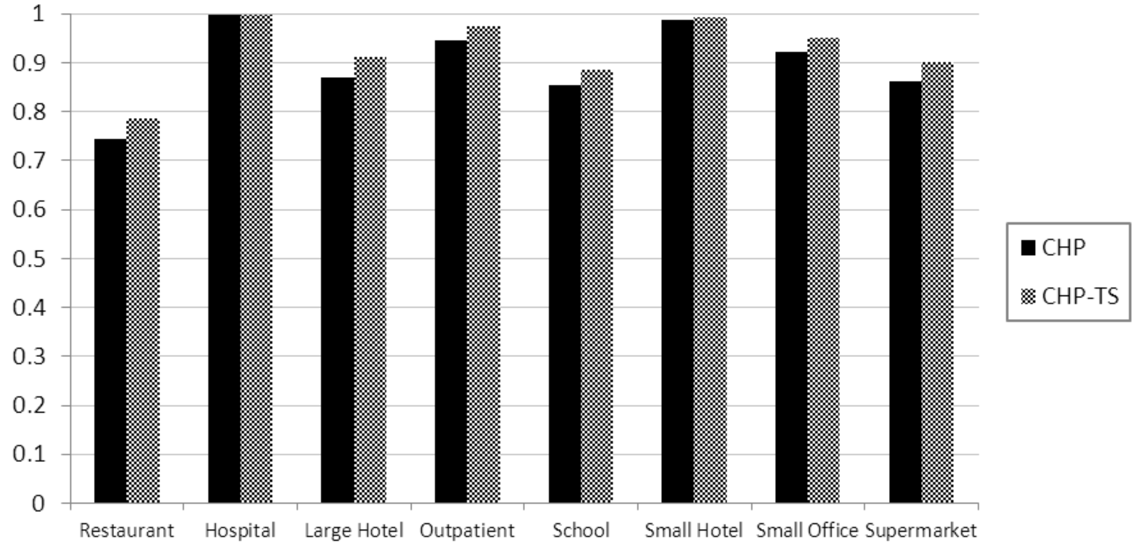

Figure 6.14 Average R_h values for the fraction of required heat provided over one year by CHP and CHP-TES systems for eight building types

Hospital

Figure 6.15 presents the reductions in cost, PEC, and CDE with respect to the reference case obtained with a CHP system and CHP-TES systems with varying thermal storage capacities for the hospital building. The hospital has the largest PHR_b over the year compared with the other buildings, with a value of 2.41. This indicates that the building requires more than twice as much electrical energy as thermal energy. Therefore, CHP-TES has less opportunity to make an impact on the economic, energetic, and environmental analysis. Figure 6.15 illustrates that the CHP-TES system does not reduce cost, PEC, and CDE more than a CHP system alone. The reduction from the reference case differs by less than 1% between the CHP system and any of the CHP-TES systems.

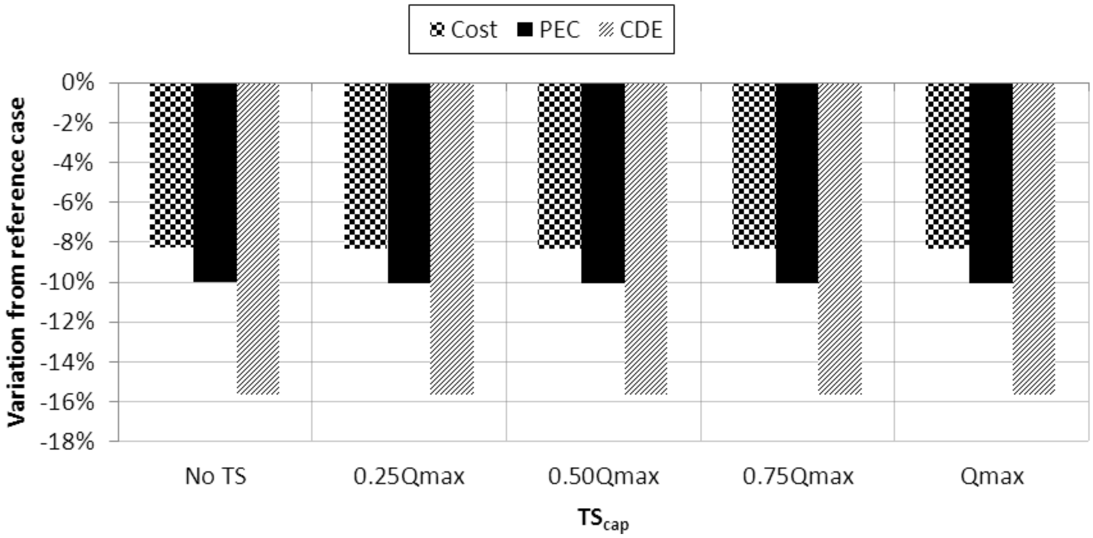

Figure 6.15 Variation of Cost, PEC, and CDE from reference case for CHP without TES and CHP-TS with varying TES_{cap} for a hospital

The $R_{h,CHP}$ and $R_{h,CHP\text{-}TS}$ values are both 0.998 (Figure 6.14), indicating that the CHP system alone meets almost all of the building's thermal load, and adding TES will not provide additional benefits. The required boiler size for each case also remains the same, at 687 kWh, indicating that the maximum hourly thermal load which must be met by the boiler is not reduced by the addition of TES. Therefore, for this type of building the addition of TES to the CHP system does not add any benefits.

Large Hotel

Figure 6.16 presents the reductions in cost, PEC, and CDE with respect to the reference case obtained with a CHP system and CHP-TES systems with varying thermal storage capacities for the large hotel building. As can be seen in Figure 6.14, the CHP-TES system does reduce cost, PEC, and CDE more than CHP alone. As the size of the TES device increases, these reductions become more favorable. Similar to the full service restaurant, once TES_{cap} is about 75% of Q_{max}, the gains resulting from additional thermal storage capacity are very small. The PHR_b of the large hotel is 1.17, larger than that of the restaurant but much smaller than that of the hospital.

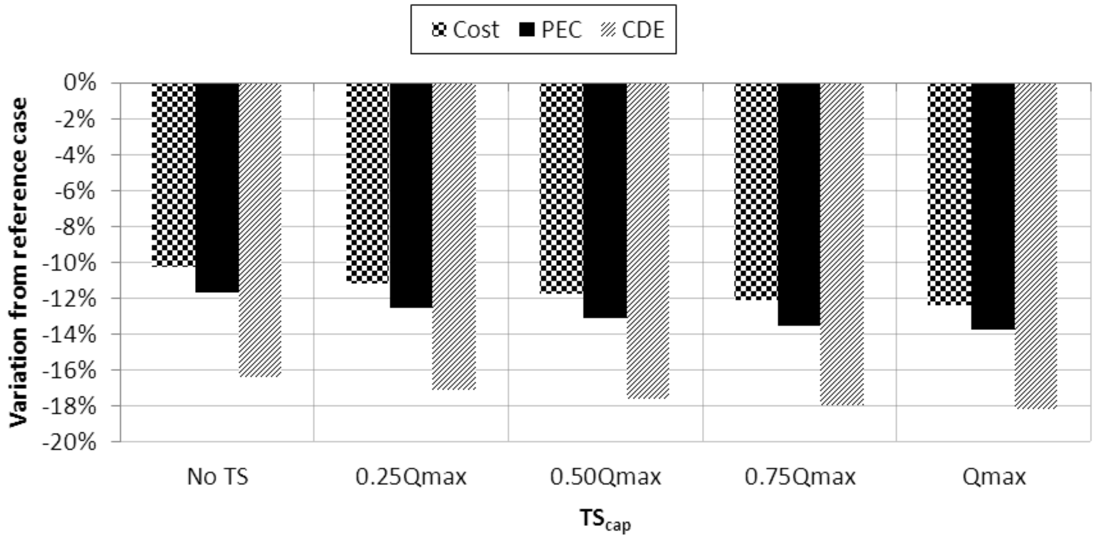

Figure 6.16 Variation of Cost, PEC, and CDE from reference case for CHP without TES and CHP-TES with varying TES_{cap} for a large hotel

The $R_{h,CHP}$ and $R_{h,CHP\text{-}TS}$ values are 0.871 and 0.912 (Figure 6.14) representing a 4.7% possible increase in the fraction of thermal load supplied by the CHP system. The required boiler size decreases when TES is added to the CHP system, from 1361 kWh to 1329 kWh. The reduction is the same whether TES_{cap} is $0.25Q_{max}$ or equal to Q_{max}. This is only a 2.4% reduction in the overall size of the boiler required to meet the building's thermal energy requirement. However, it illustrates that the CHP-TES system is functioning as desired, by reducing the peak thermal load required from the boiler.

Outpatient

Figure 6.17 presents the reductions in cost, PEC, and CDE with respect to the reference case obtained with a CHP system and CHP-TES systems with varying thermal storage capacities for the outpatient building. The outpatient building has a PHR_b of 1.22, just larger than the large hotel building, and the CHP-TES system does reduce cost, PEC, and CDE more than CHP alone. As the size of the TES device increases, these reductions become more favorable. Again, once TES_{cap} is about 75% of Q_{max}, the gains resulting from additional thermal storage capacity are very small.

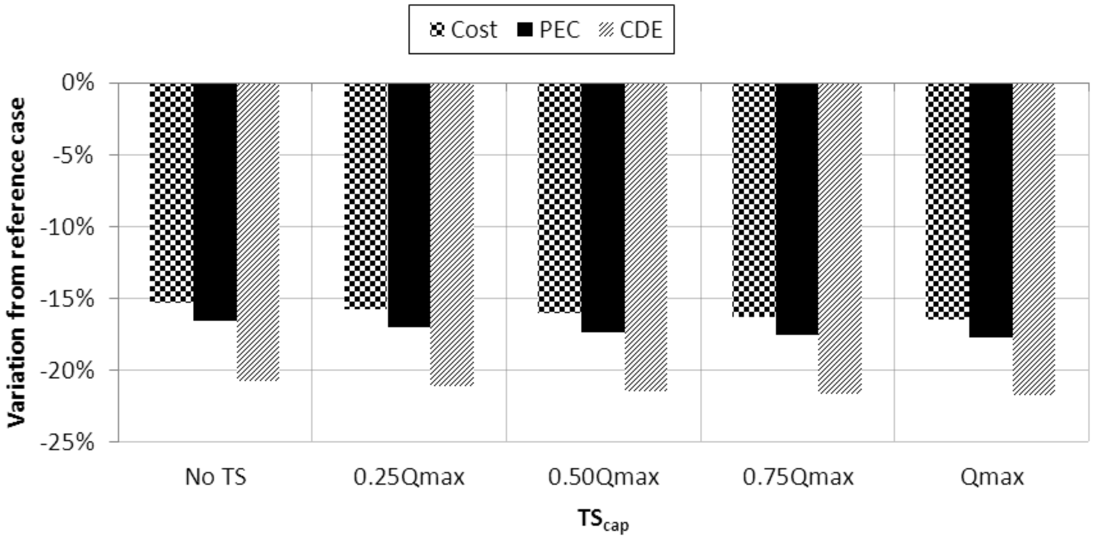

Figure 6.17 Variation of Cost, PEC, and CDE from reference case for CHP without TES and CHP-TES with varying TES_{cap} for an outpatient building

The $R_{h,CHP}$ and $R_{h,CHP\text{-}TES}$ values are 0.945 and 0.974 (Figure 6.14) representing a 3.1% possible increase in the fraction of thermal load supplied by the CHP system. The required boiler size for each case remains the same, at 227 kWh, indicating that the maximum hourly thermal load which must be met by the boiler is not reduced by the addition of TES.

Primary School

Figure 6.18 presents the reductions in cost, PEC, and CDE with respect to the reference case obtained with a CHP system and CHP-TES systems with varying thermal storage capacities for the primary school building. The primary school building has a PHR_b of 1.31, just larger than the outpatient building, and Figure 6.18 illustrates that the CHP-TES system does reduce cost, PEC, and CDE more than CHP alone. As the size of the TES device increases, these reductions grow, but the improvement slows somewhat as TES_{cap} approaches Q_{max}.

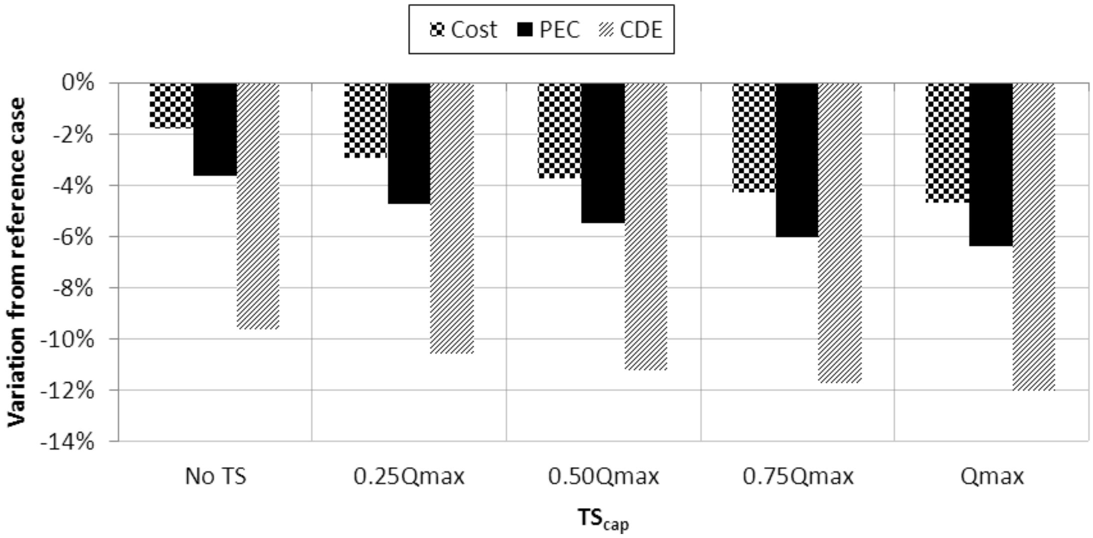

Figure 6.18 Variation of Cost, PEC, and CDE from reference case for CHP without TES and CHP-TES with varying TES_{cap} for a primary school

The $R_{h,CHP}$ and $R_{h,CHP\text{-}TES}$ values are 0.855 and 0.884 (Figure 6.14) representing a 3.5% possible increase in the fraction of thermal load supplied by the CHP system. The required boiler size for each case remains the same, at 928 kWh, indicating that the maximum hourly thermal load which must be met by the boiler is not reduced by the addition of TES.

Small Hotel

Figure 6.19 presents the reductions in cost, PEC, and CDE with respect to the reference case obtained with a CHP system and CHP-TES systems with varying thermal storage capacities for the small hotel building. The small hotel has the second largest

PHR_b after the hospital, with a value of 2.37. Similarly, the CHP-TES system does not reduce cost, PEC, and CDE more than a CHP system alone. As with the hospital building, the reduction from the reference case differs by less than 1% between the CHP system and any of the CHP-TES systems.

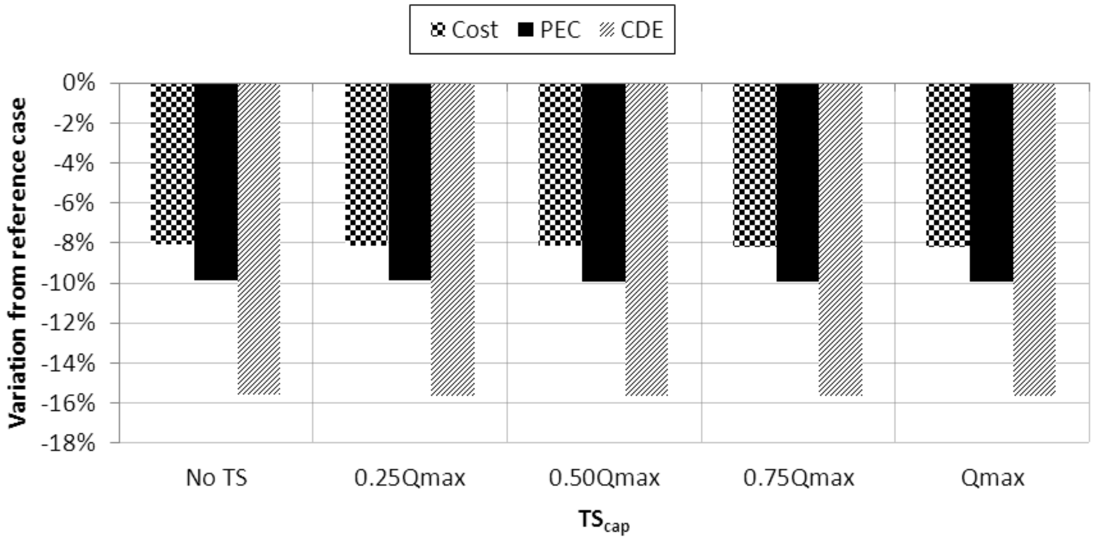

Figure 6.19 Variation of Cost, PEC, and CDE from reference case for CHP without TES and CHP-TS with varying TES_{cap} for a small hotel

The $R_{h,CHP}$ and $R_{h,CHP\text{-}TS}$ values are 0.988 and 0.992 (Figure 6.14) representing only a 0.3% possible increase in the fraction of thermal load supplied by the CHP system. As with the hospital building, the value for $R_{h,CHP}$ is almost 1 and adding TES will not provide additional benefits. The required boiler size for each case also remains the same, at 76 kWh, indicating that the maximum hourly thermal load which must be met by the boiler is not reduced by the addition of TES. The addition of a TES device is not beneficial for this particular case.

Small Office

Figure 6.20 presents the reductions in cost, PEC, and CDE with respect to the reference case obtained with a CHP system and CHP-TES systems with varying thermal storage capacities for the small office building. Although the small office has a relatively large PHR_b of 2.27, the CHP-TES system does reduce cost, PEC, and CDE more than CHP alone. As the size of the TES device increases, these reductions grow, but the improvement slows somewhat as TES_{cap} approaches Q_{max}.

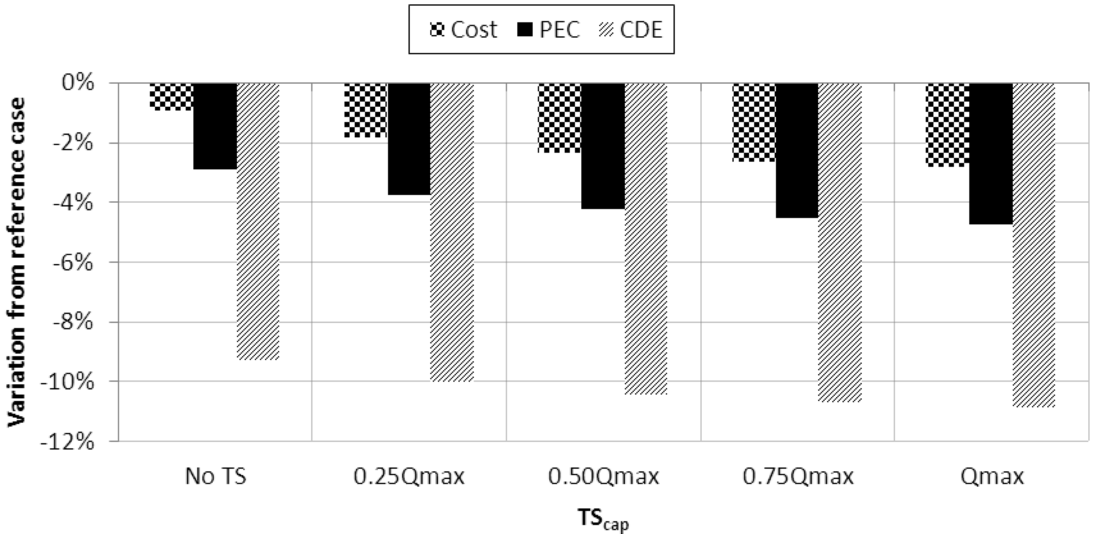

Figure 6.20 Variation of Cost, PEC, and CDE from reference case for CHP without TES and CHP-TES with varying TES_{cap} for a small office

The $R_{h,CHP}$ and $R_{h,CHP-TS}$ values are 0.922 and 0.950 (Figure 6.14) representing a 3.0% possible increase in the fraction of thermal load supplied by the CHP system. The required boiler size for each case remains the same, at 51 kWh, indicating that the maximum hourly thermal load which must be met by the boiler is not reduced by the addition of TES. However, because of the variation in the thermal demand of the small office building, the CHP-TES system often makes supplemental heat from the boiler unnecessary, even though the size of the boiler required to meet Q_{max} remains the same. Therefore, even though a much larger portion of the building's overall energy needs is in the form of electrical energy, a properly sized CHP-TES system can relieve the thermal load in such a way as to reduce operational cost, PEC, and CDE.

Supermarket

Figure 6.21 presents the reductions in cost, PEC, and CDE with respect to the reference case obtained with a CHP system and CHP-TES systems with varying thermal storage capacities for the supermarket building. The supermarket building has a PHR_b of 1.50, just larger than the primary school building, and the CHP-TES system does reduce cost, PEC, and CDE more than CHP alone. As the size of the TES device increases, these reductions grow, but the improvement slows somewhat as TES_{cap} approaches Q_{max}.

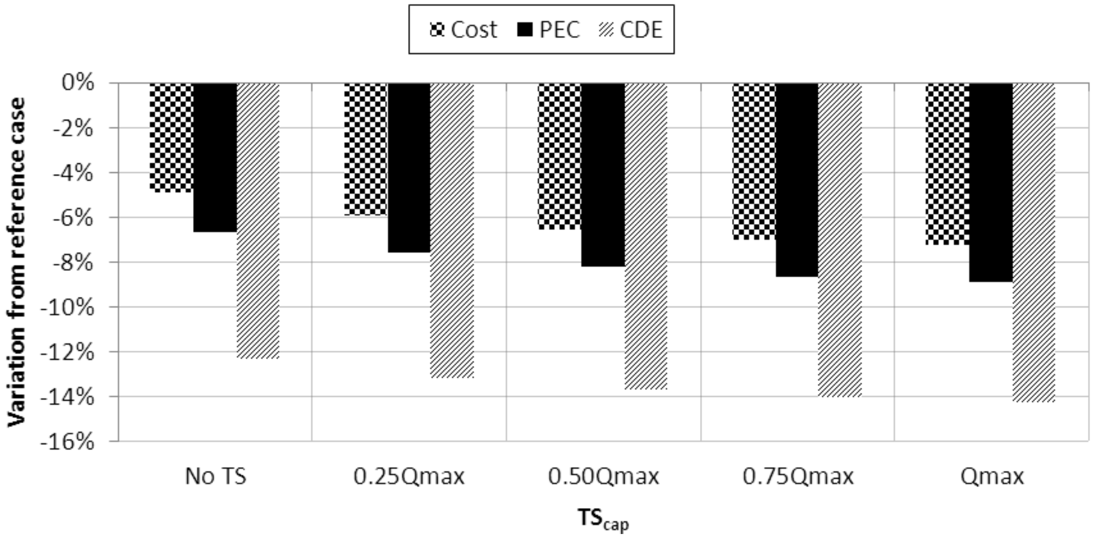

Figure 6.21 Variation of Cost, PEC, and CDE from reference case for CHP without TES and CHP-TS with varying TES_{cap} for a supermarket

The $R_{h,CHP}$ and $R_{h,CHP\text{-}TS}$ values are 0.863 and 0.900 (Figure 6.14) representing a 4.3% possible increase in the fraction of thermal load supplied by the CHP system. The required boiler size for each case remains the same, at 1204 kWh, indicating that the maximum hourly thermal load which must be met by the boiler is not reduced by the addition of TES.

Discussion of the Chicago study

In general it can be seen that for all the evaluated building the use of a CHP system reduces the cost, PEC, and CDE. The addition of TES does reduce cost, PEC, and CDE more than CHP alone for all selected buildings except for the hospital and small hotel buildings. The results indicate that the building PHR is one of the factors that affect the potential of TES to provide benefits when combined with a CHP system. The hospital and the small hotel buildings are the two buildings with the highest PHR among the selected buildings that indicates that the building needs more electrical energy than thermal energy. As previously shown [58], a high R_h value is beneficial in terms of reducing cost, PEC, and CDE, and it was shown that a larger increase from $R_{h,CHP}$ to $R_{h,CHP-TS}$ indicated greater potential for TES to further reduce cost, PEC, and CDE. Also, it is important to highlight that for all buildings the CDE is the parameter that benefits more from the use of CHP-TES system, followed by the PEC and operational cost.

Summary and Conclusions from Chicago study

This chapter presented a methodology to investigate the benefits of a thermal energy storage option combined with a CHP system. The methodology was applied to eight different commercial building types located in Chicago, IL.

The results of this study indicate which types of commercial buildings may show benefits from CHP-TES systems and which types are unlikely to benefit from the addition of TES. Because any TES device will require additional capital which is not accounted for in this analysis, it is desirable that the addition of TES should provide substantial economic benefits in terms of reduced fuel costs, and reduce or eliminate the requirement for supplemental heating. Cold climates such as that of Chicago are generally better for CHP due to the increased heating requirements compared with warmer climates, but adding TES will not always reduce the need for a supplemental boiler or significantly reduce the operating costs, even if the TES device is large compared with the building's maximum heating demand.

For the hospital and small hotel buildings, the addition of TES would not provide any additional benefits over a properly sized CHP system. These are the buildings with the largest PHR_b values, indicating that the building demands much more electrical energy rather than thermal energy. Therefore, the building rarely needs to use the excess thermal energy stored in the TES device.

Sizing a TES device to be 75% or more of the maximum hourly thermal requirement is not recommended. The increased cost associated with such a large device provides very little return in the form of reducing cost, PEC, and CDE, even without taking capital costs into consideration. For the six buildings in which TES reduced cost, PEC, and CDE, these benefits appeared even when the TES device was sized at 25% of Q_{max}, the smallest thermal capacity size which was modeled here. The appropriate TES_{cap} for an actual building will be determined based on the capital and maintenance costs associated with the particular TES system to be installed. If the TES device reduces the necessary boiler size, this may also be taken into account; however, based on the buildings studied, a significant reduction in boiler size is unlikely. Because the maximum thermal load occurs at a time step when the TES device does not have energy stored, the maximum thermal energy required from the boiler in a one-hour time step cannot be reduced in most cases.

While thermal storage will provide some benefit in most cases, it is not recommended that the PGU size is larger for a CHP-TES system than it would be a for a similar CHP system.

As a general guideline, for the evaluated buildings, when the PHR_b is greater than 2.3, the addition of TES is unlikely to provide any additional benefit when added to a CHP system. However, the potential benefits from TES will also vary according to how the thermal energy requirements of the building change over time. If the thermal load varies from hour to hour or day to day, TES is more likely to contribute to balancing the variation in thermal energy requirement.

The assumptions made about the ideal TES device mean that the potential benefits in terms of reduced cost, PEC, and CDE are the maximum reductions which could be produced with a perfect TES device; actual devices will be subject to thermal losses and other limitations on the system. Therefore, if it is determined for a particular building that the addition of TES may be beneficial, these results may indicate a general storage capacity range to be considered for the TES device, based on the maximum possible thermal energy stored in the device relative to the maximum heat load for the building under consideration. At this point, one or more types of TES devices may be considered and the performance characteristics of the actual device should be accounted for in the engineering analysis [64, 68, 94].

Thermal Loss Study with Water Tank TES

CHP systems with thermal storage have been demonstrated to show cost, emissions, and energy benefits in addition to those of a CHP system in the previous sections. However, the thermal storage device was assumed to be perfectly insulated. The thermal losses from thermal storage over time, or the characteristics of an actual TES device were not considered at all. Here, one situation in which CHP-TES shows potential benefits is investigated with respect to the necessary tank size and losses from the tank.

Description

The case of a full service restaurant building in Houston is chosen as described in the section on the restaurant in Houston. For the range of PGU sizes studied, CHP-TES showed greater reductions in cost, emissions, and PEC than CHP alone, as shown in Figure 6.6. Also, the addition of TES reduced the need for a supplemental boiler in this case.

A sensible hot water TES tank is proposed. Liquid water is a simple and commonly used substance for heating thermal storage [20]. The large tank which was considered for this case was assumed to have the capacity to store 220 kWh of thermal energy. Therefore, the dimensions for the simplified tank model will be chosen such that it will be able to hold the same amount of thermal energy.

Methodology

The necessary volume of water in the tank is calculated using the volumetric thermal capacity of water, 4.17 MJ/m^{3}K [64].

$$Volumetric\ thermal\ capacity * V * \Delta T = TES_{cap} \qquad 6.30$$

where V is volume of water, TEScap is the thermal storage capacity, and ΔT is the temperature difference between the fully “charged” state at TEScap and the “discharged” state at a lower temperature. TEScap is the taken to be 220 kWh, corresponding to the maximum thermal energy required by the building in one hour as determined from the results of the EnergyPlus simulation. Here, ΔT is taken to be 60°C as the thermal storage will operate between a maximum temperature of 85°C and a low temperature of 25°C. The maximum temperature is chosen to be well below 100°C in order to avoid the costs of pressurizing the tank [20, 64] and the minimum temperature is assumed to be near room temperature. If the storage tank is located outdoors, the variation in the discharge temperature must then be accounted for in the analysis. The necessary volume when Equation (6.30) is solved for V is therefore:

$$V_{req} = 111.8\ \mathrm{ft}^3 = 3.165\ m^3 = 836.2\ gal \qquad 6.31$$

For reference, home water heater tanks are typically in the 20-80 gallon range [95].

A tank model is created with a radius of 2.61 ft and height of 5.22 ft in order to provide the chosen thermal storage capacity. The tank's volume is therefore:

$$V_{tank} = \pi r^2 h = 112.1\ \mathrm{ft}^3 \qquad 6.32$$

This is similar to the required volume and results in a thermal storage capacity of 220.7 kWh.

The tank is assumed to be insulated. The Department of Energy recommends that a home water tank be insulated with an R-value of 12 to 25 [95], so for the indoor tank in this study, an R-value of at least 18 is desired. A commonly available insulation material is selected, urethane foam, with a low thermal conductivity of k = 0.026 W/(m*K) [96]. Therefore, the necessary thickness of insulation is determined by:

$$R\text{-}value = \frac{thickness_{insulation}}{k_{insulation}} \qquad 6.33$$

For a thickness of 3.5 in, R-value = 19.4 ft^2R hr/Btu. This meets the design requirement. The original model of the tank with dimensions is shown in Figure 6.22.

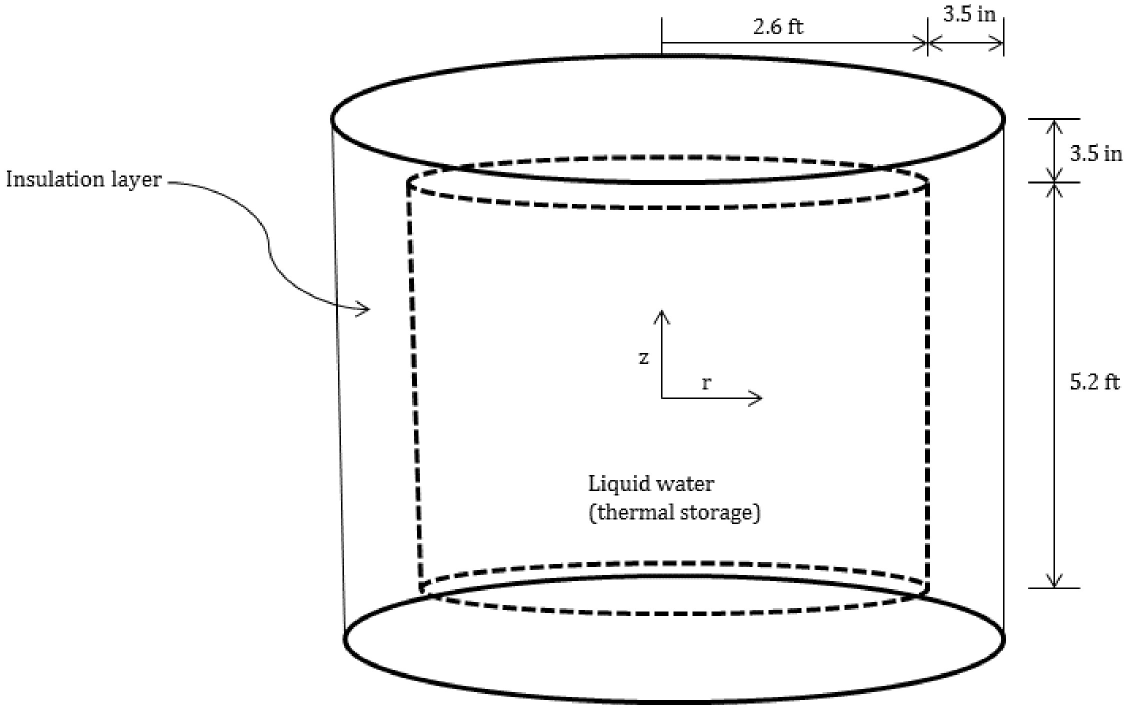

Figure 6.22 Original basic tank model

For the cylinder containing water, the governing equation is [97]:

$$\frac{1}{\alpha_{water}} \frac{\partial T_{water}}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r}\left(r \frac{\partial T_{water}}{\partial r}\right) + \frac{\partial^2 T_{water}}{\partial z^2} \qquad 6.34$$

where α_{water} is the thermal diffusivity of liquid water (assumed constant with respect to temperature), T_{water} is temperature within the water, t represents time, r represents radial distance, and z represents lengthwise distance measured from the center of the cylinder as shown in Figure 6.22.

Likewise, for the hollow cylinder made up of insulation, the governing equation is:

$$\frac{1}{\alpha_{insulation}} \frac{\partial T_{insulation}}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r}\left(r \frac{\partial T_{water}}{\partial r}\right) + \frac{\partial^2 T_{insulation}}{\partial z^2} \qquad 6.35$$

where $\alpha_{insulation}$ is the thermal diffusivity of insulation (assumed constant with respect to temperature) and $T_{insulation}$ represents temperature within the insulation later.

For both Equations (6.34) and (6.35), temperature is a function of r, z, and t. The temperature at the interface must be equal, and the two partial differential equations would need to be solved simultaneously in order to determine the temperature change inside the water tank. Additionally, if convection at the surface of the insulation is considered, this adds complexity to the boundary conditions.

In order to simplify the mathematics, the problem is approximated as one large cylinder as shown in Figure 6.23. Rather than considering two separate interfaces, one between the water and insulation, and one between the insulation and surroundings, the tank is considered to be a lumped system.

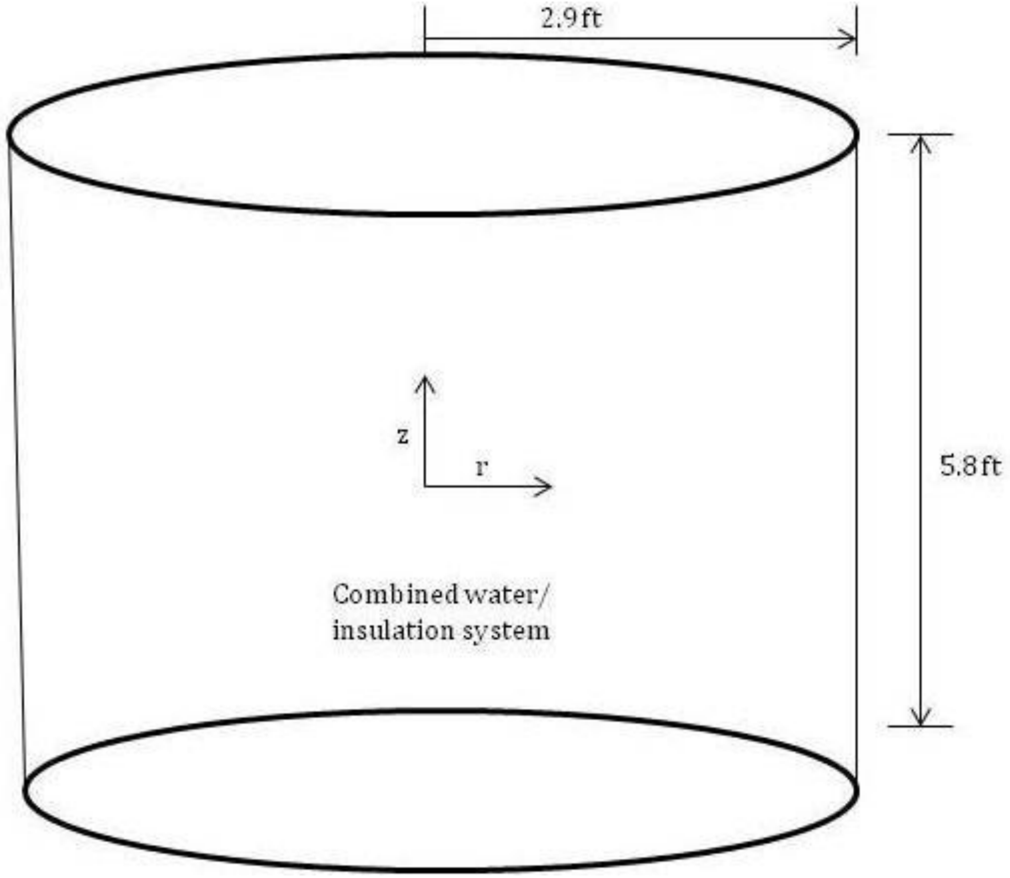

Figure 6.23 Revised simplified tank model

The solution for this problem is known, and may be obtained from the multiplying the results of the infinite cylinder conduction problem (Figure 6.24**a**) with the infinite wall conduction problem (Figure 6.24**b**) because the desired solution is an intersection of the two infinite solutions [96]. The infinite cylinder problem considers temperature as a function of r only, and the infinite wall problem considers temperature as a function of distance from the center only (here, the z-coordinate).

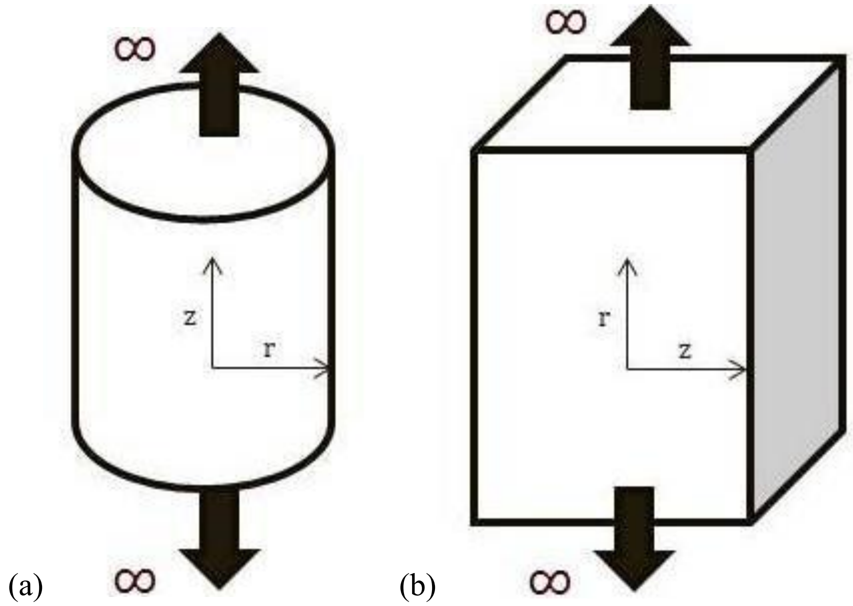

Figure 6.24 Conduction problems: **(a)** Infinite cylinder **(b)** Infinite wall

It is assumed that convection heat transfer from the insulation to the surrounding air is not a critical part of the analysis (convection is expected to be minimal for an indoor tank when compared with an outdoor tank) and the outer edge of the insulation is taken to be at a constant 25°C. The following additional assumptions were made for this initial feasibility analysis: volumetric thermal capacity of water does not vary with temperature; the entire volume of water in the tank is assumed to be an active zone; the volume of the heat exchanger within the tank is not accounted for; the heat losses near inlet and exit piping are not accounted for; convection within the tank is ignored; density of water is assumed to be constant over the given temperature range, which is valid for subcooled water; and the steel tank wall itself is neglected because the thermal resistance of steel will be quite low compared with the thermal resistance of the insulation and the water itself.

The solution for the temperature within the tank for the modified model is now given by:

$$T(r,z,t) = T_c(r,t) * T_w(z,t) \qquad 6.36$$

where T(r,z,t) represents the temperature in the cylinder based on the r,z coordinates as shown in Figure 6.23 at a given time; $T_c(r,t)$ represents the solution to the infinite cylinder problem, which is a function of radius as shown in Figure 6.24, and time; and $T_w(z,t)$ represents the solution to the infinite wall problem, which is a function of z-coordinate as shown in Figure 6.24**b**, and time.

The solutions to these problems are presented as given by Myers [98] as Equations (6.37) and (6.39) below. The analytical solutions are both comprised of an infinite series, but for practical reasons only the first six terms of each series were used for these computations.

$$T_c(r,t) = T_\infty + 2(T_{max} - T_\infty)\sum_{n=1}^{6} \frac{J_0(\lambda_n r)\exp\left(-\lambda_n{}^2 \propto t\right)}{\lambda_n R J_1(\lambda_n R)} \qquad 6.37$$

where T_∞ is the ambient temperature, 25°C, T_{max} is the maximum temperature allowable for the water, 85°C, R is the cylinder radius of 2.9 ft, $\lambda_n R$ are the roots of the Bessel function $J_0(\lambda_n R) = 0$, and α is an overall volume-weighted average thermal diffusivity for the cylinder, determined using equation (6.38).

$$\propto = \propto_{water} VF_{water} + \propto_{insulation} VF_{insulation} \qquad 6.38$$

where α_{water} and $\alpha_{insulation}$ are the thermal diffusivities of the two materials, and VF represents the volume fraction of the whole cylinder that is water versus insulation.

$$T_w(z,t) = T_\infty + 2(T_{max} - T_\infty)\sum_{n=1}^{6} \frac{sin(\lambda_n L)}{\lambda_n L} \cos(\lambda_n z) \exp(-\lambda_n{}^2 \propto t) \tag{6.39}$$

where L is one half the total height of the cylinder, 2.9 ft, and $\lambda_n L$ = (2n-1)π/2.

The product of the two solutions in Equations (6.37) and (6.39) gives the temperature of the water at a location in the tank of Figure 4 at a certain time. In order to examine the time for the "discharge" of thermal energy, the temperature was evaluated at the center of the cylinder, at r=0, z=0, for a conservative estimate. This location would be the slowest to cool, being as far away as possible from the low-temperature boundary.

Based on the simulation results [99], the maximum storage time necessary for a restaurant building in Houston was among the longest of the buildings studied, at 30.5 days or 2,635,000 seconds.

Results

In order to present the results in a clear graphical format, the temperatures shown are nondimensionalized as follows, so that $\theta = 1$ corresponds to $T = T_{max}$ (fully charged) and $\theta = 0$ corresponds to $T = T_\infty$ (fully discharged).

$$\theta = \frac{T(r,z,t) - T_\infty}{T_{max} - T_\infty} \tag{6.40}$$

The nondimensional temperature was plotted against the elapsed time in days for the restaurant as shown in Figure 6.25. This method is not accurate for the first few hours due to a conflict between the initial condition ($T = T_{max}$ at $t = 0$) and boundary condition ($T = T_\infty$ for all $r = R$), so the first half day is not shown in Figure 10. It is noted by Myers [98] that the series given in Equation (6.39) is slow to converge when the nondimensional time given in Equation (6.41), below, is near 0. For t = 30.5 days, the nondimensional time $\bar{t}$ = 0.701.

$$\bar{t} = \frac{\alpha t}{L^2} \qquad 6.41$$

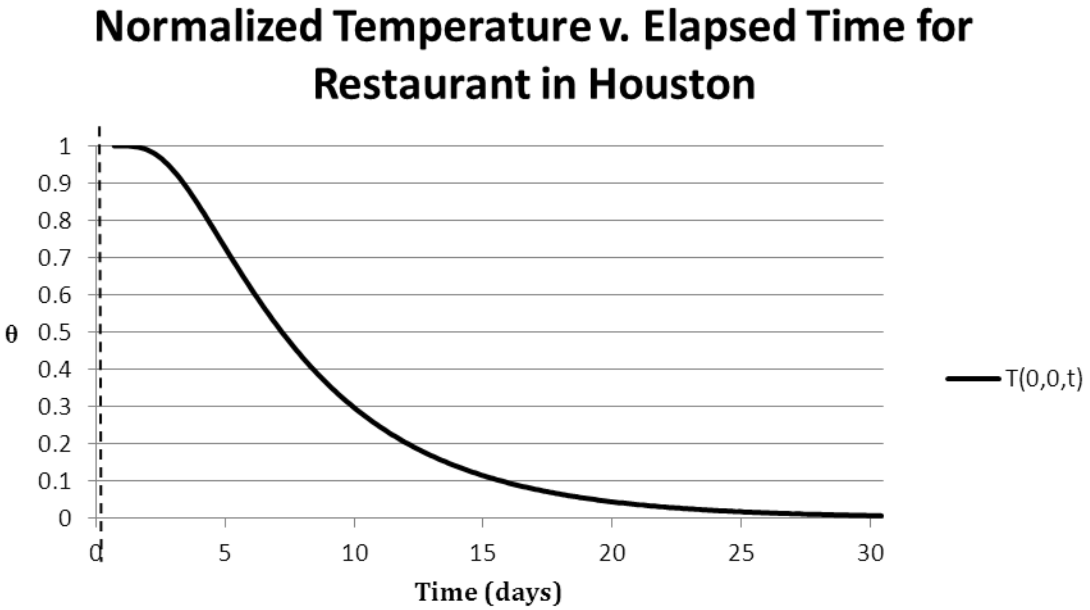

Figure 6.25 Nondimensional temperature variation with time over a 1 month period

Discussion and Conclusions from Case Study

With regard to small thermal storage times, such as a few hours, the work from the preceding sections need not be modified to account for thermal losses from an indoor water tank, as the temperature of water will likely remain the same over this period of time if the tank is reasonably insulated.

For long thermal storage times, such as the time given for the restaurant case, it is not reasonable to expect the thermal storage tank to hold its thermal energy over this time period. Even a well-insulated tank will likely have lost its heat and reached near-thermal equilibrium with its surroundings after so many days.

For intermediate times, such as several days or one week, the results are not considered accurate enough to be conclusive and further study is necessary. The assumptions made for this work mean that the results are not definitive, and in questionable situations another approach is warranted. It is desired to obtain a solution to the original equations developed for the basic model without the lumped approach. It is difficult to find readily available software which can solve these equations symbolically, and the finite element method is suggested as an appropriate approach. The convection boundary condition could also be incorporated into these equations. Weather data, including temperature variation, could be imported from EnergyPlus [88] for the appropriate location. For a large outdoor tank, the variation in temperature and even wind conditions could be used to change the boundary conditions of the tank on a daily or even hourly basis. The characteristics of the storage tank (such as length, radius, insulation type and thickness) could be varied in order to find an optimal setup which minimizes heat loss. If the system is sized for an actual building, a commercially available tank could be selected and evaluated using the step-by-step method of Hyman [20] along with proper piping and internal heat exchanger coils, and the internal volume occupied as well as the thermal losses near the inlets and exits might also be accounted for if a more accurate solution is needed.

CHAPTER VII

CONCLUSIONS

CHP systems were analyzed for their potential to reduce costs, emissions, and PEC in commercial buildings over the standard case where electricity is purchased from the grid and heat is provided by a boiler. CHAPTER I explained these potential benefits from CHP systems and their use in the U.S. CHAPTER II reviewed previous work addressing these benefits for a CHP system alone and with thermal energy storage.

CHAPTER III investigated the necessary relationship between electricity price and fuel price for a CHP system to show potential for cost reduction. The necessary cost ratio and, from the cost ratio, the necessary spark spread were expressed in terms of system component efficiencies when all of the electricity and heat were consumed by the building. A method for calculating a simple payback period based on fuel and electricity costs and system component efficiencies was also presented. Case studies were presented for three different simulated building types in three different climate locations, where the minimum spark spread was analyzed for a CHP system operating at constant load without the assumption that all electricity and heat were useful. It was shown that when the CHP heat and electricity output is entirely used, increases in electrical or thermal efficiencies of the PGU produce linear increases in overall system efficiency. When the heat produced is not entirely used by the building, the sizing of the CHP system (its output relative to the building demand) affects the minimum spark spread and minimum cost ratio, with larger CHP sizes causes larger minimums in order for CHP to show potential for producing economic benefits.

CHAPTER IV applied the methods used in CHAPTER III to analyze reductions in CDE and PEC. An emissions spark spread and a primary energy spark spread were expressed in terms of component efficiencies. Three case studies were presented for three simulated buildings in 16 climate locations and the minimum emissions spark spread and primary energy spark spread were presented for each location. Again, increasing the thermal recovery efficiency of the CHP system reduced the minimum difference necessary for CHP to show emissions and energy benefits.

CHAPTER V further investigated the potential for CHP system to reduce emissions, including carbon dioxide, nitrous oxides, and methane. In order to study variations among building types, nine models of commercial buildings were simulated in one location where CHP could potentially reduce emissions. The ideal ratio for heat produced by the CHP system to heat demanded by the building was presented for emissions reduction. When the actual ratio approaches this ideal, the CHP system has less excess heat production, and therefore makes better use of the fuel energy and has the lowest possible emissions.

Because the percentage of unused heat was proven by Chapters CHAPTER III through CHAPTER V to be a critical predictor of the potential for CHP to produce economic, emissions, and energy benefits, CHAPTER VI considered the option of adding thermal energy storage to a CHP system. TES allows for excess thermal energy to be stored and retrieved at a later time. The potential for CHP-TES systems to show benefits beyond those of a CHP system was investigated, first for different locations and differently sized CHP systems, then for different building types and differently sized TES systems. The TES system was considered to be able to store thermal energy for an unspecified time without losses. Adding TES for a building with varying thermal demand could often reduce the need for a supplemental boiler, but could rarely eliminate the need for one. The assumption of an ideal TES device without thermal losses was investigated in one case study using a water tank. It was found that thermal losses are not significant when thermal energy is stored for a number of hours, but the assumption is invalid for a number of weeks. Over a period of several days to one week, further analysis will be required.

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